Five-Year Plan 2010–2015

Building a Vision for the Future

TRIUMF

TRIUMF

Five-Year Plan 2010–2015

Building a Vision for the Future

Editors-in-chief: Melva McLean, T.I. Meyer
Assistant Editors: Byron Jennings, Rob McPherson,
Chris Oram, Shirley Reeve
Graphics and Figures: Mindy Hapke
Proof-reader: Lorraine King
Co-op Students: Nicole Dublanko, Sandra Fleming

TRIUMF's activities are supported through a combination of public funds, revenues generated from commercial activities, and small contributions received through scholarships, awards, and personal donations. We gratefully wish to acknowledge the following sources of support (in alphabetical order): Canada Foundation for Innovation, Canadian Institutes of Health Research, Province of British Columbia, National Research Council Canada, and Natural Sciences and Engineering Research Council.

For additional copies of this report or for more information, please contact: Strategic Planning and Communications Office, TRIUMF
4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada.

Telephone: (604) 222-1047
E-mail: communications@triumf.ca
Website: www.triumf.ca

It is designed and laid out by Rayola Graphic Design and printed by Printorium Bookworks, both of Victoria, BC Canada.

Printed on Productolith Gloss Text, 80lb., which contains
10% post-consumer recycled fibre and is FSC-certified.
Cover printed on Carolina 10pt. C1S.

Table of Contents

Chapter 1

Overview

Mission Statement

TRIUMF is Canada's national laboratory for particle and nuclear physics. It is owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada with building capital funds provided by the Government of British Columbia. Its mission is:

- To make discoveries that address the most compelling questions in particle physics, nuclear physics, nuclear medicine, and materials science;
- To act as Canada's steward for the advancement of particle accelerators and detection technologies; and
- To transfer knowledge, train highly skilled personnel, and commercialize research for the economic, social, environmental, and health benefit of all Canadians.

TRIUMF was founded in 1968 by Simon Fraser University, the University of British Columbia (UBC), and the University of Victoria to meet research needs that no single university could provide. The University of Alberta joined the TRIUMF consortium almost immediately. There are currently seven full members and six associate members from across Canada in the consortium that governs TRIUMF.

Since its inception as a local university facility, TRIUMF has evolved into a national laboratory while still maintaining strong ties to the research programs of the Canadian universities. The science program has expanded from nuclear physics to include particle physics, molecular and materials science, and nuclear medicine. TRIUMF provides research infrastructure and tools that are too large and complex for a single university to build, operate, or maintain.

Since its opening in 1969, the laboratory has received more than $1 billion of federal investment and $40 million from the Province of British Columbia. The provincial contributions fund the buildings, which are owned by UBC and located on an 11-acre site in the south campus of UBC.

There are over 350 scientists, engineers, and staff performing research on the TRIUMF site. It attracts over 500 national and international researchers every year and provides advanced research facilities and opportunities to 150 students and post-doctoral fellows each year. In addition to the onsite program, TRIUMF serves as a key broker for Canada in global research in particle, nuclear, and accelerator physics.

Members

University of Alberta
University of British Columbia
Carleton University
Université de Montréal
Simon Fraser University
University of Toronto
University of Victoria

Associate Members

University of Guelph
University of Manitoba
McMaster University
Queen's University
University of Regina
Saint Mary's University

www.triumf.ca

Preface

I started as TRIUMF director in May 2007. I came from the University of Pennsylvania where I had established a research group in particle physics that reached into neighbouring topics such as accelerator science and technology and medical physics. What attracted me to Canada, and to TRIUMF, was the distinct impression that the laboratory was at a tipping point. “The stars and planets were aligned,” as they say, so that opportunities, capabilities, resources, and key partners were all coming together. This transformational moment is a product of careful planning and hard work by past directors and the user community and more importantly, the alignment of nation-wide, even global, forces for progress. If there is a theme that pervades the following pages, it is simply this: TRIUMF is poised for a transformation—of itself and of its value and impact for Canada as a whole. We should seize this opportunity.

My sense of the tremendous opportunity facing TRIUMF has only grown as I have gotten to know the laboratory, the broader community, and its broad spectrum of patrons and supporters. TRIUMF is not just a laboratory, or just a joint venture by a consortium of universities, or just a leading element of national research enterprise: it is a value statement by Canada about the long-term importance of strategic investments in science, technology, and innovation. TRIUMF’s accomplishments in basic research (particle and nuclear physics, molecular and materials science, nuclear medicine, and information technology), international partnerships, and commercial successes with Canadian companies are the proof behind this statement. And since an opportunity like the present moment has been long in the making, the timing is perfect to move aggressively forward. As Canada considers its place in an increasingly globalized world, TRIUMF can help with innovations in medical isotopes, the next-generation of computer networking and processing, commercializing world-leading technologies, and by attracting the world’s best and brightest to live and work in Canada.

In articulating a vision for the future of TRIUMF and in preparing this Five-Year Plan, an enormous number of individuals have contributed a great deal of time and effort. It would be impossible to acknowledge them all, and so I will simply extend my appreciation here: thank you to everyone.

Finally, I would like to comment on the organization of this report. It is layered so that audiences of different backgrounds and interests may quickly navigate to a section that offers what they need. The report has also been published into two formats to reduce paper consumption: one includes the full 850-page manuscript, the second only includes the Executive Summary, Vision, and Partnerships chapters with the full report available on a compact disc in the rear pocket of the publication. It is our hope that after reading this proposal for the future of TRIUMF, you are excited by our plans. If so, please drop me an email at director@triumf.ca.

Sincerely,

Nigel S. Lockyer
Director of TRIUMF

1

Executive Summary

The world economy is increasingly based on knowledge as a driver of productivity. For the foreseeable future, scientific discoveries and technological innovation will be the most powerful engine for economic growth. Excellence in these areas derives from substantial investments in state-of-art technical infrastructure and from the talents of highly skilled, highly educated individuals. However, success and leadership in a knowledge economy requires much more. The knowledge must be relevant and timely. TRIUMF, Canada's national laboratory for particle and nuclear physics, is poised to help Canada be a leader in the science-and-technology knowledge economy.

TRIUMF's vision for the next decade brings together university, industrial, and international partners in three priority areas with the promise of true competitive advantage. The vision includes providing leadership in the transforming field of nuclear medicine, building a new superconducting accelerator for generating not-yet-discovered heavy isotopes at Canada's world-class isotope beam facility, and participating fully in the international Large Hadron Collider (LHC) project at CERN. All three areas have potential for significant scientific, economic, and societal impact.

TRIUMF has been involved with Canada's innovations in nuclear medicine and at the forefront of this field for decades: from one of the first PET scanners in the country to study of the underlying biological mechanisms of Parkinson's disease to a 30-year partnership with MDS Nordion for the production and distribution of 15% of Canada's medical isotopes. Nuclear medicine is undergoing a revolution and has great potential for dramatically improving health care for all Canadians. TRIUMF's work to design "tracer" molecules or drugs and label them with radioactive medical isotopes allows researchers to image their location in the body with high precision. This breakthrough capability is penetrating into every area of disease screening. It will soon be possible to image—and pinpoint—disease metabolism or cancerous tumour construction using positron-emission tomography (PET) imaging. Monitoring tumour metabolism during cancer therapy, or even just monitoring where a drug goes in the body, will transform medicine and treatment models. Canadians will be able to access this high level of screening through positron-emission tomography (PET) scans and a ready supply of medical isotopes connected to various types of "designer" molecules. As radiotracer-labelled designer molecules and drugs become more specific and target metabolic activity in the body more precisely, the demand for these life-saving technologies will soar. The day will come soon when every hospital in Canada will insist upon the ability to deliver a single-patient dose of a specific radiotracer quickly and easily.

At TRIUMF, the skills, capabilities, and technology exist to design, develop, and market an "espresso-maker" style unit that would use a cyclotron to produce the specific medical isotope, combine it with the tracer molecules using micro-fluidic "chemistry on a chip," and then deliver a single dose at the push of a button. Such a small, user-friendly unit would be in instant demand all around the world. TRIUMF is the only institution able to catalyze a national effort to develop this technology. TRIUMF has deep expertise in cyclotrons, medical-isotope production, and radiochemistry; it has established partnerships with clinical researchers in neurology, oncology, and cardiology as well as agreements with commercial partners such as MDS Nordion and Advanced Applied Physics Solutions, Inc. (AAPS). TRIUMF brings together science and technology for national and international impact.

TRIUMF is home to a world-class rare-isotope beam facility, ISAC. It is arguably one of the premier centres in the world, and for specific species of beams, the best. This branch of nuclear physics has the potential to reach the scientific holy grail of a single unified theory of nuclear physics. The proposed expansion of TRIUMF's isotope-beam facilities has the potential for a triple impact: doubling the productivity of the existing infrastructure and equipment, enabling a scientific home run in the field of fundamental physics for Canada, and studying the next generation of medical isotopes. The European Union, collectively France, Germany, Japan, and the US individually, are all seeking new major accelerator projects in this area; worldwide investment exceeds $4 billion. TRIUMF has a lead position in this pack and with the right investment, could become the top institution in this field for a decade and beyond.

The LHC project is expected to begin taking data in 2008-2009 and could fundamentally change the way we think about our world. It may discover properties of space and time that only science fiction could have imagined. TRIUMF brokered the international partnership that has put Canadian scientists as integral collaborators in the LHC project. The Canadian contributions to the accelerator, detector, and data centre are recognized throughout the international particle physics community as a measure of Canadian excellence. The LHC Tier-1 Data Centre at TRIUMF provides Canada access to the technology of global grid-computing in a leadership role. The accelerator, detector, and computing systems are all working, commissioned and ready for data while Canadian graduate students are preparing for discovery.

TRIUMF has a superb international reputation not just as a subatomic physics laboratory but also as a laboratory that partners successfully with industry. Transferring technology to Canadian business is a major goal of the 2010–2015 Five-Year Plan. TRIUMF is known internationally for its work with MDS Nordion, a global health and life-science company, with which it received the NSERC 2004 Synergy Award. Another TRIUMF-inspired company, D-Pace, was awarded the 2007 Synergy Award. In 2008, TRIUMF received a National Centres of Excellence award to create a commercialization partner, AAPS, Inc. TRIUMF recently partnered with PAVAC Industries, Inc., a small Canadian electron-beam welding company, to transfer high technology. In early 2008, the team announced the first "Made in Canada" superconducting radio-frequency cavity—only five other companies in the world have this capability in what will become a globally competitive market.

This plan takes full advantage of discovery potential, impact on society, state-of-the-art technical infrastructure, a highly talented pool of scientists, engineers, technicians, entrepreneurs, and graduate and undergraduate students.

This plan aligns with the Government of Canada's new science and technology strategy by building on excellence and strengthening Canada's research and economic connections to the world—and the world back to Canada. TRIUMF has contributed to Canada's global leadership in the physical sciences and the plan supports the next generation of that success.

This plan is bold: it calls for an investment of $328 million from the Government of Canada over 2010–2015.

This plan declares that Canada can be a lead nation in the science-and-technology knowledge economy of the 21st century.

Enoncé de mission

TRIUMF est le laboratoire canadien pour la physique nucléaire et la physique des particules. TRIUMF est géré par un consortium d'universités canadiennes à partir d'une contribution administrée par le Conseil National de Recherches Canada. Les bâtiments qui abritent le laboratoire sont financés par le gouvernement de la Colombie Britannique.

Sa mission est de :

- générer des avancées scientifiques qui répondent aux questions les plus importantes en physique des particules, en physique nucléaire, en médecine nucléaire et en physique des matériaux.
- maintenir et développer le savoir-faire canadien en matière d'accélérateurs de particules et des technologies de détecteurs.
- transférer les connaissances, former du personnel de haute compétence et commercialiser la recherche du laboratoire pour générer des retombées économiques, sociales et environnementales au profit de tous les Canadiens.

TRIUMF a été établi en 1968 par l'université Simon Fraser, l'université de la Colombie Britannique (UBC) et l'université de Victoria pour supporter des installations de recherches que chacune individuellement ne pouvait se permettre. L'université d'Alberta s'est très vite jointe au consortium. Aujourd'hui il y a sept partenaires principaux et six partenaires associés de toutes les régions du Canada qui gèrent le projet en co-tutelle.

Depuis sa fondation comme institut régional, TRIUMF a évolué en un laboratoire national qui maintient des liens privilégiés avec les universités participant à ses programmes de recherche. Le programme scientifique, initialement centré sur la physique nucléaire s'est étendu à la physique des particules, aux sciences des matériaux et des molécules et à la médecine nucléaire. TRIUMF possède des installations et des outils de recherche qui sont trop importants et complexes pour être construits, opérés et entretenus par une seule université.

Depuis son ouverture en 1969, le laboratoire a reçu plus d' $1 milliard en investissement du gouvernement fédéral et plus de $40 millions de la province de Colombie-Britannique. La contribution provinciale finance les bâtiments qui sont la propriété de UBC et sont localisés sur un site de 4.4 hectares sur son campus sud.

Il y a plus de 350 scientifiques, ingénieurs et employés supportant les recherches faites sur le site de TRIUMF. Plus de 500 visiteurs du Canada et du monde entier visitent le laboratoire chaque année pour exploiter l'équipement de pointe mis à leur disposition et environ 150 étudiants et boursiers postdoctoraux bénéficient de cet environnement de choix. De plus TRIUMF agit comme maître d'œuvre dans les grandes collaborations internationales en physique des particules, physique nucléaire et technologies des accélérateurs.

Members

University of Alberta
University of British Columbia
Carleton University
Université de Montréal
Simon Fraser University
University of Toronto
University of Victoria

Associate Members

University of Guelph
University of Manitoba
McMaster University
Queen's University
University of Regina
Saint Mary's University

www.triumf.ca

Avant-propos

En mai 2007, je commençais mon terme comme directeur de TRIUMF. J'arrivais de l'université de Pennsylvanie ou j'avais établi un groupe de recherche en physique des particules qui touchait aussi aux domaines connexes des sciences et technologies des accélérateurs et en physique médicale. Ce qui m'a attiré au Canada et à TRIUMF, c'était la réalisation que ce laboratoire était mûr pour une nouvelle phase très prometteuse. « Les étoiles et les planètes semblaient être parfaitement alignées » comme on dit, de sorte que occasions, possibilités, ressources et partenaires-clés étaient tous à portée de main. Cette conjecture est le produit d'une planification minutieuse de la part des directeurs qui m'ont précédé et de la communauté que dessert le laboratoire; plus important encore, il y avait aussi une résonance avec les ambitions nationales et même internationales. Si il y a un thème qui lie les pages qui suivent, c'est simplement ceci : TRIUMF est à la croisée de chemins qui pourraient le conduire à une transformation de sa valeur intrinsèque et de son influence sur le Canada tout entier. Nous devons saisir cette occasion.

Mon intuition n'a fait que de se confirmer alors que j'apprends à mieux connaître ce laboratoire, la communauté qu'il dessert et le cadre général de ses organismes de tutelle et de ses supporters. TRIUMF n'est pas seulement un laboratoire, un projet commun par un partenariat d'universités, ou simplement un des éléments phares de l'effort national en recherche: c'est l'évidence même de la valeur pour le Canada des investissements stratégiques en science, technologie et innovation. Les réussites de TRIUMF en recherches fondamentales (en physique des particules, en physique nucléaire, en science moléculaire et science des matériaux, en médecine nucléaire et techniques de l'information), les partenariats internationaux, et les succès commerciaux avec des compagnies canadiennes sont la preuve même de cette évidence. Et puisque cette conjoncture est le fruit d'efforts soutenus par le passé, le moment est venu de saisir cette occasion unique. Alors que le Canada se positionne dans un monde de plus en plus globalisé, TRIUMF peut l'y aider grâce à des découvertes sur les isotopes médicaux, sur les nouvelles méthodologies de réseautage et de calcul sur grille, en commercialisant des techniques de pointe et en attirant les meilleurs talents mondiaux pour s'installer et travailler au Canada.

Pour définir cette vision du futur de TRIUMF et pour préparer ce plan quinquennal, un grand nombre de personne ont contribué, sans compter, temps et effort ; il serait impossible de les citer individuellement, alors je leur dit simplement : merci à vous tous.

Enfin, je voudrais faire quelques commentaires sur l'organisation de ce rapport. Il est structuré en sections pour que toute audience, quelque soit son intérêt, puisse y trouver rapidement celle qui lui convient. Ce plan est publié en deux versions pour réduire la consommation de papier: L'une d'elles comporte la version intégrale de 850 pages, la seconde comprend seulement le sommaire, l'énoncé de mission et le chapitre sur les partenariats tandis que la version intégrale est disponible sur un disque compacte inséré dans la pochette de distribution. Nous espérons qu'après lecture de cette proposition, vous serez aussi enthousiaste que nous pour ce plan. Si tel est le cas, laissez nous le savoir en communiquant avec moi à l'adresse électronique suivante : director@triumf.ca.

Amicalement,

Nigel S. Lockyer
Directeur de TRIUMF

1

Sommaire

L'économie mondiale est de plus en plus basée sur l'exploitation des connaissances comme moteur de productivité et d'innovation. Dans le futur, les découvertes scientifiques et les avancées technologiques formeront le plus puissant générateur de croissance économique. La compétence dans ces domaines est actuellement basée sur des investissements de pointe en infrastructure technique et sur une main d'œuvre hautement éduquée. Cependant pour réussir dans ce nouvel ordre économique il faudra beaucoup plus. Les connaissances doivent être non seulement appropriées mais aussi acquises au bon moment. Le laboratoire national pour la physique nucléaire et la physique des particules, TRIUMF, est prêt à relever ce défi pour aider le Canada à trouver sa place dans ce nouvel ordre économique.

En amenant les trois secteurs - universitaire, industriel et international- à collaborer étroitement sur une vision à long terme, TRIUMF promet de générer un avantage compétitif de premier ordre dans trois domaines de compétence prioritaires pour le Canada. Le projet quinquennal propose de participer en tant que leader à la révolution qui se dessine en médicine nucléaire, de construire un nouvel accélérateur supraconducteur qui permettra de produire de nouveaux isotopes lourds pour l'installation ISAC, qui a acquis une renommée mondiale pour ce qui est des faisceaux accélérés d'isotopes, et de jouer un rôle de partenaire à part entière dans le projet mondial du Grand collisionneur de hadrons (LHC) au CERN. Ces trois activités ont le potentiel de générer des retombées scientifiques, économiques et sociétales de grande importance.

Par ses collaborations passées et présentes en médicine nucléaire, TRIUMF a été à la fine pointe de ce domaine : ainsi TRIUMF a établi la première caméra à Emission de Positrons (TEP) dans le pays pour l'étude des phénomènes biologiques reliés à la maladie de Parkinson et pendant les dernières trente années, TRIUMF a développé un partenariat avec MDS –Nordion pour la production commerciale d'isotopes médicaux. Actuellement 15% des isotopes utilisés au Canada proviennent du site de TRIUMF. Une révolution se dessine en médecine nucléaire qui promet de grandement améliorer les soins pour tous les Canadiens. Le développement à TRIUMF de sondes moléculaires qui peuvent être marquées par des isotopes radioactifs détectables par la Tomographie à Emission de Positrons (TEP) permettra de les localiser de façon très précise dans le corps humain. Cette avancée technologique affectera tous les secteurs du diagnostique médical. Il sera ainsi possible de suivre le métabolisme des maladies ou de comprendre la construction des cellules cancéreuses grâce à la TEP. En étant capable de suivre en temps réel la réponse des tumeurs aux traitements thérapeutiques, ou en déterminant précisément où se localise un médicament dans le corps humain, on affectera directement le traitement possible des malades et on élaborera des stratégies beaucoup plus efficaces contre les maladies. Chaque canadien pourra avoir accès à ces diagnostiques basés sur la TEP et aux nouveaux isotopes attachés à des molécules spécifiques à leur cancer. On peut déjà anticiper que ce type de diagnostique et de médicaments personnalisés sera alors la norme en médicine nucléaire et sera exigé de tout centre hospitalier au Canada et de par le monde.

TRIUMF possède les compétences humaines, la capacité technique et les technologies qui pourront développer des unités qui produiront, grâce à un cyclotron miniaturisé, une dose spécifique d'un isotope de choix, de l'attacher à une molécule personnalisée grâce à des techniques chimiques faisant appel à des micro-fluides, et de délivrer dose par dose un médicament personnalisée. Une telle machine « espresso » sera aisément commercialisable sur le marché mondial.

TRIUMF est la seule institution nationale qui réunit tous les éléments pour produire une telle unité. TRIUMF a une expérience unique au monde en cyclotrons, en production d'isotopes médicaux , en radiochimie moléculaire. TRIUMF a établi des partenariats de recherche en neurologie, oncologie et cardiologie.TRIUMF a monté des partenariats commerciaux avec MDS-Nordion et le Centre d'Excellence ETPP (Exploitation des Techniques de Pointe en Physique). TRIUMF combine ainsi science et technologie pour maximiser son efficacité au niveau national et international.

TRIUMF a développé au cours des dix dernières années une installation de classe internationale pour la production de faisceaux isotopiques très rares (ISAC) qui est actuellement la meilleure au monde pour certains faisceaux très recherchés. Dans ce domaine TRIUMF peut donc contribuer de façon unique à la recherche d'un modèle ultime de la physique nucléaire et est devenu un lieu de prédilection pour les chercheurs. Dans le plan proposé, l'efficacité du laboratoire sera triplée pour pouvoir livrer simultanément plusieurs faisceaux à ses nombreux usagers, utilisant de façon plus pertinente les installations qui ont été construites avec l'aide des organismes de financement de la recherche comme le CRSNG, la FCI et leurs partenaires internationaux.

L'Union Européenne, l'Allemagne, la France, les États-Unis et le Japon investissent dans de nouvelles installations en construisant leurs propres accélérateurs d'isotopes. La somme des investissements engagés dans ce domaine dépasse les $4 Milliards de dollars. TRIUMF est actuellement en tête de ce peloton et entend y demeurer en proposant des améliorations à son système ISAC.

Le LHC devrait commencer à prendre des données cette année et devrait changer de façon fondamentale notre vision de l'univers. On pourrait mettre en évidence de nouvelles propriétés de l'espace-temps inattendues. TRIUMF a été le maître d'œuvre de la participation canadienne à cet effort mondial. Les contributions canadiennes à la chaîne des accélérateurs du CERN, au détecteur ATLAS et au centre de calcul Tier-1 sont citées en exemple du savoir-faire canadien. Le centre LHC Tier-1, financé par la FCI et le gouvernement de la Colombie Britannique, utilise les techniques de calcul sur grille qui ont été développées spécifiquement pour ces genres d'applications à l'échelle planétaire.

Les contributions canadiennes à l'accélérateur, au détecteur et au centre de calcul Tier-1 fonctionnent toutes déjà et de nombreux étudiants sont anxieux d'y faire de nouvelles découvertes.

TRIUMF a acquis une renommée internationale non seulement en recherches fondamentales mais aussi par son approche pour créer des partenariats avec les industries canadiennes. Le transfert à l'industrie canadienne des technologies de pointe émergeant de TRIUMF est un des buts principaux du prochain plan quinquennal du laboratoire. TRIUMF est déjà perçu internationalement comme un leader dans ce domaine grâce à son travail avec MDS-Nordion, une compagnie qui fait affaire dans le domaine de la santé et des sciences de la vie. Ce partenariat a reçu le prix Synergie 2004 du CRSNG.

Une autre compagnie, D-PACE, fondée par un étudiant de TRIUMF a reçu le prix synergie 2007 du CRSNG. En 2008, TRIUMF a reçu un octroi du réseau des centres d'excellence canadiens pour créer une agence de commercialisation ETPP Inc. Plus récemment, TRIUMF s'est associé à une petite compagnie de Richmond (C.B.), PAVAC, spécialisée dans la soudure par faisceaux d'électron, pour lui transférer une technologie de pointe. Au début de 2008, l'équipe a annoncé une première au Canada : la production d'une cavité radio–fréquence supraconductrice au niobium. Seules cinq compagnies au monde sont capables de tels exploits et seront capables de servir un marché important à l'échelle mondiale.

Le plan quinquennal de TRIUMF optimise le riche potentiel de découvertes scientifiques, d'impact sur la société canadienne, de capacité d'une infrastructure technique de première classe, d'un personnel talentueux incluant scientifiques, ingénieurs, techniciens, entrepreneurs, et du groupe toujours très apprécié des étudiants des premier et deuxième cycles universitaires.

Ce plan s'aligne naturellement sur les priorités du gouvernement canadien exprimées dans le document sur sa stratégie en science et technologie en capitalisant sur l'excellence du laboratoire et en renforçant les liens réciproques entre les communautés scientifiques et économiques du Canada et du reste du monde. TRIUMF a été un élément clé de l'hégémonie du Canada en recherches dans les sciences dures, et aspire à le demeurer pour les générations futures.

Ce plan quinquennal est ambitieux: il demande un investissement de $328 millions du gouvernement canadien pour la période 2010–2015.

Ce plan présuppose que le Canada peut devenir une nation-phare qui saura exploiter son avantage en science et technologie pour établir une économie du savoir au 21ième siècle.

Support for TRIUMF and its Five-Year Plan

"[I consider] the 5-YP [Five-Year Plan] to be transformational in that it cleverly uses TRIUMF's core competencies a) accelerator technology, b) detector technology, c) scientific computing and large-scale data management, and d) isotope production to expand and further strengthen the Laboratory's scientific "business lines"…. [T]he plan maximizes the educational and societal benefits for Canada and provides the best possible return on the investment."

—Dr. Robert V.F. Janssens,
Director, Physics Division, Argonne National Laboratory (USA), and Chair, Advisory Committee on TRIUMF

"The BC Cancer Agency has benefited greatly from TRIUMF's unique capabilities and expertise towards successfully establishing PET/CT capabilities for the benefit of British Columbians…. The BC Cancer Agency's clinical PET/CT program currently relies on the daily supply of F-18 by TRIUMF, in order to provide the best possible diagnostic profile and optimized treatment plan for cancer patients in the province. This truly is a win-win situation for everyone, and would not have been possible without TRIUMF's assistance and existing infrastructure."

—Dr. Don Wilson,
Medical Director for the Centre of Excellence for Functional Cancer Imaging, British Columbia Cancer Agency

"We have always appreciated the high level of competence and the spirit of collaboration of the TRIUMF staff. We look forward to continuing this collaboration in future years in order to exploit the full potential of the LHC and to prepare our field for a long and fruitful future."

—Lyn Evans,
Project Leader, Large Hadron Collider,
CERN (Geneva, Switzerland)

"One of the reasons that I decided to move to BC is that my research will be greatly enhanced by the nearby presence of TRIUMF. In fact I have said I would not have come to BC if TRIUMF were not there. TRIUMF offers not only technical expertise, but also a compelling research program into the next generation of medical isotopes."

—Dr. Francois Benard,
BC Leadership Chair in Functional Cancer Imaging,
British Columbia Cancer Agency

"TRIUMF has designed and built what has been internationally recognized as the best cyclotron[s] in the world."

—Professor Mingwu Fan,
former president of the China Institute of Atomic Energy and former president of Huazhong University of Science and Technology

"At the present moment, TRIUMF is poised for a significant transformation—a transformation that would dramatically expand its impact and value for Canada."

—Professor Feridun Hamdullahpur,
Vice-President (Research and International),
Carleton University, and Chair, TRIUMF Board of Management

"The Five-Year Plan articulated in this report, which details a set of implementation strategies that realize this vision, is as ambitious as it is impressive. It is a program that holds promise to significantly increase the scientific output of the lab by capitalizing on TRIUMF's strengths."

—Professor Colin Gay,
University of British Columbia, and Chair,
TRIUMF Policy and Planning Advisory Committee

Chapter 2

The Vision: Giving Canada the Advantage, 2010–2015

Chapter 2

The Vision: Giving Canada the Advantage, 2010–2015

Introduction

In order to seed discoveries and maintain one of the highest standards of living in the world, Canada must be aggressive in investing in fundamental and translational research. This research requires state-of-the-art infrastructure and highly skilled workers who are interconnected with each other and the world's scientific and technical research network. As a national laboratory with deep roots in the academic community, TRIUMF is ideally positioned to play a lead role in this effort.

TRIUMF is one of the world's leading subatomic physics laboratories. It brings together dedicated physicists and interdisciplinary talent, sophisticated technical resources, and commercial partners in a way that has established the laboratory as a global model of success. With its large user community, composed of international teams of scientists, post-doctoral fellows, and graduate and undergraduate students, TRIUMF pursues a rich portfolio of physics, chemistry, nuclear medicine, and materials science research. The advances ensuing from this research will enhance the health and quality of life of millions of Canadians, launch new high-tech companies, create new high specificity drugs, help us to understand the environment, enable the development of new materials, and spur the imaginations of our children who want to know their place in the universe.

The TRIUMF Five-Year Plan report presents a strategy for achieving this vision. Building on TRIUMF's international reputation and partnerships with universities, industry, and the global research community, key opportunities will be exploited with potentially breakthrough results for Canada. TRIUMF is an international leader in research with rare-isotope beams, focusing on advances in nuclear physics and material sciences. The vision includes significantly expanding those capabilities including new applications in the medical use of rare isotopes, with TRIUMF developing Canadian leadership in nuclear medicine in a revolutionary era in this field. TRIUMF continues to pursue its internationally leading role in particle physics, including hosting an information technology centre connected to the world-wide network of centres being deployed to analyze the next generation of particle physics data. GRID computing technology being developed for particle physics at TRIUMF will be critical to the success of Canadian science, business, and academia.

In all areas of the TRIUMF Five-Year Plan, there is substantial potential for industrial partnerships, skill enhancement, product development, and commercial spinoffs. For example, the nuclear medicine revolution will drive the need for a new generation of small cyclotrons with connected chemistry on a chip (so called microfluidics) that would be placed in every hospital in Canada. Exploitation of Canadian accelerator expertise, coupled with advances in biomarkers connected to new medical isotopes, will be necessary to develop such a product. Seeding this effort will have tremendous return on investment for Canada and, again, TRIUMF is well positioned to lead the effort.

Above all, the Five-Year Plan is a call for action. The present moment represents a tremendous opportunity for TRIUMF—and Canada—to make a global impact. This opportunity arises from key investments made in the past by the Government of Canada and the Province of British Columbia. This opportunity should not be lost.

2.1

The Way Forward

TRIUMF's operations are supported through a contribution via the National Research Council (NRC) Canada in five-year funding increments. The present performance period completes March 31, 2010. This report reviews recent accomplishments, proposes a plan for 2010–2015, and summarizes the resource needs. In the context of the laboratory's mission, TRIUMF's five-year planning process has identified targeted opportunities that are ripe for exploitation: they build on TRIUMF's successes, play to Canadian strengths, and promise high-impact results.

The goals of the TRIUMF Five-Year Plan are:

- Substantially expand TRIUMF's rare-isotope beam program;
- Lead the coming revolution in nuclear medicine;
- Expand Canadian access to international science;
- Pursue advanced accelerator technologies;
- Exploit targeted opportunities for commercialization with partners such as Advanced Applied Physics Solutions, Inc.; and
- Train the next generation of leaders in Canadian science, technology, and innovation.

To achieve these goals, the plan proposes a set of interconnected facilities and capital initiatives (see Figure 1). The plan includes an electron linear accelerator (e-linac) with a new target station; the initial stage would be completed by 2013. This facility will launch a new thrust in the rare-isotope program,

Timeline of TRIUMF

Early Cyclotron Era

BC Nuclear Physicists agree on Meson Factory

1965

UBC, Victoria, and SFU establish TRIUMF
AECB awards $100k
Alberta joins joint venture

1966

approximately doubling the beam time available to Canadian researchers. The accelerator developments will cement TRIUMF's and Canada's role as leaders in the international accelerator network. A new specialized actinide beam line, also exploiting the new target station, would be constructed and operational by 2015. The electron linear accelerator and new proton beam line, together with the new target station, are tightly linked and use overlapping space and common infrastructure.

In life sciences, the plan calls for an initiative in nuclear medicine supported by new facilities, strategic hires, and enhanced partnerships. In addition to

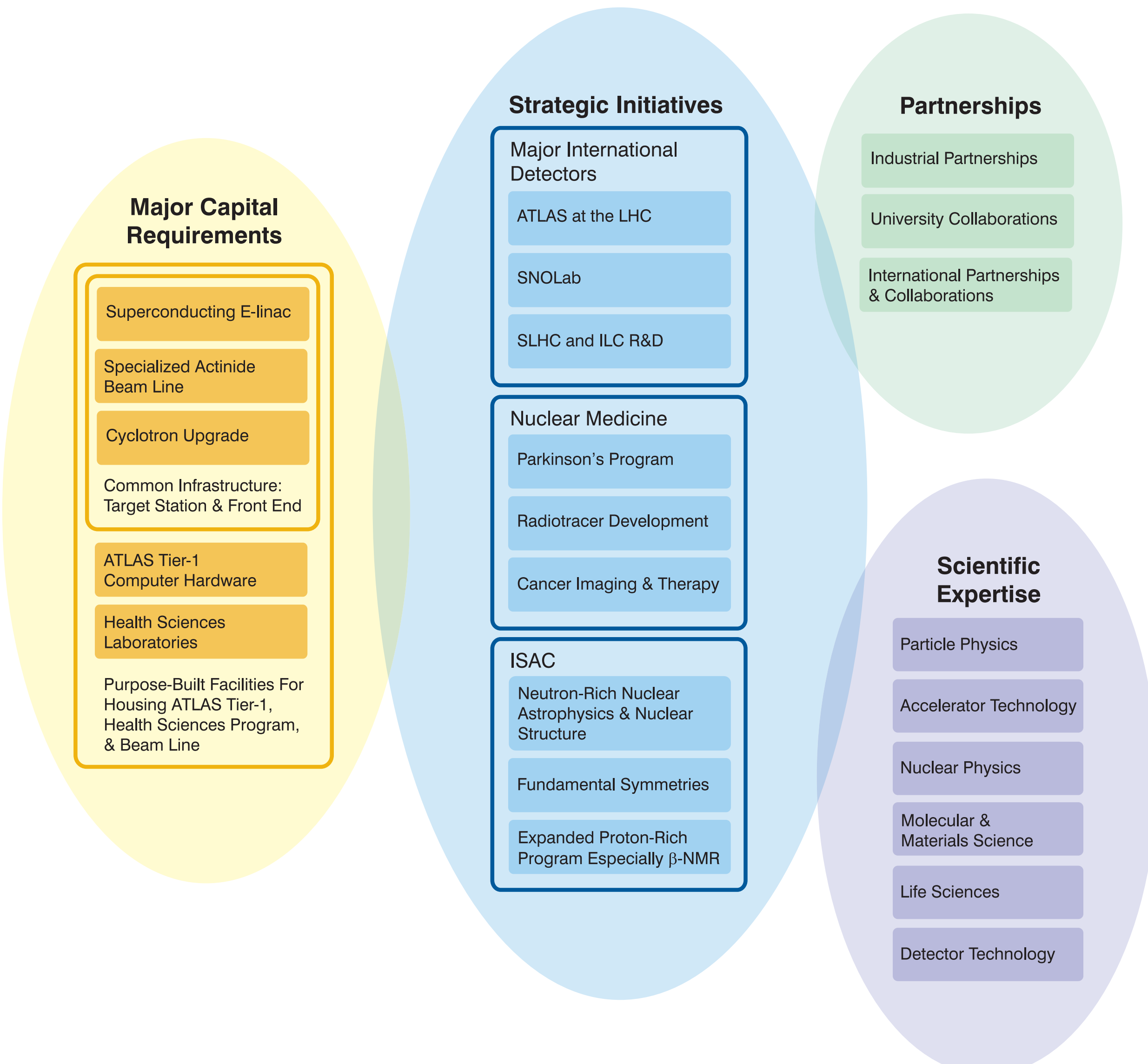


Figure 1: The TRIUMF Five-Year Plan in schematic form. The proposed strategic initiatives will draw on TRIUMF's established partners and scientific expertise and will be supported by new capital investments.

exploiting the new accelerators for research with novel medical isotopes, TRIUMF proposes to lead a national effort with the University of British Columbia to advance the development of new radiotracers for medical imaging.

The plan calls for full support of the expanded ATLAS Tier-1 Data Centre, including strong intellectual contributions to the emerging field of GRID computing. Coupled with the Centre, TRIUMF will establish an ATLAS national analysis centre. In addition, TRIUMF will perform accelerator development in support of future particle physics initiatives. Finally, the plan calls for TRIUMF to support university and SNOLAB collaborations through detector development and other infrastructure support.

The total funds sought to fulfill this vision are $328 million over five years. Cognizant of the necessary constraints that must be considered in the public policy arena, the report also includes an analysis of several different implementation strategies that explore various tradeoffs and reduced-scope programs.

The Five-Year Plan has been carefully evaluated and reviewed by a series of committees including the TRIUMF Policy and Planning Advisory Committee, the TRIUMF Users' Group, and international committees of technical experts. The strengths and weaknesses of the proposed projects, international interest, competitiveness, and the potential for commercial and industrial benefits were all evaluated. The ability of TRIUMF to efficiently manage the program was also a crucial part of building the proposed program.

2.2

Alignment with Canada's Science and Technology Strategy

TRIUMF's proposed program is well aligned with Canada's priorities outlined in *Mobilizing Science and Technology to Canada's Advantage*, released in 2007. This report outlines the advantages to Canada of a strong science and technology enterprise. It is organized around four principles: promoting world-class excellence, focusing on priorities, encouraging partnerships, and enhancing accountability; and three competitive advantages: the knowledge advantage, the people advantage, and the entrepreneurial advantage. In this section, the TRIUMF plan is discussed in terms of this framework, focusing first on the four core principles and then on the three competitive advantages.

Principle: Promoting World-Class Excellence

TRIUMF's research programs are internationally recognized for excellence and innovation. TRIUMF's impact on Canada's status as a gateway to interna-

PEOPLE

THE UNIVERSITY OF GUELPH

Nuclear Structure Group

The University of Guelph joined the TRIUMF consortium as an associate member in 2003. TRIUMF has helped the Group develop a strong research program in nuclear structure and, in return, the Group has increased TRIUMF's presence in central Canada.

The Group performs research in nuclear structure, precision tests of the standard model, and nuclear astrophysics in TRIUMF's ISAC-I and ISAC-II facilities. Since the appointments of Dr. Carl Svensson in 2001 and Dr. Paul Garrett in 2004, the Group has grown to seven full-time graduate students, two post-doctoral fellows, and several undergraduate students. The Group is very active in the TIGRESS and 8π collaborations, with Dr. Svensson as Principal Investigator for both. Dr. Garrett is also the Principle Investigator for the DESCANT project.

The superallowed Fermi β-decay program using the 8π spectrometer and fast-tape-transport system located at GPS1 has been a prime focus of the Group's research. To date, this research has been the subject of four M.Sc. and one Ph.D. theses, with another Ph.D. pending. The nuclear structure program, using both the 8π and TIGRESS spectrometers, has been the subject of one M.Sc., with two M.Sc. theses and one Ph.D. in progress. The Rn EDM and DESCANT design work is the basis of research for another two M.Sc. students. ■

tional science and technology programs is significant. The laboratory attracts world-class researchers to Canada while simultaneously recruiting and training Canadians in internationally leading fields. For example, TRIUMF attracts hundreds of top international researchers to Canada to use the laboratory's world-leading ISAC rare-isotope beams, while also enabling Canadian scientists to play leading roles in breakthrough projects abroad such as the ATLAS project at the Large Hadron Collider (LHC), the largest scientific undertaking in history, or the new Japan Proton Accelerator Research Complex (J-PARC) neutrino project in Japan. TRIUMF also supports Canadian researchers who are designing and building state-of-the-art experiments for SNOLAB.

Principle: Focusing on Priorities

TRIUMF's expertise and capabilities have led to a high demand from the Canadian and international community for support of many diverse projects. TRIUMF has established a robust review process for picking key projects that will have the most significant national and international impact. Part of the process is working with the university community to develop the NSERC Subatomic Physics Long-Range Planning Committee report and then using the resulting plan in setting TRIUMF's own priorities.

> "The most important things happening in the world today won't make tomorrow's front page.… They'll be happening in laboratories—out of sight, inscrutable and unhyped until the very moment when they change life as we know it. Science and technology form a two-headed, unstoppable change agent."
>
> **— Joel Achenbach, *Washington Post* staff writer**

Principle: Encouraging Partnerships

TRIUMF has a strong history of partnerships with universities, international research organizations, and industry. Indeed, a consortium of universities formed the lab. Four recent members of the consortium are highlighted in boxes in this section. University partnerships include the ATLAS Tier-1 Data Centre funded by the Canada Foundation for Innovation via Simon Fraser University. The Centre has a world-leading GRID computing technology capacity, and by 2011 will house Canada's largest academic computer, with a storage capacity of up to 15 petabytes (15 million gigabytes). TRIUMF also has strong partnerships with Canadian industry that are discussed in a later subsection. In the current Five-Year Plan, new initiatives with AAPS, Inc. and PAVAC Industries, Inc. will significantly increase TRIUMF's commercial partnerships.

Principle: Enhancing Accountability

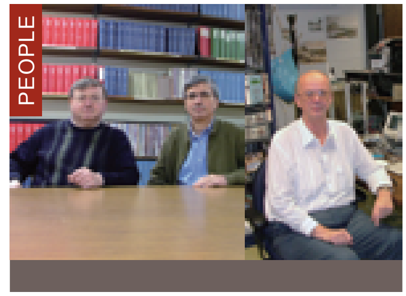
TRIUMF has a 40-year history of using public funds responsibly, the result of a strong review system, and a well-established accounting system. The laboratory's progress and accomplishments are carefully monitored by three oversight committees: the Advisory Committee on TRIUMF; the multi-Agency Committee on TRIUMF, which is chaired by the President of the National Research Council, and on which both the President of NSERC and the Deputy Minister of Industry Canada sit; and, the TRIUMF Board of Management, which represents the university joint venture. TRIUMF's success in meeting the goals of the last Five-Year Plan contribution agreement is shown in Section 2.4.

Advantage: Global Excellence in Research

TRIUMF will contribute to Canada's global excellence in research in the following ways:

- Excel globally in research areas of national priority;
- Provide leadership and intellectual contributions for the development of innovative techniques and technologies;
- Engage in the continued development of GRID computing technology;
- Increase scientific publications, citations, and involvement in international conferences; and
- Increase investment in key areas ripe for discovery.

TRIUMF is one of the leading laboratories in the world for studying rare isotopes, and in some instances is the best. Scientists at TRIUMF are able to study the conditions of supernovae explosions—the deaths of super massive stars—in the laboratory. Using rare-isotope beams, researchers can explore the origin of the chemical elements heavier than iron such as copper, silver, and gold. Investment worldwide in this rare-isotope research will exceed C$4 billion in the next decade. These discoveries will feed into the knowledge base for next-generation nuclear reactors, will help us understand the behaviour of advanced materials under extreme conditions, and will train people for the nuclear industry. By connecting subatomic physics with research in other areas, TRIUMF will continue to develop and contribute to research in materials and to a world-renowned life sciences program that utilizes medical isotopes combined with positron emission tomography (PET) detectors. TRIUMF's experimental facilities and the core scientific programs of particle and nuclear physics are finding new and crucial applications in the studies of molecular and materials science, as well as nuclear medicine. With over a thousand users, from international teams of scientists to post-doctoral fellows and graduate and undergraduate students, TRIUMF brings together human talent and sophisticated technical resources (see Figure 2).



L'UNIVERSITÉ DE MONTRÉAL
Particle Physics Group

The collaboration between the Particle Physics Group of l'Université de Montréal and TRIUMF began in the 1970s with experiments on rare pion and muon decays. In 2007 l'Université de Montréal became a full member of the TRIUMF Joint Venture. This change reflects broad recognition and integration of the particle physics research programs at TRIUMF and Montréal and joint work on the ATLAS experiment in particular.

The Group also collaborates with TRIUMF on detector research and development through the Laboratory of Advanced Detectors Development (LADD) program, which is supported by the Canada Foundation for Innovation. One LADD antenna is based in Montréal and another at TRIUMF.

The Group's researchers use TRIUMF infrastructure for access to the ATLAS Tier-1 Data Centre. The Group and TRIUMF also collaborate on TIGRESS, TACTIC, ALPHA, and PIENU, as well as life sciences projects. In the future, the collaboration will broaden to include research in biophysics, imaging, nuclear medicine, the International Linear Collider, and SNOLAB experiments.

TRIUMF's resources benefit all senior researchers, as well as graduate students and post-doctoral fellows. Recent TRIUMF hires who did their graduate work at l'Université de Montréal are Dr. Isabel Trigger and Dr. Reda Tafirout. ■

PEOPLE

SAINT MARY'S UNIVERSITY

Subatomic Physics Group

Saint Mary's University became an associate member of TRIUMF in 2004. The affiliation with TRIUMF has enhanced Saint Mary's University activity in subatomic physics. Two subatomic physicists at Saint Mary's University, Drs. R. Austin and R. Kanungo, use the ISAC facility. A third scientist, Prof. J. Clyburne, is actively involved in the μSR program.

For Dr. Austin, the high-quality rare-isotope ion beams delivered to the 8π, GPS, and TIGRESS facilities are especially attractive. Rare isotopes studied through decays and Coulomb excitation reactions give Dr. Austin and her collaborators insights into the nuclear equation of the state far from stability, near where elements are created in stars. Six undergraduates have worked with Dr. Austin at TRIUMF.

TRIUMF has also played a pivotal role in Dr. Kanungo's research career. The laboratory's ISOL-type rare-isotope beam facility attracted her to pursue her research in Canada. TRIUMF's high-quality and high-intensity beams have inspired her to start a program of transfer reactions for unstable nuclei.

Dr. Jason Clyburne holds a Tier-II Canada Research Chair in Environmental Science and Materials. His research interest is in materials chemistry. He uses muonium to generate highly reactive radicals and studies their structure using a suite of techniques broadly known as μSR. ■

TRIUMF focuses on what is important. Its research efforts target selected key scientific questions considered to be most important by the Canadian and international scientific community. These research thrusts are drawn from the NSERC Long-Range Plan for subatomic physics, the community-based decadal plan for condensed matter and materials science, and the research statement of the Michael Smith Foundation grant for research at the Pacific Parkinson's Research Centre.

1. Search for the new physics that must lie beyond the standard model of particle physics and determine the role of the elusive neutrino in the evolution and fate of the universe.

2. Identify and characterize the dark matter that is believed to make up most of the matter in the universe. Seek to connect its existence to processes beyond the standard model.

3. Probe the origins of the heavy elements which are believed to have been made in the fiery deaths of massive stars.

4. Understand and master the process by which simple underlying interactions give rise to complex phenomena.

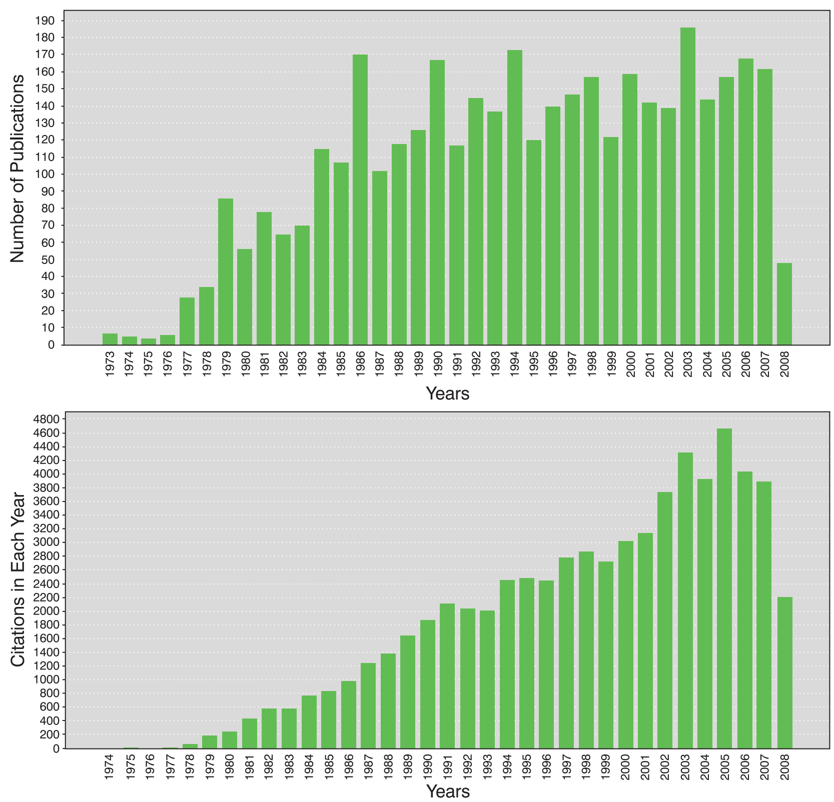


Figure 2: TRIUMF publications and citations since 1973 and 1974 respectively. The TRIUMF science program has produced 900 scientific publications in the last 5 years and more than 4,000 since 1973. NOTE: at the time of preparation, totals for 2008 were not yet available.

5. Identify and control the underlying biochemical and biological mechanisms that contribute to the onset of neurological disease or lead to cancer

TRIUMF's unique capabilities and resources allow Canada unprecedented access to these compelling topics. For instance, through ISAC at TRIUMF and ATLAS at the LHC, Canadians are able to probe the particle and nuclear physics of the first 400,000 years of the history of the universe as well as the ongoing stellar furnaces that power the stars and create the heavier elements found on earth and elsewhere around the universe. The formation of heavy atomic nuclei and our understanding of the fundamental physics behind the structure of nuclei are areas where we seem to be on the edge of much deeper understanding, where important measurements are within our grasp. Additional discussion of these five scientific drivers is provided in Section 2.5.

Advantage: Enabling and Equipping the Next Generation of Leaders

TRIUMF will contribute to the development of Canada's students and science and technology workforce in the following ways:

- Attract international scientists and students to work at TRIUMF;
- Enhance Asia-Pacific scientific personnel exchange;
- Create undergraduate and graduate student research opportunities;
- Establish initiatives to attract and retain talent from traditionally under-represented communities;
- Increase the engagement of Canadian universities in the TRIUMF program; and
- Participate in international student research exchange.

TRIUMF attracts talent from around the globe to Canada: more than 500 top graduate students, post-doctoral fellows, and researchers perform research at TRIUMF each year. For example, TRIUMF has recently recruited two of the world's most elite scientists from the United States and Germany, respectively, to lead core programs at the laboratory. TRIUMF also hosts major international conferences that attract the international science and technology community to Canada. Nearly 600 accelerator physicists will attend LINAC08 in Victoria. In 2009, the International Particle Accelerator Conference will attract 1,500 scientists to Vancouver, and, in 2010, 800 physicists will attend the International Nuclear Physics Conference, also in Vancouver. Not only do TRIUMF conferences support the Canadian tourism industry, they also showcase Canada as a premier destination for advanced research and technology.

TRIUMF is a high-tech engine of employment and training. It supports over 350 regular, full-time scientific and technical staff. The laboratory is a common destination for graduating engineers and technicians because the challenging technical environment ensures competitive training. These highly

PEOPLE

JON STOESSL

Professor
Director, Pacific Parkinson's Research Centre

Jon Stoessl received his M.D. from University of Western Ontario (UWO) in 1979, followed by an internship at McGill University, and a neurology residency at UWO. In 1984, he moved to the University of British Columbia and spent two years working with Donald B. Calne and the PET program.

Dr. Stoessl pursued further training in neuropharmacology in England after which he joined the faculty at UWO. In 1996, he returned to UBC, where he currently directs the Pacific Parkinson's Research Centre, which uses PET as its major research tool to investigate the causes of Parkinson's, the basis for complications of advanced disease and its treatment, and the role of dopamine in signaling reward and expectation. The Centre's research is supported by a Team Grant from the Canadian Institutes of Health Research, a Research Unit Award from the Michael Smith Foundation for Health Research, a Centre Grant from the Pacific Alzheimer Research Foundation, and numerous operating grants.

The Centre's research program is inextricably linked with TRIUMF's Life Sciences program and heavily dependent upon its expertise in the development, production, and delivery of radiotracers.

Jon holds a Tier-1 Canada Research Chair. In 2007, he was appointed a Member of the Order of Canada. ■

Early Cyclotron Era

1979
First new pion/muon beam line, M13
Pion cancer therapy program starts

1980
Prince of Wales starts medical isotope flow
PET camera construction begins (2nd in Canada)
TPC built to study rare decays (1st use in an experiment)

PEOPLE

CARL SVENSSON

Professor, University of Guelph

Carl Svensson received his B.Sc. and Ph.D. degrees in physics from McMaster University in 1995 and 1998, respectively. His Ph.D. thesis, "Collectivity in A ~ 60 Nuclei: Superdeformed and Smoothly Terminating Rotation Bands," used the Canadian 8π Gamma-Ray Spectrometer at the Tandem Accelerator SuperConducting Cyclotron facility at the Chalk River Laboratories, as well as the US Gammasphere Spectrometer, to study the microscopic structure of collective motion in nuclei. Following a post-doctoral fellowship at Lawrence Berkeley National Laboratory, Dr. Svensson joined the faculty at the University of Guelph in 2001.

Drawn by the unique research opportunities available at TRIUMF, Dr. Svensson was instrumental in relocating the Canadian 8π Spectrometer to TRIUMF and establishing it as a major international user facility at ISAC-I. In 2003, he and collaborators from TRIUMF and six Canadian universities received a C$8.063M six-year Major Installation Grant from NSERC to construct TIGRESS experiments at ISAC-II.

Carl is the winner of the John Charles Polanyi Prize in Physics (2001), a prestigious E.W.R. Steacie Memorial Fellowship (2008), and the Herzberg Medal (2008). ■

skilled personnel then move on to successful careers in other sectors of business. TRIUMF trains the next generation of leaders; it attracts students to Canada to learn from the best. More than 50 students per year participate in on-site internships and co-op programs.

TRIUMF proposes to expand its ability to attract, train, and retain highly skilled talent for Canada, doubling the present number of about 500 students and scientists per year who perform research at the facility. First, with the proposed expansion of the capacity and capability for rare-isotope beams experiments, TRIUMF will attract the best and brightest international students the Canadian university program. Second, the construction of the e-linac and the addition of the dedicated actinide beam line, TRIUMF will become a premier facility in the world for nuclear physics and thereby a destination of choice for workers in science, technology, engineering, and medicine.

In addition to these two programs, TRIUMF's programs in modern GRID computing for the LHC and nuclear science will prepare personnel for high-paying careers in information and communication technologies and nuclear power and engineering.

> "At the recent National Summit on American Competitiveness, retired chairman and chief executive of IBM Louis Gerstner remarked that, "In a knowledge-based global economy, skills are what matter" in the long run."

Advantage: Bridging the Academic and Commercial Sectors

TRIUMF will contribute to Canada's entrepreneurial competitiveness in the following ways:

- Triple the economic impact from technology transfer and commercialization with partners such as Advanced Applied Physics Solutions, Inc. (AAPS);
- Forge new industrial partnerships related to TRIUMF's world-recognized leadership in medical-cyclotron design;
- Establish a major new partnership with India in accelerator science;
- Connect radiotracer know-how with drug-development activities at the major pharmaceutical companies; and
- Establish a new partnership with MDS Nordion in radiotracer development.

The TRIUMF science research program serves as a springboard for developing innovations that lead to the commercialization of research. A number of Canadian companies, MDS Nordion, D-Pace, PAVAC Industries, ACS, and

Early Cyclotron Era

1981: KAON Factory studies begin; Erich Vogt becomes Director of TRIUMF

1982: Isotope pipeline to UBC hospital installed; Completion of n-p and p-p program; AECL Commercial Products ships first isotopes from TRIUMF

AAPS, have benefited from the expertise TRIUMF has developed. For instance, the BC-based company D-Pace was started after Dr. Morgan Dehnel graduated with his Ph.D. based on work at TRIUMF. D-Pace now licenses TRIUMF-developed technologies and has contracted to provide a dozen high-value ion sources to Japan. This partnership won national recognition in 2007 with the NSERC Synergy Award. TRIUMF's "nose" for good business also led to a renewal of its highly successful, 30-year-old relationship with MDS Nor-

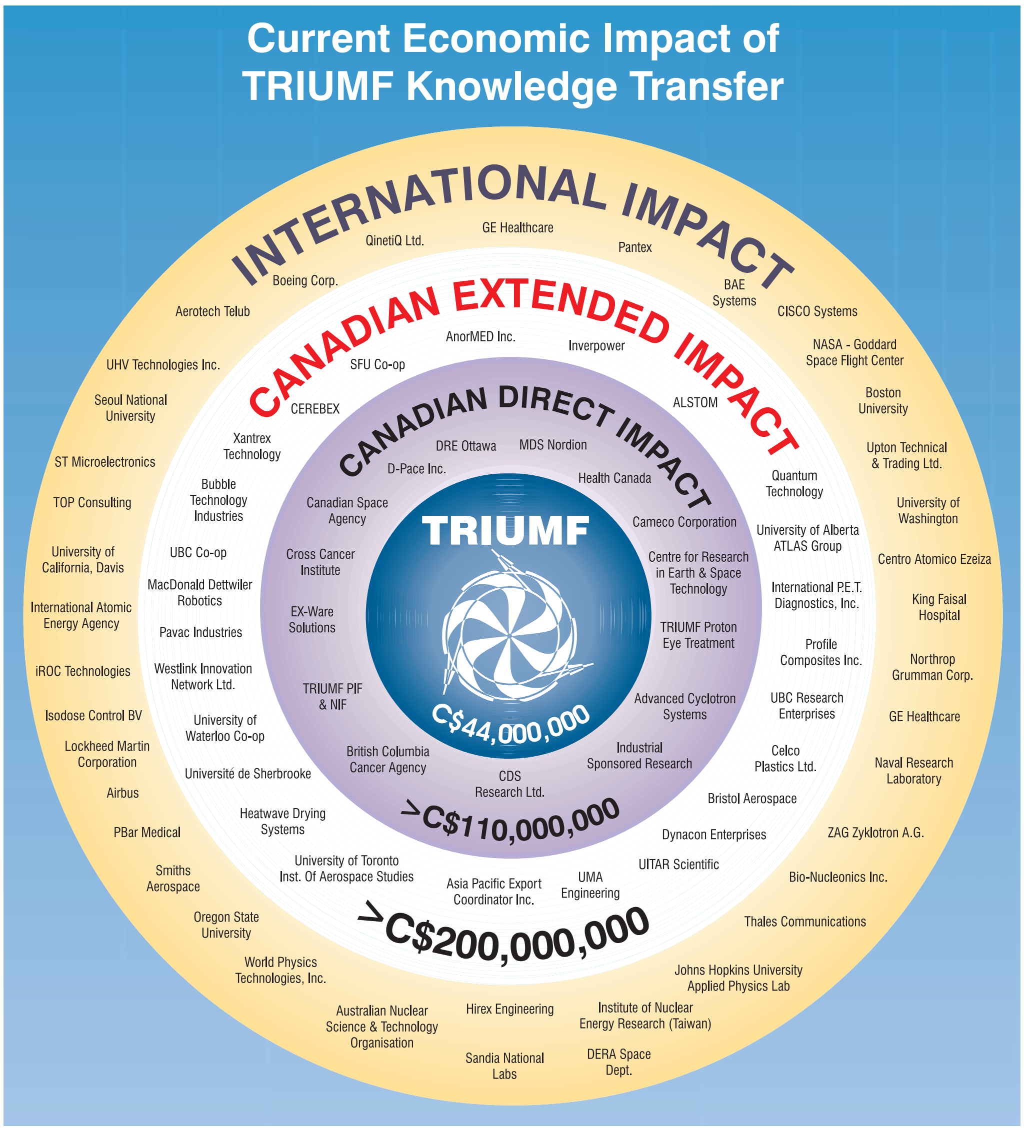


Figure 3: The innermost ring shows the annual public investment in TRIUMF via the NRC contribution agreement. This investment results in jobs, purchase orders, and other contract work. The surrounding rings show the activities resulting from TRIUMF programs that increase the sum of economic activity. For example, in the Canadian Direct Impact domain, fees paid by the BC Cancer Agency to purchase FDG for PET scans are included.

PEOPLE

THE UNIVERSITY OF TORONTO

Particle Physics Group

The University of Toronto (U of T) has been involved with TRIUMF since the laboratory's founding in the 1970s and in 2000 joined the TRIUMF Joint Venture as a full member university. The group has played key roles in both TRIUMF's development and its leadership with roles during the development of TRIUMF's nuclear astrophysics program.

In the 1990s, when U of T reduced its effort in nuclear physics and built up a larger effort in particle physics, TRIUMF provided infrastructure support for the large instruments needed for these experiments. In particular, TRIUMF has provided significant resources to the construction of the ATLAS detector, the highest priority particle physics experiment for both U of T and Canada. From 1995 to 2007, U of T's Dr. R. Orr served as the ATLAS Canada spokesperson. The ATLAS Tier-1 Data Centre sited at TRIUMF was launched in 2006 with support from the Canada Foundation for Innovation (CFI) and the B.C. Knowledge Development Fund. The U of T was one of the principle supporters for this initiative and serves as a national institutional user.

Members of the Group have played various roles within TRIUMF governance. As one example, Dr. P. Sinervo was chair of the NRC Advisory Committee on TRIUMF from 1999 to 2004 and has been a member of its Board of Management since 2004. In 2002, TRIUMF and the U of T agreed to create a joint appointment, currently filled by Dr. P. Savard (pictured above), who works on the ATLAS project. ■

dion and a second Synergy Award. The TRIUMF/MDS Nordion partnership for the production and sales of accelerator-based medical isotopes generates more than \$25-\$30 million of private revenue each year. The next generation of business deals, commercialization agreements, and innovations is at hand.

> "The standard of living in Western Europe and the United States has been sustained for several decades by new products, services and businesses, the result of leading-edge research and development. — **Bill Destler, President of Rochester Institute of Technology, quoted in "A new relationship,"** ***Nature*** **453:12 853 (2008).**"

The impact of TRIUMF's activities on the economy of Canada is quite broad. In terms of direct impact, the high degree of leveraging applied to the public investments is impressive. Figure 3 captures this type of direct economic impact on several different scales, showing that a federal investment through NRC of about \$44 million stimulates more than \$200 million of economic activity for Canada. In addition, Figure 4 shows TRIUMF 5-year accumulated economic impact, exceeding more than \$500 million in 2005–2010 and projected to double to more than \$1 billion in the next five years.

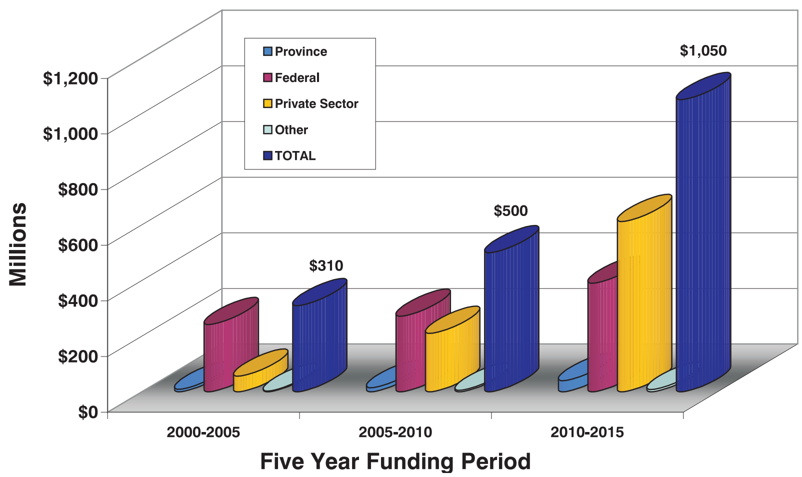


Figure 4: History of TRIUMF-driven investments, separated by source, in five-year periods, including provincial contributions and federal investments by NRC, CIHR, NSERC, and CFI. The private sector category totals activity directly attributed to TRIUMF, such as sales of medical isotopes by MDS Nordion using contract staff from TRIUMF.

2.3

Gateway to Global Science & Technology

TRIUMF serves as a key broker for Canada in global research in particle, nuclear, and accelerator physics. In addition to its core research programs, TRIUMF provides the scientific and technical staff needed to support Canadian scientists and students performing experiments at international facilities, such as the LHC at CERN, in Geneva, Switzerland, and the J-PARC facility in Japan. In return, scientists come from abroad to TRIUMF and Canada to conduct experiments and share their research. These international collaborations engage Canadian scientists and allow Canadian industry to benefit from the rapid advances and progress made in research from all over the world (see Figure 5). These collaborations include university groups, research organizations, and the high-tech international industry.

While the world community works collaboratively, there is also intense international competition in leading fields. For TRIUMF, this is particularly true for the ISAC program (see Figure 6) where rare-isotope beam physics is recognized as having enormous discovery opportunities, commercial potential, and security implications. As a result of this potential, France, Germany, Japan, and the United States are constructing new facilities at considerable expense. The European Union is also considering a major facility named EURISOL. TRIUMF has leading detector facilities and the knowledge to produce rare isotope beams, but the window of opportunity to exploit ISAC before the world catches up is limited. TRIUMF must exploit its current facilities while building the next generation of rare-isotope beam drivers during this five-year plan to keep Canada at the forefront of international rare-isotope science for the next decade.

> The 2008 report of the Working Group on Nuclear Physics to the OECD's Global Science Forum stated, "The new facilities and upgrades that are now under consideration will ensure the continuing success of nuclear physics, with an estimated investment worldwide of four billion US$ during the next decade. The discoveries and technical advancements that will result from the implementation of the global roadmap for nuclear physics will make important contributions to other scientific fields and national and societal priorities. The forefront research facilities in the global roadmap are needed to attract and train a next generation of scientists for research and national needs."

Figure 5: TRIUMF's partners around the world.

Figure 6: Leading international rare-isotope beam facilities. The proposed US FRIB facility has not yet been sited.

Young National Laboratory Era

NRC adds Tech Transfer to TRIUMF mandate
Regina becomes associate member
1989

TR30 installed
ISAC design starts
1990

2.4

A Proven Track Record

Review and oversight processes have been put in place to ensure that TRIUMF's responsibilities are being carried out. These reviews show that TRIUMF meets and exceeds expectations. The extensive system of advisory committees, well populated by world-leading experts, is a key mechanism for TRIUMF to remain at the forefront of global research activities. Each committee meets at TRIUMF, takes written and oral testimony, and then prepares a written report for the director or the president of the NRC summarizing their views on the present program and recommendation for moving forward most effectively. These meetings are typically public and well attended by members of TRIUMF's scientific and technical staff as well as collaborators from nearby universities and research centres. These advisory committees serve as an effective conduit for keeping TRIUMF scientists abreast of global advances and vice versa. For instance, the Accelerator Advisory Committee, presently chaired by Mark de Jong of the Canadian Light Source, provides technical and strategic advice to the TRIUMF accelerator division as it undertakes projects both on- and off-site. The Canadian physics community also has a direct connection to the laboratory through the Policy and Planning Advisory Committee, composed of members from 15 Canadian universities. The local community stays involved via a Citizen's Advisory Board (see Box 2.1).

The Government of Canada provides funding for TRIUMF through a Contribution Agreement between TRIUMF and the NRC. TRIUMF is accountable to NRC for all its financial and scientific activities, and the Contribution

Agreement identifies specific obligations TRIUMF must undertake and complete successfully within NRC-specified timelines (see Table 1). TRIUMF reports to NRC every four months on its success in meeting the Contribution Agreement deliverables and reports the expenditures incurred to do so. In addition, TRIUMF submits an annual audited financial report to NRC. TRIUMF also reports on its scientific and financial progress in meeting its obligations to the Advisory Committee on TRIUMF (ACOT), which meets twice a year. The Agency Committee on TRIUMF (ACT) also meets semi-annually to review TRIUMF's financial progress and technology transfer activities. The Peer Review Committee meets once every five years and reports to NRC on all TRIUMF activities carried out during the five years under review.

The TRIUMF Five-Year Plan proposes a common vision to all partners, and its success will depend on the support of all stakeholders. Each agency faces its own set of objectives, constraints, and funding mechanisms. TRIUMF's success is attributable to the past success of these partnerships. For example, the

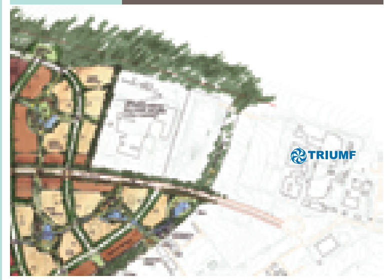
NRC Deliverable	TRIUMF Completion
Completion of 20 medium beta accelerator cavities by the end of 2006.	All 20 cavities were completed early in 2006.
Completion of 20 high beta accelerator cavities in 2009.	TRIUMF has qualified the supplier and ordered the 20 cavities. On March 31, 2008, the cavities began arriving on site and installation and testing began. The project has a planned completion date of early 2009.
Completion of the accelerator cooling system in 2008.	Cooling system was fully installed, tested and commissioned by early 2008.
Commission of one experimental location to provide unique exotic isotope beams to approved high profile experiments by the end of 2006.	The MAYA detector was installed on SEBT2 in 2006 and a successful experiment was performed in early 2007.
Commission 3 experimental locations to provide unique exotic isotope beams to approved high profile experiments by the end of 2009.	The 3 experimental locations are: • SEBT2 – MAYA detector installed and ran an experiment in 2007 • SEBT3 – TIGRESS ran an experiment in the fall of 2007 • SEBT1 – HÉRACLES is being refurbished and will be installed on SEBT1, which will be constructed in 2008. The first experiment will be in early 2009. A fourth experimental location is planned. • SEPT3B – is scheduled for completion in 2009. EMMA detector is under construction and its first experiment will take beam in late 2009.

Table 1: TRIUMF's deliverables for 2005–2010 as described in the NRC Contribution Agreement.

ATLAS Tier-1 Data Centre was initially funded by CFI in 2007. The ATLAS-Canada collaboration chose to site the Centre at TRIUMF because of the existing infrastructure and technical expertise as well as its synergies with the experimental program. The province of British Columbia provided matching funds in addition to the industrial vendor IBM. CFI provided operating funds for about five years; these funds covered the costs of commissioning and preliminary operations. As the CFI award period ends in 2011, responsibility for the ATLAS Tier-1 Data Centre will naturally transition to TRIUMF and its university members. As proposed in this plan, support for the operations and personnel costs of the Centre are requested through the NRC Contribution Agreement. When the ATLAS experiment begins collecting data in late 2008, NSERC-funded faculty and research scientists from around Canada will rely on the Centre to conduct their work. TRIUMF serves as the natural vehicle for what is truly recognized as a joint initiative of CFI, NRC, NSERC, and the Government of British Columbia.

Historically, the BC provincial government has supported the capital infrastructure requirements for buildings and physical plants needed for TRIUMF. The proposed five-year vision depends on a continuation of this agreement: the expansion of the nuclear medicine program requires a new building; the planned growth of the ATLAS Tier-1 Data Centre requires serviced floor space; and the proposed new beam lines require an underground tunnel to connect the main accelerators with the experimental end stations. It is anticipated that these elements of this TRIUMF Five-Year Plan will be supported through negotiations with the provincial government.

Box 2.1



Part of the Community

TRIUMF is located on the south campus of the University of British Columbia (UBC). Its two closest neighbours are also research institutes: the NRC Institute for Fuel Cell Innovation and FPInnovations. Nestled alongside the Pacific Spirit Regional Park, this industry, technology, and innovation area is attracting a growing number of Vancouver residents. UBC has recently constructed new homes for a neighborhood.

TRIUMF is an active and responsible member of this expanding community. TRIUMF staff members live in the area and serve as informal TRIUMF ambassadors for the residents and their civic association, the University Neighbourhoods Association (UNA). Many residents have already taken a TRIUMF tour or attended a Saturday morning lecture. During summer 2008, TRIUMF and UNA launched an evening lecture series held in the neighbourhood's Old Barn Community Centre. The lectures are aimed at a family audience and provide the residents a chance to learn more about TRIUMF's work.

In September 2008, TRIUMF will participate in the annual Barn Raising, at which more than 3,000 people are expected. In addition to contributing planning and logistical support, TRIUMF will present free public tours and demonstrations of physics and radiation safety.

TRIUMF has organized a Citizens Advisory Board, which will provide guidance and advice to the TRIUMF director to ensure that community concerns and ideas are addressed.

Young National Laboratory Era

Ocular melanoma treatment begins
TRINAT first traps atoms
HERMES detector components to HERA
Commercial radiation effect testing with protons starts
1995

BaBar central wire chamber construction approved
1996

2.5

Scientific Motivation for the Plan

This section discusses each of the science questions in more detail, emphasizing the importance and relevance to Canada of the pursuit of these research thrusts.

1. What new physics lies beyond the standard model of particle physics? Does the elusive neutrino have a role in the evolution, and fate, of the universe?

2. What is the mysterious dark matter that is believed to make up most of the matter in the universe? Does it have a role in the processes beyond the standard model?

3. How and where are the heavy elements produced?

4. How do simple underlying interactions lead to complex phenomena?

5. What are the underlying biochemical and biological mechanisms that contribute to the onset of neurological disease or lead to cancer?

What New Physics Lies Beyond the Standard Model of Particle Physics?

For more than a century, physicists have sought a unified theory to explain all the fundamental forces and particles in the universe. The result is a stunningly successful theory that reduces the complexity of microscopic physics to a set of concise laws. Nevertheless, these same quantum ideas fail when applied to cosmic physics. Some fundamental pieces are missing; gravity, dark matter, and dark energy must have quantum explanations. Despite these deficiencies, the standard model of particle physics, which has been primarily tested at LEP and the Tevatron program at Fermilab near Chicago has successfully predicted new particles and their interactions to fantastic accuracy (see Box 2.2). Canada has had a key role in this work.

Without an additional ingredient, the standard model has difficulty explaining or even accommodating the non-zero masses of the matter particles and the weak force carriers. Theorists overcome this challenge using the Higgs mechanism, which gives the "vacuum" an energy density and properties to interact with massless particles to give them an apparent mass as their progress is slowed by "dragging" on the vacuum. This mechanism predicts the masses of the weak force carriers, but the masses of the matter particles are simply inserted into the standard model in an *ad hoc* way that leads one to assume there must be more fundamental interactions that explain how mass is created. Even with this trick, the standard model does not explain how interactions evolve at energies above the masses of the W and Z satisfactorily, referred to as the "Terascale" (see Figure 7).

Measurements currently constrain the Higgs mass to be less than about 200 GeV/c^2 and it should be directly observable at the LHC over the next few

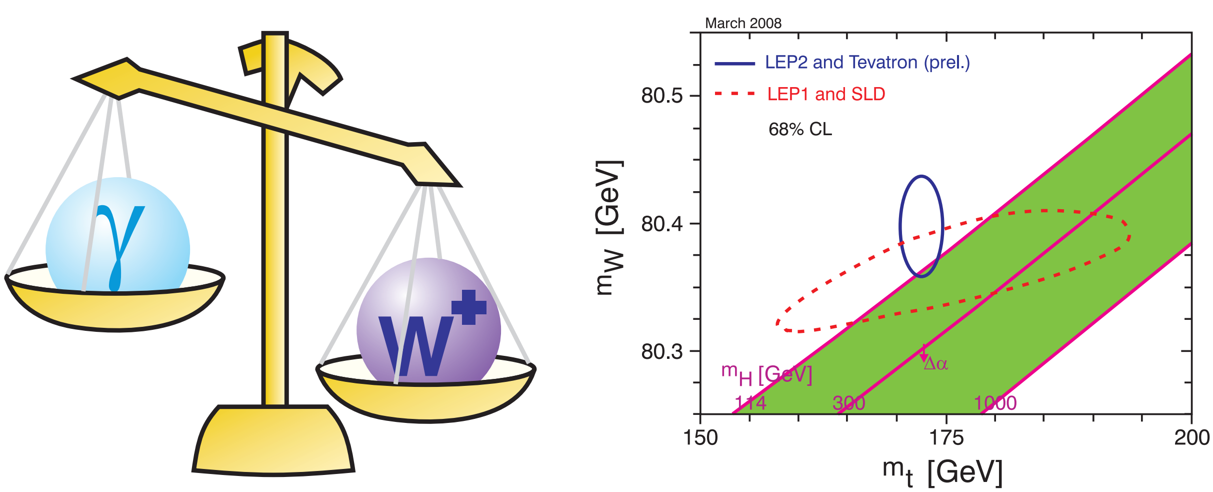


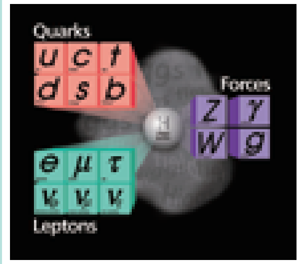
Figure 7: The Higgs mechanism gives mass to the elementary particles and, in turn, has its mass constrained by other measurements. Direct measurements of the W and top-quark mass are shown in the blue ellipse, while indirect constraints from precision measurements affected quantum-mechanically by the W and top masses are contained in the red dotted region. Also shown are contours of Higgs masses, illustrating that the Higgs mass must be below about 200 GeV/c^2 for the standard model to be consistent.

years. The discovery of the Higgs would confirm that the standard model is the correct description of matter and forces at lower energies. Nevertheless, the standard model has too many free parameters to be satisfying: a theory is desired which can predict more of what we do observe and more of what is still beyond the reach of our experiments. It is also very difficult to keep the theory quantum mechanically stable if there isn't new physics within the energy reach of the LHC. Possible models of new physics include supersymmetry (which stabilizes quantum mechanics with new particles) or models with large extra spatial dimensions beyond the three presently known (which requires a completely new theory of quantum gravity that could be observable at the LHC). TRIUMF has been key to Canadian participation in LHC accelerator construction, and now hosts the ATLAS/LHC Tier 1 computing centre and Canadian ATLAS analysis centre. TRIUMF enables the more than 150 Canadian scientists, post-doctoral fellows, and students at 10 universities to be leaders in the most exciting era in fundamental interaction physics in decades.

Another recent success in experimental probes has been the confirmation that neutrinos have mass and that the different neutrino flavours mix. These observations from the Sudbury Neutrino Observatory (SNO) and Japanese Super Kamiokande experiments have revolutionized our understanding of the neutrino. While neutrinos must have non-zero masses to mix, we do not understand how they, or the other matter particles, acquire mass. Neutrino masses are much smaller than the masses of any other particles, and that seems unnatural. Two prongs of experimental neutrino physics are proceeding that will address the critical behaviour of this elusive particle: long-baseline neutrino beam measurements like the T2K project in Japan, and experimental searches for the conversion of neutrinos into their anti-particle in the SNOLAB project. The TRIUMF vision includes critical contributions to both these projects.

This scientific quest is inspiring and profound for many people and Canada's strong role in it attracts the best and brightest to join the research teams directly or to explore careers in science, technology, engineering, and mathematics. The mind-stretching possibilities regularly challenge the limits of technology in new ways that give rise to breakthrough innovations.

Box 2.2



Standard Model of Particle Physics

The standard model of particle physics has evolved over the past four decades with the goal of describing the universe at its most elementary level. The main ingredients are the "matter" particles, including the electron and the "up" and "down" quarks that make up the proton and neutron, as well as the force carriers such as the photon of electromagnetism. The electron has a partner called the "neutrino," which was first inferred from missing energy in nuclear decays, but which has since been observed in experiments both at accelerators and in deep-underground, low-background facilities such as the Sudbury Neutrino Observatory.

Matter particles may be grouped into three generations. These additional generations include heavier versions of the electron called the muon and tau lepton, each with its corresponding neutrino, as well as the strange, charm, bottom, and top quarks. The massless photon is now known to have not only massless counterparts called gluons, which mediate the strong force that holds protons and neutrons together, but also close siblings called the W and Z bosons that mediate weak nuclear interactions and have masses nearly 100 times larger than a hydrogen atom. The source of these masses is critical to our completion of the standard model. The missing piece is called the Higgs boson. If it exists, Canadian scientists will be members of the team who will observe it at the CERN Large Hadron Collider. U.S. Under Secretary for Science Raymond Orbach refers to the Higgs boson as the "discovery of the century." ■

> In a report to the US government, committee chair and Princeton University President Emeritus Harold T. Shapiro wrote, “Particle physics plays an essential role in the broader enterprise of the physical sciences. It inspires US students, attracts talent from around the world, and drives critical intellectual and technological advances in other fields.” **— National Research Council, *Revealing the Hidden Nature of Space and Time: Charting the Course for Elementary Particle Physics*, Washington, D.C.: National Academies Press, 2006, p. 2.**

What is the Mysterious Dark Matter that is Believed to Make Up Most of the Matter in the Universe?

Dark matter and dark energy are critical to our understanding of the evolution of the universe. Dark matter was first hypothesized as an explanation for

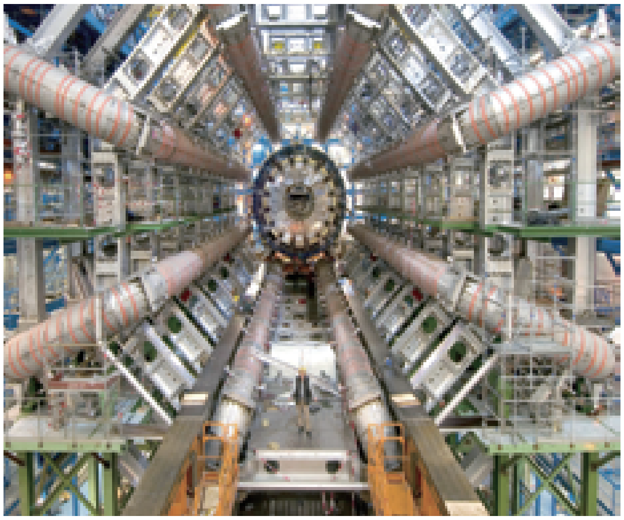


Figure 8: NASA composite image of the Bullet Cluster is shown on the left. The distribution of visible matter from X-ray observations is in red, and the total mass distribution of dark matter inferred from gravitational lensing of distant galaxies is in blue. The analysis is strongly indicative of dark matter dominating the mass of the cluster. The ATLAS detector under construction is shown on the right in this CERN image.

observed rotation curves of galaxies which defied ordinary gravity; more matter was present in the galaxies than was visible to our telescopes. The existence of dark matter has been more recently confirmed by studies of distant objects as shown in the NASA image of the bullet cluster in Figure 8.

We do not know the composition of dark matter even though it accounts for about 80% of the mass of universes, with the remaining 20% composed of stars, planets, and interstellar dust. Many studies of Big Bang cosmology have indicated that the dark matter must be composed of weakly interacting particles with masses in the range of a few hundred GeV/c^2 (1 GeV/c^2 is the mass of a hydrogen atom). This is an exciting prospect because detection of such particles is within the reach of our next generation of low-background underground experiments at SNOLAB.

New particles with masses near 100 GeV/c^2 could also be directly produced in the LHC. Indeed, theories of physics beyond the standard model, especially supersymmetry, contain new particles which would be exactly what is required to act as dark matter in the universe. This could lead to the tremendously exciting prospect of both measuring relic dark matter at SNOLAB while simultaneously producing and studying dark matter at ATLAS. TRIUMF will empower all of these Canadian researchers by providing the needed engineering and infrastructure resources in both of these pioneering projects.

This research thrust is driven by the basic human desire to know the universe; in addition to the intellectual and cultural benefits of pursuing the mystery of dark matter, Canadians can expect to reap the benefits of new ultra-sensitive detector technologies developed along the way.

> "As a national endeavour, particle and nuclear physics has significant value for Canada. The 2006 report *Perspectives on Subatomic Physics in Canada 2006–2016* of the NSERC Long-Range Planning Committee stated, "In this century, subatomic physics will change our understanding of the world and help establish our place in the cosmos. Canadians must participate in these discoveries." **— Subatomic Physics Long-Range Planning Committee, *Exploring the Subatomic Realm*, Ottawa: Natural Sciences and Engineering Research Council, 2006, p. 1.**"

How and Where are the Heavy Elements Produced?

While scientists have made excellent progress over the past 50 years in determining the origin of the light elements, just where the heaviest elements were created remains elusive. That is, scientists cannot say for certain where metals

Box 2.3

Nuclear Physics and Rare Isotopes

Nuclear physics is the study of the principles that govern phenomena of the nucleus, and rare-isotope science is the study of the behaviour and interactions of those nuclei that are unstable, exotic, and rare. By studying physical processes that transform nuclei into other nuclei, scientists learn how to control and predict these phenomena and learn about the origins of the chemical elements in the universe. The study of rare isotopes allows scientists to expand the understanding of nuclear physics in two general ways: (1) rare isotopes present "extremes" to physicists and thereby leverage the testing of the basic understanding of nuclear physics, and (2) rare isotopes themselves play an important role in extreme environments like those inside stars, supernovae, or nuclear reactors.

The field of rare-isotope science can be described in the following way: Atoms that make up everyday matter on earth are predominantly stable: that is, they retain their identity in terms of their elemental and chemical nature (the number of neutrons and protons remains constant over time). The nuclei located at the centre of each atom comprise over 99.9% of the mass of the visible universe; however, many other nuclei can be formed and play important roles.

These nuclei are exotic isotopes (having different numbers of neutrons) of the stable atoms found on earth. These nuclei are quite rare because they are radioactively unstable and decay away into other more common nuclei. These rare isotopes still play an important role in the evolution of the universe, from allowing the sun to shine to fueling the explosions of supernovae. These nuclei, when created on earth, also have important applications such as in nuclear medicine. ■

like copper, gold, and silver come from. Even though the precise location of this heavy-element formation is unknown, it is believed to have taken place through the *r*-process, a series of rapid neutron fusion reactions in a very hot environment with an extremely high density of free neutrons that produces heavy, radioactive nuclei not occurring naturally on earth (see Box 2.3). In this process, once all the free neutrons were captured, the radioactive nuclei decayed, yielding roughly half of the elements heavier than zinc.

Although the rough outline of the *r*-process is adequately understood, the details, such as where and how it occurs, are not. For this reason, astronomical observations are crucial. For example, Figure 9 shows a supernova remnant located in the Large Magellanic Cloud, a small satellite galaxy of the Milky Way about 160,000 light years from earth. The remnant consists primarily of gas streaming outward from the centre at a speed of nearly 10,000 km per second. As revealed by the colours in the image, this supernova remnant contains vast amounts of hydrogen, oxygen, and sulfur. In addition to these elements, smaller quantities of the heavy elements such as gold produced by the rapid capture of neutrons are presumably dispersed by the explosion into the interstellar medium, where they mix with the ejecta of previous supernova explosions and enrich the stars that will form from this material. Measurements of the abundance patterns of the elements heavier than barium in the oldest stars in the Milky Way Galaxy reveal that these old stars exhibit very similar abundance patterns as newer stars while they pre-date the mixing and dispersion of the heavier elements by any other process. These striking similarities represent strong evidence that the *r*-process produces the heaviest elements in nearly the same way every time and that this production is associated with massive stars, whose short lives end in cataclysmic supernova explosions.

Figure 9: LMC N 49, an expanding remnant of a core-collapse supernova that exploded more than 100,000 years ago. Now more than 40 light years across, this expanding cloud of gas and dust carries the elements produced in the explosion into interstellar space where they can be incorporated into succeeding generations of stars and planets. Credit: NASA and The Hubble Heritage Team (STScI/AURA).

Theoretical models of exploding stars have been investigated extensively, but all of the detailed models constructed to date have difficulties generating the conditions that lead to the r-process. These calculations require knowledge of the physical properties of nuclei that have never even been observed, let alone studied in detail. Only by systematically measuring the properties of the highly unstable, neutron-rich nuclei believed to take part in the r-process can one hope to arrive at a quantitative understanding of the relative abundances of the different elements produced and pinpoint the astronomical sites where it occurs. TRIUMF will contribute significantly to our understanding of the formation of the heavy elements by studying the masses and lifetimes of neutron-rich heavy nuclei produced with the proposed e-linac photo-fission driver.

> In 2008, the European Physical Society released a position paper on "Energy for the Future." Included in the report's recommendations was the following, "A research, development, and demonstration for the nuclear option [for electric power generation] also requires support for basic research on nuclear and relevant materials science, since only in that way will needed to find novel technological solutions be obtained."

Understanding the complex reaction mechanisms of nucleosynthesis will shed light on technological problems as diverse as nuclear-materials engineering, optimization of the fuel cycle in nuclear power plants, and modeling of non-linear, dynamical systems. Breakthroughs in this area can even address long-standing questions about the origins of life.

How Do Simple Underlying Interactions Lead to Complex Phenomena?

Complex phenomena are commonplace in nature, whether they are patterns of weather, the properties of solids, or the behaviour of the excited states of nuclei. Behind these complex phenomena, there are frequently very simple rules. For example, the basic interaction between electrons, and between electrons and atomic nuclei, is quite simple, but out of this simplicity comes the whole complexity of molecular and materials science. Two examples of TRIUMF's contribution to this quest are highlighted below. The example from materials science is the occurrence of superconductivity at liquid nitrogen temperatures (high-temperature superconductors) and the example from nuclear physics is halo nuclei (nuclei with neutrons orbiting a core nucleus).

Superconductivity

Electronic conductors (metals and semiconductors) are solids in which some of the electrons are free to move from atom to atom, accounting for many of their characteristic properties such as their high optical reflectivity and, of course, their electrical conductivity. In fact, in a pure, highly ordered crystal at low temperature, they can travel through thousands or even millions of atoms without scattering, either from other electrons or from the atomic nuclei. In some metals at even lower temperatures, however, the mobile electrons do begin to interact. Surprisingly, this interaction is often attractive in contrast to that between free electrons which is repulsive and leads to a pairing of electrons at a special kind of phase transition (like the condensation of water vapour to liquid) where the free electrons condense into a superfluid (a liquid with no viscosity) that conducts electricity with no losses at all, i.e., the material has become a superconductor. The attractive interaction that pairs the electrons in conventional (low-temperature) superconductors like mercury or niobium requires the medium of intervening atomic nuclei and results in electron pairs that have a simple symmetry called *s*-waves.

In some unconventional electronic conductors, however, the electrons are strongly interacting, even at ambient temperature. Such interactions often inhibit the mobility of the electrons and result in a material that is magnetic, with each of the localized electrons contributing as a tiny magnet to the overall magnetism of the material. Through chemical modification, it is possible to introduce mobile electrons into such materials. It is found that this rapidly destroys the static magnetism and yields rather poorly conducting metals or semiconductors; however, the conductivity occurs not through mobile independent electrons but through a fluid of strongly interacting, nearly localized electrons. In some very special cases, these electrons also exhibit a superconducting transition, which can occur at much higher temperatures than the conventional superconductors. In the case of the highest temperature superconductors, the mobile electrons reside in a square lattice of copper oxide, and the paired electrons have a more complex symmetry called *d*-wave. The unconventional symmetry of the electron pairs is clear evidence that the attractive interaction is not the conventional one involving only the underlying lattice of atomic nuclei. It is thought that the attractive interaction originates in the magnetic interactions that characterize the material in the absence of mobile electrons, but much remains to be understood.

> A 2007 report assessing the case for a next-generation rare-isotope facility in the United States concluded that, "Nuclear structure and nuclear astrophysics constitute a vital component of the nuclear science portfolio in the United States. Moreover, nuclear-structure-related research provides the scientific basis for important advances in medical research, national security, energy production, and industrial processing." **— National Research Council, *Scientific Opportunities with a Rare-Isotope Facility in the* United States, Washington, D.C.: National Academies Press, 2007, p. 3.**

Experiments done at TRIUMF's Centre for Molecular and Materials Sciences (CMMS) have been extremely important in the study of high-temperature superconductors and related "strongly correlated electron systems." For example, there are many questions about how an interface with another material or a free surface will modify the properties of such systems. For the copper oxide high-temperature superconductor, the *d*-wave electron pairing is destroyed by scattering from any interface that cuts the copper oxide square lattice diagonally. Such an exotic superconductor may seem unlikely, but similar complex magnetic superconductors have been found by another team of CMMS researchers using μSR.

Mastering the art and science of high-temperature superconductivity is key to eventually designing materials that would be superconducting at "room" temperature. Such breakthroughs would enable, for instance, huge savings in electrical-power transmission over the large distances from power generation plants.

Halo Nuclei

Although discovered two decades ago, halo nuclei are an exotic form of nuclear matter that continue to defy the considerable scientific efforts focused upon them. Only recently have intense beams at TRIUMF made many experimental investigations possible. Teetering on the edge of nuclear stability, the properties of halo nuclei have long been recognized as one of the most stringent tests of our understanding of the nuclear force. In such exotic nuclear systems, the binding energy of one or more nucleons is sufficiently low such that a "halo" of nuclear matter is formed in the classically forbidden region surrounding a tightly bound core. Lithium-11 belongs to a special category of halo nuclei called Borromean, after the Borromeo family's coat of arms symbol that shows three rings linked in such a way that breaking one link, frees the other two. That is, the two-body siblings formed by removing one neutron (^{10}Li) or the ^{9}Li nucleus (2n) are unbound as separate entities. Recently, interest in this archetypical two-neutron halo ^{11}Li has been renewed because of improved measurements of its halo-neutron correlation (the MAYA experiment at ISAC) and charge radius. The latter allows one to distinguish the tight core of protons and neutrons and the satellite neutrons of the halo.

The charge-radius determination was made using measurements of isotope shifts. This method uses state-of-the-art atomic physics methods, both experimental and theoretical, to probe the atomic nucleus. These experiments address key questions such as how big the ^{11}Li nucleus and its halo are, and how the halo neutrons correlate to each other and the core. However, the answers are limited by the knowledge of the mass of ^{11}Li. Because of conflicting experimental results, the knowledge of the mass of ^{11}Li has been historically poor. However, very recently, first measurement of the ^{11}Li mass using a new state-of-the-art Penning trap spectrometer was carried out at the TITAN facility at ISAC. Penning traps are the most precise devices for making mass measurements, but were until now not able to trap these light unstable atoms. TITAN holds two world records in this area: it has measured the shortest-lived and the lightest isotopes. With a half-life of only 8.8 milliseconds, ^{11}Li is the shortest-lived isotope whose mass has been so precisely measured. Using these results, a new two-neutron separation energy (which indicates how tightly the two halo neutrons are bound to the core) of 369.15(65) keV for ^{11}Li is obtained (see Figure 10).

Halo nuclei represent an extreme of nuclear matter that tests the mathematical models of nuclear physics in new ways. Improvements in understanding nuclei will shed light on material behaviour in high neutron flux situations such as the next generation of nuclear reactors. Insights derived from this research will contribute to the next generation of technologies that could incor-

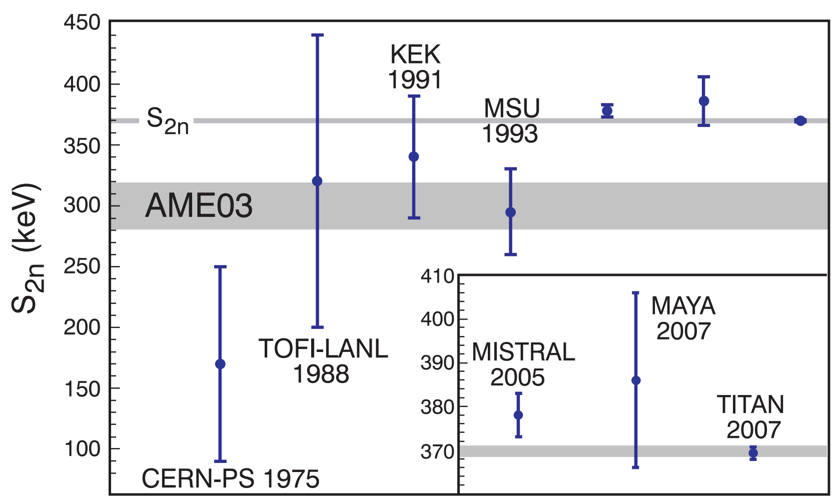


Figure 10: Measurements of the two-neutron separation energy made at TRIUMF in late 2007 using the TITAN experiment. These measurements not only show that the world average was inaccurate; they also dramatically improve the overall precision.

porate a small number of basic principles to deliver sophisticated performance (such as in nanoscale science and technology).

What Are the Underlying Biochemical and Biological Mechanisms that Contribute to the Onset of Neurological Disease or Lead to Cancer?

A nuclear medicine revolution is underway. Advances in biomarkers connected to radioisotopes are expected to allow the observation of the metabolism of disease and the detailed construction of tumours. TRIUMF is perhaps better positioned than any laboratory in the world to take full advantage of this revolution, which would include the production of a new generation of mini-cyclotrons, highly engineered target assemblies, as well as the radio and cold chemistry needed to generate the radiotracers. Two areas where radiotracers are making a large impact are Parkinson's disease and cancer imaging and therapy.

Parkinson's Disease

Parkinson's disease (PD) is one of the most common neurodegenerative disorders, with a prevalence of 1-2 in every 100 people over 65 years old in the Canadian population. The origins and the mechanisms of PD are not completely understood, although it is now recognized that gene mutations can

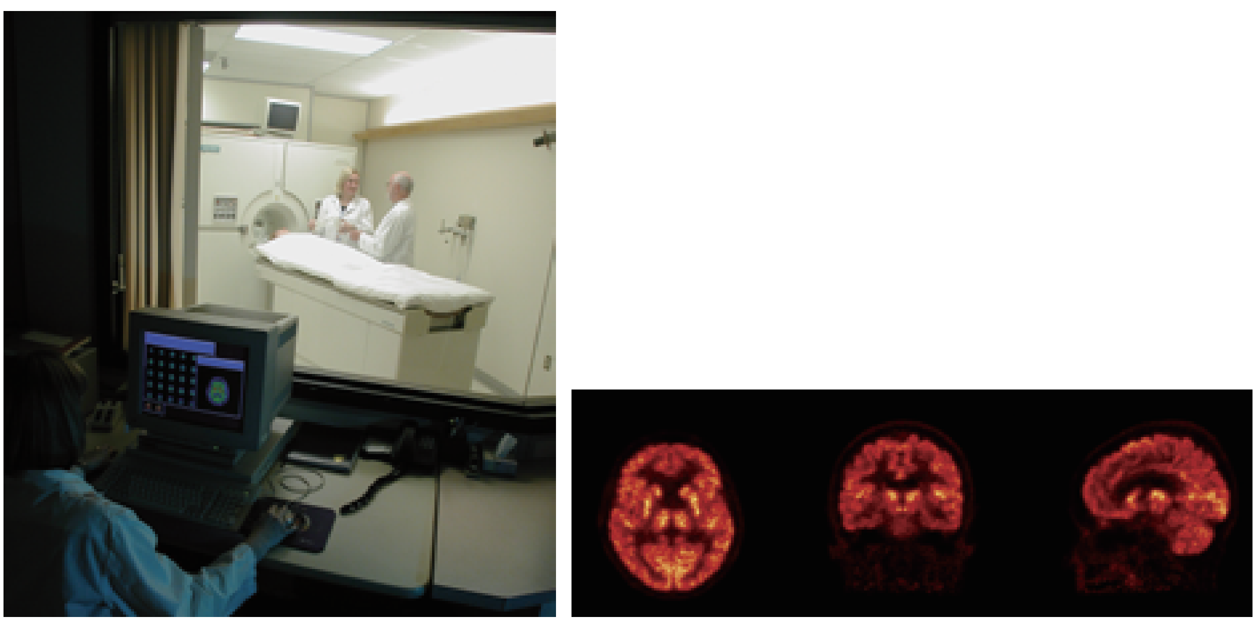


Figure 11: PET scan of a patient showing the exam room in a research clinic; a PET scan showing metabolic activity in the brain is shown on the right.

contribute to its development. PD is a complex disorder or syndrome where clinical symptoms appear when there is already significant degeneration of the dopamine producing neurons. No efficient treatment is currently available. Using PET scans (see Figure 11) to image subjects who are genetically at risk provides an excellent opportunity to investigate pre-clinical changes, with the ultimate goal of understanding the disease's etiology and associated neurochemical changes. This work might ultimately allow the use of neuroprotective therapies designed to halt or slow disease progress prior to symptom development in subjects at risk. TRIUMF's partnership with the Pacific Parkinson's Research Centre in this area has identified commonalities among Parkinson's, Alzheimer's, and even some mood disorders such as depression and compulsive gambling.

> PET scans using ^{18}F-FDG can spot various types of dementia early, according to results of a 548-patient study that appeared in the Journal of Nuclear Medicine. Using "optimized analysis" of FDG-PET scans "allows one to accurately detect and classify different types of dementia, including AD, frontotemporal dementia and Lewy body dementia at the very mild stages of disease," said the lead researcher from the New York University School of Medicine. **— Reuters News Release, New York University School of Medicine, 27 March 2008.**

Cancer Imaging and Therapy

Currently, approximately 3,000 patients (including several hundred children) each year benefit from ^{18}F-FDG produced by TRIUMF in partnership with the BC Cancer Agency (BCCA). The BCCA has purchased a TRIUMF-designed cyclotron from Advanced Cyclotron Systems, Inc. (a Canadian company) that should be commissioned in about one year and housed in its own facility.

With the recent addition of a research chair in functional cancer imaging and the purchase of a small animal micro-PET/CT scanner at the BCCA, the scope of the TRIUMF life sciences program will extend into cancer research. TRIUMF will be providing isotopes for pre-clinical and clinical research to BCCA, such as ^{18}F-Fluoroestradiol (for breast cancer imaging) and ^{18}F-EF5 (hypoxia imaging). A new BCCA program will be identifying key genes associated with breast cancer, using high-throughput genome-wide siRNA screening. By selectively inactivating individual genes through thousands of iterations, researchers can identify key genes that are essential for breast cancer growth and proliferation. The proteins associated with these genes can then be identified and characterized, and complementary radio-labelled probes can be designed to interact with these proteins for diagnostic or therapeutic purposes.

The combination of world-class expertise in isotope production using cyclotrons, basic target research, radiochemistry, instrumentation research, molecular biology of cancer, pre-clinical expertise in imaging, advanced cancer therapeutics, and clinical imaging research is unique. Both TRIUMF and the BCCA have expressed a keen interest in expanding their collaboration to advance cancer research.

Advanced clinical research using nuclear-medicine will drive breakthroughs in medical imaging, diagnosis, and therapy by revealing the biomolecular origins of neurological disease and cancer. Improved health care and substantial savings in disease treatment are expected by using PET imaging techniques for early detection.

> "We now have the opportunity to develop highly personalized medicine, in which each patient and disease can be individually characterized at the molecular level to identify the treatment strategies that will be most effective. Nuclear medicine techniques that image biochemical function *in vivo* can facilitate the development and implementation of such tailored treatment."
>
> **— U.S. National Academies, Advancing Nuclear Medicine through Innovation, Washington, D.C.: National Academies Press, 2007, p. 8.**

2.6

Conclusion

TRIUMF is a unique vehicle for bringing together the public and private sectors for research and innovation. By taking on the technical challenges necessary to probe some of the most compelling questions in physical science, the laboratory stretches not only its own technical capabilities but also those of its commercial and business partners. The result is a robust network of organizations (see Figure 12) all striving for innovative breakthroughs using an unconventional mix of academic knowledge, the wisdom of experience, and sheer creative talent.

The plan presented is bold. It is a plan that will transport the laboratory to a significantly higher level of international recognition and leadership, which is what Canada needs if it is to be among the leaders in the quest for knowledge economies. It is a plan that will build on the success of the existing program, the high quality human capital available in Canada, and the potential of our universities' finest students. It is a plan that will attract the best and brightest from around the world to Canada to create a new team to execute the plan and move Canada forward. It is a plan that will meet the expectations of Canadians in their country.

> "The book on the 21st century is, of course, yet to be written, but if history teaches any lesson it is that no nation has an inherent right to greatness. Greatness has to be earned and continually re-earned. In fact, few nations, great or ordinary, have survived to enjoy the third century of their existence. Nations that take their technologic leadership for granted will be particularly vulnerable in this fast-moving global community... **— Mr. Norman Augustine, retired chairman and chief executive officer, Lockheed Martin Corp.**"

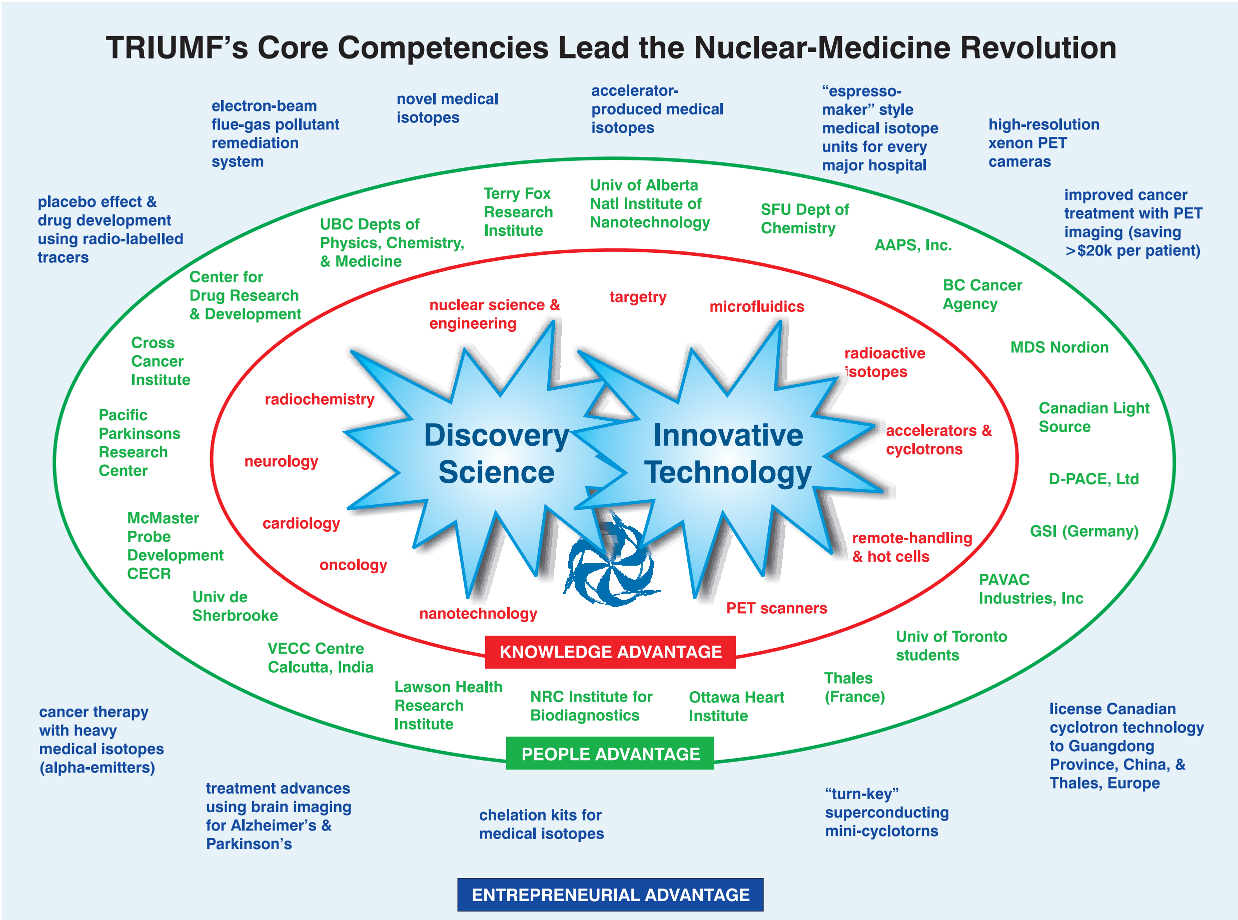


Figure 12: Example of TRIUMF's network of science and technology resources, partnerships and connections, and entrepreneurial opportunities in the area of nuclear medicine. Because of TRIUMF's core competencies in accelerators, isotopes, and radiochemistry, it is poised to make pivotal contribution to the Canadian revolution in nuclear medicine. This is only possible because of TRIUMF's network of partners, all of whom contribute to the progress of the science, technology, and engineering workforce of the country.

Chapter 3

Partnerships: TRIUMF, Canada, and the World

Chapter 3

Partnerships: TRIUMF, Canada, and the World

3.1

TRIUMF's Role in the Canadian University Research System

Introduction

Canadian research is largely driven by the research programs of Canadian universities. In many fields, including nuclear and particle physics, the scientific quest for a greater understanding of nature exceeds the resources of any single institution. A national laboratory, working closely with the university community and drawing together the strengths and capabilities of many institutions, is required. In the context of the Canadian nuclear physics community, this requirement led to the founding of TRIUMF. Launched in 1968 by three universities as a local facility for intermediate-energy nuclear physics, TRIUMF has now grown to be a nationwide effort. The laboratory has also expanded its fields of research from nuclear physics to include particle physics, molecular and materials science, and nuclear medicine. TRIUMF and its user community lead Canada in the search for answers to important science and technology questions.

JESS BREWER

Professor, UBC

Jess Brewer graduated from Trinity College, Hartford, CT in 1967 and completed his graduate work at the University of California at Berkeley. He obtained an M.A. in 1969 and his Ph.D. in High Energy Physics on the topic of muonium chemistry in liquids in 1972. He moved to UBC-TRIUMF in 1973 to help set up a μSR facility, which is now the only one left in the Western Hemisphere. He has been a major factor in the success of the TRIUMF μSR program and an indefatigable advocate for and developer of μSR.

Dr. Brewer is currently a professor in the Department of Physics and Astronomy at UBC and a founding member of the CIfAR Quantum Materials program. He was the recipient of the Killam Research Prize in 1996, the Imagine UBC Professor of the Year in 2003, a Lifetime Achievement Award from the International Society for μSR Spectroscopy in 2005, and Brockhouse Medal of the CAP in 2008.

In 2007, Jess published his first science fiction short story and plans to get back to his original career path as a writer. ■

TRIUMF is an integral part of the Canadian research community. It is owned and operated by a consortium of Canadian universities. The Board of Directors, which has representation from 13 Canadian universities, guides the overall direction of the laboratory. The Policy and Planning Advisory Committee, established in 2008, has members from 15 different universities and provides detailed input into TRIUMF's policy and planning decisions.

As part of the subatomic physics community, TRIUMF scientists participate with university-based physicists in developing the Natural Sciences and Engineering Research Council (NSERC)'s long-range plans for subatomic physics. TRIUMF uses these community-based plans, which discuss the long-term objectives of the field, to develop its own priorities. TRIUMF's decisions about which projects to undertake are also guided by its policy of supporting only those projects that have been independently peer reviewed and endorsed by the scientific community.

TRIUMF's contribution to the Canadian academic community results in world leading advances in science. TRIUMF has many resources to contribute. These include human resources like research scientists, engineers, and technicians. In addition there are physical resources: high quality beams of protons, muons, and rare-isotopes as well as detectors used in conjunction with these beams, facilities for making detectors and detector components. Because TRIUMF has a large user community, it can maintain specialized equipment and resources that can be utilized sequentially by different groups.

The mix of resources at TRIUMF is very different than at a university. This results in different synergies than are possible at a university. In fact, TRIUMF's main strength is that it has a range of resources, both human and hardware, that can be applied coherently to a given problem. A typical TRIUMF user from the Canadian research community obtains technical support, collaborates with on-staff scientists, and may use a TRIUMF project engineer. This is in addition to any use of the physical resources. University-based researchers want to work with TRIUMF because these resources simply are not available at their home institutions. Scientists at TRIUMF become the key points of contact for their research. This contact helps foster collaborative partnerships among Canadian researchers and between Canadian researchers and their international colleagues. TRIUMF also provides salary support (in whole or in part) for about a dozen scientists resident at Canadian universities. This support strengthens the scientific and intellectual ties between TRIUMF and the universities. In addition, as an active research centre, TRIUMF maintains an atmosphere that promotes intellectual activity through seminars, visitor programs, and workshops. Tying it all together is a management structure geared to maximizing the science impact for Canada.

TRIUMF adds significant value to the Canadian academic community in a number of areas including molecular and materials science, subatomic physics, and nuclear medicine. However, its largest impact is in subatomic physics. To quantify this impact, consider the NSERC grants awarded to subatomic physics in fiscal year 2006–2007.[1] During that year, the total NSERC budget for subatomic physics was C$22.4 million. Of this amount, approved proposals with at least one TRIUMF-supported signatory accounted for C$12.1 million while those without a TRIUMF signatory but which used TRIUMF facilities in some manner accounted for another $C4.6 million. Taken together, 74% of the

1 See Appendix B for additional statistics.

NSERC budget for subatomic physics involves TRIUMF. If theory grants are excluded, TRIUMF's involvement with experimental subatomic physics is 86% (C$16.4 million out of C$19.3 million). Included in this figure are projects like TIGRESS and ATLAS as well as projects like the Sudbury Neutrino Observatory (SNO), for which TRIUMF supports two scientists and supplies some infrastructure. What these figures show is that TRIUMF is involved in a large fraction of the Canadian experimental subatomic physics program.

The CFI (Canada Foundation for Innovation) program has had a dramatic impact on the Canadian university research program. Although TRIUMF cannot apply directly for CFI funds because they are available only to university researchers, university teams can apply for CFI awards for projects to be based at TRIUMF. TRIUMF's capabilities have been expanded because a number of universities have elected to compete for, and win, support for TRIUMF-based projects. From 2003–2008, CFI awarded the universities more than C$35 million (including matching funds) to expand TRIUMF's capabilities and competencies. Examples of successful CFI-funded experiments based at TRIUMF are the ATLAS Tier-1 Data Centre, the M20 beam line, the Laboratory for Advanced Detector Development, and projects led by researchers at Saint Mary's University and the University of Guelph.

TRIUMF is well recognized as a key part of the national research infrastructure in subatomic physics by subatomic physicists. However, molecular and materials science researchers and life sciences researchers both exploit the laboratory's unique beams, specialized tools, and expertise.

Molecular and materials science researchers use TRIUMF's muon beams, rare-isotope ion beams, and associated instrumentation (see Section 5.1.4). Working with TRIUMF, the university user community pioneered this area of

Collaboration Or Facility	Major Detector Contribution	Major Accelerator Contribution	Beam or Isotopes	TRIUMF Scientist	Canadian Intellectual Leadership
HERMES					
BaBar					
ATLAS					
T2K					
TIGRESS					
G0, QWEAK					
μSR Facility					
Accelerator R&D					
Medical Technology					

Table 1: The diverse nature of the Canadian university collaborations in which TRIUMF is involved. The representative collaborations are listed vertically, while typical TRIUMF contributions are listed horizontally. The shaded blocks indicate areas in which TRIUMF's contribution is strong.

condensed-matter research. The Canadian Association of Physicists' recent award of The Brockhouse Canada Prize for "Outstanding Experimental or Theoretical Contributions to Condensed Matter and Materials Physics" to J. Brewer (UBC) for his work on μSR recognizes this pioneering role.

The TRIUMF Life Sciences program is built on the lab's unique ability to use its accelerator technology to produce isotopes, radiopharmaceuticals, and radiotracers for the diagnosis and treatment of disease. The centrepiece of this program is the TRIUMF/UBC PET Centre, a joint TRIUMF-university venture that studies the origins, progression, and treatment of Parkinson's disease and other neurological diseases such as Alzheimer's. The PET Centre, established in 1980, also dedicates substantial resources to basic research in psychiatry, the genetic causes of neurodegeneration, and diabetes. It is one of only a few centres in the world capable of this broad, multidisciplinary research program.

The PET Centre depends critically upon TRIUMF and its production of isotopes. In 2005, the British Columbia Cancer Agency (BCCA), the Vancouver Hospital and Health Sciences Centre, and the TRIUMF/UBC PET Centre opened a Centre of Excellence for Functional Cancer Imaging. This centre, with the first publicly funded PET/CT scanner in British Columbia, will improve cancer diagnosis and treatment for patients, build research programs for the discovery, development, and application of new radiotracers, and promote collaboration with a national and international network of functional imaging programs.

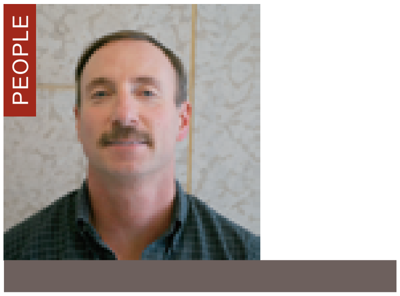
No discussion of the TRIUMF-university relations would be complete without a discussion of students and training. Although TRIUMF itself does not grant degrees, it works with the university community to enhance students' and post-doctoral fellows' training and research experience. A separate section of the Five-Year Plan is devoted to this topic and we just indicate the scope of the program here. Between 2003 and 2008, 319 undergraduate students worked at TRIUMF and 104 Ph.D. and 203 M.Sc. degrees were awarded for work done at least partially at TRIUMF.

Examples of TRIUMF's Relationship with University Partners

TRIUMF's partnerships and collaborations with the Canadian academic community are as diverse as the projects and researchers who undertake them. One of TRIUMF's core strengths in its interactions with this community is flexibility, its ability to approach collaborations in a variety of ways (see Table 1 for a sample of TRIUMF's involvement in a number of different experiments). The three most prevalent approaches are now discussed with an example of each type.

University Collaborations Exploiting ISAC's Rare-Isotope Beams

For collaborations undertaking subatomic research at TRIUMF, the laboratory provides particle beams of the desired species, intensity, and energy. Typically, these collaborations include a TRIUMF scientist as well as a specialized apparatus that is already commissioned and operational. In instances where new equipment is being used, it is typical for TRIUMF personnel to be heavily



CINP

The Canadian Institute of Nuclear Physics (CINP) is a recent initiative of the Canadian nuclear physics community. CINP's mission is to provide a formal organization to represent fairly and to advocate effectively the interests and goals of the Canadian nuclear physics research community to relevant agencies and parties. The Institute anticipates a broad range of activities, including the fostering of nuclear physics collaborative research and networking, the enhancement of nuclear physics education in Canada, and outreach.

The CINP is owned by Institutional Members and operated by Institutional and Individual Members for the benefit of nuclear physics research and education in Canada. Individual (faculty and associate) membership is open to any Canadian resident who has sufficient training and competence in the discipline of nuclear physics to enable that individual to play a significant role in the activities of the Institute. The affairs of the Institute are managed by a Board of Directors, elected by the Institutional Members. The founding President of the CINP is Dr. Garth Huber, a Professor at the University of Regina.

The Institute's community interacts strongly with TRIUMF. Many use the rare-isotope beams TRIUMF provides while others make use of the infrastructure support. Both are crucial to the continuing health of nuclear physics in Canada. The Institute and TRIUMF anticipate a long and mutually beneficial collaboration.

involved in the specification, design, procurement, and commissioning of the new equipment. The actual equipment for individual experiments and most of the detector facilities are funded from outside resources, either Canadian or foreign.

Example: TIGRESS

TIGRESS is a state-of-the-art γ-ray escape suppressed spectrometer for use at the ISAC-II facility. A preliminary CFI grant through the University of Guelph for C$0.6 million was used for initial prototyping. A collaboration headed by Carl Svensson, consisting of eight university-based and two TRIUMF-based physicists, applied for NSERC funding in the autumn of 2002. NSERC awarded the collaboration C$8 million over six years. This award is the largest single NSERC grant ever awarded for nuclear physics. A follow-up CFI grant through Saint Mary's University added an additional third of a million dollars for electronics. Eight of the twelve modules of the full spectrometer are now on site, and three experiments have been performed.

TRIUMF has contributed substantially to this university-based, and university-led collaboration, first and foremost by providing the rare-isotope beams and the dedicated beam line needed to deliver them to the apparatus. Secondly, TRIUMF provided specialized dedicated laboratory services and personnel, engineering support, design office and machine shop time, and installation technicians. While these services may be routinely available at laboratories, the size of the TIGRESS project meant that these contributions were substantial. Finally, two TRIUMF research scientists, G. Hackman and G. Ball, oversaw the day-to-day management of the project and did a lot of the hands-on work that was necessary to make the spectrometer a reality.

The TIGRESS spectrometer provides a world-leading detector system to exploit the beams that only ISAC-II can supply. This unique combination of detectors and beams was only possible because the Canadian university research community, TRIUMF, NSERC, CFI, and foreign collaborators worked together to make it a reality.

Canadian University Involvement at Foreign Laboratories

For experiments with Canadian university involvement at foreign laboratories, TRIUMF normally contributes in the areas of design, fabrication, and installa-

Scientist	Position in ATLAS Canada	Relationship with TRIUMF
Rob McPherson	Spokesperson/Principle Investigator	TRIUMF Resident
Doug Gingrich	Deputy Spokesperson	TRIUMF-University joint appointment
Mike Vetterli	Computing Coordinator	TRIUMF-University joint appointment
Isabel Trigger	Physics Coordinator	TRIUMF Scientist

Table 2: The four principle management positions in ATLAS Canada.

tion of portions of the experimental apparatus. In several instances, there has also been a contribution of systems, such as a set of magnets or power supplies for the accelerator being custom built for the experiment. In large collaborations, TRIUMF scientists often assume senior roles in the management of the collaboration.

Example: ATLAS

The ATLAS collaboration comprises about 2,000 scientists from 167 institutions in 37 countries. Canada represents 4% of the collaboration. The Canadian involvement started in 1991 with research and development from the University of Victoria and the University of Montreal. TRIUMF joined the team in 1994 and led the Canadian accelerator contribution to the large hadron collider. TRIUMF has subsequently been a major player in the experiment and presently hosts one (and the only one in Canada) of the ten ATLAS Tier-1 computing centres that process the data from the experiment.

With the support of NSERC, Canadians made major contributions to the construction of ATLAS, and this effort had a very significant TRIUMF component. Canadians were prominent in the construction of ATLAS primarily in the end-cap calorimeters, but more recently have significant involvements in the luminosity monitor, the diamond beam-conditions monitor, and the trigger.

The Canadian group in ATLAS comprises about 150 people, of whom 41 are university faculty or TRIUMF scientists. The TRIUMF involvement includes five Canadian faculty members who are TRIUMF-university joint appointments, and five TRIUMF resident research scientists. This group is heavily involved in the management of ATLAS Canada (see Table 2). Four Canada Research Chairs (M. Dobbs, W. Taylor, B. Vachon, and M. Vincter) are members of the ATLAS collaboration, as are five of the eight Institute of Particle Physics scientists (F. Corriveau, R. McPherson, S. Robertson, R. Sobie, and R. Teuscher).

It is difficult to provide meaningful quantitative measures of Canadian involvement in the ATLAS experiment. Presently, Canada's participation in the senior management of the collaboration exceeds what might be expected by its 4% involvement in the overall project. Canadians hold two of the 63 senior ATLAS positions, which require approval of the full collaboration. This includes the Collaboration Board Chair, C. Oram, for 2006–2007. Over the past 15 years or so, the Canadian fraction of the leadership has fluctuated but has been consistently high.

Molecular and Materials Science

For experiments in molecular and materials science, Canadian university-based teams provide the samples to be studied, while TRIUMF provides the beam, detection equipment, and data acquisition program. Typically, the focus is on a specific scientific problem (for example, high temperature superconductivity or novel magnetic materials) requiring multidisciplinary investigation. TRIUMF acts as a user facility providing valuable and frequently unique services, but it is often one of several resources used by the group of experimenters.

PEOPLE

IPP

The IPP (Institute of Particle Physics) is a non-profit corporation, operated by 14 institutional members across the country for the benefit of particle physics in Canada. The Institute, funded by NSERC, employs 8 faculty-equivalent research scientists who lead the Canadian efforts in major particle physics experiments around the world and has 200 individual members from universities and labs across the country. The IPP nurtures and coordinates Canada's participation in international particle physics experiments by identifying a core set of experiments that form the IPP physics program. In addition, the IPP leads community planning exercises for NSERC and the NRC and supports particle physics outreach and education efforts. The IPP Director serves as Canada's representative on the International Commission for Future Accelerators and acts as a point of contact for the Canadian particle physics community with major laboratories around the world.

William Trischuk, IPP's current director, has been a member of the Department of Physics at the University of Toronto for 12 years. He is a member of the ATLAS collaboration, where he has built and is commissioning the beam monitoring and abort system. In the past, he has led the Canadian group on the CDF experiment at Fermilab, where he pioneered precision measurements of the W boson mass. In the early 1990s, he was a CERN staff member and became a world leader in the development and construction of precision solid state, vertex detector systems.

There is a strong working relationship between IPP and TRIUMF. TRIUMF scientists lead two (Pi2E and T2K) of the experiments that make up the IPP physics

CONTINUES ▸

Example: ß-NMR / ß-NQR

As implemented at TRIUMF, β-detected nuclear magnetic resonance (β-NMR) uses a low-energy ISAC-I radioactive ion beam as a novel depth-resolved local probe of the properties of thin films and heterostructures. This is an extremely technologically important field of materials science. The β-NMR team consists of three principal investigators from TRIUMF-member universities: A. MacFarlane (UBC, Chemistry), R. Kiefl (UBC, Physics), and K. Chow (University of Alberta, Physics). These three researchers have driven the development of this novel technique, with TRIUMF playing an enabling role.

While the primary isotope of interest, ^{8}Li, is easily produced by the ISAC-I surface ionization source at TRIUMF, these experiments require a spin-polarized beam. This has been achieved through the efforts of TRIUMF scientist P. Levy using an in-flight laser polarization scheme. This complex task is now routine and highly reliable.

β-NMR uses low-energy beams to study phenomena in thin structures (less than about 200 nm thick and as thin as 2 nm). It requires an ultra-high vacuum sample environment with residual pressures in the range of 10^{-9} torr. The design challenges imposed by such criteria necessitated a significant investment, largely by TRIUMF, in design and construction of specialized beam lines. In addition, the TRIUMF Centre for Molecular and Materials Science (CMMS) contributed significantly with technical personnel supported by NSERC's Major Facilities Access grants program. For example, CMMS leader S. Kreitzman designed the system that provides the radio-frequency magnetic field essential for many measurements. TRIUMF also contributed half the salary of a post-doctoral fellow position for the development of β-NMR. The series of scientists that have occupied this position have contributed significantly to technical advances as well as to the scientific productivity of the program.

The novel technique of zero field beta-detected pure-nuclear quadrupole resonance (β-NQR) was first demonstrated at TRIUMF [Salman *et al.*, Phys. Rev. B 70, 104404 (2004)] in a second spectrometer. The β-NQR spectrometer has recently been upgraded with NSERC-funded cryogenic and TRIUMF-funded deceleration capabilities, enabling this new technique to be fully exploited in the study of materials. To maximize the use of valuable ISAC-I beams, the β-NMR team, with TRIUMF technical support, implemented a fast electrostatic switch, allowing the near simultaneous operation of the two spectrometers, and effectively doubling the available experimental time.

The financial contribution of university researchers to this effort has been largely through NSERC-funded personnel in the form of graduate students, post-doctoral fellows, undergraduate students, and NSERC-supported CMMS personnel. However, recently infrastructure funding, in excess of $100,000 since 2005, has been obtained from the NSERC Research Tools and Instruments program to develop spectrometer capabilities.

The β-NMR facility provides an excellent example of the initiating role that TRIUMF plays in research that would be inconceivable in its absence. It also illustrates the potential synergies that exist when university-based research operates in concert with the scientific expertise and infrastructural capabilities of a national facility like TRIUMF.

▼ CONTINUED

program. Significant portions of the IPP program depend critically on TRIUMF contributions. Canadian participation in the BaBar experiment at SLAC was made possible only through TRIUMF's agreement to allocate substantial and critical technical resources and personnel to the assembly of the BaBar central drift chamber.

TRIUMF accelerator expertise was much sought after by CERN during the design phase of the Large Hadron Collider, resulting in prominent, in-kind contributions to the accelerator complex. Subsequently, Canadian researchers have played a leading role in the ATLAS experiment due to TRIUMF leadership in the detector construction and the establishment of a Tier-1 computing centre. Currently, TRIUMF's technical contributions to the design, assembly and testing of major pieces of the T2K near detector are helping Canadians retain their position as the largest foreign contingent on the experiment. ■

3.2

TRIUMF as Canada's Gateway to the World

The pursuit of key questions in physics requires the pooled talents and resources of multiple nations. As a national laboratory on the global stage, TRIUMF is Canada's keystone in international subatomic physics and provides a specialized facility for the international molecular and materials science community. It enables Canadian scientists to make leading contributions in international science projects both in Canada and abroad. Furthermore, by connecting to world-leading efforts, Canadian researchers not only maximize their accomplishments but also access developments around the globe. Ultimately, by having a globally competitive research program with strong international connections, TRIUMF helps attract and retain the best talent for Canada.

What are the benefits to Canada of an international program?

Science, by its very nature, is not confined by international boundaries. Not only does the intellectual quest of science unite humanity, it increasingly requires the combined efforts of many nations to move forward. No country can insulate itself from the global scientific community without seriously handicapping its own scientific and technological ability. This is especially true for a country like Canada with only a modest percentage of the global research community. International connections provide contact with the very best talent, increase the opportunities for collaboration, and allow access to facilities that Canada by itself could never afford. They also allow Canada to attract, train, and retain its brightest minds. Through its strong international connections, TRIUMF, like the Canada Research Chairs (CRC) program, helps attract and retain stellar scientists who would otherwise be lost to Canada.

International connections and collaborations are also the precursors to international business and trade. These strong international connections help Canadian industry benefit from progress made in research from all over the world. For instance, TRIUMF is collaborating with a local company, PAVAC Industries Inc. (PAVAC), to develop Canadian capability in the manufacture of high technology, superconducting radio-frequency cavities (see section 5.3). This initiative would not have been possible without TRIUMF's collaborations with scientists and technical experts based in Germany, Italy, and the USA.

What does it mean to have an international program?

International partnership is a two-way street. In order to participate on the international stage and reap the rewards, Canada must contribute on a level commensurate with its involvement and expected return. Our national laboratories, TRIUMF and SNO/SNOLAB, are Canada's contribution to the set of global subatomic physics facilities. These laboratories have unique capabilities and strong international reputations because of sound investments at the provincial and federal levels as well as the combined efforts of the Canadian scientific community. Internationally leading scientists come to Canada to perform experiments at these laboratories. However, partnership in the international science community also requires involvement in and contributions to projects located outside Canada. The resulting combination of onshore and offshore facilities provides the necessary balance, attracting the best scientists to Canada while enabling the best Canadian scientists to work either at home or abroad.

The international collaborations fostered by TRIUMF extend beyond subatomic physics. For example, the TRIUMF Centre for Molecular and Materials Science (CMMS) benefits from its strong international user community (see Section 4.2.3.1). In the last 5 years, 84 of its experiments[2] had Canadian participation, 56 Japanese, 33 European, 22 American, and 3 South American.

Gateway to the Global High-Technology Community

Canada's world-leading expertise in key areas makes it a welcome member of international scientific collaborations, and in turn we benefit by accessing significantly more expertise and technology than would be possible if all

2 These numbers are obtained from an analysis of Molecular and Materials Science Experiments Evaluation Committee proposals.

developments were done domestically. TRIUMF is the lynchpin of this international involvement, fostering two-way information flow. It has memoranda of understanding with 32 foreign institutions in 16 different countries and has played key roles in Canadian involvement in international projects[3] in Europe, Japan, and the United States. Canada would not have had the same level of visibility or influence in these international experiments without the many TRIUMF contributions detailed elsewhere in this report. These contributions were only possible because TRIUMF combines the traditional strengths of a national laboratory with strong ties to the university research community.

Conversely, foreign collaborators are attracted to TRIUMF by its facilities and expertise. These visitors include senior scientists, post-doctoral fellows, students, and technical experts. Visitors come for lengths of time from a day to a year or two. Some bring equipment or materials, but all bring knowledge or expertise that strengthens the local scientific community.

Examples

International collaborations in science arise for three primary reasons. First, the specialized nature of the facility merits only a few sites worldwide. The original TRIUMF meson factory, ISAC-I and the CMMS fall into this category. Secondly, the undertaking benefits from, but does not require, the pooling of intellectual and physical resources to complete the task expeditiously. The international aspects of the undertaking tend to be limited in this case, but the benefits are very real as can be seen in the example of TITAN given below. Thirdly, the undertaking is too large for any one country to accomplish successfully alone. Therefore, many countries must collaborate in the enterprise, from detector and accelerator development, to construction, to the extraction of the physics results. The ATLAS and T2K experiments, described below, are examples of these collaborations.

Canada, through TRIUMF, is involved in partnerships following each of these models at a level appropriate for the size of the country. Several examples are highlighted here.

The TITAN Facility

The TITAN project exemplifies the role that TRIUMF plays as a beacon attracting international expertise to achieve Canadian objectives. Not only was this Canadian project significantly enhanced by foreign hardware and expertise, the facility has also achieved global pre-eminence and regularly attracts foreign researchers.

TITAN was first proposed in 2002 as a spectrometer for short-lived isotopes using a Penning trap. What distinguishes it from any other mass spectrometer is its ability to trap highly charged ions; all other such spectrometers work with singly or double charged ions. The critical component that provides the "charge-state boosting" is the electron beam ion trap (EBIT). Canada had limited expertise in the design and construction of an EBIT, and one had never before been coupled to a rare-isotope beam facility. These challenges were

3 These projects include ATLAS, T2K, BaBar, HERMES, G0, and Q_{weak}. Additional analysis is presented in Appendix B.

ISABEL TRIGGER

TRIUMF Research Scientist

Isabel Trigger graduated with a B.Sc. from McGill in 1994 and went on to complete an M.Sc. and a Ph.D. at the Université de Montréal between 1994 and 1999. Her M.Sc. thesis, "Evolution du spectre de dépôts énergétiques dans les détecteurs au silicium irradiés en protons," studied the ultimate performance of silicon-based precise tracking detectors in the presence of radiation for the LHC. Her Ph.D., "Mesure des couplages trilinéaires anomaux des bosons de jauge avec le détecteur OPAL au LEP," included definitive measurements of the self-coupling of standard model gauge bosons and is considered one of most challenging experimental analyses performed at the Large Electron Positron (LEP) Collider.

Dr. Trigger was awarded the competitive CERN Research Fellowship in 1999, leading to the exceptionally rare offer of a CERN research staff position in 2001. She personally performed the most general and comprehensive search for the "chargino" particles predicted by supersymmetric theories. Isabel was also a leader in the CERN team designing and testing the alignment system that monitors the relative positions of the 22 m diameter ATLAS endcap muon chambers with 50 μm accuracy.

In 2005, TRIUMF recruited Dr. Trigger to lead the establishment of an ATLAS physics analysis group. She is currently the ATLAS-Canada physics coordinator. ■

overcome thanks to TRIUMF's connection to the Max-Planck Institute for Nuclear Physics (MPI-K) in Heidelberg, Germany.

The Heidelberg EBIT group was developing a system for deployment at DESY (Deutsches Elektronen Synchrotron). A joint project was initiated and a memorandum of understanding was signed outlining the tasks of the two partners, MPI-K and TRIUMF. TRIUMF provided expertise for coupling trap systems to an accelerator-based beam line, and MPI-K contributed its unique EBIT expertise. Two identical EBIT systems were built at Heidelberg; one was shipped to Hamburg and the other delivered to TRIUMF.

During the entire two-year construction and commissioning phase, the TITAN group stationed a post-doctoral researcher and a graduate student in Heidelberg. In the final stage, two TRIUMF scientists joined them. Both the student and the post-doc have returned to Canada, bringing their newly acquired expertise. A group from Heidelberg came to help set up their equipment and integrate it into the TITAN experiment. A second Canadian post-doctoral researcher, who had previously worked at Heidelberg, is now in charge of the TITAN-EBIT and brings unique expertise to TRIUMF. In the meantime, having successfully operated the system at TRIUMF, the researchers from MPI-K are planning to carry out experiments in Vancouver. Moreover, upgrades at ISAC-II now foresee an EBIT charge breeder based on the local expertise gained from this international collaboration.

The ATLAS Experiment

The ATLAS experiment at CERN is an example of TRIUMF's role as the keystone of Canadian participation in the world's largest scientific endeavors (see Section 4.2.1.2.1). ATLAS was conceived to undertake the incredible task of searching for, and understanding, the origin of mass, the highest priority in particle physics. To obtain the high energy needed for this quest, the accelerator (the Large Hadron Collider (LHC) based on novel superconducting magnet technology) required an international collaboration. The experiment has taken a decade and a half to design, build, and commission, even with the combined efforts of 2,000 scientists and a corresponding army of technical staff. Every country with a significant scientific community, including Canada, is involved.

With the resources and talent of TRIUMF at its disposal, the Canadian particle physics community was able to actively participate in the ATLAS and LHC projects. TRIUMF accelerator physicists had unique expertise for the design and construction of critical parts of the accelerator. The resulting accelerator contributions were a necessary part of the Canadian investment in the project. TRIUMF scientists and technical staff were also crucial to helping the Canadian university community contribute to the design, construction, and commissioning of the ATLAS detector.

TRIUMF is also home to the ATLAS-Canada Data Centre, funded by the Canada Foundation for Innovation. This centre will pre-process the raw data from the experiment prior to analysis by Canadian and foreign researchers. It will also provide domestic detector experts access to raw data for detailed calibration and monitoring.

Canada is now in a position to reap the scientific rewards of this monumental international undertaking. The rewards promise to be the most exciting advances in decades in our understanding of the fundamental nature of matter. Not surprisingly, four CRC chairs are involved in this exciting research, and

TRIUMF has managed to attract CERN staff member, Dr. Isabel Trigger, back to Canada to lead Canadian analysis efforts of ATLAS data.

T2K

Neutrino physics illustrates the international nature of science and how Canada plays a leading role in international projects. Discoveries of neutrino oscillations in solar and atmospheric neutrinos by Super-Kamiokande (Japan) and SNO (Canada) opened an exciting new era in neutrino physics. Building on these successes, TRIUMF and Japanese scientists initiated the T2K (Tokai to Kamioka) long baseline neutrino project in 2000. This project has become the flagship neutrino project and has grown into an international collaboration of 12 countries from Europe, Japan, and North America, including all the G8 nations. The Canadian group introduced key components of the experimental design such as the off-axis beam concept; ν_{ue} appearance analysis method with water Čerenkov detectors, and CP violation studies. These tools have become standard in all next-generation, neutrino oscillation projects.

TRIUMF accelerator/beam line expertise provided critical input to the neutrino beam line design including a concept for dual kickers to abort and extract the beam, novel optics to transport the 1 MW primary proton beam, and a feasibility study for an innovative focus/bending combined function magnet. Handling of the extremely high radiation is paramount at a neutrino facility. For this TRIUMF engineers, in collaboration with KEK (Japan) and the Rutherford Appleton Laboratory group (UK), contributed to the design and construction of the remote handling mechanism in the target station.

For the detector construction, the Canadian group is in charge of some of the most challenging and critical items of the project: the time projection chamber (TPC), fine-grained calorimeter (FGD), and optical transition radiation detector (OTR). These projects are led by university researchers: TPC by D. Karlen (University of Victoria); FGD by S. Oser (UBC); and OTR by S. Bhadra (York University). These high-profile international contributions were only possible with strong support from TRIUMF, whose high quality work and expertise are recognized internationally. At the same time, accumulated detector expertise such as precision machining of the large TPC, development of scintillator extrusion techniques and fabrication of readout electronics, will be important assets for future Canadian projects.

The high profile Canadian role in the T2K collaboration attracted excellent young scientists to Canada, such as S. Oser (UBC, CRC Chair, Sloan Fellow) and Hirohisa Tanaka (UBC, IPP research scientist).

Collaboration with the Variable Energy Cyclotron Centre in India

The Variable Energy Cyclotron Centre (VECC) in Kolkata is managed and operated by the Government of India's Department of Atomic Energy. The first large accelerator at the centre was commissioned in 1980. VECC is presently commissioning a superconducting cyclotron and several rare-isotope beam accelerators, and they are planning the construction of several additional linear accelerators. TRIUMF's technical expertise in accelerator systems and its reputation for scientific excellence make it a natural partner for the VECC research program. VECC and TRIUMF are both members of the world-wide

Tesla Technology Collaboration (TTC), a collaboration of 45 institutes engaged in the free exchange of knowledge and technology aimed at applications of superconducting RF accelerator technology. A formal collaboration (Memorandum of Understanding) in superconducting radio-frequency technology between TRIUMF and VECC is being prepared.

TRIUMF and VECC are both developing plans to build new 50 MeV superconducting radio-frequency electron linear accelerators, referred to as "e-linac photo-fission drivers," to produce rare-isotope beams using actinide targets. The collaboration with VECC will allow the TRIUMF e-linac project to proceed on a faster time schedule by sharing technical expertise, resources, and costs. This arrangement benefits VECC in a similar manner. The Canadian and Indian e-linac facilities would follow the Organization for Economic Co-operation and Development recommendation that rare-isotope beam facilities be regionally based.

The goal of the first phase of the VECC-TRIUMF partnership is to develop jointly a single cavity horizontal test cryomodule. Two will be built: one for VECC and the other for TRIUMF. The cavities will be constructed by PAVAC, a local company, thereby bringing industrial activity and expertise to Canada. TRIUMF and VECC will fully develop all aspects of cavity production: high- and low-level RF techniques, power distribution schemes, and 2K cryogenics implementation. Scientific and engineering staff of VECC and TRIUMF will collaborate to develop the design and subsequently to build the required infrastructure. It is expected that Indian physicists and engineers will make extended visits to TRIUMF to share and jointly develop technical expertise. This partnership is an example of TRIUMF's ability to attract foreign-based researchers and investments to Canada.

3.3

TRIUMF's Role in Creating Synergistic Relationships with Commercial Partners

Although driven by a primary mission focusing on basic research, TRIUMF has positioned itself as a bridge across the traditional "valley of death" that separates inspiration and discovery from product development and commercialization in the marketplace. TRIUMF drives product development and commercialization in three different categories:

1. TRIUMF's expertise is in demand by companies who are looking to enhance their revenue-generating activities. By selling this expertise, either through licenses or by contracting out employees, TRIUMF not only helps these companies, it increases its own expertise and capabili-

ties. The award-winning relationship between TRIUMF and MDS Nordion is an example of this type of interaction.

2. TRIUMF trains people in specialized areas of expertise, and these people, in turn, take their expertise work in existing companies or to start new companies. Dehnel – Particle Accelerator Components and Engineering, Inc. (D-Pace), based in Nelson, BC, was started by Dr. Morgan Dehnel, a scientist who received his training at TRIUMF.
3. TRIUMF, as a laboratory doing leading-edge research, frequently requires equipment that is not available off-the-shelf but must be developed in conjunction with commercial suppliers. The expertise developed by these suppliers, with TRIUMF's help, then aids the supplier to generate additional business and, in some cases, significantly increase its top line. Richmond-based PAVAC Industries Inc. (PAVAC) is a prime example of TRIUMF helping a local company develop commercial expertise, in this case for superconducting cavity constructions.

Table 1 lists TRIUMF's significant business partners and the manner in which the lab interacts with them. "Enabling" cuts across all three of the categories and can involve many difference conduits for the transfer of knowledge. "Licensing" falls into Category 1. "Sales and Contracts" or Category 3 include cases where TRIUMF buys from companies at the same time it transfers knowledge to them. To illustrate how the transfer of expertise happens in practice, we highlight three different companies and show how each of the three categories works, keeping in mind, however, that most companies fall into more than one category.

Collaboration	Country	Enabling	License	Sales / Contracts
Advanced Applied Physics Solutions	Canada			
Advanced Cyclotron Systems	Canada			
Alstom	Canada			
CDS Research Ltd.	Canada			
Celco Plastics Ltd.	Canada			
CNC Machining	Canada			
D-Pace	Canada			
IE Power	Canada			
Isodose Control	The Netherlands			
MDS Nordion	Canada			
Pavac	Canada			
Profile Composites Inc.	Canada			
Superior Electroplating	Canada			
Thales	France			
UMA Engineering	Canada			
Upton Technical & Trading	Taiwan			

Table 1: TRIUMF's Significant Business Partners and Industrial Connections

Category 1: MDS Nordion

MDS Nordion is a division of MDS Inc., a transnational health and life sciences company based in Kanata, Ontario. It specializes in radioisotope production and radiation-related technologies used to diagnose, prevent, and treat disease. It supplies over two-thirds of the world's medical isotopes used for diagnosing heart disease, brain disorders, and infections. Its Vancouver facility on the TRIUMF site provides more than 15% of Canada's supply of medical isotopes.

The first therapeutic isotope Nordion produced at the Vancouver facility was Palladium-103 used in prostate brachytherapy. This isotope was developed in conjunction with TRIUMF using the first TR30 cyclotron, a cyclotron based on a TRIUMF design. MDS Nordion's new state-of-the-art commercial cyclotron facility at TRIUMF was completed on January 30, 2003. In May 2003, the company started using a second, newly purchased TR-30 cyclotron. Subsequently, with the official activation of the second beam in September 2003, Nordion has been able to double its production capacity of the Palladium-103 radioisotope. This improved production capability from the new machine is estimated to provide additional products for up to one million nuclear medicine procedures around the world each year.

MDS Nordion has licensed medical isotope production knowledge from TRIUMF. In addition, the three small cyclotrons Nordion uses for isotope production are owned and operated, under contract, by TRIUMF. A low-energy proton beam from the main TRIUMF cyclotron is also used to produce heart-imaging isotopes for MDS Nordion. These activities generate royalty income for TRIUMF and help Nordion compete in the global market. If TRIUMF did not exist, the MDS Nordion Vancouver operation would cease as well: the highly skilled labour TRIUMF supplies for this particular work is simply not available anywhere else in Canada. In return for its support of MDS Nordion, TRIUMF benefits from MDS Nordion's skill and experience in commercial production, marketing and transport of isotopes.

A 1995 report by the US Institute of Medicine's Committee on Biomedical Isotopes cited the TRIUMF-MDS Nordion relationship as a model of public-private partnership, one that could be emulated in the United States. The report stated that the Department of Energy: "… should encourage such a partnership between one or more for-profit institutions and at least one not-for-profit institution (university, national laboratory, or some combination) to operate NBTF [National Biomedical Tracer Facility]."

TRIUMF and MDS Nordion won the Natural Sciences and Engineering Research Council of Canada (NSERC) 2004 Synergy Award for Innovation for their outstanding 26-year university-industry partnership. The award was one of only seven awarded that year, and one of two granted in the Large Companies category.

Category 2: Dehnel – Particle Accelerator Components and Engineering, Inc. (D-Pace)

D-Pace is a TRIUMF spin-off company that provides state-of-the-art engineering products and services to the particle accelerator industry. Its founder and president, Dr. Morgan Dehnel received his graduate training at TRIUMF. D-Pace specializes in complete beam line system designs, charged particle transport systems, as well as components for cyclotrons, ion implanters, and linear accelerators, including quadrupole and dipole magnets, vacuum boxes, and beam diagnostic devices. The internationally recognized D-Pace hires out its highly knowledgeable and professional staff to work with engineers and managers of other companies, most notably in the semiconductor industry on ion implantation, and at institutes, such as the Institute of Nuclear Energy Research in Taiwan, on ion source and beam line technologies.

The years of close co-operation between TRIUMF and D-Pace took a major step forward in December 2001 when D-Pace licensed a group of cyclotron component technologies from TRIUMF. The company has since generated sales from the ion source technology it licensed from TRIUMF in Europe and Asia. Since the licensing relationship began, TRIUMF has provided assembly space for training D-Pace's staff and has allowed D-Pace to subcontract TRIUMF when its specialized services are not available elsewhere in Western Canada. D-Pace worked with TRIUMF staff to document much of the lab's know-how into manufacturing drawings and technical manuals, thus preserving valuable knowledge for training and future use. Combined with the licensed technologies, this information is available to both parties through a cross-licensing feature in their agreement.

With continuing encouragement and support from TRIUMF, D-Pace has grown into a successful business that has an impact on both the national and local economies. D-Pace has doubled its revenues in each of the past four years and now has customers from France, Japan, South Korea, Taiwan, the Netherlands, and the United States. D-Pace's success in Nelson, BC has resulted in the hiring of local subcontractors in scientific modeling, electronic engineering, technical writing, web design, marketing, business development, and machining. Moreover, Dr. Dehnel is a founding member of five non-profit organizations dedicated to improving the scientific, technological and business sectors in the Kootenay region in British Columbia, as well as supporting local schools' science and technology programs through judging, donations, and lectures.

TRIUMF and D-Pace won the 2007 Synergy Award for Innovation for small- and medium-sized companies. This award was one of only seven given to university-industrial partnerships within all of Canada.

Category 3: PAVAC Industries, Inc.

On April 14, 2008, a team of BC scientists and engineers drawn from the TRIUMF laboratory and PAVAC Industries, Inc., announced that they had entered into an elite worldwide league of groups that are able to manufacture ultra-sophisticated superconducting accelerator technology. The BC team was able to fabricate, assemble, and test a high-tech device known as a "superconducting radio-frequency cavity" or SRF cavity. These superconducting devices are assembled into modules to form next-generation accelerators with applications in health care, environmental mitigation and remediation, advanced materials science, and high-energy physics. This success is a first for Canada and registers the country as one of only five countries in the world with this coveted capability.

The TRIUMF team had sought out PAVAC Industries, Inc., in Richmond, BC for their expertise in the tricky step of careful welding in a vacuum. PAVAC is a world leader in developing commercial high-energy electron beam applications, most notably the PAVAC LASTRON beam for electron-beam welding, which was integral to the manufacture of the cavities. TRIUMF scientists had developed the first stage of the project using cavities fabricated in Italy. During the second stage of the project, the TRIUMF/PAVAC partnership was formed with the goal of developing a "Made-in-Canada" solution. PAVAC's contract with TRIUMF has translated into a $C600,000 pay cheque for the company. The newly acquired capability will enable PAVAC to bid for other projects at major laboratories and institutions around the world.

Conclusion

A recent Statistics Canada study found that "…it is the broad set of university degree holders in a city that is consistently connected to job growth. However, the effectiveness of this group is enhanced when combined with a higher share of scientists and engineers—specialized workers who are directly involved in developing and implementing innovations" [Statistics Canada, *The Daily*, Jan. 8, 2008]. Statistics Canada found a correlation among technology, science, and industry. TRIUMF and its commercial partners reveal the mechanisms behind the correlations. MDS Nordion, D-Pace, and PAVAC all illustrate the different ways a high-technology facility seeds technological development and job growth.

Chapter 4

Successes: Impacts 2003–2008

Chapter 4

Successes: Impacts 2003–2008

4.1

Introduction

Over the past five years, TRIUMF's programs in scientific research, education, and commercialization have enjoyed considerable success—and many have had substantial impact. This section describes those successes. Ultimately, these programs are based on pure research in subatomic physics and exploit the opportunities provided by TRIUMF's core facilities and its synergy with the university research community. TRIUMF actively applies the expertise developed for subatomic physics to other areas of research, to the recruitment and training of the next generation of technological leaders, and to the generation of entrepreneurial opportunities. Areas for expansion beyond subatomic physics have been carefully chosen so that TRIUMF's unique capabilities can help resolve additional important science questions and provide health and economic advantages to Canadians. Thus, the core program of nuclear, particle, and accelerator physics has expanded to cover key niche areas in life sciences and molecular and materials science. Consequently the TRIUMF research program has become interdisciplinary with cross-fertilization among different areas of the program.

In the pursuit of scientific excellence, TRIUMF has developed three core competencies that thread through all its activities. TRIUMF's primary core technical competency is the design, operation, and use of particle accelerators and related beam lines. The facilities associated with this competency include the cyclotron itself, the additional accelerators detailed in the next chapter, the beam transport lines, targets for producing secondary beams and high-power beam tuning stations. They generate and provide the beams required for the "end users" of the rare-isotope program at ISAC, the Centre for Molecular and Materials Science (CMMS) program, and major experiments such as TWIST and PIENU. All the secondary beam experiments rely on sophisticated beam transport and in addition much of the rare-isotope program relies on additional acceleration of the secondary beams. The life sciences program requires rare-isotopes produced by the TR13 cyclotron and the expertise acquired operating the 500-MeV cyclotron. The Canadian teams participating in T2K and ATLAS have used TRIUMF accelerator expertise to expand the capabilities of the laboratories where these experiments are based. Many of TRIUMF's successes with private-sector partners are driven by its accelerator expertise.

The second core technical competency that runs throughout the research program is the production, isolation, and use of rare-isotopes. This is especially true for the ISAC program, the life sciences program, commercialization including MDS Nordion, and the βNMR/βNQR segments of the CMMS program. This competency also distinguishes TRIUMF as one of a few facilities in the world with the skill and expertise to provide comprehensive training in nuclear science and engineering, medical isotopes, and related areas.

The third core competency is the expertise required to build and operate detector facilities. These state-of-the-art facilities are essential for all of TRIUMF's scientific activities — ISAC, CMMS, ATLAS, T2K, and life sciences.

Taken together, these core competencies allow TRIUMF to pursue a world-class research program that has real impact in scientific understanding, training the next generation of leaders, and commercialization of technology. This chapter outlines recent achievements in each of these areas. Although the topics are organized by scientific thrust, it is important to recognize that the TRIUMF program cuts across the traditional disciplinary distinctions in academia. The following examples highlight these types of synergies.

Among the highlights of the past five years is the precision measurement of the mass of ^{11}Li, an anomalously large nucleus. It is the shortest-lived isotope that has ever been studied in a Penning trap and demonstrates the potential of the TITAN facility which has recently set world records in absolute and relative accuracy for measurement of nuclear masses. The mass measurement is one of a series of measurements that elucidates the properties of halo nuclei and ^{11}Li in particular and relies on TRIUMF's ^{11}Li beams — the world's most intense (see the section on halo nuclei). The rare-isotope program at ISAC, of which TITAN is a part, attracts outstanding graduate students to Canada and provides training for workers in the nuclear science and engineering industries (medical isotope production and use, nuclear energy) that cannot be obtained elsewhere in Canada.

In particle physics, TRIUMF has worked closely with the Canadian university community to make significant contributions to the recently commissioned ATLAS detector at the Large Hadron Collider at CERN. The ATLAS Tier 1 data centre, located at TRIUMF, will be the largest academic computer in Canada by 2011 and will allow Canadians to reap the benefits of one of the largest scientific endeavors ever undertaken. In another leading particle physics field, Canadian contributions to the T2K long-baseline neutrino experiments, enabled by the TRIUMF laboratory, will make it possible to address critical questions in one of the most compelling fields in fundamental research.

As a multi-program laboratory, TRIUMF also supports interdisciplinary projects that cut-across the traditional academic departments. The ALPHA project is a perfect example; the Canadian team includes particle physicists, condensed-matter physicists, atomic physicists, and accelerator scientists in a premier experiment to trap and study antihydrogen at CERN. TRIUMF scientists are involved in all aspects of the experiment; electronics and data-acquisition software developed at TRIUMF play a key role in ALPHA, highlighting the synergies of inter-laboratory collaboration.

In the life sciences area, TRIUMF continues its world-leading partnership with the Pacific Parkinson's Research Centre. TRIUMF's expertise in radioactive-isotope production has driven the production of world-leading radio-tracers, enabling otherwise impossible medical diagnostic techniques. Through this and other activities, TRIUMF's life sciences program is literally saving lives every day.

The CMMS has developed unique capabilities, for example the high transverse spin polarized muon beams, and has made important advances in both pure and applied science. The centre has helped understand the properties of high-temperature superconductors and it has worked on green chemistry; for example, the properties of zeolites used in the petrochemical industry have been studied along with hydrogen storage for energy applications. TRIUMF's expertise and its irradiation facilities have also enabled technical investigations of condensed-matter physics processes in radiation environments with implications for applied technologies.

TRIUMF is internationally recognized as an example to be emulated in the area of commercialization and it continues to have success in the commercialization of its new ideas. It has won two NSERC Synergy awards, one with MDS Nordion and the other with D-Pace, for its successful transfer of knowledge to Canadian industry. The small company, D-Pace, was created by a former TRIUMF graduate student and has used licensed expertise from TRIUMF to develop and sell ion sources. TRIUMF has also received a Centre of Excellence for Commercialization and Research (CECR) award to establish a commercialization partner company called Advanced Applied Physics Solutions, Inc. The CECR award will contribute $14.95 million over 5 years to link major discoveries with commercial interests and bring them to the marketplace.

The TRIUMF laboratory was founded as a laboratory for fundamental nuclear physics research, leading to the development of core technical competencies in accelerator physics and advanced particle detector techniques while maintaining an environment of national collaboration with the Canadian university community and international collaboration with world-leading laboratories. These competencies have enabled continued Canadian excellence in international particle and nuclear physics while also providing opportunities for unique leadership roles in disciplines such as nuclear medicine, medical imaging and molecular and materials science. TRIUMF has also actively motivated generations of students to choose high-tech careers, and successfully led the commercialization of advanced technologies to the benefit of the Canadian economy and general public. TRIUMF is a unique resource in Canada, paying dividends across its entire program.

4.2

Advancing Knowledge

4.2.1

Subatomic Physics

4.2.1.1

Rare-Isotope Beam Experiments

4.2.1.1.1

Introduction

There is a worldwide renaissance in nuclear science, driven by new and unexpected experimental results from improved experimental techniques, theoretical breakthroughs, and expanded applications. In all three areas, TRIUMF plays a leading role now. It is poised to play an even larger role in the future.

Experimentally, new facilities to produce and use radioactive isotopes far from the valley of stability are being proposed and built worldwide. Previously our understanding of nuclei was based mostly on stable nuclei or nuclei near the line of stability. Now we are exploring the limits of stability and how nuclear properties change in these regions. There are multiple motivations for these facilities and the study of isotopes far from stability: Explosive stellar events such as novae and supernovae are controlled by the properties of such short-lived isotopes. The synthesis of heavy elements follows paths through the landscape of these short-lived isotopes. Important tests of the fundamental symmetries of nature are also possible with rare isotope beams. Underlying all these are the intellectually challenging questions of how nuclear properties and structure evolve as we move from the valley of stability; creditable calculations of stellar explosions and nucleosynthesis require accurate knowledge of nuclear structure.

TRIUMF currently has an active program with radioactive isotopes, exploiting light nuclei and neutron-deficient nuclei. TRIUMF's beams, in many cases world leading, are matched with a similarly world leading set of experimental apparatuses. The funding agencies, NSERC and CFI plus foreign agencies, have validated TRIUMF's program by supplying the multi-million dollar funding for these experiment apparatuses. One apparatus alone, TIGRESS, cost more than eight million dollars. With the additional beam lines and the wider range of isotopes proposed in the present plan TRIUMF will be able to fully exploit its experimental faculties and continue leading the world in this field.

There have recently been profound changes in the theoretical understanding of the properties of nuclei. This is largely driven by new theoretical insights and increased computer power. In particular, the roles of the renormalization group and effective interactions are now much better understood. It is now realized that the strong repulsive short-range interaction that has plagued nuclear physics since its inception can be tamed by renormalization techniques to generate an interaction appropriate for the energy scale of low energy nuclear physics. New many body techniques, the no-core shell model or coupled cluster calculations, are now using the improved interactions to calculate the nuclear properties without the introduction of any free parameters. With the recent hire of A. Schwenk, a leader in this revolution, and our active Theory Group TRIUMF is now in a position to take a leadership role in the new developments and to increase the impact the new theoretical developments will have on experimental studies.

Once the objects of academic curiosity, rare isotopes, are now a mainstay in medicine. Nuclear medicine uses short-lived isotopes for real time imaging, diagnostics, medical research, and treatment. TRIUMF's long-term involvement in this area has assisted MDS Nordion in developing a successful business selling accelerator-produced isotopes. TRIUMF is also involved in other life sciences programs such as PET studies of Parkinson's disease.

4.2.1.1.2.1

The Structure of Halo Nuclei

Introduction

Physicists have been able to study the atomic nucleus for over half a century, but until recently this exploration could only be done with stable nuclei, including for example, the nuclei of metals such as iron and silver, and gases such as oxygen and hydrogen, which are found in abundance on our planet. These nuclei are called stable because they have a fairly balanced number of protons and neutrons and remain intact; they do not undergo natural decay processes. Beyond the stable nuclei, an enormously wide variety of unstable exotic nuclei exist in the universe in a variety of stellar environments. The nucleus of an isotope that has too many or too few neutrons compared to the number of protons is unstable and the imbalance of energy within the nucleus will cause these nuclei to decay into stable nuclei. Unstable nuclei are part of nature and often act as pathways for creating the stable nuclei found on Earth.

Exotic nuclei often don't occur naturally on Earth and they don't remain in existence very long. They could not be produced by physicists until recently, resulting in only a partial view and understanding of the nucleus. It was only two decades ago that our view of the nucleus was revolutionized when the short-lived nucleus ^{11}Li was found, a nucleus with an exotic nuclear halo structure.

A halo nucleus is oversized and fragile, the exact opposite of a stable atomic nucleus, which is small and dense. The outermost neutrons, called the halo neutrons, are found an unusual distance away from the core nucleus, forming a halo around it (Figure 1). ^{11}Li is a ^{9}Li nucleus with two additional halo neutrons, making the nucleus as large as a ^{208}Pb nucleus, having 208 protons and neutrons compared to 11 in the lithium isotope.

Lithium-11 is a unique three-body quantum systems composed of $^{9}\mathrm{Li}+n+n$, known as a Borromean system, where any two of the subsystems taken together are unbound, meaning there is not sufficient energy present to hold them together. In the vast sea of nuclear species these objects are located at the extreme edge of existence, far away from the valley of stable nuclei.

The nuclear halo is characterized by one or two weakly bound nucleons, a factor of 10-20 times less bound than in stable nuclei, forming a spatially extended low-density halo around a compact core. Formation of halo requires the weakly bound nucleons to have a significant probability to reside outside the range of the potential of the core. This phenomenon of quantum mechanical tunnelling of the wave function is possible for nucleons with small one- or two-neutron separation energies and for residing in orbitals with low angular momentum, typically l=0 and 1, such that the effect of the centrifugal barrier is minimal. The existence of a nuclear halo and the above requirement necessarily points towards the fact that the nuclear orbitals undergo a change in their ordering as they move away from the valley of stability. This rearrangement therefore leads to a major change of the shell structure that has formed a basic pillar of nuclear physics; the subsequent changes in shell structure for unstable nuclei are quite unlike the electron shells of atomic physics that stay the same for all elements of the periodic table.

The high quality rare-isotope beams (RIB) at ISAC-I makes TRIUMF one of the world's premiere facilities on which to perform precision measurements of nuclear halos and to probe into the evolution of nuclear shell structure as we move away from the valley of stability. Specifically, the high intensity, best quality ^{11}Li beam at ISAC-I has led it to play a very important role in defining the nuclear halo. Some of the significant findings in this direction are discussed below. The long-term goal, as we gain access to heavier unstable nuclei, is to unravel the unknown isospin dependence of nuclear structure.

Results and Progress

Correlation of Halo Neutrons in ^{11}Li

The correlations of the two halo neutrons in ^{11}Li are expected to differ from the nuclear correlations in stable nuclei for several reasons. First, the two halo

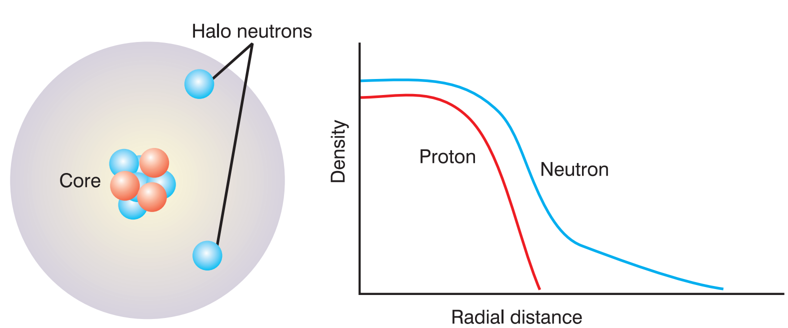


Figure 1: Schematic view of a two-neutron halo.

neutrons are somewhat decoupled from the core and therefore have very small overlap with the wave function of protons inside the core. Secondly, the halo neutrons are very weakly bound and close to the neutron emission threshold. Thus, the continuum states might have important effect on the neutron-neutron correlation. Thirdly, the low density of the halo neutrons suggests possible changes in the pairing correlation. Two extreme modes for spatial correlations can be imagined. In the first, the two neutrons are located on opposite sides of the core, *i.e.*, 180° apart, and this mode is known as the cigar configuration. In the second, the two neutrons are on the same side of the core, and this mode is known as the di-neutron configuration. Over the last decade, various attempts have been made to elucidate the two-neutron correlation. Experiments at TRIUMF have made a significant impact on unveiling the halo neutron configuration in ^{11}Li.

Two-neutron Transfer Reaction ^{11}Li(p,t)^{9}Li

The two-neutron transfer reaction is a highly sensitive way of probing the correlation of the halo neutrons. The shape and magnitude of the angular distribution carries information on the neutron orbitals and the spatial and momentum correlations. This pioneering halo experiment was the first performed at the new ISAC-II facility.[1] It used an active gas target TPC-type detector, MAYA, from GANIL in Caen, France. The reaction was performed at two different energies, E/A = 3.6 MeV and 5 MeV, in order to disentangle structure and reaction effects on the angular distributions.

A new interesting observation was the population of ^{9}Li in its first excited state (½⁻), shown in the Q-value spectrum in Figure 2a. A complete understanding of this population is still underway. If this is not a reaction effect, then it indicates a new component in the halo neutron wave function of ^{11}Li, namely

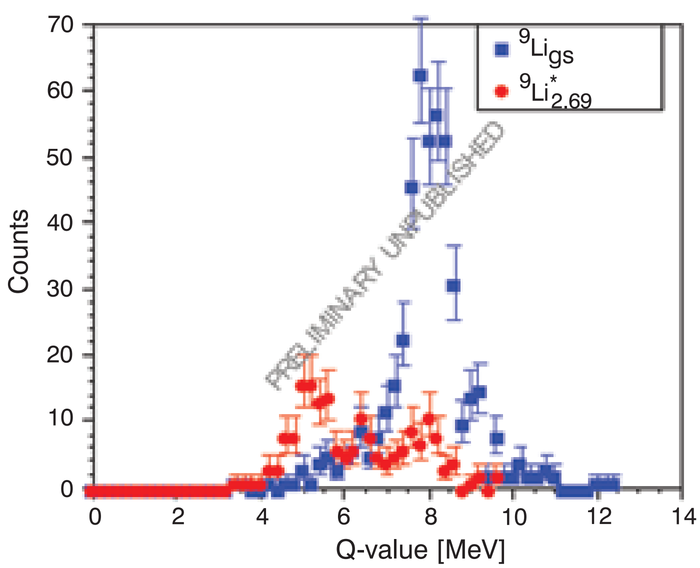


Figure 2a: Q-value spectrum for ^{11}Li(p,t)^{9}Li reaction. The squares (blue) show ^{9}Li ground state while the circles (red) show the ^{9}Li excited state.

1 I. Tanihata *et al.*, Phys. Rev. Lett. 100, 192502 (2008).

the coupling of the two neutrons to J=1⁺ and/or 2⁺ configuration, in addition to the J=0⁺ configuration.

The angular distribution is shown in Figure 2b. The backward rise in the cross section is indicative of a dominating sequential transfer process. The large magnitude of the cross section can be explained with a high *s*-wave component of the two-neutron wave function. The curves in Figure 2b are results of a preliminary theoretical effort to understand the two-neutron correlation using coupled channel calculations with the simultaneous and sequential transfer processes added coherently. The different curves show three-body wave functions of ^{11}Li based on the Fadeev model that differ in the neutron-neutron correlation and *s*-wave fraction. The P0, P2, P3 models have *s*-wave fractions of 3%, 35% and 45%, respectively. The data favour the two neutrons being on the same side of the core. However, it is clearly seen that the calculations do not reproduce the detailed features of the angular distribution. The high-quality data will provide a strong constraint on the wave function of ^{11}Li, and further theoretical testing and improvements of the nucleon-nucleon interaction will be required.

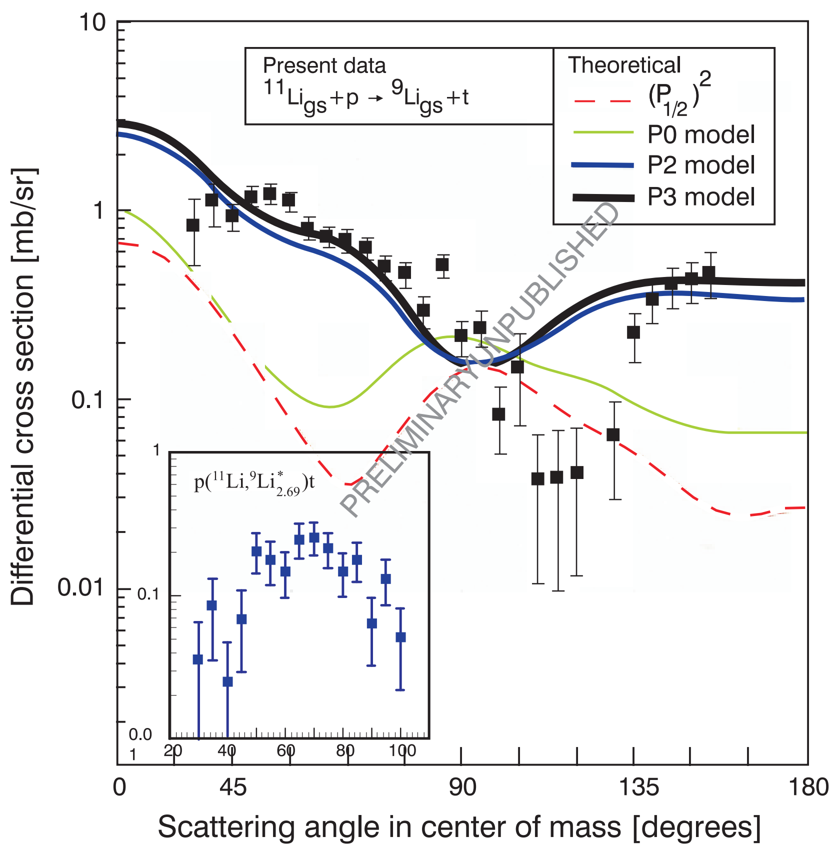


Figure 2b: The angular distribution data for ^{11}Li(p,t)^{9}Li (squares). The curves are coupled channel calculations using different model wave functions as explained in the text.

Charge Radius of ^{11}Li

A general question is whether the formation of the neutron halo affects the proton distribution in ^{11}Li. Moreover, the proton distribution in ^{11}Li should also influence the arrangement of halo neutrons. The formation of the neutron halo can be probed by measuring the isotopic shifts of different lithium isotopes. Here, the isotope shift refers to the modification of the electron binding energy due to different number of neutrons for the same element. Only TRIUMF has sufficiently intense beams to do these experiments. The observations in Figure 3 show a gradual decrease of the charge radius moving from ^{6}Li to ^{9}Li, after which it abruptly rises for ^{11}Li. This may be expected due the difference in the centre of mass of ^{11}Li and the centre of mass of the ^{9}Li core, with the interpretation that the two neutrons are correlated on the same side of the core. The observed rise in charge radius compared to various theoretical model predictions seems to be best explained with a combined effect of neutron correlation and core excitation. Charge-radius determination provides, together with the mass measurements, the most sensitive tests of sophisticated nuclear theory in systems where *ab initio* calculations can be performed.

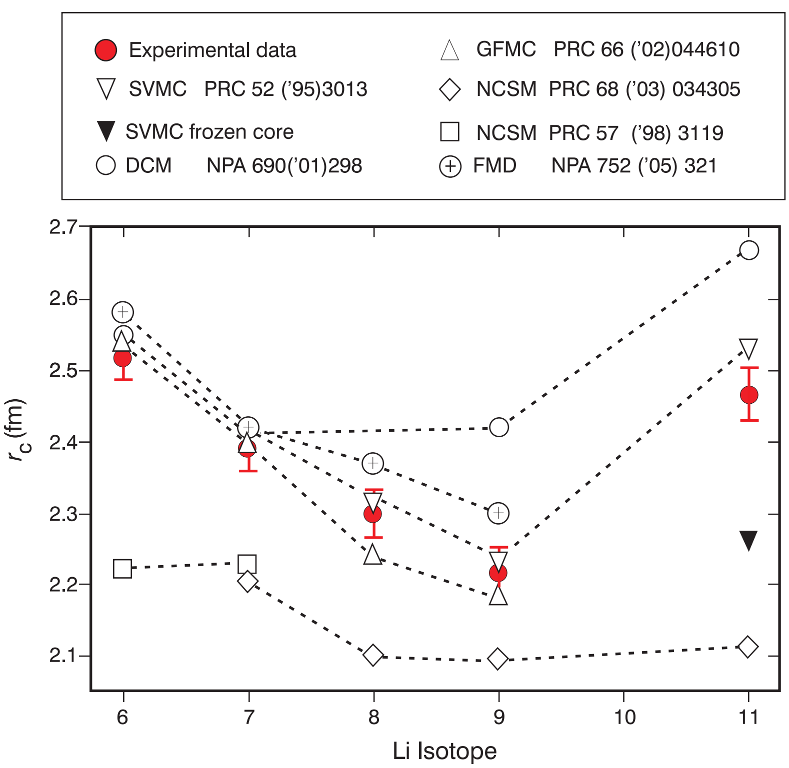


Figure 3: Charge radii for $^{6\text{-}11}$Li. (Figure adopted from Phys. Rev. Lett. 96 (2006) 033002.) The red filled circle shows the experimental data. The other symbols are the different theoretical calculations. SVMC= Stochastic Variational Monte Carlo, DCM = Dynamic Correlation Model, GFMC = Green's Function Monte Carlo, NCSM = No core shell model, FMD = Fermionic molecular dynamics.

Masses of Halo Nuclei

Mass measurements for halo nuclei are of very high importance for two reasons: mass measurements give access to the neutron separation energy, determining how tightly the halo neutrons (or protons in the case of proton halos) are bound. It gives a concrete experimental anchor point to fine tune theoretical models. Moreover, masses are key to the determination of charge radii. The charge radius comparison to the matter radius determines the scale of the halo. The most sensitive way to measure the charge radius is via isotopes-shift laser spectroscopy. The laser spectroscopy is extremely precise and sensitive; however, it provides only indirect access. The measured shift needs to be deconvolved with the mass shift and the field shift, which requires precision atomic theory calculations, which in turn need experimental input on the same level of precision. In the case of light nuclei around mass 10, the required mass precision is on the order of 1 keV/c^2.

Recently, high precision mass measurements of halo nuclei have been carried out with the newly commissioned TITAN Penning trap mass spectrometer at TRIUMF. TITAN has the unique capabilities to carry out direct precision mass measurements (as compared to indirect reaction-based measurements) on short-lived nuclei, due to the very versatile modular set up of the spectrometer. Mass measurements of short-lived halo nuclei ^{8}He, ^{11}Be, and ^{11}Li were carried out. Lithium-11 is the shortest-lived isotope for which Penning-trap mass measurements have been performed. The precision achieved was around 1 keV for all three isotopes, corresponding to an improvement of a factor of 20 for ^{8}He (see Figure 4a) and for ^{11}Li (see Figure 4b), and an almost decade long controversy between conflicting precision measurements could be solved with the first direct Penning trap mass result.

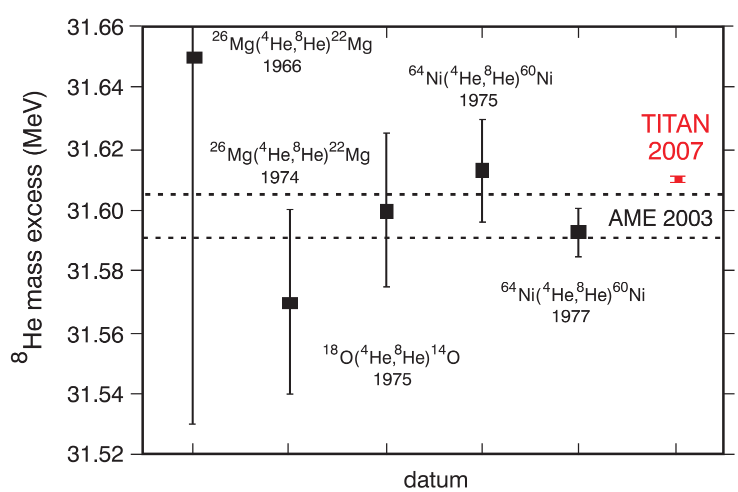


Figure 4a: Comparison of mass excess of ^{8}He measured using different methods as labeled in the figure.

Spectroscopy of ^{10}Li : The Unbound Sub-system of ^{11}Li

The resonances in the neutron-unbound subsystem, ^{10}Li, play important roles in our understanding of the two-neutron halo in ^{11}Li. Several experiments have sought to obtain a picture of the low-lying resonance in ^{11}Li. The earlier experiments based on fragmentation production processes provided a signature for the existence of resonances, though their resonance energies could not be well determined. The one neutron ^{9}Li(*d,p*)^{11}Li transfer reaction at Michigan State University's NSCL facility suggested either one resonance ~ 300±15 keV or two resonances of 200 keV and 700 keV. On the other hand, the reaction experiments at the same energy at CERN's ISOLDE facility showed existence of a *p*-wave resonance around 376 keV and a low-lying *s*-wave virtual with a negative scattering length ~ 13-24 fm. A recent experiment at TRIUMF has begun to clarify the resonance situation in ^{10}Li through a one-neutron transfer from ^{11}Li, by the ^{11}Li(*p,d*)^{10}Li reaction. The analysis of these data is presently in progress.

Beta Decay of ^{11}Li

The beta decay of ^{11}Li offers indirect ways to constrain the wave function of the halo neutrons. Experiments at TRIUMF have sought to identify the decay channels that occur exclusively in the halo and also the channel that involves only the core neutrons keeping the halo intact.

The beta decay of the halo has been found to occur through the beta-delayed deuteron emission from ^{11}Li. This weak channel, with a branching ratio of $1.3\text{x}10^{-4}$, is nearly two orders of magnitude stronger than the delayed deuteron emission from ^{6}He. It has been well understood from the ^{6}He decay that the beta-delayed deuteron emission from the core nucleus interferes destructively with that from the halo, thereby reducing the total beta-delayed branching ratio. The relatively larger beta-delayed branching ratio for ^{11}Li suggests that the decay occurs mainly in the halo.

On the other hand, the major beta-decay branch proceeds through beta-delayed one-neutron emission. Within these possible delayed neutron decay

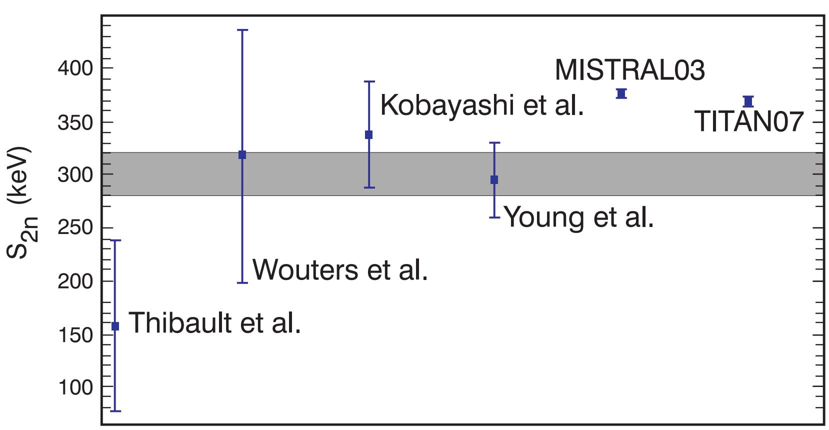


Figure 4b: Comparison of two-neutron separation energy for ^{11}Li from different mass measurements as labeled in the figure.

paths, it was observed that decay of the 8.81 MeV unbound level in ^{11}Be proceeds to two bound states of ^{10}Be, 2_2^+ and 2^-. This pattern is interpreted as the emission of one of the surviving halo neutrons in the $s_{1/2}$ orbital leading to the 2^+ state in ^{10}Be, while the halo neutron in the $p_{1/2}$ orbital gives rise to the 2^- state in ^{10}Be[2]. These experiments provide important and unique information about the decay processes of halo nuclei.

Levels in ^{11}Be from Beta-delayed Decay of Polarized ^{11}Li

The beta-delayed gamma and neutron decay from polarized beams provides a unique and unambiguous way to determine the spin and parities of the excited states in the daughter nucleus. This method takes advantage of the fact that the allowed beta decay from a nucleus shows an angular distribution that is proportional to the angle of emission, asymmetry parameter, and polarization of the nucleus. The asymmetry parameter takes different discrete values depending on the possible spin and parities. Polarized beams for radioactive species are presently available only at TRIUMF, particularly for halo nuclei.

The levels of the one-neutron halo nucleus ^{11}Be were investigated using the beta decay of polarized ^{11}Li at TRIUMF. New spin and parity assignments could be made for several excited states. The new findings were important to revise our understanding on the 8.82 MeV level in ^{11}Be, which was previously attributed to be a halo-survival state from ^{11}Li based on an assumption of $5/2^-$ spin for this state. Measurements of the decay, including neutron detection, will be possible at the 8π facility after upgrades.

Halo Features in ^{12}Be: ^{11}Be(*d,p*γ)^{12}Be

Lithium-ll is a Borromean nucleus with a two-neutron halo. The question remains whether non-Borromean nuclei can also have a two-neutron halo structure. The lightest nucleus that is attractive to investigate this feature is ^{12}Be (the N=8 isotone located just above ^{11}Li). Unlike ^{11}Li, the two-neutron separation energy of this nucleus is fairly large $S_{2n} = 3.673 \pm 0.015$ MeV, and its subsystem ^{11}Be is a one-neutron halo nucleus. ^{11}Be$_{gs}$ has been found to have an abnormal spin $J^{\pi}=½^+$, with the last neutron dominantly occupying the $2s_{1/2}$ orbital. Adding one more neutron to ^{11}Be, to form ^{12}Be$_{gs}$(0^+) raises the question of whether this neutron also resides in the $2s_{1/2}$ orbital, filling it up, or whether the pairing between the two neutrons inhibits them from residing in the *s*-orbital and therefore more likely that they occupy the *d*-orbital. Furthermore, recent observation of a long-lived 0^+ state in ^{12}Be(0_2^+; 2.24 MeV) makes it important to probe whether ^{12}Be exhibits halo features in this excited state instead of its ground state. There has been no investigation yet to ascertain this. The long-lived state is mixed in the ^{12}Be beam that is used in fragmentation-type RIB facilities to study ^{12}Be. The conclusions on ^{12}Be$_{gs}$ from such investigation therefore might be influenced by the ^{12}Be(0_2^+; 2.24 MeV) state.

In order to exclusively investigate the halo features, a reaction that is specifically selective to the *s*-wave occupation of the neutrons is desirable. To this end, the one neutron transfer to ^{11}Be$_{gs}$ through the ^{11}Be(*d,p*γ)^{12}Be reaction is investigated at TRIUMF. Through this reaction we are able to investigate

2 F. Sarazin *et al*., Phys. Rev. C 70 (2004) 031302R.

simultaneously the *s*-wave component in $^{12}Be_{gs}(0^+)$ as well as the long-lived excited state of $^{12}Be(0_2^+; 2.24$ MeV). The reaction is performed in coincidence with gamma rays in order to unambiguously separate the population of the $^{12}Be(2^+;2.1$ MeV) and $^{12}Be(0_2^+; 2.24$ MeV). This pioneering transfer reaction in coincidence with gamma detection for unstable nuclei is accomplished using the TIGRESS segmented Germanium detector array and segment silicon detectors. A preliminary test was performed in December 2007 that clearly indicated the population of the $^{12}Be_{gs}$ as well as excited states.

Change of Shell Closure in *N*=6, 8 Region

The confirmed existence of the halo in ^{11}Li and also in ^{11}Be shows that the last one or two neutrons in these nuclei abnormally occupy the $2s_{1/2}$ orbital, instead of the $1p_{1/2}$ orbital. This shows that the $2s_{1/2}$ orbital is lowered compared to its location in stable nuclei. The intruder $2s_{1/2}$ orbital into the *p*-shell region leads to a quenching of the *N*=8 shell gap. This has been discussed based on a lower excitation energy of the first excited state in *N*=8 nuclei, ^{12}Be as well as the *s*-wave occupation in this nucleus. The above described study on ^{12}Be, through $^{11}Be(d,p\gamma)^{12}Be$ reaction, will help to shed light on this.

Theoretical calculations investigating changes in shell closure have suggested the possibility of a gap appearing at *N*=6 for neutron-rich nuclei. This was investigated at TUDA, TRIUMF through the $^{9}Li(d,t)^{8}Li$ reaction probing the ground state configuration of the *N*=6 isotone ^{9}Li. The spectroscopic factor obtained (Figure 5a) for the neutron to occupy the $p_{3/2}$ orbital provides us the signature of the shell gap at *N*=6. It was found to be largely different from an earlier work at ISOLDE. The total spectroscopic factor for neutrons in the $p_{3/2}$ orbital is found to decrease in going from *Z*=5, 6 to *Z*=3, 4 isotopes (see Figure 5b). The evolution of the *N*=6 subshell gap shows (Figures 5b, c) that the gap is larger for stable nuclei, *i.e.*, *Z*=5, 6 nuclei, and decreases as one comes down to neutron-rich *N*=6 isotones with *Z*=3, 4. However, since the *N*=8 shell gap has disappeared the reduced *N*=6 shell gap then shows shell-closure like features in this region. It is probably because of this reason that ^{9}Li has the smallest charge radius in chain of Li isotopes. The *N*=6 helium isotope, ^{8}He, also has a reduced charge radius and stronger binding compared to ^{6}He.

Disappearance of Shell closure in *N*=20 region

The disappearance of the conventional *N*=20 shell closure is considered, in the light of the shell model, to be due to increased binding of the *2p2h* (particle-hole excitation in *sdpf* shells) intruder configuration compared to the normal 0*p*0*h* spherical configuration. Interest lies in identifying the nuclei for which the mixing of intruder configuration sets in. Calculations for the Na isotopes indicate that this change should occur from ^{29}Na. Beta-delayed gamma decay of $^{29}Ne \rightarrow {}^{29}Na$ have identified levels in ^{29}Na that are interpreted to be consistent with the Monte Carlo shell model predictions including intruder mixing. This has led to the present understanding that in Na isotopes ^{29}Na marks the onset of the breakdown of *N*=20 shell gap. To confirm on the amount of mixing of the intruder configuration experimentally, the Coulomb excitation of ^{29}Na has been investigated at TRIUMF using the TIGRESS gamma detector array and BAMBINO silicon detectors. The first excited state of ^{29}Na was observed to be excited (see Figure 6). The B(E2) value derived will be able to place constraints on the intruder mixing in this nucleus. The B(E2) for the first excited

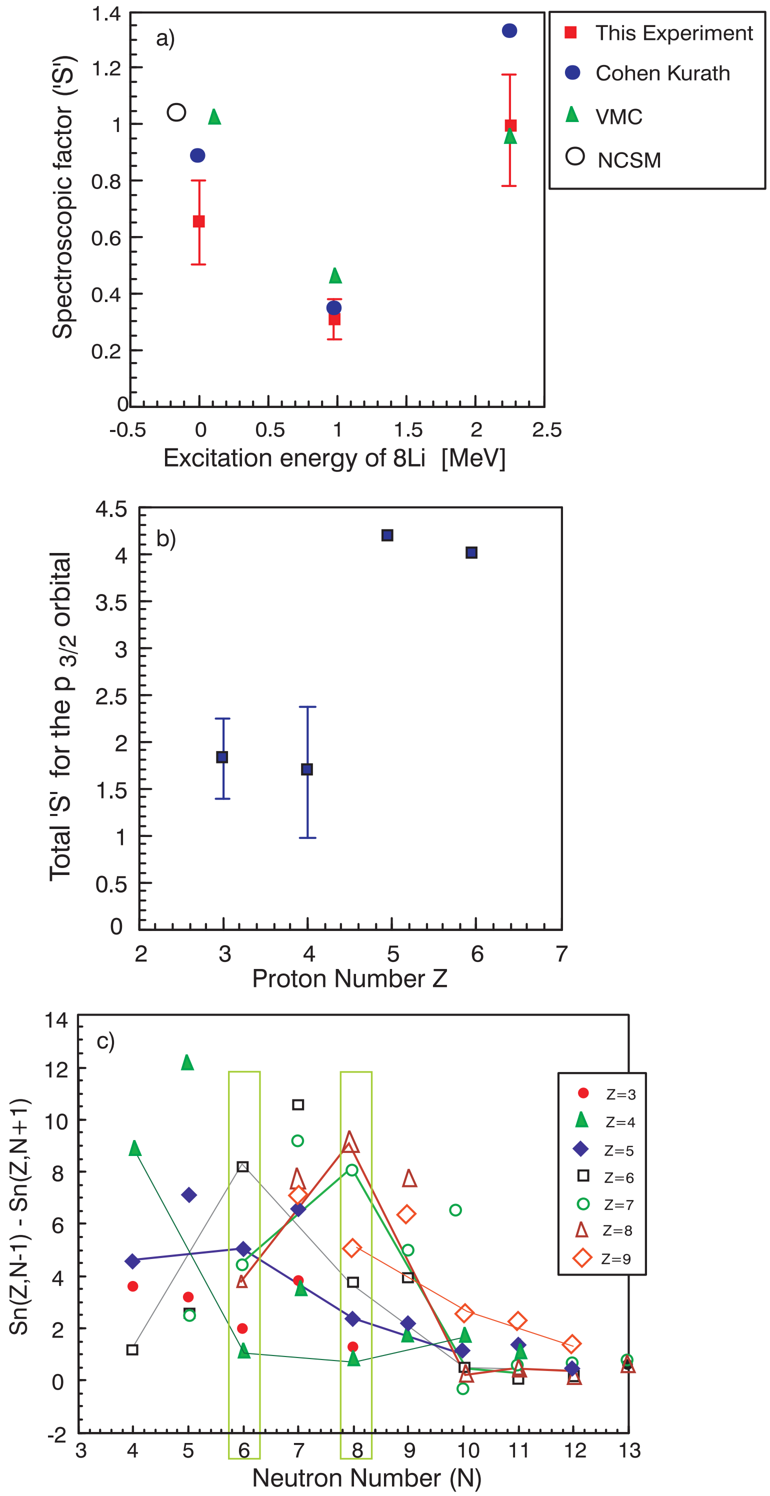


Figure 5: (a) Spectroscopic factors for (^{9}Li,^{8}Li) overlaps compared to various theoretical predictions. VMC = Variational Monte Carlo, NCSM = No core shell model. (b) Total spectroscopic factors for $p_{3/2}$ orbital in the N=6 isotones from Li to C. (c) A measure of shell gap at N=6 and N=8 from the difference in one-neutron separation energy. The lines join isotopes with even neutron number (N). Adopted from R. Kanungo et al., Phys. Lett. B660, 26 (2008).

state $5/2^+$(72 keV) → $3/2^+$(g.s.) is highly sensitive to the configuration mixing. A change in mixing ratio from 0 to 42% corresponds to an increase in B(E2) from $111e^2fm^4$ to $135e^2fm^4$. This will therefore help in illustrating the gradual evolution of breakdown of N=20 shell closure for Na isotopes. The capability of performing Coulomb excitation below the barrier and with sufficient cross section at ISAC-II makes TRIUMF an important facility for these measurements.

Partners

In Canada: McMaster University, Simon Fraser University, Saint Mary's University, TRIUMF, University of Guelph, University of Manitoba, University of Toronto.

International Partners: Belgium (1), France (1), Germany (2), Japan (2), Spain (3), United Kingdom (3), United States (4).

TRIUMF's Role

The experiments described above were performed at the TRIUMF ISAC-I facility, primarily by using the on-site detector facilities, which include TIGRESS, TITAN, and TUDA. An additional detector system, MAYA, an active target, was brought to TRIUMF from GANIL. The efficient usage of the best-suited facility for the experiment illustrates TRIUMF's capacity for easy adaptability, which provides scientists with the optimum facilities to achieve their physics goals.

TRIUMF personnel as well as associated Canadian university personnel have often been the principal investigators for many of the above projects. In projects where spokespersons are non-TRIUMF personnel, TRIUMF has provided intellectual and infrastructure support.

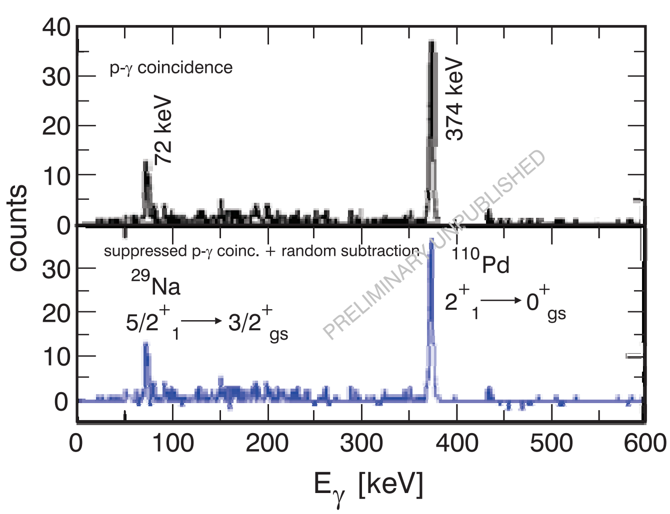


Figure 6: Gamma rays observed in the Coulomb excitation of ^{29}Na.

4.2.1.1.2.2

The Structure of Heavy Nuclei

Introduction

The atomic nuclei that exist in the universe are mainly hydrogen and helium, comprising 98% of the total nuclei. The remaining 2% are the "heavy" elements, including iron, copper, and gold and they have not been fully investigated or understood. Using various techniques, particularly interesting short-lived forms of the heavy elements can be created that test our understanding of nuclear structure, provide vital data for understanding the energy generation in stars and other astronomical events like supernovae, and may provide a glimpse of the physics beyond the standard model of particle physics.

Research into the structure of heavy nuclei, which in the present context implies nuclei with mass greater than 20 (the sum of the numbers of protons and neutrons), is focused on two main themes. The first theme is the evolution of shell structure where neutrons and protons orbit the centre of a nucleus analogous to the orbiting of electrons in shells about the centre of the atom. The second theme is the development and evolution of collective excitations in nuclei, which depends on the composition of the nuclei (the number of protons and neutrons) and how these particles interact with each other. The two themes, evolution of shell structure and the development and evolution of collective excitations in nuclei, are intimately connected because collective modes are emergent only when there are a sufficient number of valence nucleons that will support the degrees of freedom required. A prime example of this is the development of the rotational degree of freedom: a number of valence nucleons of both protons and neutrons must be present, obtained either by the filling of orbitals in open shells, or by the breaking of pairs in closed shells, such that the quadrupole-quadrupole interaction causes the onset of a static deformation required to break spherical symmetry.

The development of rare-isotope beams worldwide has opened new vistas in nuclear structure research, allowing for the exploration of structure at the extremes of the proton-to-neutron ratio and the isospin degree of freedom. TRIUMF's ISAC-II facility has been very active in this field of research, with the number of dedicated experiments growing. The program will expand with the development of additional neutron-rich species produced from an actinide target.

Results and Progress

Evolution of Shell Structure

Physicists have known for some time that the locations of orbitals for both protons and neutrons evolve with proton and neutron number, and to a large degree, these have been determined for nuclei on the neutron-deficient side of the valley of stability. However, drastic changes in shell structure have been predicted in some theories for neutron-rich nuclei that have dramatic consequences for the limits of stability and the location of the *r*-process path (see section 4.2.1.1.3 on nuclear astrophysics). Some of the most striking observations are the appearance of new magic numbers and the disappearance of others resulting in rotational-like behaviour in nuclei once predicted to have a closed shell structure. Such a situation is encountered in the "island-of-inversion" region near ^{32}Mg, where the re-arrangement of orbitals is thought to be due to the weakening of a spin-dependent proton-neutron force. However, substantial uncertainties in the level scheme of ^{32}Mg remain — only the first-

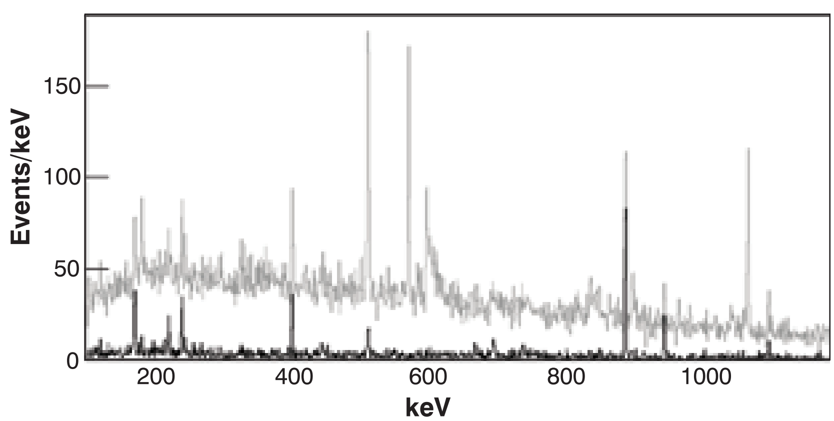


Figure 1: Projections of the γγ coincidence matrix (light spectrum) and βγγ coincidence matrix (dark spectrum) resulting from ^{32}Na β-decay. The use of the β-particle coincidence removes the uncorrelated background allowing for the transitions to be identified and placed in the ^{32}Mg level scheme. From C.M. Mattoon et al., Phys. Rev. C 75, 017302 (2007).

excited state has a firm spin-parity assignment, and there is substantial debate over the location of the first 4^+ state.

In the first experiment using the combination of two spectrometers called SCEPTAR (Scintillating Electron Positron Tagging Array) and 8π, the β decay of $^{32}Na \rightarrow {}^{32}Mg$ was explored. While the beam intensity of only a few ions/s was insufficient to perform the detailed spectroscopy needed for spin-parity assignments, many previous transitions were confirmed, with additional transitions incorporated into the level scheme including a new level assigned. Figure 1 displays portions of the projection of the $\gamma\gamma$ coincidence matrix, without the requirement of a β-particle coincidence (light-grey curve) and with a β-particle coincidence (dark curve), allowing the firm identification of the transitions resulting from the β-decay of ^{32}Na. Further experiments await the development of the actinide target that will increase the yield of ^{32}Na ions by orders of magnitude.

As part of a program to study the relationship between the shell structure and collectivity, the first experiment that used TIGRESS at ISAC-II was completed in summer 2007. Beams of ^{29}Na, which borders the "island of inversion", at a rate of 400 – 600 s^{-1} were Coulomb excited by a target of ^{110}Pd. The γ-rays from both the ^{29}Na beam and the ^{110}Pd target were observed with sufficient statistics that should allow the $B(E2)$ values to be extracted with an uncertainty of <15%, and may represent the lowest-rate Coulomb-excitation experiment to date.

While used to investigate the ability of the 8π spectrometer to make lifetime measurements to a precision better than 0.1% required for the Fermi superallowed β-decay program, the β-decay of ^{26}Na provided detailed spectroscopy of ^{26}Mg and the extraction of the *B(GT)* values. Shell model calculations were found to be in excellent agreement with the *B(GT)* values up to 7 MeV excitation energy.

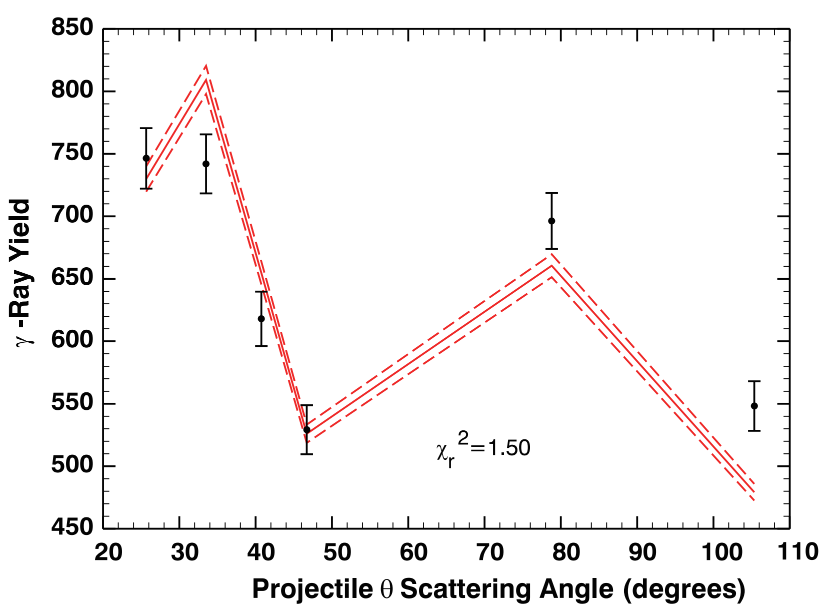


Figure 2: Yields of the ^{21}Na 332-keV $5/2^+ \rightarrow 3/2^+$ transition as a scattering angle. The curves represent calculated yields using the GOSIA code.

Studies have also been made on the neutron-deficient side of the valley of stability. In the first measurement with the TIGRESS detectors, beams of ^{21}Na/^{21}Ne and ^{20}Na were accelerated using ISAC-I to an energy of 1.7 MeV/u and Coulomb excited using a ^{nat}Ti target which had an effective thickness of about 450 μg/cm^2. The structure of ^{21}Na is of interest due to its proximity to the proton drip line (^{19}Na), whereas the structure of ^{20}Na is important for the determination of the ^{19}Ne(p,γ) reaction rate. The $B(E2;5/2^+ \rightarrow 3/2^+)$ values for ^{21}Ne and ^{21}Na mirror nuclei were deduced from the γ-ray yields, as shown in Figure 2, measured relative to the ^{48}Ti $B(E2;2^+ \rightarrow 0^+)$ value. The ^{21}Ne result is in excellent agreement with previous results. The ^{21}Na $B(E2;5/2^+ \rightarrow 3/2^+)$ value is approximately 50% larger than in ^{21}Ne, indicating a much higher degree of collectivity than expected from shell model calculations. Preliminary results have been published. Analysis of the ^{20}Na yields is in progress.

Investigation of Collective Excitations

Nuclei near the Z=50 closed shell exhibit many features expected for spherical vibrational systems. The Cd nuclei, in particular ^{110,112}Cd, have in fact been used as paradigms of vibrational or, in the language of the Interacting Boson Model, $U(5)$ structure for the past several decades. Recent measurements using the $(n,n'\gamma)$ reaction, however, have begun to cast doubt on the appropriateness of the vibrational interpretation. As part of a much wider program to study the evolution of shell structure in the Cd and Pd nuclei as neutron number N=82 is approached, the β-decay of ^{112}Ag was studied with the 8π spectrometer in July 2007. Beams of ^{112}Ag approaching 10^6 ions/s were used in the first experiment, with the 8π incorporating the Detector Array for multi-Nucleon Transfer Ejectiles (DANTE) array of BaF_2 detectors. Analysis of the data has commenced, but already previous unknown collective transitions between excited states have been observed in the γγ coincidence spectra.

The N=90 region of nuclei has been the subject of intense study over the past

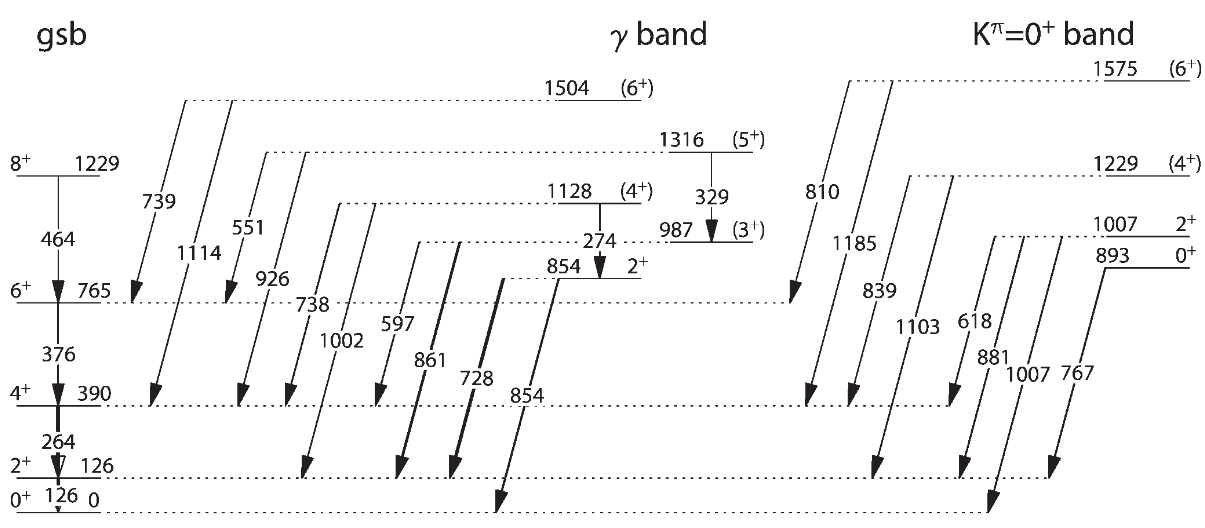


Figure 3: Partial level scheme for ^{160}Er established from ^{160}Tm decay observed with the 8π spectrometer. From P.E. Garrett et al., Acta Physica Polonica B 38, 1169 (2007).

several decades, and remains at the forefront of structure research due to the suggestion that there exists a phase transition in the shape degree of freedom in nuclei near to ^{152}Sm, with *N*=90 the critical point. New models of structure have been developed based on solutions to the Bohr Hamiltonian, with ^{150}Nd, ^{152}Sm, and ^{154}Gd cited as the best examples of the new benchmark. Many *N*=90 nuclei can be produced copiously at ISAC-I, and the 8π spectrometer has been used extensively in a program of very detailed measurements seeking critical weak branches that provide sensitive tests of these structure models. Beams of *A*=156, 158, and 160 have been studied with the goal to examine the *N*=90 nuclei ^{156}Dy, ^{158}Er, and ^{160}Yb. Because of the need to observe very weak γ-decay branches between highly excited states, very high-statistics data sets are needed, often resulting in more than 1 TB (1000 GB) of data collected in experiments. Data analysis is still ongoing, with some preliminary results on the *N*=92 nucleus ^{160}Er, which is important to establish systematics in the region, shown in Figure 3.

The evolution of isomeric states in neutron-rich nuclei is of wide interest, as these shed light on the interplay between single-particle and collective degrees of freedom. A program of study has commenced to search for the very high-spin isomers in the mass 180 region — the long-lived $t_{1/2}$=31 year, K^π=16$^+$ isomer in ^{178}Hf being the famous example. The first experiment in this program utilized a source of ^{178}Hf to seek weak, high-multipolarity branches from

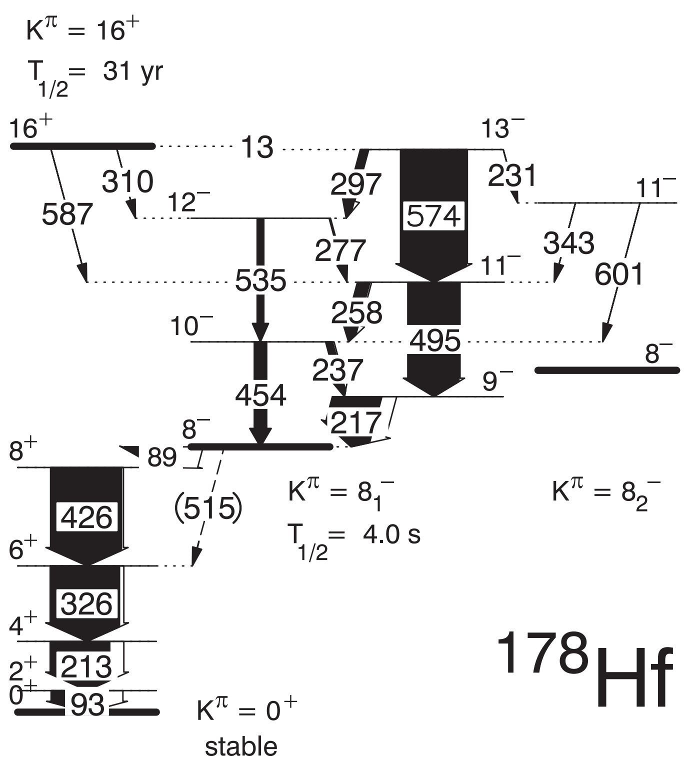


Figure 4: Level scheme following the decay of the $t_{1/2}$ = 31 y K^π=16$^+$ isomer in ^{178}Hf observed with the 8π spectrometer. The 310 keV M4 and 587 keV E5 transitions are newly placed. From M.B. Smith et al., Phys. Rev. C 68, 031302(R) (2003).

the high-spin isomeric state. New transitions with *M4* and *E5* multipolarity were identified, representing the first definitive observation of direct γ-ray emission from the isomer as shown in Figure 4. This observation extended the knowledge of hindrance factors for *K*-forbidden transitions to very high-spin levels. Further work investigating the heavy Tm isotopes discovered a new isomeric state in ^{174}Tm with a half-life of 2.29 s. The use of the Pentagonal Array for Conversion-Electron Spectroscopy (PACES) Si(Li) detectors was crucial in establishing the isomeric decay scheme and spin-parity of the parent state, as shown in Figure 5, due to the highly converted nature of the 152 keV *E3* transition.

Partners

For the 8π spectrometer, in Canada: McMaster University, Queen's University, Saint Mary's University, Simon Fraser University, and the University of Guelph. International Partners: Georgia Institute of Technology and the Lawrence Livermore National Laboratory in the US.

For TIGRESS, in Canada: McMaster University, Saint Mary's University, Simon Fraser University, University of Guelph, and the University of Toronto. International Partners: Georgia Institute of Technology and the Lawrence Livermore National Laboratory, University of Rochester (US), and the University of Liverpool (UK).

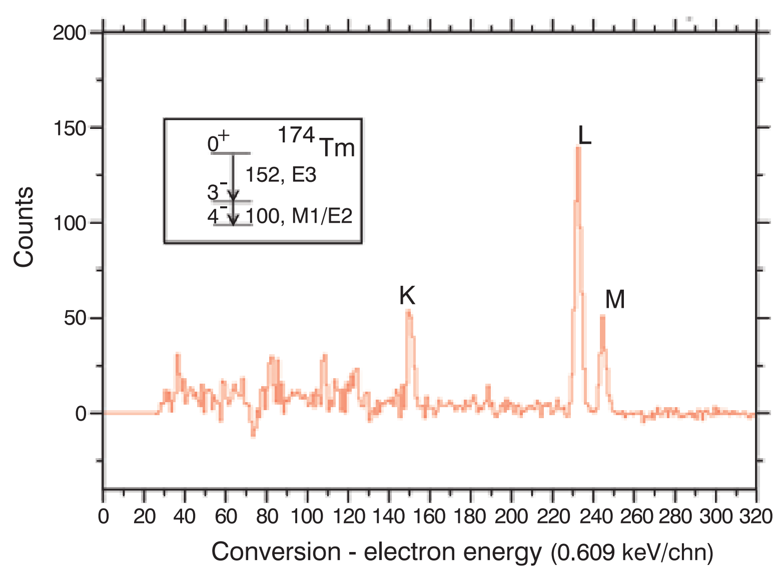


Figure 5: Conversion electron spectrum in coincidence with the 100 keV γ-ray in ^{174}Tm. The use of PACES was critical in establishing the isomer decay scheme (inset). From R.S. Chakrawarthy et al., Phys. Rev. C 73, 024306 (2006).

TRIUMF's Role

TRIUMF contributes greatly to the operation of the 8π and TIGRESS spectrometers, providing a full-time technician as well as two staff scientists. For the 8π spectrometer, in addition to the manpower, TRIUMF has provided design work for SCEPTAR and PACES auxiliary detectors, and funding for the electronics for DANTE. For TIGRESS, TRIUMF has provided an additional technician during the crucial building phase of the frame, a large amount of design effort, machine-shop time, and data acquisition support.

The scientific programs have benefited greatly from the development of new ion sources, especially the laser-ion source TRILIS, and continued beam development.

4.2.1.1.3

Nuclear Astrophysics

Introduction

Nuclear astrophysics brings together the latest developments in astronomy and theoretical and experimental nuclear physics in a quest to understand the origins and evolution of all the naturally occurring chemical elements in the universe, without which the world as we know it would not exist. Nuclear astrophysics requires an intimate knowledge of the inner workings of stars, particularly either those that die in energetic explosions such as supernovae or undergo cataclysmic thermonuclear blasts, such as novae and X-ray bursts. All the chemical elements except the very light hydrogen, helium, and lithium were created in nucleosynthesis processes in hot stellar environments such as stars, novae, and supernovae. The underlying processes that govern the evolution of these objects are the interactions between atoms, and the microscopic properties of individual nuclei.

The field of nuclear astrophysics aims to solve the mystery of the origins of the chemical elements and to understand the physics and evolution of cataclysmic variable stellar systems such as novae and X-ray bursts. Sophisticated models are used to predict and reproduce the observations seen with the latest generation of astronomical observational tools. Crucially, the nuclear physics input to the models is based on laboratory measurements, making these models as close to reality as current technology and techniques allow. Most of the key nuclear reactions that are important to the study of these environments involve short-lived radioactive nuclei.

The ISAC facility at TRIUMF is the ideal location to study these nuclei and their reactions because of its combination of beams of short-lived nuclei, variable-energy accelerators, and a suite of world-class experimental facilities. The nuclear beams, the accelerators, and experimental facilities have been optimized for studying reactions of astrophysics interest.

Results and Progress

Current research indicates that the observed abundances of the chemical elements, measured in carbonaceous chondrites (meteorites) and the solar atmosphere, have arisen via a series of nucleosynthesis processes occurring in the quiescent burning phases of stars and various explosive burning scenarios. The taxonomy of these processes reflects the geographical landscape of the resulting isotopic abundances (see Figure 3 in Chapter 2), with the A > 74 stable isotopes on the neutron-deficient side of stability being denoted the "*p*-nuclei" and are produced via a so-called "*p*-process". The majority of nuclei in the valley of stability are produced by the "*s*-process," a series of slow neutron captures on stable seed nuclei with a nucleosynthesis path that involves stable nuclei mostly. The neutron-rich and the heaviest nuclei are produced by the "*r*-process," a series of rapid neutron captures.

While some general details of these nucleosynthesis processes are known, the detailed picture remains shrouded in mystery. The *s*-process, what could be described as the least complex of the three processes, is fairly well described by the canonical distribution, an "astrophysics-free" model resulting from the exposure of an iron-rich initial composition to a parametric neutron-flux distribution.

The *r*-process in contrast, is one of the greatest mysteries in astrophysics. The abundance peaks seen in the isotopic distributions were quickly realized to have arisen due to the presence of closed neutron shells, and that the process must involve a series of rapid neutron captures way out into unexplored neutron-rich territory, competing at every turn with photodissociation reactions and beta decay. The global and specific nuclear properties of the nuclei involved in this path are needed in order to construct a realistic model of the *r*-process. Required properties of the nuclei include the ground-state masses (in order to calculate neutron-separation energies), beta decay half-lives and branching ratios, nuclear excited state properties, and radiative-capture reaction rates.

Thus the measurement of these properties in neutron-rich nuclei constitutes the major justification for the proposal to develop neutron-rich nuclear beams at TRIUMF. Another very important thrust has been focused on questions related to processes on the neutron-deficient side of stability due to the availability of accelerated radioactive ISOL beams at intensities unique in the world. The large range of experimental facilities at ISAC have exploited these beams to delve into the realms of explosive hydrogen and helium burning in sites such as supernovae, X-ray bursts, and classical novae.

Explosive Hydrogen Burning and Characteristic Gamma Emitters

A large effort exists to measure the reactions involved in explosive hydrogen burning, which is thought to occur in hydrogen-rich hot places such as accreting binary systems, both X-ray binaries and classical novae, and supernovae. In these systems, reaction rates of proton capture and other charged-particle reactions are required not only to construct viable physical models of the systems, but also to enable predictions and reproductions of observables such as luminosity curves, ejected isotopic abundances and, most relevantly, yields of characteristic γ-ray emitting radioisotopes observed by the latest generation of space-based telescopes. The γ-ray emitters, such as ^{18}F, ^{22}Na, ^{26}Al, ^{60}Fe, and ^{44}Ti, have long been sought after as diagnostic tools of explosive stellar models. Gamma rays from ^{26}Al and ^{60}Fe have now been observed in the bulk of the interstellar medium in our galaxy, while γ-rays from ^{44}Ti have been observed in an individual supernova remnant.

The most hoped-for observational signal in γ-ray astronomy, for classical novae, is the 1,275 keV γ-ray from the decay of ^{22}Na ($t_{1/2}$=2.6 yr). Because model predictions indicate that it is made prolifically in the set of reactions of the thermonuclear runaway in a nova explosion, its decay can provide a detectable flux of γ-rays for such space-based observatories as the European Space Agency's International Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellite. Sodium-22 is synthesized within the NeNa cycle via a

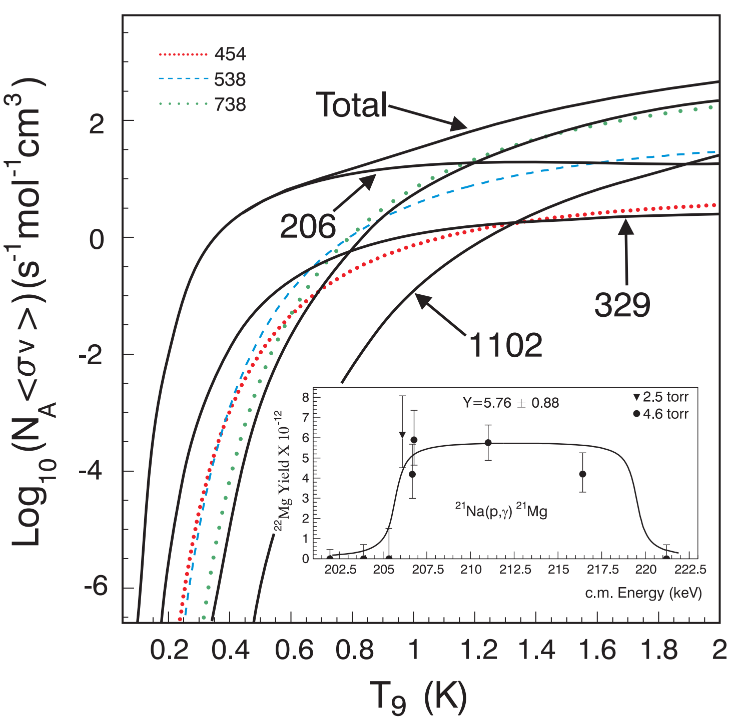


Figure 1: Temperature-dependent reaction rates for the ^{21}Na(p,γ)^{22}Mg reaction, showing contributions from some of the resonances measured at DRAGON. **Inset:** Thick-target scan over the narrow, dominant 206 keV resonance.

reaction sequence involving many stable and radioactive isotopes. Estimates predict a detectable ^{22}Na signal from novae within a distance of around 1000 parsecs of Earth. Peak temperatures in the thermonuclear runaway reach 0.4 x 10^9 K in some O-Ne nova models, and hence resonant reactions dominate these reaction pathways in a centre-of-momentum energy regime of ~100 to ~1000 keV for proton capture reactions. Present theoretical estimates of the relevant nuclear structure have insufficient accuracy to enable reliable reaction rate calculations. Vital experimental information on the strengths and positions of resonances is required to enable credible model predictions of sufficient accuracy to satisfy the capabilities of the observational satellite-based instruments.

Until very recently, several reactions contributing to the formation and destruction of ^{22}Na were unknown experimentally. Amongst them, ^{21}Na(p,γ)^{22}Mg was known to have a large influence on the synthesized ^{22}Na yield. In addition, a brute-force, γ-ray spectroscopy measurement recently revealed a previously unknown resonance in the ^{22}Na(p,γ)^{23}Mg reaction, which threw that reaction rate into considerable uncertainty.

Measurement of the ^{21}Na(p,γ)^{22}Mg Reaction

At ISAC-I, a large campaign has been waged to determine experimentally the ^{21}Na(p,γ)^{22}Mg reaction rate. A direct measurement (see Figure 1) of all the known resonances in the reaction was made with the DRAGON facility using an accelerated ^{21}Na beam of energy range 200A–1500A keV impinging on a windowless re-circulating hydrogen gas target (see report on DRAGON Facility). Each of these resonances was measured down to the 20% uncertainty (1σ) level required for the nova models [J.M. D'Auria *et al.*, Phys. Rev. C 69

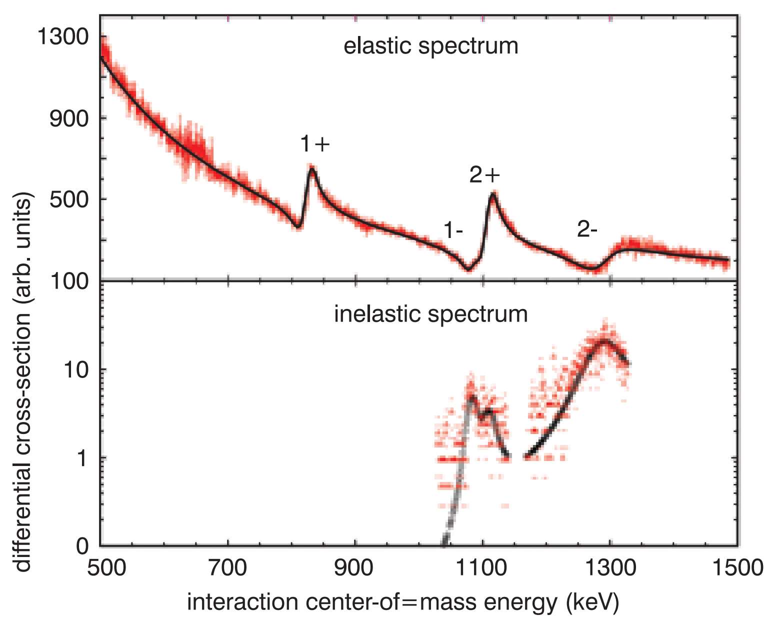


Figure 2: TUDA excitation function from ^{21}Na(p,p) and ^{21}Na(p,p') scattering, fitted with a multichannel R-matrix.

(2004)]. In parallel, the complimentary TUDA facility performed resonant elastic scattering studies with the ^{21}Na beam impingent on a CH_2 target, in the centre-of-momentum energy range 500–1500 keV/c^2, identifying states in the ^{22}Mg compound nucleus, both known and previously unknown, and using R-Matrix fits to attempt spin-parity assignments, partial width, and resonance energy measurements (see Figure 2). These data enabled an ordering of the ^{22}Mg level scheme, which determined that all the contributing resonances to the ^{21}Na reaction had been measured directly by DRAGON. Consequently, the ^{21}Na(p,γ)^{22}Mg reaction is considered the most well-measured reaction rate involving a rare-isotope nucleus and is often cited as a textbook example of how such measurements are made.

The ^{21}Na(p,γ)^{22}Mg reaction rate determined at TRIUMF was stronger than the limited theoretical estimates, leading to a faster destruction of ^{22}Na during the thermonuclear runaway and consequently a smaller ejected yield. Taken alone, this would somewhat increase the detectability distance of a classical nova, an important consideration when attempting to observe a nova with a γ-ray observatory. However, accurate estimates will not be possible until all the contributing reactions have been put on a firm experimental basis as has the ^{21}Na(p,γ)^{22}Mg reaction.

One such reaction, and the next target for the TRIUMF astrophysics program concerning the production of ^{22}Na, is the measurement of a newly discovered ^{22}Na(p,γ)^{23}Mg resonance. This reaction can best be studied by exploiting the massive intensities of ^{22}Na produced by ISAC-I's high power silicon carbide targets to implant ^{22}Na targets and to perform a traditional prompt γ-ray measurement. The DRAGON group has successfully implanted several of these targets and designed a dedicated high-vacuum chamber, which has been constructed and installed at the Center for Experimental Nuclear Physics and Astrophysics (CENPA) at the University of Washington, Seattle. These TRIUMF targets will be used in conjunction with the intense and high quality tandem-produced proton beam to measure the resonance to high accuracy, further slashing the uncertainties of the nova ^{22}Na production rate and giving reliable estimates of ^{22}Na fluxes for astronomers. This measurement is now underway.

Measurement of the ^{26g}Al(p,γ)^{27}Si Reaction

Also of significant importance to explosive hydrogen burning scenarios is the synthesis of the radioisotope ^{26}Al. This isotope, with its characteristic γ-ray at 1809 keV, has long been a target for γ-ray astronomers. Because of its relatively long half-life [$t_{1/2}$=(7.2±0.2)x10^5 yr], it provides insufficient flux given the ejected yields from stellar objects to enable detection from an individual source. However, the bulk of the ^{26}Al produced in our galaxy from all sources does provide enough γ-ray flux to be measured (see Figure 3).

Since its first detection by the NASA High Energy Astronomy Observatory HEAO-3 satellite, its distribution in our galaxy has been extensively studied, most recently using the INTEGRAL satellite, which was able to show that the material was co-rotating with the visible matter in the galactic plane using Doppler-shift studies of the 1809 keV line. The observed distribution of ^{26}Al is correlated with the 83 GHz microwave "free-free" map denoting the ionized interstellar medium, suggesting that its concentration in regions of high star formation points to massive stars as progenitors. Indeed, recent massive star models, including core-collapse supernovae and the Wolf-Rayet phases of more massive stars, can produce a total amount of ^{26}Al that is commensurate with observations when incorporated into galactic chemical evolution models. However, significant contributions from other sources such as Asymptotic Giant Branch (AGB) stars and classical novae cannot be ruled out, and past nova models have predicted that up to 20% of the total observed ^{26}Al could come from novae. This percentage is, however, at odds with observation, and the nova models, to be creditable, must be based on experimental reaction rates that give the correct ejected yields of ^{26}Al.

Of the reactions that affect ^{26}Al production in the thermonuclear runaway of a classical nova, the ^{25}Al(p,γ)^{26}Si and ^{26g}Al(p,γ)^{27}Si reactions are particularly important (here the suffix g denotes the ground state of ^{26}Al as opposed to the 6-second lifetime isomeric state at 226 keV, which is not significantly thermally populated at nova temperatures). The ^{25}Al(p,γ)^{26}Si reaction is an ISAC-I high-priority approved experiment, which required additional research and development for producing an intense ^{25}Al beam. However, an intense ^{26g}Al beam is possible because of the long half-life of the isotope and the substantial production factors in an ISAC-I high-power silicon carbide target. The uncertainty in the ^{26g}Al(p,γ)^{27}Si reaction lay in the dominant, isolated, narrow resonance at 184 keV, being previously assigned with a strength of 65 μeV from shell model estimates with significantly large uncertainty. An unpublished direct measurement of this resonance in normal kinematics yielded a value of 55 μeV. The uncertainty in the reaction rate led to a large uncertainty in the predicted ^{26}Al ejected yield from nova, so it was considered vital that the unpublished measurement was confirmed using an independent measurement utilizing a different experimental technique.

Using the TRIUMF Resonant Laser Ion Source (TRILIS), peak intensities of 5 x 10^9 accelerated ^{26}Al ions per second were achieved at DRAGON. The reaction yield was of the order 3 x 10^{-13} reactions per incident ion, and only the superior primary beam suppression capabilities of the DRAGON separator were enough to enable the measurement of the 184 keV resonance strength. Using the detection signature from DRAGON's BGO detector array, it was possible to determine the location of the narrow resonance within the extended

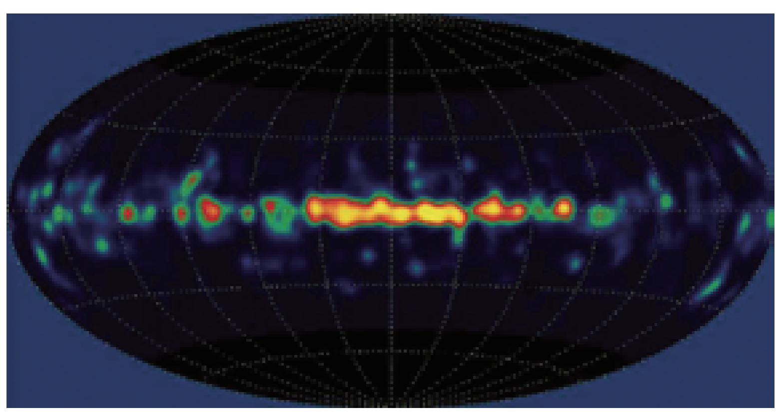


Figure 3: COMPTEL All-Sky map of the Galactic distribution of ^{26}Al, as determined by the flux of the characteristic 1809 keV gamma ray.

gas cell and, comparing to stopping powers also measured at DRAGON, to derive the resonance energy with high accuracy (see Figure 4). The resulting resonance strength of 35±7 μeV is lower than the adopted value, while the measured resonance energy of 184±1 keV is 4 keV smaller than the adopted value. These quantities were used in a spherically symmetric, implicit hydrodynamic nova code in Lagrangian formulation to estimate an ejected ^{26}Al yield based on as much experimental information as possible while neglecting the still uncertain ^{25}Al(p,γ)^{26}Si rate. It was found that the newly measured 184 keV resonance strength resulted in a 20% increase in the ejected yield with respect to the adopted value.

The conclusions of this work are that the paradigm of novae as a small but significant source of secondary ^{26}Al in the galaxy remains supported, and further investigations of the ^{25}Al(p,γ)^{26}Si reaction and to some extent the ^{23}Mg(p,γ)^{24}Al reaction are required to put this conclusion on a firm experimental footing with nuclear uncertainties eliminated. These results were reported in *Physical Review Letters.*

^{44}Ti Formation in the Alpha-Rich Freeze-out Phase of Core-Collapse Supernovae

One of the significant observations of an astrophysical characteristic γ-ray emitting radioisotope is the detection of ^{44}Ti ($t_{1/2}$=58.9±0.3 yr) in the Cassiopeia A (Cas A) supernova remnant at ~3.4 kiloparsec distance. Enough flux of the characteristic 68, 78 and 1157 keV γ-rays resulting from the decay of the daughter ^{44}Sc are detectable from this remnant to enable a determination of the ejected ^{44}Ti yield, immediately giving a diagnostic for supernova models. A ^{44}Ti yield has also been inferred from the light curve of supernova 1987A that

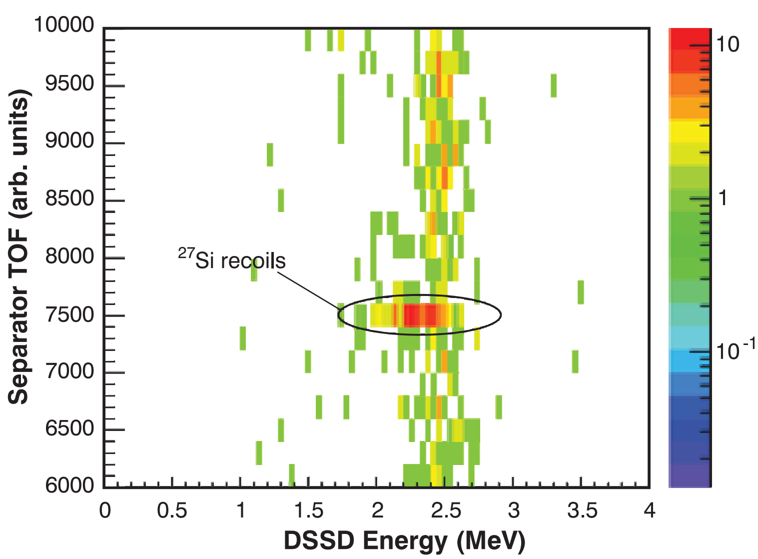


Figure 4: Detected Energy vs Time-of-flight plot showing gamma-coincident ^{27}Si recoils from the extremely weak ^{26}Al(p,γ)^{27}Si reaction against a random background.

is similar to the one observed in the Cas A remnant. Meteoric grains of presolar origin also show ^{44}Ca over-abundances thought to come from *in situ* decay of supernova-produced ^{44}Ti.

The all-sky survey of the ^{44}Ti characteristic γ-ray, however, shows no unambiguous identification of ^{44}Ti sources other than Cas A, and by inference, SN1987A. This survey is at odds with the expected flux given the presently adopted galactic supernova rate and current 1D models of supernova explosions, which show ^{44}Ti ejected yields a factor of 2-10 smaller than observed in Cas A. The models also fail to reproduce the $^{44}Ti/^{56}Ni$ ratio inferred from the SN1987A light curve or the solar system abundance ratio of $^{44}Ca/^{56}Fe$. The predictions of these core-collapse models are highly dependent on the location of the boundary where material falls back on to the neutron star or black hole, or becomes ejected and available for observation. Here, a detailed understanding of the formation of ^{44}Ti can lead to constraints on the underlying physics in the model.

The production and destruction reaction rates of ^{44}Ti are a crucial part of this understanding, and it is known that the value of certain rates can affect the ejected ^{44}Ti mass fraction by a large amount. Of these rates, the direct production of ^{44}Ti via alpha-capture on ^{40}Ca has a significant influence on the final ^{44}Ti yield and was imbued with a large uncertainty. Two experimental attempts to measure the $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction, one originally motivated from nuclear structure studies using the traditional prompt-γ technique at discrete energies and the other using the technique of TRILIS to derive a total cross section integrated over the relevant energy range to supernova temperatures were undertaken. A large discrepancy existed between the rates derived in these two studies, with the accelerator mass spectrometry measurement resulting in a total strength up to ~5 times larger than that of the prompt γ-ray measurement.

DRAGON is the ideal instrument to measure this reaction because of the isotopically pure gas target, superior beam suppression, and coincidence measurement of de-excitation γ-rays and ^{44}Ti recoils enabling a clean, energy-dependent measurement that avoids possible sources of systematic error inherent in the other techniques. The DRAGON study includes experimentally measured efficiencies and stopping powers. A $^{40}Ca^{++}$ beam was produced using the off-line ion source and accelerated to energies between 0.605A MeV and 1.153A MeV at intensities of around 1 x 10^{10} ions/sec. With the beam impingent on the windowless helium target with a thickness of 1-4 x 10^{18} atoms/cm^2, a complete excitation function of the yield of ^{44}Ti from the $^{40}Ca(\alpha,\gamma)^{44}Ti$ was obtained in the energy region E_{cm}=2.11-4.19 MeV.

This experiment utilized the novel technique of using thin silicon nitride foils to boost the charge state of the recoiling product nuclei after the gas target to allow maximum efficiency of transmission of the selected M/q in the separator. A ^{48}Ti beam was also used to measure the equilibrium charge-state distributions after the gas cell and the charge state booster foil. The resulting energy-dependent cross section showed marked differences from the prompt γ-ray data; in particular, substantial resonance strength was observed in regions between narrow resonances identified in the prompt γ-ray experiment. Although the strength of the strong resonances at higher energies in the reaction was in good agreement with the prompt γ-ray data, the DRAGON result was higher by a factor two in the low-energy regime (see Figure 5).

The reaction rate used in the supernova ^{44}Ti yield estimations was based on the Hauser-Feshbach statistical model of the NON-SMOKER code scaled to fit available resonance data on self-conjugate nuclei. Compared to this result, which appeared to agree with the prompt γ-ray data, the DRAGON result is higher by around 40%. The results suggest that the level density in ^{44}Ti is higher than previously thought and, in fact, the non-scaled NON-SMOKER statistical model rates agree well with the DRAGON measured rates. The predicted mass fraction of ^{44}Ti ejected in a Cas A type event is now higher by 40% compared to the previous estimates of the scaled Hauser-Feshbach approach. The measurement uncertainties in the DRAGON work translate to an uncertainty of ±3% in ejected ^{44}Ti yield, much lower than the uncertainty in the observed yield and a substantial improvement compared to the discrepancy seen between previous experimental works. Thus, the use of ^{44}Ti as a supernova diagnostic is put on a firmer experimental footing where the remaining uncertainties are dominated by the model physics. The remaining nuclear physics uncertainties relevant to ^{44}Ti yield in supernovae are the strengths of the ^{44}Ti(α,*p*) and ^{45}V(*p*,γ) reactions.

Stellar Evolution and Helium Burning in Massive Stars

In the quest to uncover the secrets of nucleosynthesis, reliable stellar models are required, especially for massive stars that become the progenitors of core-collapse supernovae and are responsible for a large deposition of nucleosynthetic yield into the interstellar medium. The evolution of such a supernova progenitor is sensitively dependent on the conditions in the star during core and shell helium burning. In particular, the triple-alpha reaction and the ^{12}C(α,γ)^{16}O reaction take place simultaneously, depending on stellar mass, and their ratio determines the subsequent C/O ratio in the ashes of nuclear burning. The composition of these ashes then determines decisive global properties of the evolving star such as the convective energy transport conditions and entropy in the core, the subsequent burning shell positions and, therefore,

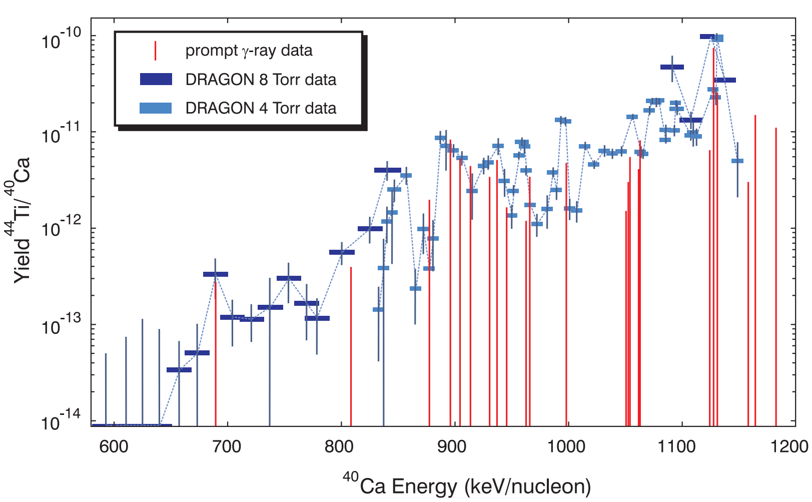


Figure 5: Excitation function of the ^{40}Ca(α,γ)^{44}Ti reaction in the astrophysical energy range as measured by DRAGON, shown against previous experimental data.

whether the star initiates C- and Ne-burning stages or skips straight to O burning. All these conditions have a drastic effect on the nucleosynthetic yields in the star.

The reliability of stellar evolution models hinges on the value of the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate at helium burning temperatures (~1-2 x 10^8 K). The Holy Grail of stellar astrophysics is therefore the value of the $^{12}C(\alpha,\gamma)^{16}O$ cross section at the mean interaction energy of 300 keV. Because the cross section there is of the order 10^{-17} barns, direct measurements of sufficient accuracy are simply impossible. A rate with an uncertainty of less than 10% is required to make the stellar models reliable to the required level of accuracy.

All attempts to determine the astrophysical *S*-factor at 300 keV, S(300), have done so by extrapolating measurements taken at higher energies while taking into account known resonances, and most importantly including known information for the vital subthreshold resonances corresponding to the ^{16}O 1^- and 2^+ states at 7.17 MeV and 6.917 MeV respectively, for the ground-state transitions. This has been achieved using a variety of reactions and experimental techniques but, where radiative-capture measurements have been performed, it has been done using both normal and inverse kinematics.

What has been ignored in the past is the radiative capture with a cascade transition through the first excited 0^+ state in ^{16}O at 6.049 MeV. This capture has been ignored because that state decays purely through e^+e^- production and therefore no high-energy, secondary γ-ray exists following the low-energy primary γ-ray to be observed in an experimental set-up. Because of the experimental difficulty in observing this transition, it has been wrongly assumed to be small.

The DRAGON facility detects reaction products from radiative-capture reactions in inverse kinematics, in coincidence with de-excitation γ-rays

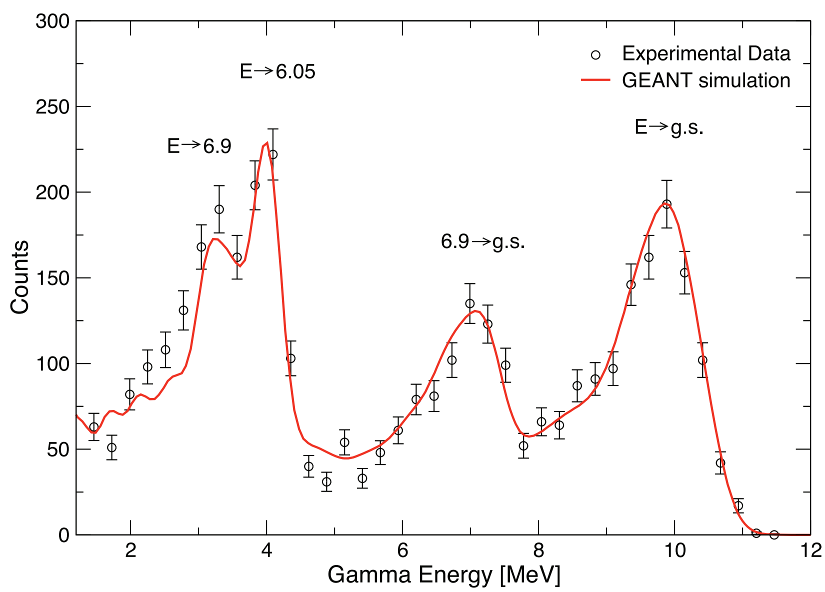


Figure 6: DRAGON gamma-ray spectrum for the $^{12}C(\alpha,\gamma)^{16}O$ reaction, shown with GEANT simulation results which include pair-decay from the 1st excited state of ^{16}O.

around the target position. Therefore, it provides a layer of background rejection and sensitivity beyond the non-inverse approach. An experiment was conducted in which a ^{12}C beam of up to 3 x 10^{11} ions/sec with energies in the range E_{cm}=2.22-5.42 MeV was impingent on the windowless helium target at pressures of 4 to 8 torr. The resulting BGO energy spectra for events in coincidence with detected ^{16}O recoils were analyzed in comparison with GEANT3 simulations including the pair-decay of the ^{16}O first excited state, showing excellent agreement for the known branching ratios in cascades from the resonance or direct capture reactions (see Figure 6). In this way, an excitation function was constructed, in particular for capture and decay through the 6.049 MeV state, which has been observed here for the first time.

Using R-Matrix fits, including both the E1 and E2 contributions to this cascade, an extrapolation was made (see Figure 7) that takes into account the interference between higher lying resonances, direct capture, and the subthreshold resonances. A value of the *S*-factor of $S_6\overline{H}_0(300) = 25^{+16}_{-15}$ keVb was determined from this data [C. Matei *et al.*, Physical Review Letters 97 (2006)]. Given the value of $S_{total}(300)$ = 170 keVb for static helium burning argued from stellar nucleosynthesis models, and the fact that this *S*-factor is required to less than 10%, the cascade through the first excited state of ^{16}O can no longer be ignored and makes up a significant proportion (15%) of the total reaction strength. This conclusion is only made possible due to the unique capabilities of the DRAGON facility.

The results of this work are an important step in the quest to know the $^{12}C(\alpha,\gamma)^{16}O$ reaction strength at helium burning temperatures to high accuracy, and the reliability of stellar nucleosynthesis models depends on them.

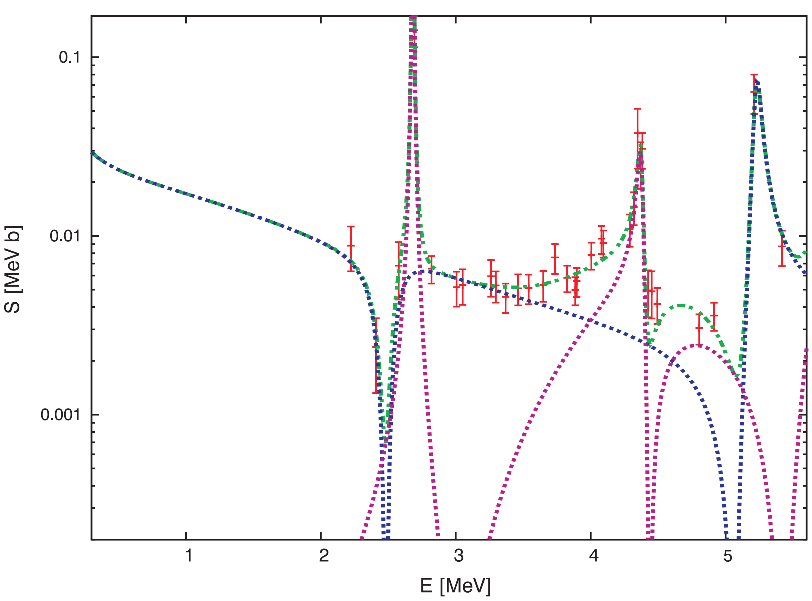


Figure 7: S-factor for cascades through the 6.0 MeV state in ^{16}O in the $^{12}C(\alpha,\gamma)^{16}O$ reaction, fitted with R-Matrix and including both the E1 (short-dashed), E2 (dotted) and total (long-dashed) components.

The Nuclear Trigger for X-ray Bursts

Type I X-ray bursts are fascinating objects. They are thought to occur when H- or He-rich matter accretes onto the surface of a neutron star in a binary star system and erupts into a thermonuclear runaway. This runaway causes a massive increase in radiated power and a corresponding sequence of proton- and alpha-induced reactions up the proton-rich side of stability, known as the *rp*- and αp-processes. As the fuel in the runaway is used up, the burst dies down, only to have the fuel build up again before a further runaway, often leading to a regular bursting pattern. Models of X-ray bursts have been studied prolifically over the last decade, resulting in the inclusion of a large network of nuclear reaction rates using input parameters, most of which remain unmeasured and are based solely on shell model, analogue state considerations, or statistical model estimates.

Several mysteries arise in reconciling models with observed X-ray bursts. For example, bursts are observed only in systems where the accretion rate is lower than around 30% of the Eddington accretion rate, whereas some models predict that all accretion rates up to the Eddington luminosity should result in X-ray bursts. The key to solving this mystery may lie in the breakout from the hot, β-limited CNO cycle into the *rp*-process. This thermonuclear runaway is by a sequence of nuclear reactions that occur at a critical temperature and density. The reaction sequence $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\alpha,p)^{21}Na$ is the main breakout route, carrying the most reaction flux once the runaway has been established. However, the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction appears to be the real trigger for the X-ray burst, causing the pre-burst temperature instability and initiating flow into the *rp*-process that allows the runaway to start, raising the temperature to levels where the main breakout path can occur. The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction has, for around two decades, played this crucial role in hot-CNO breakout, depending on the strength of a dominant resonance at ~500 keV, corresponding to the $3/2^+$, 4.0 MeV state in ^{19}Ne. The strength of this resonance is known to be weak, making a direct measurement of the radiative-capture rate extremely difficult and requiring extraordinary ^{15}O beam intensities (> 1 x 10^{10} ions/sec). If such a beam were available, DRAGON, which was optimized to study this reaction, would be used in a direct measurement. So far, however, an ^{15}O beam of sufficient intensity has been difficult to develop anywhere. Therefore the focus has been on deriving the 4.0 MeV state's resonance strength via indirect measurements to determine the alpha-decay branching ratio of the state and its lifetime so that the resonance strength can be derived via

$$\omega\gamma = \frac{(2J+1)}{2} B_\alpha (1 - B_\alpha) \frac{\hbar}{\tau}$$

where B_α is the alpha-branching ratio and τ is the mean lifetime of the state.

At ISAC-I, two measurements of the lifetime of the 4.0 MeV state have been carried out using the Doppler-shift attenuation method. Using an implanted ^3He target and the reaction $^3He(^{20}Ne,^4He)^{19}Ne^*$ (here, the asterisk denotes an excited nuclear state) at 34 MeV to populate the 4.0 MeV and other states, the recoiling ^{19}Ne nucleus was decelerated in the dense Au target, leading to a angle-dependent Doppler shift of the γ-ray energy. The γ-rays were detected using a high-purity germanium detector at 0° with respect to the beam axis. Gamma-rays corresponding to transitions from seven states in ^{19}Ne lying at excitation energies from 1.536-4.602 MeV were observed, including the 4.0 MeV state. Using a line shape analysis of the γ-ray from the 4.0 MeV state to the ground state, and the γ-ray from the 4.0 MeV → 1.5 MeV state, a joint-likelihood analysis yielded a lifetime of 6.9±1.5(stat.)±0.7(syst.) fs (see Figure 8). With this result, and the lifetime measurements of the other six states, all astrophysically relevant states (with the exception of the 4.378 MeV state) have been measured in this work to sufficient precision to constrain the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate when combined with a precision measurement of the α-branching ratios. The TRIUMF experiment represents the most precise measurement of the lifetimes of these states in ^{19}Ne ever, and was successful largely because of the highly efficient experimental set-up, high-quality beam at the ISAC facility.

To determine the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate at X-ray burst temperatures, it is

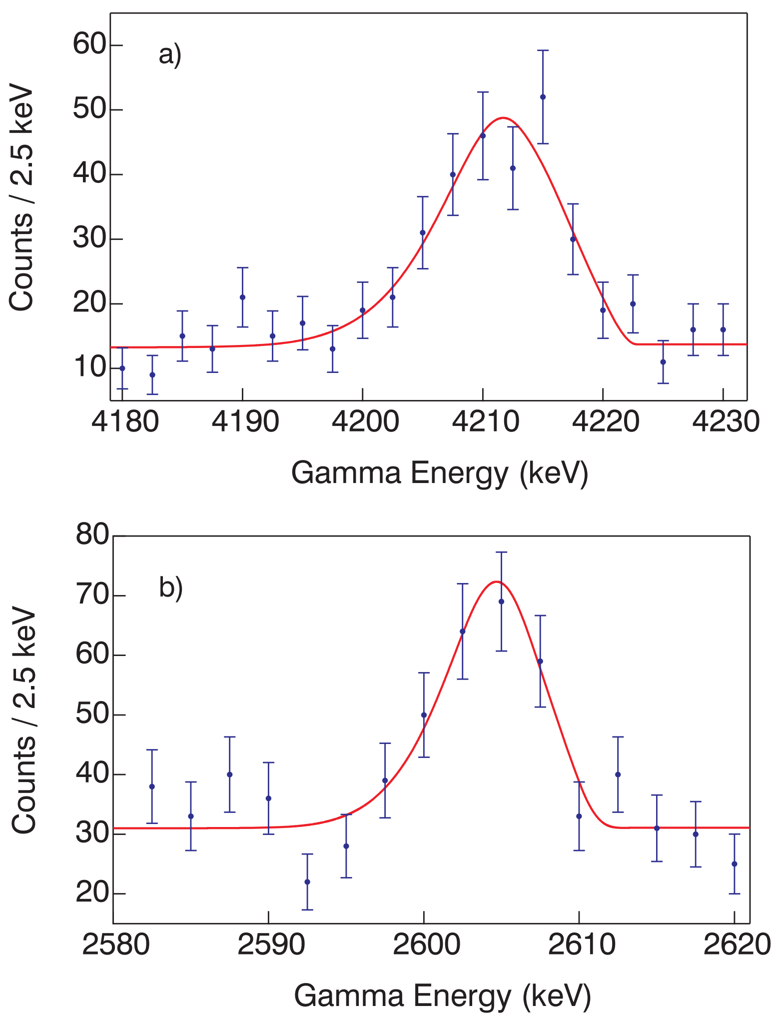


Figure 8: Doppler-shifted line shapes due to two transitions of the 4035 keV level in ^{19}Ne, populated in the TRIUMF $^{3}He(^{20}Ne,^{4}He)^{19}Ne$ experiment, from which the state lifetime was extracted.

now required to measure the alpha-decay branching ratio of the 4.0 MeV state experimentally. Recent attempts to do this have only succeeded in putting upper limits on the value, but until a direct measurement of this resonance strength can be made at some point in the future, the alpha-decay measurements remain the only viable way to determine this rate experimentally.

Additional Studies and Future Directions

In addition to the work summarized above, the ISAC-I program has also contributed both experimental and theoretical work in the region of solar nucleosynthesis and the ^{7}Be(p,γ)^{8}B reaction.

In 2007, the focus was on producing fluorine beams to study the ^{18}F(p,α)^{15}O reaction, the most significant reaction pertaining to the production of ^{18}F in explosive hydrogen burning, thought to produce the earliest potentially observable 511 keV γ-rays in a nova explosion. An initial study using the TUDA facility at somewhat reduced beam intensities measured excitation functions for both the ^{18}F(p,p)^{18}F and ^{18}F(p,α)^{15}O reaction. Initial R-Matrix studies of this high-quality data have shown several features at odds with previous experiments and some recent theoretical estimates. This measurement may have significant implications for the production of ^{18}F and was only possible because of the excellent performance of the FEBIAD ion source installed at ISAC-I. Further optimization of the source will allow even higher beam intensities, and more studies in the low-energy astrophysical regime concerning ^{18}F are planned in 2008.

In 2008, a new nuclear astrophysics detector, TACTIC, will be commissioned. TACTIC is an ion tracking chamber that will be used, like TUDA, to study the nuclear reactions of astrophysical significance with charged particles in their exit channels. The chamber operates at very low beam energies, has a very large acceptance, and is tolerant of high beam fluxes. These characteristics make it an ideal detector for measuring the small cross sections associated with nuclear astrophysics. The initial experiment will be to measure the cross section of ^{8}Li(α,n)^{11}B, which is a seed reaction starting off the r-process.

The DRAGON facility aims to tackle two important reactions in 2008–2009 involved in explosive hydrogen burning: the ^{33}S(p,γ)^{34}Cl reaction, crucial in determining the yields of ^{33}S potentially deposited in meteoric grains of nova origin; and ^{23}Mg(p,γ)^{24}Al, a never-before studied reaction important for ^{26}Al production in novae and the flow of the rp-process. The latter reaction is made possible due to newly achieved intensities of ^{23}Mg using ISAC targets and the TRIUMF Resonant Laser Ion Source (TRILIS).

Beyond these experiments, new and unique beams are planned for the areas of astrophysics described above. These challenging beams will allow experiments to be done that will advance the understanding of astrophysics of neutron-deficient nuclei. World leadership in the field of nuclear astrophysics will remain a major thrust of TRIUMF-ISAC's physics program. The DRAGON facility will remain the best instrument in the world for these important experiments.

All of the experiment studies listed above were led by TRIUMF scientists, in close partnership with a host of international collaborators. The experiments also attracted the participation of students, who benefited from the high-quality training available at TRIUMF. The scientists of the DRAGON and TUDA facilities continue to work closely with world experts in modeling classical novae, supernovae, stellar evolution, and X-ray bursts to identify important nuclear reactions and advance results in this field.

Partners

In Canada: Deep River, McMaster University, Queen's University, Simon Fraser University, University of Alberta, University of British Columbia, University of Guelph, l'Université de Montréal, University of Northern BC, University of Prince Edward Island, University of Toronto, and the University of Victoria.

International Partners: Austria (1), Belgium (1), China (1), France (2), Germany (5), India (1), Ireland (1), Israel (1), Italy (2), Japan (1), the Netherlands (1), Scotland (1), Spain (2), the United Kingdom (3), and the United States (7).

TRIUMF's Role

Nuclear astrophysics constitutes a significant part of TRIUMF's core scientific outlook, and the laboratory continues to provide the necessary infrastructure support for this program. The facilities involved in performing astrophysics research themselves rely on dedicated annual budgets for maintenance, repair, and operation. TRIUMF is also responsible for ensuring targeted and groundbreaking beam development to ensure that the experiments within this program can be performed. Nuclear astrophysics experiments often require the highest intensity and most challenging exotic rare-isotope ion beams. A key part of this beam development strategy is the investment, both in financial and personnel terms, in ion-source technology and target chemistry.

TRIUMF also provides a dedicated core of staff scientists involved in, and some who specialize in, nuclear astrophysics research. Personnel includes these grant-eligible board-appointed employees: G. Ball, L. Buchmann, B. Davids, P. Delheij, J. Dilling, G. Hackman, D. Hutcheon, A. Olin, C. Ruiz, and P. Walden.

4.2.1.1.4.1

Superallowed β-Decay Studies

Introduction

The standard model of particle physics describes nature on the sub-microscopic scale, specifying the basic constituents of our universe and the forces that act among them. Understanding one of those forces, the weak force, depends critically on β-decay studies. Such studies are also important for explorations of nuclear structure and the fundamental properties of quarks.

β-decay occurs when there are either too many protons or too many neutrons in a nucleus, making the system unstable. One or more of the excess protons or neutrons is transformed into the other so the nucleus can move to a more stable state with a more balanced number of protons and neutrons. Although the numbers of protons and neutrons in an atom's nucleus change during β-decay, their sum remains the same.

For some β-decays, the structure of the nucleus is very similar before and after the β-decay and the decay happens faster than for most other β-decays. This special type of decay is a "superallowed β-decay." Because nuclear structure uncertainties are small for these decays, precision measurements of them can be used to test the hypothesis for the nature of the weak interaction and determine the properties of quarks.

To describe the decays, three types of measurements are necessary. The first is a measurement of the masses of the atom before and after the decay. The second is the time it takes for the decay to occur. The third is the fraction of the decays that go to the final state of interest. At TRIUMF, we are able to do all three types of measurements and independently determine the decay properties. TRIUMF's recent high-precision lifetime measurements have contributed significantly to the understanding of the decay properties.

High-precision measurements of the *ft* values for superallowed $0^+ \rightarrow 0^+$ Fermi β-decays between isobaric analogue states provide demanding and fundamental tests of the standard model description of electroweak interactions. To first order, because neither spin nor orbital angular momentum can be transferred in these decays, the axial-vector current does not contribute, and these transitions can be described solely in terms of the vector current. As a consequence of the conserved vector current (CVC) hypothesis, which stipulates that the vector coupling constant for semi-leptonic weak interactions, G_V, is not renormalized in the nuclear medium, the *ft*, and corrected *ft* values (denoted *Ft*), for decays between isospin T = 1 isobaric analogue states can be expressed as:

$$Ft = ft(1 + \delta_R)(1 - \delta_C) = K / [\, 2G^2_V(1 + \Delta_R)\,] = \text{constant},$$

where K is a constant, *f* is the statistical rate function, *t* is the partial half-life for the transition, δ_R and Δ_R are the nucleus-dependent and nucleus-independent radiative corrections respectively, and δ_C is a nuclear-structure dependent correction that accounts for the breaking of perfect isospin symmetry by Coulomb and charge-dependent nuclear forces.

Presently there are 13 *Ft* values between the exotic nuclei ^{10}C and ^{74}Rb that have been determined to precisions of 0.5% or better, 8 of which are known to

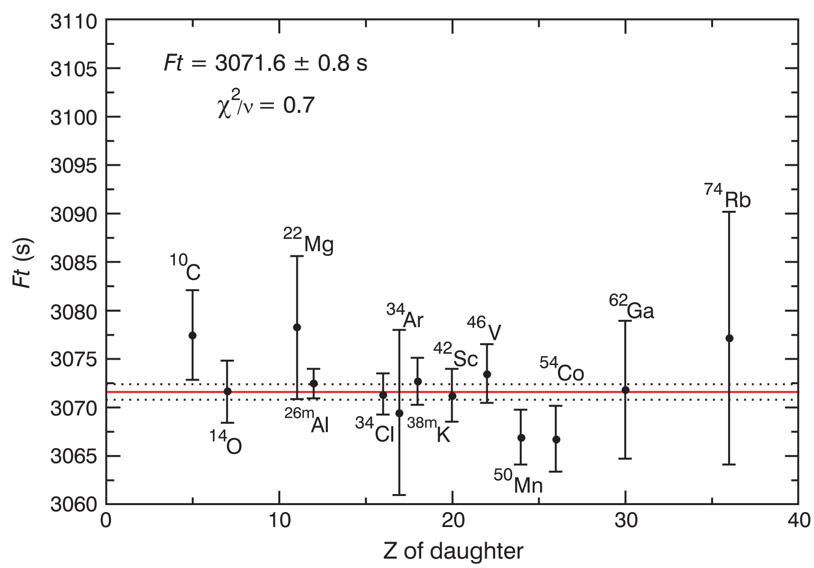


Figure 1: Present status of the *Ft* values for the 13 most precisely determined superallowed decays and the overall weighted average *Ft* with corresponding statistical uncertainty and reduced χ^2 value. The data are taken from I.S. Towner and J. C. Hardy, arXiv:0710.3181vi [nucl-th] Oct 2007 and updated to include new results from G. F. Grinyer et al., Phys. Rev C 77, 015501 (2008) and G. F. Grinyer et al., Nul. Inst Meth. A 579, 1005 (2007).

better than 0.1% (see Figure 1). The present world average *Ft* value is $3072.4(8)_{Ft}(9)_{\delta C}$ s, where the average *Ft* value has been increased by 0.85 s to account for a theoretical uncertainty associated with a small discrepancy between two independent calculations of the isospin symmetry-breaking corrections. The first error is statistical and the second is the theoretical systematic uncertainty. These 13 high-precision *Ft* values have confirmed the CVC hypothesis at the level of 1.3 x 10^{-4}, which sets limits to the level of 1.3 x 10^{-3}on the existence of possible scalar interactions that couple to left-handed standard model neutrinos. Together with the Fermi coupling constant from purely leptonic muon decay G_F, these measurements provide the most precise determination of the up-down element of the Cabbibo-Kobayashi-Maskawa (CKM) quark mixing matrix. The present value of V_{ud}, obtained from superallowed Fermi β-decay is given by

$$V_{ud} = G_V/G_F = 0.97416(13)_{Ft}(14)_{\delta C}(18)_{\Delta R},$$

where the uncertainties are due to the corrected *ft* values, the systematic discrepancy associated with the isospin symmetry-breaking corrections, and the nucleus-independent radiative correction, respectively.

The value of V_{ud} from the superallowed decays must be combined with the values of V_{us} = 0.2257(21), which is determined from semi-leptonic neutral and charged K decays and V_{ub} = 0.00431(30). The unitarity test of the top row of the CKM quark-mixing matrix yields

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999,$$

a result that satisfies the unitarity requirement at the level of 0.1% precision, and is insensitive to the existence of the third quark generation since V^2_{ub} is very small. The agreement with unitarity is an important test of the standard model description of electroweak interactions. More importantly the small uncertainty in this unitarity test places stringent limits on any possible "new physics" beyond the standard model. New physics constrained includes the existence of right-handed currents, additional interaction types (scalar, pseudo-scalar, or tensor interactions), and unknown higher order quark generations. Further improvements in both V_{ud}, the most precisely determined CKM matrix element, and V^2_{us} will constrain new physics beyond the standard model through the test of CKM unitarity and clearly remains highly desirable. This work is the responsibility of low-energy physics research. Complementary techniques to extract V_{ud}, such as free neutron and pion decays, presently result in values for V_{ud} that agree with the superallowed result but are nearly an order of magnitude less precise due to severe experimental limitations.

One of the best chances for improving these demanding tests of the standard model rests with the superallowed decays. For this reason, TRIUMF's Experiments Evaluation Committee has continuously regarded the superallowed β-decay program at TRIUMF as a top priority for ISAC and has approved several high-priority experiments. It was a major motivation for the recent construction of the TRIUMF Ion Trap for Atomic and Nuclear science (TITAN), a precision Penning trap that will be capable of providing high-precision mass measurements for many of the superallowed emitters.

Improving the overall precision in V_{ud} is a major pursuit in low-energy nuclear physics, and intense experimental and theoretical effort must continue to focus on the small theoretical corrections terms that are applied to the experimental *ft* values. The uncertainty associated with the nucleus-independent correction Δ_R has recently been reduced by a factor of two, representing a major advance in controlling the hadronic uncertainties in electroweak loop calculations. Further reduction of this uncertainty may be forthcoming if lattice quantum chromodynamics calculations can constrain the interpolation between short- and long-distance loop effects. The overall precision in V_{ud} may ultimately be limited by the systematic discrepancy between the isospin symmetry-breaking corrections.

The calculations of the isospin symmetry-breaking corrections δ_C are performed using either a shell-model diagonalization with a Woods-Saxon plus Coulomb potential, or a model that employs a self-consistent Hartree-Fock calculation. These corrections are typically subdivided into two components, $\delta_C = \delta_{C1} + \delta_{C2}$, where the first term δ_{C1} accounts for different configuration mixing among the 0^+ parent and daughter states, and the second δ_{C2} arises from differences in proton and neutron separation energies that lead to an imperfect overlap of the radial wave functions.

There is a small, but systematic, difference between the two models used to calculate δ_C that is presently the limiting factor in the overall precision of the world average *Ft* value, and may ultimately limit the precision of V_{ud} itself. A new evaluation of the isospin symmetry-breaking corrections from Towner and Hardy was recently performed and, for the first time, included core orbital excitations to the partially occupied valence shells. The addition of core orbitals to the model space was demonstrated to have a significant impact on the radial overlap correction δ_{C2}, specifically for the *fp* shell, which led to a larger adopted value of δ_C for these nuclei and hence an overall reduction in world average *Ft* value. From the previous world average of $Ft = 3074.9(8)_{Ft}(9)_{\delta C}$ s reported earlier in 2007, the new result that contains the latest calculations of the corrections for isospin symmetry-breaking is $Ft = 3072.4(8)_{Ft}(9)_{\delta C}$ representing a decrease to the overall world average by 2.5 s or more than two standard deviations. It should be emphasized that this 2.1 σ decrease to the world average *Ft* value is the single largest shift to this result in more than 20 years and is due solely to the new isospin symmetry-breaking corrections that now include core orbitals in the shell-model calculations.

Significant improvement to the overall precision in the average *Ft* value and V_{ud} therefore requires reducing, or eliminating, the systematic uncertainty assigned to δ_C, which involves discriminating between the two independent calculations of isospin symmetry-breaking. This can be achieved experimentally through high-precision measurements of the *ft* values for nuclei that show the greatest model dependencies (^{14}O, ^{18}Ne, and ^{34}Ar) or have the largest absolute corrections (all decays with $A \geq 62$). Tests of the theoretical corrections for isospin symmetry-breaking by experimental means require new measurements of β-decay half-lives and branching ratios to precisions of 0.05% or better, and β-decay Q values must be deduced to at least 0.01%. Several important measurements have already been carried out at ISAC-I, and high-quality rare-isotope ion beams for many other superallowed decays that are important for these tests are anticipated in the next five years. Combined with the recent installation of TITAN for mass measurements, all three of the experimental quantities that define the *ft* value will be measurable at TRIUMF-ISAC-I. This will solidify ISAC-I as a unique facility for precision superallowed Fermi β-decay studies.

Description of Dedicated Apparatus: GPS Experimental Station

The GPS experimental station consists of a 4π continuous gas-flow proportional counter for the detection of the β-particles and a fast tape transport system. A low-energy rare-isotope beam (~30 keV) from ISAC-I is implanted into a 25 mm wide aluminized Mylar tape. Following a collection period of ~4 half-lives, the beam is turned off and the collected sample is rapidly moved out of the vacuum chamber and into the 4π gas counter where the decay of the sample is recorded for ~25 half-lives. This cycle of collect-move-count is then repeated for the duration of every experiment and following an analysis of the obtained decay curves, the half-life is determined using techniques that have been perfected by members of the collaboration. In all of these experiments careful attention must be paid to possible sources of systematic uncertainty and thus electronic settings such as the detector voltage, non-extendable dead time and the dwell time are varied on a run by run basis. Dwell times are varied on a run-by-run basis.

Results and Progress

In the first two years of operation at ISAC-I high-precision half-life measurements for the superallowed emitters ^{38m}K and ^{74}Rb were performed, and are both the most precise half-life determinations presently reported for each of these nuclei. Preliminary tests for a γ-ray photopeak counting technique required for a high precision half-life measurement for the superallowed emitter ^{34}Ar, resulted in a publication by Grinyer *et al.* on the half-life of ^{26}Na. An

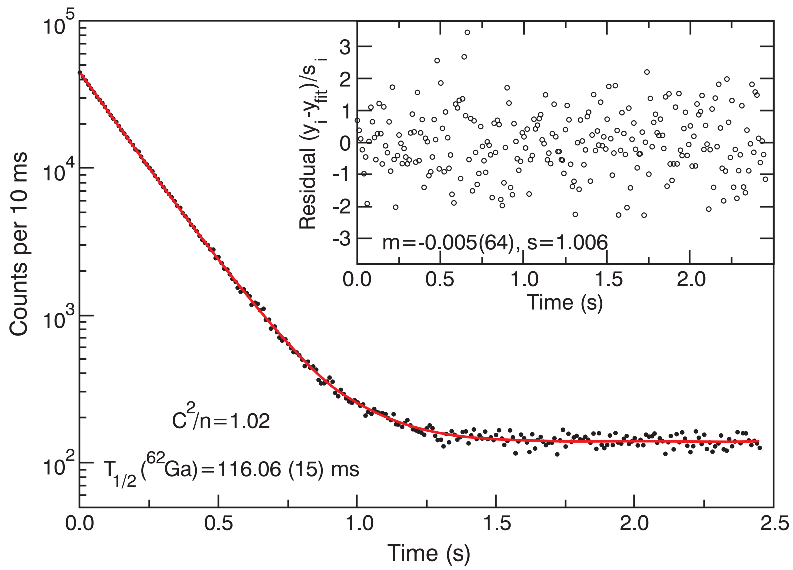


Figure 2: Dead time corrected decay curve from a single ^{62}Ga run summed over 1668 cycles.

additional publication by Hyland *et al.* reported on a half-life measurement of ^{62}Ga, using a beam of only 200 ions/s from a surface ion source.

With the inclusion of the ^{62}Ga half-life deduced during this measurement, the previous world average ^{62}Ga half-life was $t_{1/2}$ = 116.17 ± 0.04 ms and was composed of 6 measurements. This result was already precise to the level of 0.03% but was dominated by a single measurement. The ^{62}Ga yield was improved by a factor of 40 with the TRIUMF Resonant Ionization Laser Ion Source (TRILIS) and the ^{62}Ga half-life has now been re-measured at GPS. In this experiment, 56 runs were collected, each with a statistical uncertainty of ~0.15 ms. A typical dead time corrected decay curve from one experimental run is shown in Figure 2. The residuals $(y_i - y_{fit})/\sigma_i$, while not used directly in the Poisson maximum likelihood fit, remain a measure of the goodness of fit and yield a mean of $\mu = 0.005(64)$ and standard deviation of $\sigma = 1.006$, values that are consistent with the expectation of a normal distribution. The half-life of ^{62}Ga deduced in this work was $t_{1/2} = 116.100 \pm 0.022_{stat} \pm 0.012_{syst}$ ms, a result that is precise to the level of 0.022% and represents the single most precise superallowed half-life measurement ever reported. Combining this value with the 6 previous measurements establishes the world average ^{62}Ga half-life to 0.018%, which is now the most precisely determined half-life of all of the superallowed emitters. This single measurement of the half-life has resulted in a 20% improvement in the overall precision of the ^{62}Ga experimental *ft* value while simultaneously reducing its mean by 0.9 σ. The present ^{62}Ga *ft* value, $3074.3(3)_{BR}(5)_{t1/2}(10)_f$, is now established to the level of 0.04% and rivals the precision of the best measured cases at lighter masses. This new half-life measurement for ^{62}Ga at ISAC-I sets a new benchmark for ultra high-precision half-life measurements.

Description of Dedicated Apparatus: 8π Spectrometer

The 8π γ-ray spectrometer is a spherically symmetric array of 20 Compton-suppressed HPGe detectors. Between the central target chamber and the collimated HPGe detectors is the SCintillating Electron Positron Tagging ARray (SCEPTAR), a compact array of 20 plastic scintillators for beta detection. Low-energy rare-isotope ion beams (~30 keV) from ISAC-I are implanted into a 12.7 mm wide Mylar-backed aluminum tape that moves through the mutual centre of the 8π and SCEPTAR arrays. This powerful combination provides a unique tool for superallowed β-decay branching ratio measurements as the Compton-suppressed 8π HPGe array is sensitive to γ-ray transitions originating from extremely weak β-decay branches (of order 10^{-6}), while the high-efficiency of the SCEPTAR array provides a simultaneous measurement of the total beta activity.

Results and Progress

In the case of the $A \geq 62$ superallowed decays, a large number of excited 1^+ states (110 for ^{62}Ga) are predicted to lie within the Q-value window, all of which can be fed via extremely weak β-decay branches, that could not possibly all be observed experimentally. While missing any one of these weak branches would contribute a negligible bias, the sum of all of these missed branches would represent a considerable systematic loss of total decay intensity in a process described as the "pandemonium effect". One can instead use the low-lying excited 2^+ states in the daughter as collectors for the γ-decay flux from the weak and unobserved β-decay branches to the high-lying 1^+ states. The power of this technique with the unique 8π experimental facility was demonstrated in a recent experiment using a ^{62}Ga beam of 2000 ions/s provided by the TRILIS ion source. A total of 19 γ-ray transitions in ^{62}Zn were observed (see Figure 3) to follow the β-decay of ^{62}Ga which provided a measured non-analogue intensity feeding the ^{62}Zn ground state of $I^{obs}gs$ = 0.129(5)%. Combined with a shell model calculation to provide a theoretical estimate for the total unobserved ground state intensity which was conservatively estimated to be I'gs = 0.010(10)%, yields the total superallowed branching ratio of BR = 99.861(11)% for ^{62}Ga. This measurement is an order of magnitude more precise than the previous adopted value and was pivotal in establishing the ^{62}Ga *ft* value to the level of precision that rivals the best-measured cases.

Tests of the theoretical corrections for isospin symmetry breaking can be obtained for ^{62}Ga by a direct comparison of the adopted world average *Ft* value to the experimental *ft* value for this decay as determined from our recent half-life and branching ratio measurements. The result, $\delta_C = 1.41(3)_{Ft}(4)_{ft}(9)_{\delta R}\%$, is now limited by the precision in the radiative correction factor δ_R which can, in principle, be reduced by extending these calculations to higher order. High-precision studies for ^{62}Ga at ISAC-I have now motivated the need for improving the existing radiative corrections and have simultaneously provided the tightest constraint ever set on isospin symmetry-breaking in this mass region.

A second demonstration of the capabilities of the 8π spectrometer and the SCEPTAR arrays for high-precision superallowed branching ratio measurements was recently performed in an experiment that aimed to either directly measure the β-decay branching ratio of the superallowed emitter ^{38m}K to the non-analogue 0^+ state in the daughter ^{38}Ar or improve upon the previous upper limit of 19 ppm at 68% confidence. While the result of this experiment led to an improved upper limit of 8 ppm at 68% confidence, a previously unobserved γ-ray transition at 130 keV was also discovered that has been attributed to the M3 γ-decay which connects the 0+ state in ^{38m}K to the 3^+ ground state of ^{38}K. Once corrected for internal conversion the M3 γ-decay branch was determined to be 330(43) ppm, reducing the superallowed branching ratio to BR = 99.967(4)%. Since the experimental *ft* value for ^{38m}K was the most precisely determined of all superallowed emitters, this decay has provided a benchmark for precision tests of the standard model and isospin symmetry-breaking corrections in the *sd* shell for nearly a decade. The result of our measurement of this previously unobserved M3 γ-ray transition is to increase this benchmark experimental *ft* value by an entire standard deviation. This important result has been published in Physical Review Letters.

A New γ-ray Photopeak Counting Technique for High-Precision Lifetime Measurements

One of the most important quantities that must be well understood in high-precision lifetime measurements is electronic dead time, especially rate dependent dead time. In our β-counting experiments, a Lecroy 222 gate generator gives a well-defined, non-extendible dead time that is significantly longer than any series dead time preceding it. Since the response time for γ-ray detectors, especially HPGe detectors, is much slower than plastic scintillators or gas proportional counters, correcting for dead time and pulse pile-up becomes much more difficult. To address this problem the 8π electronics allows the system dead time to be measured event-by-event using a high-precision clock.

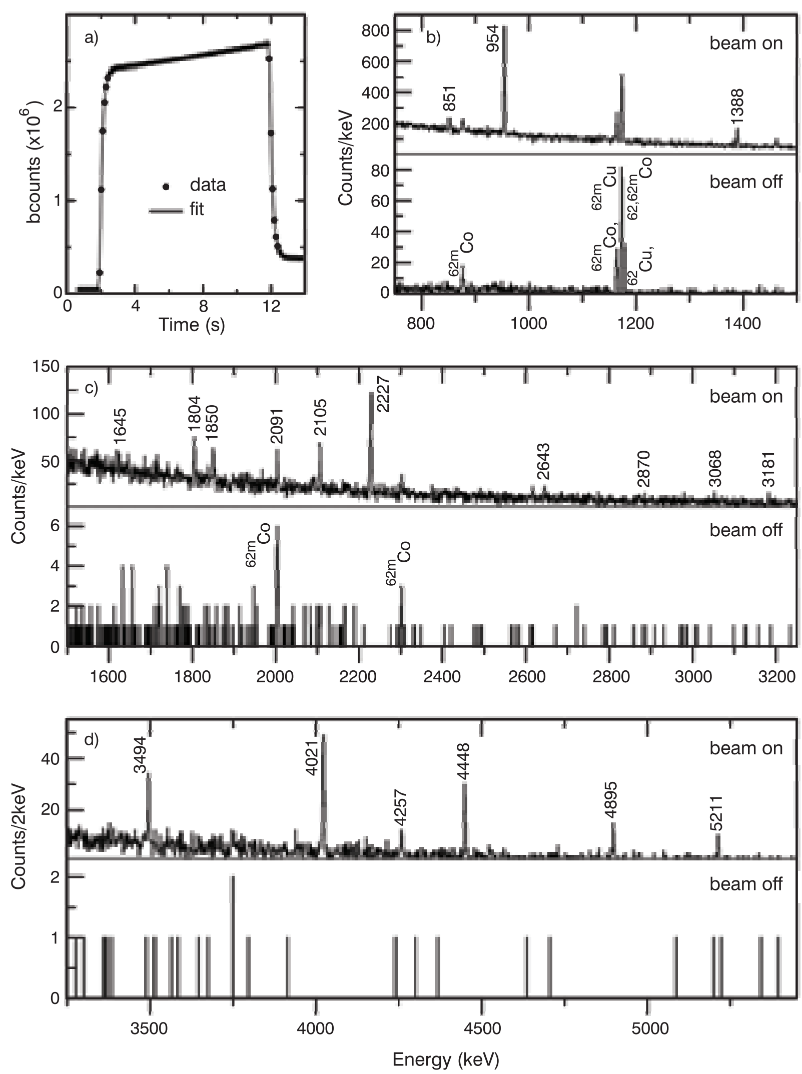


Figure 3: The γ-ray spectra obtained with the 8π spectrometer for the β-decay of ^{62}Ga: (a) β activity observed in SCEPTAR and (b)-(d) Compton and bremsstrahlung suppressed coincident γ-ray spectra for the "beam-on" (upper panels), and "beam-off" (lower panels) periods.

Results and Progress

A new method for high-precision lifetime measurements using the 8π spectrometer that quantitatively accounts for pulse pile-up has been demonstrated recently using a beam of ^{26}Na. This beam was chosen because over 99% of all decays lead to the emission of a 1809 keV γ-ray depopulating the first excited state in ^{26}Mg. Following a 1% (equivalent to 27 σ) pile-up correction to the decay-curve data gated on the 1809 keV photopeak, the half-life for ^{26}Na was determined to be $t_{1/2}$ = 1.07167(55) s, in excellent agreement with the value $t_{1/2}$ = 1.07128(25) s obtained from β-counting using the 4π gas proportional counter system at GPS. This technique has already been used to reduce the uncertainty in the half-life of the superallowed β-emitter ^{18}Ne by a factor of four.

Other Recent Measurements, and Future Plans

Since the calculated nuclear structure dependent corrections for ^{26m}Al are smaller by a factor of two than those for the other eight well-known superallowed β-emitters, it is an ideal case to pursue a reduction in the experimental error for all three relevant quantities, namely the half-life, the branching ratio and the Q_{EC} value. With the TRILIS development of a high intensity ^{26m}Al beam, it will be possible to reduce the experimental error in the *ft* value to ~0.02%. The half-life of ^{26m}Al based on a weighted average of four previous measurements has an uncertainty of 0.03%. While all previous measurements are in agreement there is only one previous measurement with a precision of less than (0.08%). Experimentally, the limit on the non-analogue decay branches for ^{26m}Al is $< 7 \times 10^{-5}$.

In October 2007, an ultra-high precision measurement of the half-life of ^{26m}Al was carried out at GPS. The statistical uncertainty obtained in this measurement is a factor of 4 smaller than the present uncertainty of the world average. This measurement was followed by a measurement of the branching ratio using the 8π spectrometer where, with a beam sample purity of 99.999%, it should be possible to reduce the experimental upper limit for the decay of ^{26m}Al to the twice forbidden 2^+ level in ^{26}Mg by a factor of 10. Analysis of these data is in progress.

When TITAN becomes fully operational in 2008, ISAC-I will have world-class facilities to measure, with high-precision, all three of the important quantities needed to determine *ft* values for superallowed β-emitters. The experiments chosen will be those which have the potential to make the highest scientific impact, namely: 1) when the previous measurements are inconsistent; 2) when the uncertainty is determined primarily by one high-precision measurement; 3) when a new high-precision measurement can confirm and/or significantly reduce the uncertainty in the experimental *ft* value; and 4) when the measurements extend to other cases, particularly those which have large isospin symmetry-breaking corrections.

Presently, we have several key lifetime and/or branching ratio experiments approved that will provide tighter constraints on the CVC hypothesis and the existence of scalar currents (^{14}O) and provide rigorous tests of isospin symmetry-breaking in the *sd* (^{34}Ar) and *fp* shells (^{46}V, ^{50}Mn, ^{66}As, ^{70}Br and ^{74}Rb) where the systematic discrepancies between model calculations are enhanced. With the continued development of suitable ion sources and the capability to handle proton beam intensities on target of up to 100 μA, ISAC-I has demonstrated that it is ideally suited to provide the rare-isotope beam needed to support this program.

Partners

In Canada: McMaster University, Queens University, Saint Mary's University, Simon Fraser, and the University of Guelph. International Partners: France (1), United Kingdom (2), and the United States (5). For partners associated with the TITAN project that contributes to this science program, please see Section 5.3.2.2.1.4.

TRIUMF's Role

TRIUMF continues to provide the infrastructure support required for this program. TRIUMF also provides a dedicated technician for 8π, TIGRESS and GPS. The facility provides the rare-isotope beams needed. For example, the first beam developed with TRILIS was ^{62}Ga. The super-allowed β-decay group was the only group to run with the prototype ECR ion source (^{18}Ne) and the first to use the new FEBIAD ion source (^{34}Ar).

TRIUMF also provides intellectual leadership. Staff scientist Gordon Ball manages the 8π and GPS programs; a second staff scientist provides support. Gordon Ball is also the Principal Investigator for the NSERC project grant in support of the GPS lifetime measurement program.

4.2.1.1.4.2

Fundamental Symmetries: Exotic Physics Searches

Introduction

The standard model provides the current theory of fundamental particles and how they interact. The theory includes strong interactions and a combined theory of weak and electromagnetic interaction, known as the electroweak theory. Over the past 30 years, the standard model of particles and forces has successfully explained a whole host of experimental results as well as provided accurate predictions of a wide variety of phenomena. Despite being one of the most thoroughly tested theories in physics, it is known to be incomplete, most notably because it fails to incorporate gravity.

TRIUMF's ISAC-I facility provides the facilities for many experiments that either test the standard model or are in search of physics beyond it. In addition to the program based around the *Ft* values from superallowed β-decay described elsewhere in this document, there is an extensive research program encompassing several groups in search of exotic particles and couplings that lie outside the standard model. These include scalar bosons, right-handed currents, tensor interactions, axions, permanent electric dipole moments, and nuclear anapole moments. Each is discussed briefly below.

Results and Progress

Within the framework of the standard model, back-to-back β-neutrino emission is essentially forbidden within superallowed β-decays ($0^+ \rightarrow 0^+$). This constraint arises from the nature of the W, vector boson exchange that requires that the produced leptons have both opposite helicity and a combined spin of one. In order for the resulting leptons to be emitted back-to-back, a scalar boson, not allowed for in the standard model, must be exchanged. The angular distribution of emitted leptons within this decay is given by:

$$W(\theta_{\beta\nu}) = 1 + b(m_\beta / E_\beta) + a(\upsilon_\beta / c) \cos \theta_{\beta\nu}$$

where the a and b coefficients are given in terms of the scalar and vector coupling constants C_V, C'_V, C_S, C'_S by:

$$a = \frac{(|C_V|^2 + |C'_V|^2) - (|C_S|^2 + |C'_S|^2)}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2}$$

$$b = \frac{-2\sqrt{(1 - (\alpha Z)^2)}\ \mathrm{Re}(C_S + C'_S)}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2}$$

Here b is the so-called Fierz interference term which has very tight constraints from the dependence of $0^+ \rightarrow 0^+$ decay strengths on $< E_\beta >$. However, as it is only dependent upon $C_S + C'_S$ it is only sensitive to scalar bosons that couple to the standard model, left-handed neutrinos, whereas the a coefficient dependence on $|C_S|^2 + |C'_S|^2$ constrains scalar interactions independent of chirality or time reversal properties.´

The above shows that, within the framework of the standard model (which gives $C_V = C'_V = 1$ and $C_S = C'_S = 0$), $a = 1$ whereas the exchange of a purely scalar boson would lead to $a = -1$. Therefore, any deviation of the a coefficient from 1 would signify the existence of a scalar boson and hence physics beyond the standard model. The TRINAT experiment, described elsewhere in this document, utilizes the unique properties of a magneto optical trap in order to be able to make a direct measurement of the β-neutrino angular distribution.

The result from the first experiment is:

$$a = 0.9981 \pm 0.0030^{+0.0032}_{-0.0037}$$

While in agreement with the standard model, this is the best general constraint on the scalar couplings in the first generation of particles. Figure 1 shows the constraints from this and other experiments. At first glance it appears that the current TRIUMF measurement is uncompetitive; however, it should be pointed out that the $0^+ \rightarrow 0^+$, superallowed Ft values are only sensitive to scalars that couple to neutrinos with standard model chirality whereas the constraints from $\pi \rightarrow e\nu$, while sensitive, are inherently more model dependent (the constraints shown are calculated assuming universal couplings). Also shown is an order of magnitude calculation of the contribution that a wrong chirality scalar interaction would make to a 3 eV/c^2 standard model neutrino (currently the best experimental limit set by tritium β-decay).

Right-Handed Currents

Many extensions to the standard model predict that parity symmetry, which is maximally violated by the weak interaction, is restored at higher energy scales. In the simplest manifest left-right symmetric models, the standard model electroweak gauge group $SU(2)_L \otimes U(1)$ is extended to include a right-handed sector and is given identical couplings, Cabbibo-Kobayashi-Maskawa matrices, and neutrino sectors. This only requires three new parameters to be introduced: the mass of the new, W_R, boson that couples to the right-handed neutrinos, a CP violating phase, ω, and an angle, ζ, describing the level of mixing between the weak ($W_{L,R}$) and mass eigenstates ($W_{1,2}$ with masses $M_{1,2}$). This gives:

$$W_L = W_1 \cos\zeta - W_2 \sin\zeta$$
$$W_R = (W_1 \sin\zeta + W_2 \cos\zeta)\, e^{i\omega}\,.$$

Nuclear β-decay experiments are sensitive to the W_R either directly or via mixing with the W_L with dependencies scaling as M_1^2/M_2^2 and $\tan\zeta$ respectively. In more general non-manifest models, the couplings for the two sectors are no longer identical thus increasing the available parameter space. It is in these models that the limits from spin-correlated β-decay experiments are the most stringent. The differing dependencies make the results from β-decay, μ-decay, and collider searches complimentary.

Measurement of the neutrino spin asymmetry in the decay of polarized ^{37}K are currently not capable of competing directly with μ-decay as measured by TWIST or direct searches at high-energy proton colliders. The exclusion regions are given in Figure 2. However, the semi-leptonic character allows for

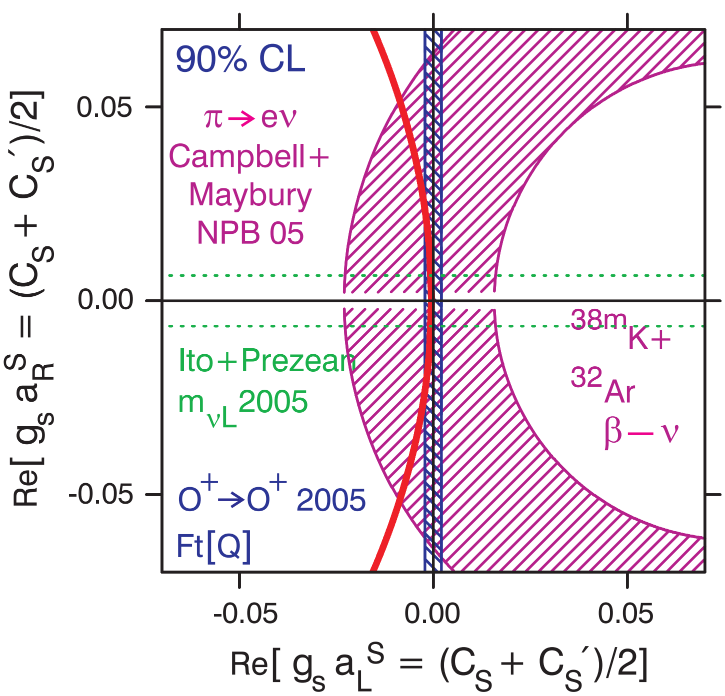


Figure 1: Constraints on first generation scalar couplings.

the constraint of the additional parameters in non-manifest left-right models. There is also sensitivity to Fierz interference terms for scalar and tensor couplings that could be as large as 0.001 in supersymmetric models. To this end, and with the experience gained, the experiment is being upgraded.

Tensor Interactions

Recently, the Pion-Beta Decay (PIBETA) collaboration at the Paul Scherrer Institute reported a statistically significant deviation from the standard model for $\pi \rightarrow \nu e \gamma$-decay that is explainable by a finite tensor interaction which can be mediated by spin-0 leptoquarks. The recoiling daughter nuclei from polarized nuclei have a spin asymmetry of A_{recoil}=-$x_1(A_\beta + B_\nu)$, where A_β and B_ν are the β and ν asymmetries respectively, when detected in singles and integrated over all recoil momenta.

In the allowed approximation, the recoil asymmetry for a pure Gamow-Teller transition is given by:

$$A_{recoil} = (5/8)(A_\beta + B_\nu) = 2C_T C'_T + (M_\beta / E_\beta)(C_T - C'_T)$$

which all but vanishes within the framework of the standard model. This makes it an almost ideal case for study as non-zero results beyond the limits of theoretical uncertainty indicate new physics. Currently the theoretical limitations are dependent on recoil order and on nuclear structure in the non-analogue transitions that have been studied in recent TRINAT experiments.

An experimental approach utilizing the unique capabilities of the TRINAT experiment (see Section 5.3.2.2.1.2) has allowed for a preliminary measurement and an accuracy of ±0.02 has been achieved. Constraints on the tensor couplings are given in Figure 3.

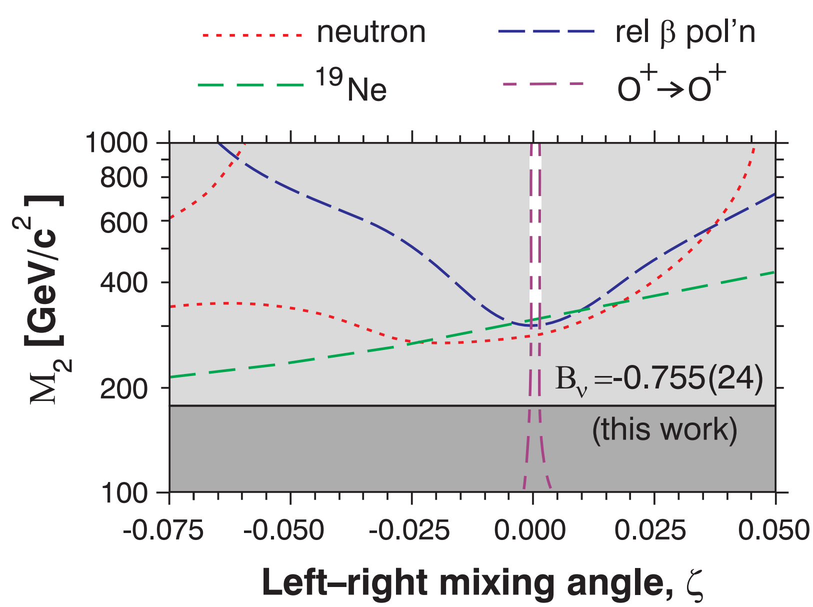


Figure 2: Exclusion plot for right-handed currents including current limits from TRINAT.

The limitations on the current limits from this experiment arise from calculations of nuclear structure parameters for the non-analogue transition. Future experiments with increased sensitivity will aim to extract these parameters experimentally independent of the new physics via a measurement of the momentum dependence of the recoil asymmetry.

Exotic Massive Particles

If a massive particle was emitted by a nuclear transition instead of a γ-ray, the recoiling nucleus would have a discrete, smaller momentum. There are perhaps a surprising number of phenomenological motivations for such signature-based searches for particles in the mass range 20-800 keV/c^2 that can be probed. For example, annihilation of $I^{\pi} = 0^+$ particles with mass 0.511 to 3 MeV into e^+-e^- pairs has been proposed to explain an observed spheroidal distribution of 511 keV γ-rays surrounding the galactic centre, as shown in Figure 4. This scalar would also be a dark matter candidate. The decay of the 556 keV 6^- ^{86m}Rb isomer can be used to study part of this mass range and will be the first test case.

The model also needs a new spin-1 exchange boson, which the experiment is also sensitive to, to mediate the interaction between the scalars. Therefore, a program using the TRINAT atom trap has been initiated that would measure the recoil nucleus momentum in the β-decay of various nuclear isomers. If a massive particle (axion) is emitted instead of a gamma, then the recoiling nucleus will have a lower momentum. Combining the unique properties of a

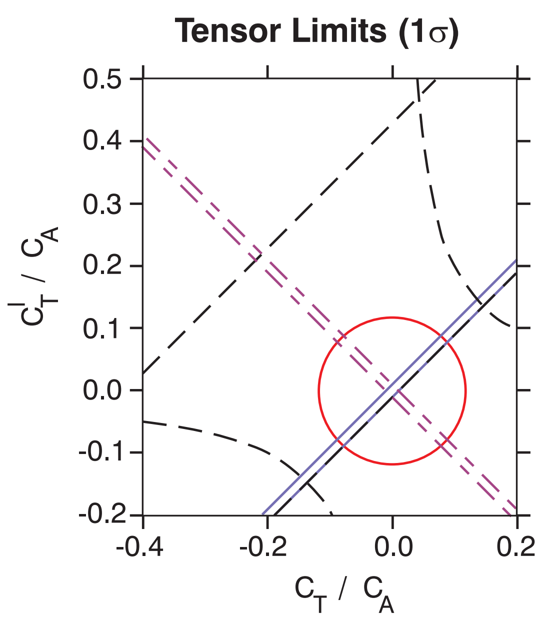


Figure 3: Exclusion plot showing complementarity of the present ^{80}Rb constraints to other measurements. Allowed regions are consistent with the standard model inside: red circle, ^{6}He β-neutrino at ORNL, blue solid lines, β+ polarization in ^{14}O, ^{10}C at Louvain, magenta dash-dot lines, m_ν naturalness.

magneto-optical trap (MOT) and modern, high-resolution spectrometer techniques developed for purely atomic physics experiments, it is possible to search for recoils with lower momentum independent of any interaction properties or lifetime of the emitted particle. Figure 4 shows the results of a simulation for an emitted particle of mass 50 keV.

Angular momentum rules favour the production of spin 0^- in transitions with magnetic multipolarity and 0^+ particles for transitions with electronic multipolarity. Therefore, utilizing the techniques developed for other experiments within the TRINAT system to polarize a cloud of atoms cooled by the MOT, the angular distributions of the emitted particles could be determined and hence the multipolarity of the emitted particles. A program of measurements has been initiated and expects first experiments within the next year.

Permanent Atomic Electric Dipole Moments

A permanent electric dipole moment (EDM) is a separation of charge along the angular momentum axis. As such, it violates time reversal as well as parity invariance. Assuming CPT symmetry T violation implies CP violation and therefore an atomic system interacting with a CP violating charge, distribution within the nucleus would acquire an EDM. Measurement of a finite electric dipole moment is a direct probe of physics beyond the standard model. Such an extension of the standard model is required to explain the cosmological baryon asymmetry in the context of Sakharov's model of baryogenesis. Currently the best limits on permanent electric dipole moments are from experiments in mercury. A collaboration from the University of Guelph, University of Michigan, Simon Fraser University, and TRIUMF is developing techniques to look for EDMs in neutron-rich Rn isotopes. Preliminary measurements at TRIUMF have allowed for techniques in gas handling to be developed as well as tests on polarizing neutron deficient Rn isotopes at the Nuclear Structure Laboratory at Stony Brook University. With the prospect of radon isotopes being delivered at ISAC-I in the near future, this experiment is now relocating permanently to TRIUMF.

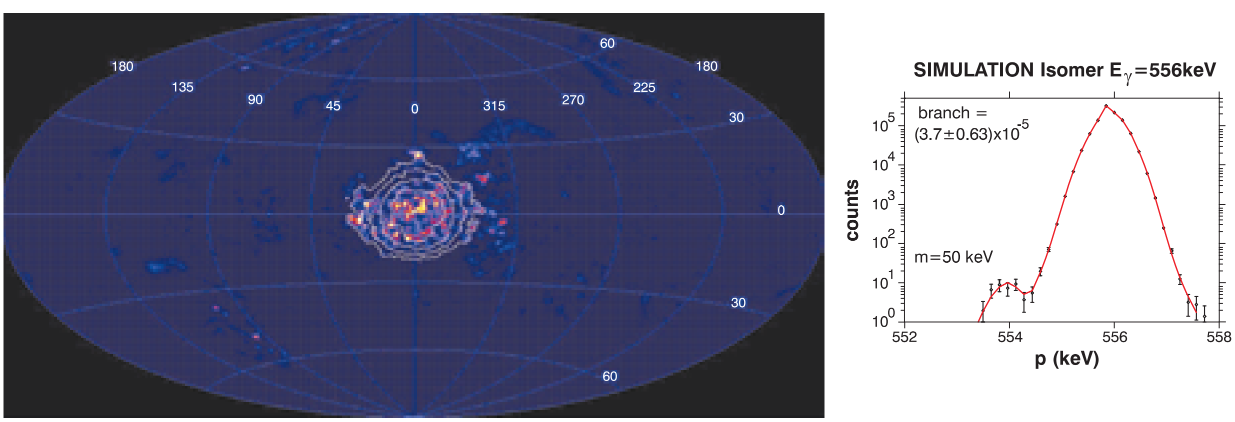


Figure 4: Left is the galaxy imaged by the INTEGRAL satellite in 511 keV γ-rays, yet unexplained. Right is the result of a simulation showing the expected distortion for a 50 keV/c2 massive particle.

Atomic Physics of Heavy, Radioactive Isotopes

As the atomic number increases, so does the wave function overlap of the nucleus with the atomic electrons. This overlap greatly enhances the sensitivity of measurements of the weak neutral current via atomic parity violation. Static anapole moments have so far only been observed in cesium nuclei. A collaboration from the University of Maryland, the University of Manitoba, and TRIUMF plans to build upon the experience gained trapping francium at the Nuclear Structure Laboratory, University of Stony Brook to start a program to measure these parity violating moments. This is one step towards a measurement of atomic parity non-conservation measurements of the weak neutral current. Currently, M1/stark interference measurements are being pursued in stable rubidium at the University of Manitoba as a test of relativistic corrections required for the atomic parity violating, many-body atomic physics calculations. This research is being complimented by a series of measurements being carried out at the University of Maryland to measure the static anapole moments with a microwave cavity. Both of these efforts plan to re-locate to TRIUMF in time to utilize the francium beams that are expected to be available in the coming years.

Partners

In Canada: Simon Fraser University, University of British Columbia, University of Guelph, University of Manitoba, and University of Western Ontario.

International Partners: Hungary (1), Israel (1), and the United States (5)

TRIUMF's Role

TRIUMF plays a pivotal role in all of the above studies. ISAC-I is unique in both the availability of high intensities of exotic, radioactive nuclei required for such experiments and the expertise and experience of running long-time line, high-precision fundamental tests. This expertise extends well beyond the scientists and experimental groups involved at TRIUMF. Over many years, the lab has developed excellent support groups in many areas, including data acquisition, detector development, and control and signal processing electronics. The technical level of support is a fundamental requirement for the future of any of these measurements.

4.2.1.2

Particle Physics Experiments

4.2.1.2.1

A Toroidal LHC ApparatuS: ATLAS

Introduction

The standard model (SM) of particle physics is an elegant theoretical model that provides the framework for our current understanding of the fundamental particles and forces of nature. A major component of this model is a theoretical quantum field called the Higgs field that is responsible for giving particles their mass. In this framework, the Higgs boson, the fundamental particle associated with the Higgs field, may be the key to understanding why elementary particles have mass.

In Einstein's theory of relativity, there is a crucial difference between massless and massive particles: all massless particles must travel at the speed of light, whereas massive particles can never attain this ultimate speed. But how do massive particles arise? The SM proposes that the vacuum of space contains the Higgs field, slowing down some otherwise massless elementary particles. Such particles would behave like massive particles traveling at less than light speed. Other particles, such as photons, are immune to this field: they do not slow down and remain massless.

Although the Higgs field is not directly measurable, accelerators could excite this field and "shake loose" the Higgs bosons. So far, experiments using the world's highest-energy accelerators have not observed any Higgs bosons, but indirect experimental evidence suggests that particle physicists are poised for a profound discovery when the ATLAS detector at the Large Hadron Collider (LHC) begins its search for the Higgs boson.

The ATLAS experiment is one of the two general-purpose detectors at the LHC at CERN, the European Laboratory for Particle Physics. The LHC is designed to accelerate intense beams consisting of thousands of bunches, each containing up to 10^{11} protons, to an energy of 7 TeV—about 7 times more energy than the present world record. The protons will collide in the heart of the detectors, allowing their constituent partons to annihilate and liberate up to 14 TeV per collision for the creation of new particles. Bunches will collide 40 million times every second, giving a luminosity of $10^{34}\ \mathrm{cm^{-2}s^{-1}}$. This unprecedented combination of centre-of-mass energy and luminosity will allow the LHC to produce previously undiscovered particles with masses of a TeV (such as the Higgs) and more in sufficient numbers to ensure their discovery, probing the phase space crucial to understanding how electroweak symmetry is broken and mass is generated. This, in turn, is expected to contribute to an understanding of the connection of gravity to the three forces already described by the SM. Among other outstanding issues, which the LHC is designed to address, are the nature of dark matter and the preponderance of matter over anti-matter in the composition of our universe.

The SM of particle physics is an effective theory that breaks down at high energies unless there is at least one additional elementary particle with a mass less than about one TeV. In the SM, this is a single Higgs boson; however, it is hoped that, as we probe higher energies, evidence will emerge for a more complete theory that will unify all of the known forces, including gravity. The energy and luminosity of the LHC were chosen to ensure that, whatever the precise nature of the new physics, previously unknown particles will be produced at the LHC in sufficient numbers to be detectable. Most theories of physics beyond the SM, such as supersymmetry, or extra dimensions, predict the existence of both Higgs bosons and dark matter candidate particles (such as the lightest supersymmetric particle, a massive particle which can interact with SM particles only through the weak force).

Higgs bosons can decay in many different ways, and the rates of the different decay modes depend on the mass of the Higgs. If the Higgs is relatively light, it will decay primarily to *b*-quark jets, which will be indistinguishable from the background. In that case, the most likely channels for discovery will be the rare decay of the Higgs to two photons (see Figure 1), with a very distinctive signature in the electromagnetic calorimeters, and the Vector Boson Fusion

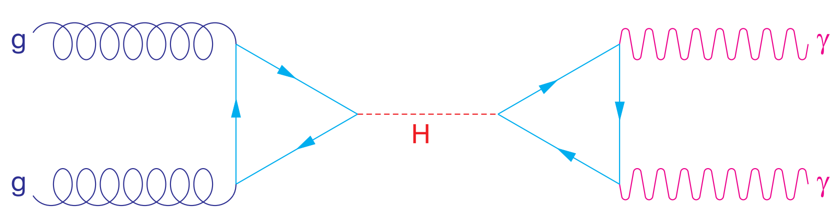


Figure 1: Simulation of Higgs produced by gluon fusion decaying to two photons.

signature (see Figure 2) of a Higgs in conjunction with two very forward jets, and no activity in the central detector except the products of the Higgs decay. A more massive Higgs can decay to two W or Z bosons, with very distinctive electron and muon signatures, and would be easier to discover. Dark matter candidates do not interact in the detector and must be found by detecting "missing transverse energy"; this requires a hermetic detector that is well calibrated for leptons, jets and electromagnetic energy.

Description of Dedicated Apparatus

ATLAS is designed to work in an extremely high-rate environment at unprecedented, multi-TeV energies; all of its sub-detectors are finely segmented to avoid occupancy problems, and it has a powerful three-level trigger system to reduce the data-flow to a manageable rate without losing interesting events. The ATLAS calorimeters are massive enough to absorb electrons and jets with energies of hundreds of GeV, and sufficiently segmented to resolve the photons in light Higgs decays. The calorimeters are geometrically designed to be hermetic, providing uniform coverage to within about 2° of the central axis of the beam pipe. The toroidal magnetic fields in the muon spectrometer are strong enough to permit measurement of TeV muon momenta to a precision of about 10%, to within about 9° of the beam pipe axis. This will ensure good reconstruction of muonic decays of very massive additional gauge bosons (called W' and Z'), which are predicted to be a spectacular signature of many new physics scenarios. The inner detector, which is surrounded by a 2-Tesla solenoid, provides excellent charged-particle momentum resolution and reconstruction efficiency. It employs vertex detectors close to the interaction region to resolve secondary vertices in τ-lepton and b-quark decays.

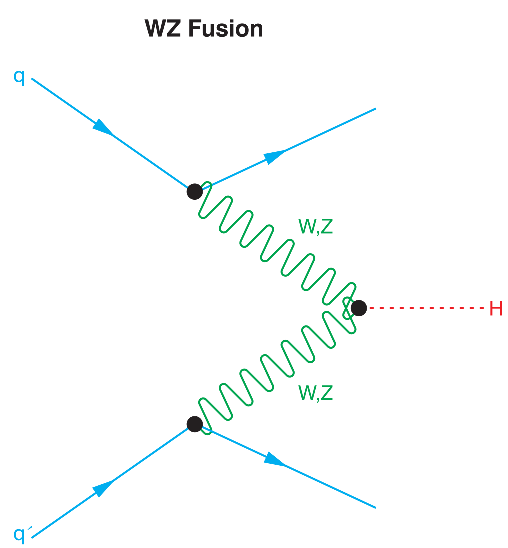


Figure 2: Feynman diagram illustrating Higgs production in vector boson fusion.

Results and Progress

Construction of ATLAS is expected to be completed by late spring of 2008 (see Figures 3 and 4). The hadronic endcap (HEC) liquid argon calorimeters, which were designed at TRIUMF, and half of which were built at TRIUMF, have been installed and cooled and are now operational. The LHC is projected to have protons circulating by summer 2008, and colliding beams a few weeks later. In the meantime, integration and commissioning tests of the detector components already installed and equipped with electronics are being performed on a regular and ongoing basis with cosmic rays. In expectation of the enormous amount of data, which will be generated by the LHC experiments, there has been a massive international effort to set up grid-computing facilities around the world to reconstruct the data and calibrate the equipment. These computing centres are organized in a hierarchy of tiers which extent around the world with “Tier 0” being at CERN itself. One of the ten “Tier-1” centres, which will process ATLAS data, is located at TRIUMF. The presence of the Canadian Tier-1 Data Centre staff at TRIUMF, in addition to the detector experts who designed and built the hadron calorimeters, and TRIUMF’s proximity to a number of ATLAS member universities, make TRIUMF a natural “analysis centre” for Western Canada. With that in mind, the number of research scientists working primarily on ATLAS analysis has increased from one to three, which will make TRIUMF a very attractive place for students and visitors and a useful resource for all of ATLAS-Canada.

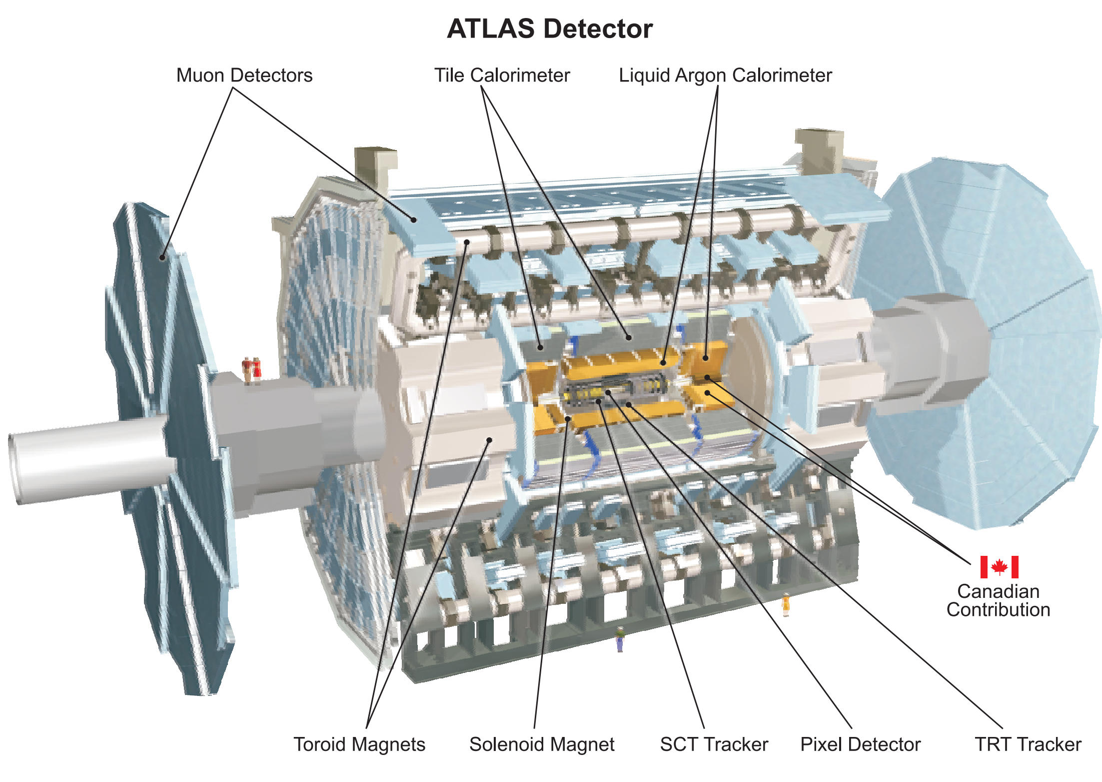


Figure 3: The ATLAS detector and its major subsystems. Image courtesy of CERN.

Partners

In Canada: Carleton University, McGill University, Simon Fraser University; University of Alberta, University of British Columbia, l'Université de Montréal, University of Regina, University of Toronto, University of Victoria, and York University.

International Partners: Over 150 institutions outside Canada, including CERN.

TRIUMF's Role

The liquid argon HECs were designed and partially built at TRIUMF. Their assembly at CERN was overseen by TRIUMF personnel, who designed the specialized tooling required for this challenging task. The radiation-hard front-end electronics for the liquid argon calorimeters were designed by a TRIUMF scientist at the University of Alberta. TRIUMF engineers made major contributions to the design and construction of the forward calorimeters (FCAL) and a TRIUMF scientist led the project to construct one third of the FCAL (FCAL2) at Carleton University. TRIUMF engineers contributed to the design, construction, and installation of the complex and delicate feedthroughs, which bring cables from the endcap and forward calorimeters out of the cryostat.

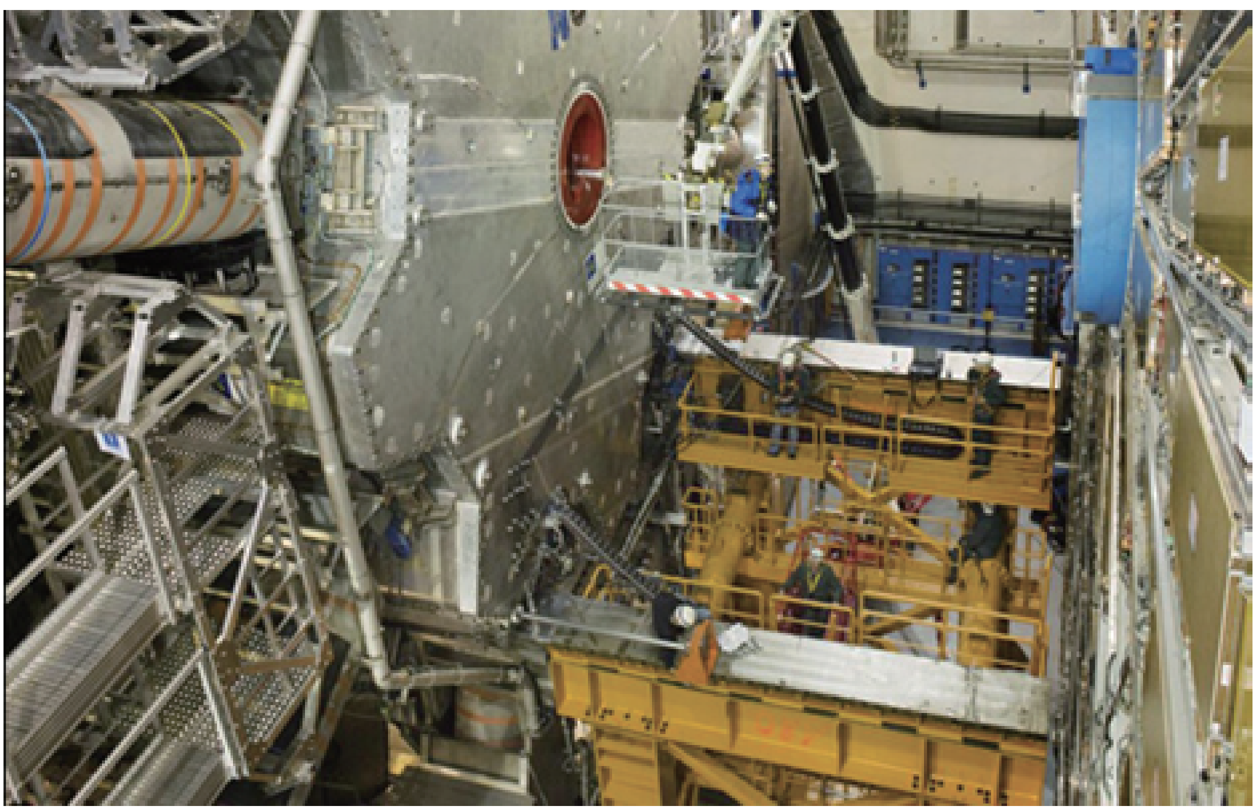


Figure 4: A recent view of the ATLAS Detector installed in its experimental cavern. Photo courtesy of CERN.

TRIUMF hosts the Canadian Tier-1 Data Centre and has coordinated the design, manufacture and transport of over 40 million dollars' worth of in-kind contributions to the LHC and upgrades to its injector complex. This contribution included the prototyping and production of components for the four LHC injection kicker systems, such as power supplies, switch tanks and pulse-forming networks, and 52 of the twin-aperture warm quadrupole magnets for focusing elements of the beam cleaning insertions of the LHC. Series production of the quadrupoles was completed by ALSTOM Canada in Tracy, Quebec. The machine contributions were funded under the last two TRIUMF five-year plans, and the Canadian Tier-1 Data Centre is funded by grants from the Canada Foundation for Innovation and the BC Knowledge Development Fund, as well as in-kind contributions from IBM.

TRIUMF Scientist C. Oram was chair of the ATLAS Collaboration Board in 2006 and 2007 and deputy chair in 2005 and 2008.

4.2.1.2.2

Tokai to Kamioka: T2K

Introduction

Neutrinos are fundamental subatomic particles, which interact with matter only through weak interaction, one of the four forces of the standard model. For instance, neutrinos are produced when nucleons decay inside a nucleus. According to the standard model, there are three types, or flavours, of massless neutrinos, which always maintain their identity. But what if neutrinos have mass?

Recent experiments, particularly at the Sudbury Neutrino Observatory (SNO), have discovered that neutrinos, once believed to be massless particles, actually have very small but non-zero masses, and they are continually changing from one type, or flavour, of neutrino into another.

T2K is a next-generation neutrino experiment that will study flavour oscillations of neutrinos produced in a man-made beam. Neutrino oscillation is the first evidence for new physics beyond the standard model. Canada has been an international leader in this discovery through the experimental work done at SNO, but the details of how neutrinos oscillate are still poorly understood, and many parameters of the oscillations are unmeasured. T2K will use accelerator-produced neutrinos, whose energy and composition can be directly controlled, to study oscillations of neutrinos as they travel hundreds of kilometres across Japan. Strong Canadian participation in this international experiment builds on, and maintains, Canada's leadership role in neutrino research.

SCOTT OSER

Associate Professor, UBC

Scott Oser graduated *summa cum laude* in 1994 from Washington University (St. Louis) and completed his Ph.D. at the University of Chicago in 2000. His thesis, “High Energy Gamma-Ray Observations of the Crab Nebula and Pulsar with the Solar Tower Atmospheric Čerenkov Effect Experiment,” used an array of mirrors at a solar power plant to detect high-energy particles striking the earth’s atmosphere.

In 2000, Dr. Oser joined the Sudbury Neutrino Observatory (SNO) group at the University of Pennsylvania, where his work helped the SNO collaboration solve the long-standing solar neutrino problem by proving that neutrinos have mass and undergo flavour oscillation. He moved to UBC in 2003 to be close to TRIUMF’s world-class facilities for detector development. He currently leads the TRIUMF group building fine-grained detectors for the T2K experiment.

In 2006, Scott, as part of the SNOLAB collaboration, was co-recipient of NSERC’s inaugural John Charles Polanyi Prize in Physics. In 2008, he received a prestigious Alfred P. Sloan Research Fellowship. ■

T2K will use the new Japan Proton Accelerator Research Complex (JPARC) proton synchrotron, under construction in Tokai, Japan to produce an intense beam of muon neutrinos that will be directed towards the Super-Kamiokande neutrino detector in western Japan. By comparing the rates and types of neutrino interactions in Super-Kamiokande to those measured by a “near detector” in Tokai, T2K will measure neutrino oscillations across a 295-km baseline with unprecedented precision. The experiment hopes to be the first to measure the small neutrino mixing angle θ_{13}, which can be determined by measuring the rate at which muon neutrinos oscillate into electron neutrinos over this distance.

TRIUMF and six Canadian universities are contributing key elements to the T2K experiment. The Canadian T2K group is building the central tracker for T2K’s near detector, which will measure the neutrino beam at its production point before the neutrinos begin to cycle through a full oscillation. The Canadian team is also building a beam monitor, based on optical transition radiation, to measure the stability of the neutrino beam itself. TRIUMF has made significant contributions to the neutrino beam line and the JPARC accelerator (see Section 4.2.4). The following sections will highlight TRIUMF’s contributions to T2K detector construction.

Description of Dedicated Apparatus

T2K will use a new near detector called the ND280, located 280 m from the beam target station, to provide crucial information about the properties and interactions of the unoscillated neutrino beam. This information will be used to predict the rate of neutrino interactions at Super-Kamiokande in the absence of oscillations, and to estimate the rate of background processes such as intrinsic ν_e beam backgrounds.

The ND280 is a large magnet-based detector that re-uses the large magnet built for the UA1 experiment at CERN. Inside the magnet is a Pi-Zero Detector (P0D), consisting of tracking layers of scintillators and lead. Downstream of the P0D is the tracker, consisting of three large time projection chambers (TPCs) alternating with two fine-grained detectors (FGDs) built from a plastic scintillator. The downstream end and the sides of the ND280 are covered by an electromagnetic calorimeter (ECAL), while slots in the sides of the magnet are instrumented with scintillators to measure the range of sideways-going muons. Figure 1 shows a cutaway view of the ND280. The P0D, TPC, FGD, and ECAL detectors inside the magnet will measure neutrino interactions from T2K’s beam near the neutrino production point and determine the energy spectrum and interaction rates of the unoscillated neutrinos. The interior volume of the magnet is approximately 3.5 m x 3.5 m x 7 m.

The TRIUMF group is responsible for major components of the ND280’s tracker. The tracker, consisting of the three TPCs and two FGDs, will be used primarily for measuring charged-current neutrino interactions. The FGD provides the target mass for neutrino interactions in the tracker and consists of 30 layers of 2 m long bars of extruded polystyrene scintillator, 1 cm x 1 cm square in cross section, with the layers alternating in the horizontal and vertical directions to provide tracking information. Each bar is read out with a wavelength-shifting fibre connected to a pixelated silicon photodiode run in Geiger mode, sometimes known as “silicon photo-multiplier.” Charged-current interactions in the scintillator will produce charged leptons and often recoil protons and/or pions, and the tracks of these particles can be reconstructed from the measured light in each bar. Tagging Michel electrons produced in the pions' decay chain can identify pions stopping inside the FGD. The electronics readout, based on custom-designed waveform digitizers, is a Canadian responsibility. The Canadian T2K group is building the FGDs at TRIUMF, and will test them in TRIUMF's M11 beam line before installation in Japan in 2009.

Penetrating particles, especially muons or electrons, and also protons or pions, will exit the FGD to reach one of the adjoining TPCs. These large-volume TPCs (2.5 m x 2.5 m x 0.9 m in size) use Micromegas modules with 70 mm^2 pads for signal amplification and readout. The TPCs precisely measure in three dimensions the trajectories of all charged particles passing through them. The track curvature in the applied magnetic field allows the charge and momentum of each particle to be determined to <10% for momenta <1 GeV/c, which in turns allows for the energy of the neutrino to be estimated. The amount of ionization in the gas is used to determine the type of particle passing through the TPC, which can be used to identify the type of interaction that produced the event. The TPCs use an Ar-CF_4-isobutane gas mixture and are read out using a custom ASIC that provides waveform digitization using a switched capacitor array. The Canadian T2K group is responsible for the mechanical construction of the TPCs, including their field cages, and for the associated gas systems. The TPCs will be fully assembled and tested at TRIUMF before installation in Tokai.

In addition to the ND280, T2K uses a number of sophisticated beam monitors to check the stability of the primary proton beam. One such monitor is the

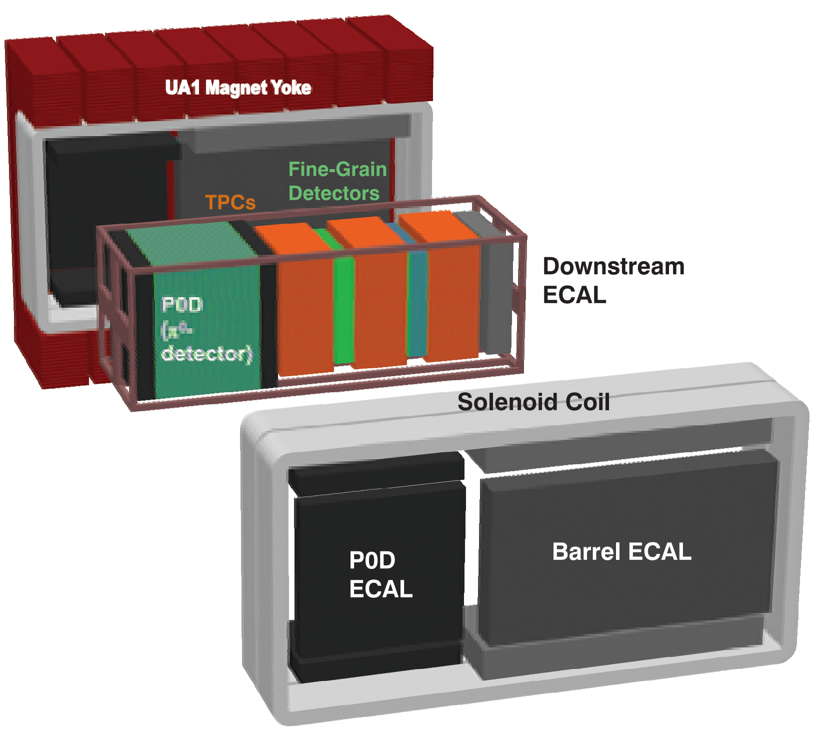


Figure 1: Exploded view of the T2K's near detector (ND280).

optical transition radiation (OTR) monitor. The OTR, which is being built by the TRIUMF, the University of Toronto, and York University groups, consists of a thin reflective foil that is inserted into the primary proton beam just upstream of the target. As the beam passes through the foil, optical transition radiation produced by the beam is reflected by an array of mirrors to a camera that images the light pattern. Small drifts in the beam position on the target will produce visible changes in the OTR image that can be used to infer the beam's impact position on the target.

The total capital cost of the Canadian contributions to the ND280 and OTR is C$2.3 million. The international cost of the T2K project as a whole is C$150 million, dominated by the costs of the beam line and civil construction in Japan.

Results and Progress

The Canadian T2K group received capital funding from NSERC in 2006, and detector construction is currently underway, with installation in Japan slated for summer 2009. In November 2006, the TRIUMF group, working with a local plastic extrusions company, successfully extruded three tonnes of polystyrene scintillator bars for the FGDs. The bar width was controlled to better than 20 μm across the entire production run, with less than 5% variation in light yield, and a negligible bar rejection rate. Tests of these bars in TRIUMF's M11 beam line show excellent light yields, in excess of 30 photoelectrons for minimum ionizing particles. In 2007, the full set of wavelength-shifting fibres was acquired and the non-readout ends were mirrored. Presently, over 80% of the scintillator bars have been glued into FGD tracking planes. The first of the two required dark boxes has also been constructed. Prototype FGD electronics, designed at TRIUMF, were tested in the M11 beam line in 2007, and the required low noise and timing resolution have been directly demonstrated. Production on the final FGD electronics will happen in summer 2008, with full detector integration scheduled for fall 2008.

The TPC group built a small-scale prototype in 2005 to demonstrate the detector concept and gain experience with micropattern readout panels. Results from this prototype have demonstrated the required levels of gas purity and electron attachment, as well as good tracking resolution. Construction of the first full-sized TPC module, known as Module 0, is currently taking place at TRIUMF. As this is the first project to use TRIUMF's large numerically controlled router, Module 0 construction serves not only to develop expertise in Micromegas TPCs, but also to develop the router facility for future detector construction of all types. Beam tests of the first completed module will take place in summer 2008, with additional tests in conjunction with the FGDs in 2008/2009. Two TPC modules, and the two FGDs, will be shipped to Tokai in summer 2009 for installation into the ND280, while the third TPC will be shipped early in 2010.

The OTR detector construction is far along. In June 2006, the OTR group tested a 15% scale prototype in an electron beam at NRC and successfully imaged transition radiation. Mechanical construction of the OTR components is underway, and the mechanical components will be installed in the neutrino beam target station in August 2008. In December 2006, the group irradiated candidate foil materials at TRIUMF to look for radiation-induced aging, particularly changes in quality of the reflective surface. No changes were seen, and additional tests are planned for 2008. The calibration scheme for the OTR includes a grid of fiducial marks on the OTR foil itself that can be used to correct for image distortions introduced by the optics. This distortion correction has recently been directly demonstrated. Testing has also been done using a diffuse light source to determine the efficiency of the OTR camera. Work has begun on data acquisition for the OTR camera, which will be installed in Tokai in February 2009.

Partners

In Canada: University of Alberta, University of British Columbia, University of Regina, University of Toronto, York University and the University of Victoria.

International Partners: France (4 institutions), Germany (1), Italy (3), Japan (8), Poland (6), Russia (1), South Korea (7), Spain (2), Switzerland (3), United Kingdom (8), and the United States (8).

TRIUMF's Role

The T2K experiment will use an off-axis neutrino beam to lower backgrounds and produce a more monochromatic beam. This off-axis beam technique was first proposed by TRIUMF in the 1990s. The TRIUMF neutrino group is one of the largest groups in the T2K collaboration, and three of T2K's major detector components (TPC, FGD, OTR) are being built at TRIUMF in collaboration with researchers at Canadian universities and international collaborators. TRIUMF provides most of the infrastructure support for the T2K Canada group, including support from the detector facilities group, design office, engineering, gas system expertise, machine shop, electronics, and data acquisitions support. TRIUMF also provides direct contributions to the design and construction of the JPARC accelerator and the beam line itself (see Section 4.2.4).

4.2.1.2.3

Sudbury Neutrino Observatory: SNO/SNOLAB

Introduction

Neutrinos are neutral, weakly interacting elementary particles; they exist in three types. Since they are only weakly interacting, they pass largely unhindered through the sun or the earth. Thus, neutrinos produced in the interior of the sun can, if detected, serve as a probe of the solar interior. Unfortunately, again because the neutrino is weakly interacting, it requires large, kiloton detectors that are shielded from other radiation by being deep underground to detect them.

In recent years, theoretical models of the sun have permitted detailed calculations of the number, or flux, of neutrinos released from the sun. These models tell us the sun produces over two hundred trillion trillion trillion neutrinos every second. Several experiments have detected solar neutrinos and found the detected number, the flux, was lower than predicted by the models. It appears that far too few neutrinos are detected than is consistent with the known energy output of the sun. This is known as the solar neutrino problem (SNP). The Sudbury Neutrino Observatory (SNO) project was undertaken to solve the SNP. Two solutions were proposed: scientists either did not understand about energy production in the sun, or they did not understand about the propagation of neutrinos.

PEOPLE

DAVID SINCLAIR

Director, SNOLAB

David Sinclair received his Honours in physics and Ph.D. degree in nuclear physics from Queen's University (1969). His Ph.D. thesis was "Leveles of 127I from 127I(n.n'γ), was completed in 1972. After graduation, he spent a year at the Niels Bohr Institute, where he studied reaction mechanisms in single nucleon transfer reactions involving heavy ions. In 1973, David became a Research Officer at Oxford University where he continued his heavy ion studies, extending the work to higher energies available with the variable energy cyclotron. He was appointed to a University Lecturership at Oxford and an Official Fellowship at St Anne's College, Oxford.

In 1984, Dr. Sinclair changed fields to work on the solar neutrino problem and to develop the feasibility for the Sudbury Neutrino Observatory (SNO). He presented the first conference talk on the SNO proposal and was corresponding author on the first paper to describe its physics capability. In 1989, he returned to Canada to become Associate Director (Science) of SNO and the first Chair of the SNO Scientific Board. In 2002, he led a proposal for the creation of SNOLAB which has now received over $C65M in federal and provincial support. Dr. Sinclair was the first SNOLAB Director. He continues to hold the position of Director of Facility Development. In addition to overseeing the construction of SNOLAB, Dr. Sinclair is the Canadian principal investigator for a project looking at the feasibility of measuring neutrino-less double-beta decay in a xenon gas counter.

In 2006, David, as part of the SNO collaboration, was co-recipient of NSERC's inaugural John Charles Polanyi Prize in Physics. He is a fellow of the Royal Society of Canada.

Initially, most physicists assumed that the difficulty lay in the models of the sun, and many exotic models were introduced to explain the neutrino deficit. The alternative explanation was that neutrinos might change in transit from the sun to the earth through a process called neutrino oscillation. Initially, the neutrino oscillation explanation did not find much favour in the physics community. However, in 1985 it was pointed out that oscillation could occur if neutrinos had mass. Opinion swung strongly in favour of neutrino oscillations, but actual proof of this process could not be found. If proof could be found, it would mean that a fundamental conservation law had to be broken: neutrinos would have to have mass. As there are far more neutrinos in the universe than any particle other than the photon, even a tiny mass could influence the total mass density of the universe.

Description of Dedicated Apparatus

Because neutrinos interact only weakly with matter, it is necessary to make a very large detector to search for them. With a large detector, however, there is the potential for large backgrounds coming either from cosmic rays or from local radioactivity. To shield the experiment from these backgrounds, SNO uses a detector, located 2 km underground in a cavern in Vale-INCO's Creighton mine (see Figure 1). The largest, deepest cavern in the world designed for human occupancy, its centre is the world's largest all-acrylic vessel. It holds 1000 tonnes of heavy water purified from radioactive contaminants to a level of about 1 atom per tonne for the critical radium activity — a level far below previous detection capabilities. The vessel had to be fabricated *in situ* from over 100 pre-formed acrylic panels. Neutrino events in the heavy water produce small flashes of light and these are recorded in an array of about 10,000 phototubes 20 cm in diameter.

The sun only produces electron type neutrinos so if the measured total flux is greater than the measured electron neutrino flux, then some of the electron type neutrinos must have changed into other neutrino types or flavours. The critical physics advantage of the SNO detector over all other solar neutrino projects is that, by using heavy water, SNO can measure both the total flux of neutrinos and electron-type neutrinos from the sun, allowing for the performance of intrinsic calibrations.

Results and Progress

The SNO project has successfully demonstrated that neutrinos oscillate and therefore have mass and the conservation of lepton flavour is violated. The total number of neutrinos produced by the sun is in excellent agreement with the solar model predictions.

The use of heavy water to measure both the total neutrino flux and the electron neutrino flux is unique and, from the beginning of the project, there was concern that no other project would be able to verify the results. The solution was to make the measurement in several different ways with different systematic effects so that the project could verify itself as much as possible.

The first measurement was made with pure heavy water in the vessel. The detection efficiency for the measurement of the total neutrino flux was then enhanced by the addition of two tonnes of NaCl to the heavy water and a second measurement was made. The salt was then removed, and counters, sensitive only to the neutrons produced by the process that measures the total neutrino flux, were installed. The results from the first two phases of the project agree. The analysis of the third phase is in progress at the time of this writing. Results have been presented in a series of publications, which to date have now been cited over 3,000 times.

Following the successful operation of SNO, the lab has decided to build a long-term facility to focus on studies in neutrinos and particle astrophysics, which require the low background environment possible only in a deep underground site. Plans are to expand the existing underground laboratory with two additional large cavities and some rooms for small experiments, prototyping, and support facilities. The construction of this facility is well advanced, and the first round of experiments is being developed. The topics to be addressed

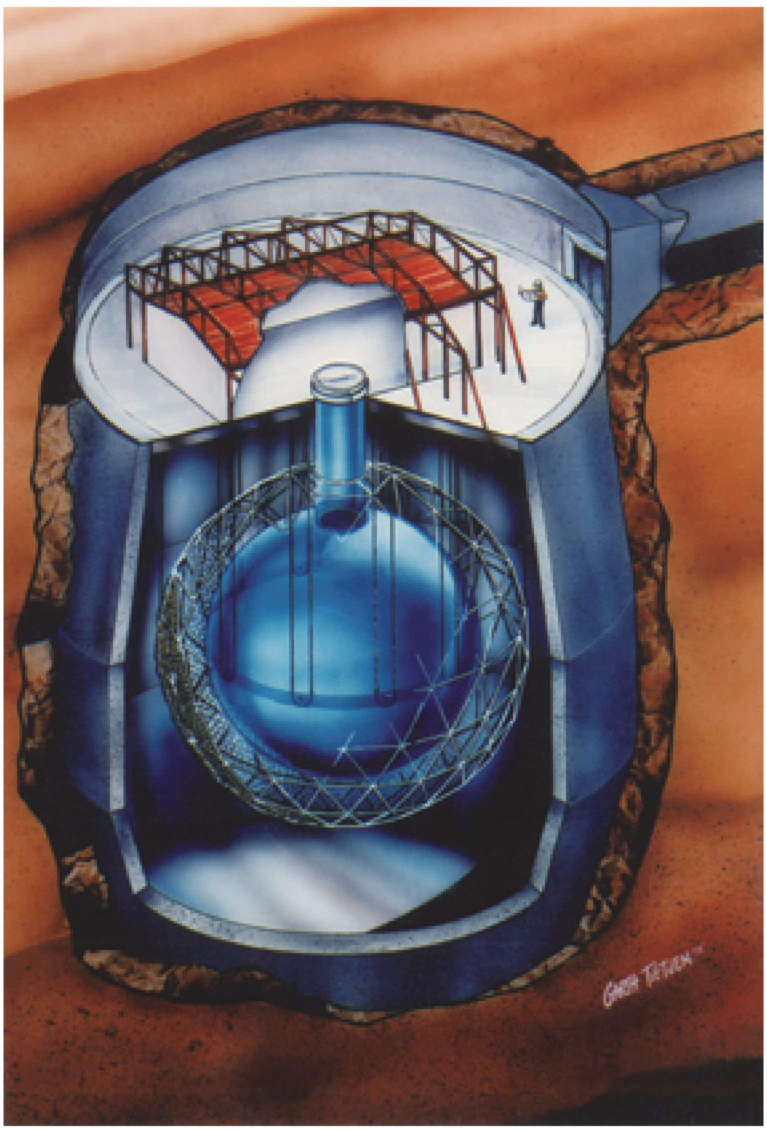


Figure 1: The SNO detector.

include studies of low energy solar neutrinos, studies of neutrinos from the earth, the search for supernova neutrinos, searches for dark matter interactions with normal matter, and searches for neutrinoless double beta decay. All of these topics build on the physics results from SNO, and all require the special low background techniques developed for the SNO project.

The SNOLAB development has been funded by awards from the Canadian Foundation for Innovation (CFI), FedNor, and the Province of Ontario. A total of $C63 million has been provided to establish this facility, with the largest award from the CFI International Facilities program. In the future, the laboratory will operate as an International Facility for Underground Science.

Partners

In Canada: Carleton University, Laurentian University, Queen's University, the University of Alberta, University of British Columbia, University of Guelph, and l'Université de Montréal. International Partners: United Kingdom (3) and United States (5).

TRIUMF's Role

During the construction phase, TRIUMF established an electronics test facility and commissioned the high voltage decoupling cards. TRIUMF also provided engineering and fabrication support for some of the major detector components, including the glove box over the heavy water and the acrylic vessel support devices. These activities were overseen by TRIUMF scientist Richard Helmer. David Sinclair, who is a joint TRIUMF Scientist/University of Carleton faculty member, was the Associate Director (Science) and Deputy Director for the SNO project. He also led the water purification and analysis teams. Both of the TRIUMF scientists were actively involved in the operation of the SNO detector and in the physics analysis.

D. Sinclair is the principal investigator for the development of SNOLAB. He was the first Director of SNOLAB and is currently the Director of Facility Development for the lab. He is also heading the Canadian team researching the feasibility of a xenon double β-decay experiment.

V. Strickland, a TRIUMF engineer located at Carleton University, has been providing support for several of the SNOLAB experiments. Most of his work has been associated with the xenon double β-decay experiments, but his expertise in finite element analysis has been critical to the development of concepts for the support of the SNO+ scintillation vessel. He has also carried out thermal modeling for the DEAP dark matter detector.

4.2.1.2.4

Precision Measurements

4.2.1.2.4.1

TRIUMF Weak Interaction Symmetry Test: TWIST

Introduction

The standard model is the best theory that physicists currently have to describe the actions and interactions of fundamental particles, the building blocks of the universe. The standard model (SM) agrees with most of what has been observed, but is widely believed to be only an approximation of a more basic and fundamental model whose properties are not yet known.

The SM leaves open many questions. For example, the SM predicts only a subset of the possible particle interactions allowed by a more general theory that satisfies all aspects of a symmetry known as Lorentz invariance. Other interactions have been omitted based on empirical observations, but are they really completely absent? Experimental tests of the SM either place limits on the strength of these interactions or more optimistically find them and show the SM to be incomplete, requiring physics beyond the standard model.

The TRIUMF Weak Interaction Symmetry Test (TWIST) is a search for deviations from the pattern of muon decays predicted by the SM. The muon is the lightest and most accessible fundamental charged particle that exists beyond those that make up the matter around us. When the muon decays, it nearly always produces an electron and two very light, elusive, neutral particles called neutrinos. This is the simplest type and the most pure example of the weak interaction, and is potentially a place where tiny effects could be observed.

High-quality beams of muons are produced at TRIUMF, and a very high-precision detector system in a high solenoidal magnetic field is used to measure accurately the direction and energy of the positive electron (or positron) produced for each of billions of positive muon decays. The pattern, or symmetry, of these decays is predicted precisely by the SM. A deviation from SM expectations, if found, would provide clues to the character of a more general description of the smallest particles in our universe. On the other hand, if no deviation is found, some hypothesized features of a more general description can be eliminated from consideration.

Description of Dedicated Apparatus

The goal of TWIST is to determine the energy and angular dependence of positrons emitted in the decay of highly polarized muons, with uncertainties of better than one part per thousand. This permits a search for possible violations of SM predictions in muon decay with order-ofmagnitude higher precision than previous experiments. An analysis of the dependence yields three of the muon decay parameters, often called the Michel parameters: ρ, δ, and ξ. The ξ parameter can only be measured along with the initial muon polarizaton P_μ, so the experiment in fact determines $P_\mu\xi$.

To accomplish its goal, the TWIST apparatus uses a high-precision, low-mass, planar detector array in a well-known magnetic field. TRIUMF has a history of producing high-quality muon beams, and TWIST takes advantage of the high polarization of a positively charged surface muon beam by guiding it along the axis of the solenoid so that it comes to rest in a thin, high-purity metal stopping target at the centre of the detector. The resulting decay positrons are tracked through the field to measure their momenta and angle of emission with respect to the muon polarization direction (the detector axis).

The detector (see Figure 1) has a symmetric array of 56 low-mass high-precision planar drift chambers, constructed to very high precision while minimizing the amount of material in the tracking region. The chambers provide precise spatial information for event classification, track identification, and track reconstruction. Planes are positioned with relative accuracy of 5×10^{-5} in the beam direction, using specially constructed glass ceramic spacers provided by Russian collaborators. Alignment in the transverse directions is accomplished by fitting straight tracks, but depends also on the wire separation accuracy of 3.3 μm rms for 6,304 sense wires in the chamber modules. Signals are amplified, discriminated, and digitized by multi-hit time-to-digital converters loaned by US collaborators.

At the centre of the array is a thin target in which the muons stop. The detector allows very precise measurement of positron decay tracks symmetrically, in forward and backward directions, while minimizing interactions that would broaden and distort the detector response function. The planar geometry means that the energy loss, which depends on the length of a track in any material in its path, has primarily a simple $1/\cos\theta$ dependence. The detector stack is in a uniform solenoidal field of 2 T, produced by a superconducting solenoid that was originally constructed as a whole body MRI field device. An external steel yoke was fabricated to produce the required field uniformity for the detector tracking volume and to contain the return field. Within the tracking volume, field map measurements determine the variations of the field as a function of position to 5×10^{-5}.

A thin scintillator records the incoming muon, providing an unbiased trigger for events. The incident beam characteristics and the beam entrance path are engineered to minimize depolarization, the knowledge of which is crucial in setting limits on $P_\mu\xi$. A low-mass, low-pressure beam measurement device based on time expansion chambers is used to record very precise information on the muon beam spatial and angular distributions, in order to optimize, measure and monitor the properties of the incoming beam.

The value of TWIST apparatus is approximately C$1.7 million from Canadian contributions, plus C$0.7 million from international (US and Russian) sources.

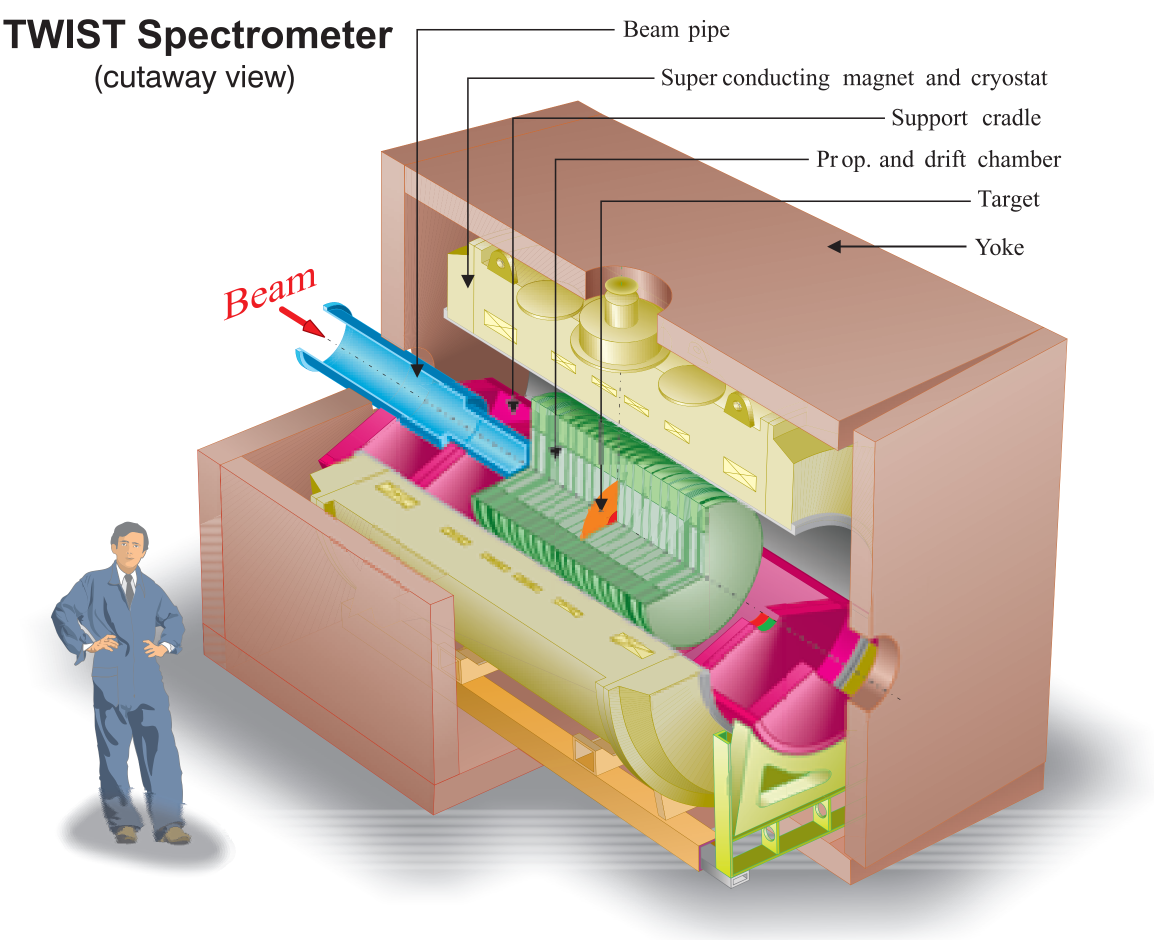


Figure 1: The TWIST spectrometer, showing the detector inside the superconducting solenoid.

Results and Progress

The muon decay parameters offer a way to describe the most fundamental purely weak interaction in nature. The TWIST results determine these decay parameters and place stringent constraints on the muon-decay space-time characteristics. While we know that the left-handed vector-minus-axial-vector interaction dominates weak processes, including those of nuclear beta decay, the limits to which other interactions (*e.g.*, scalar, tensor, and right-handed) are excluded are established best with muons. Values of specific decay parameters place limits on possible alternatives to the SM that are competitive with, and complementary to, other results from nuclear and high energy physics.

Results obtained so far are consistent with the SM, but with significant increases in precision compared with previous experiments. It should be noted that best previous results are based on data and analyses carried out 20 to 30 years ago; several attempts at better measurements have been made in the interim, but none has been successful. Blind analysis of the first TWIST data sets obtained in 2002 yielded reductions of total uncertainties by factors of 2.5 and 2.9 for the ρ and δ parameters respectively. Both factors have been increased to 5.2 following a 2007 analysis of 2004 data; these results are preliminary pending publication. Following the final TWIST analyses of data from 2006-07, a further improvement by a factor of two is within reach and would achieve the goals of the project for ρ and δ.

An analysis of the 2004 data for the $P_\mu\xi$ parameter resulted in a factor of 2.1 reduction in uncertainty. The polarization parameter presents main systematic uncertainties that are distinct fromthose of ρ and δ, and are more challenging to control and estimate. Nevertheless, we believe there will be a significant precision improvement in the TWIST result for $P_\mu\xi$ following final analysis of 2006–07 data.

Partners

In Canada: University of Alberta; University of British Columbia; University of Regina; and l'Université de Montréal.

International Partners: Russia (1); and the United States (2).

TRIUMF's Role

TRIUMF has been the primary support for more than half of the nearly 40 TWIST collaborators, including the spokesperson and leaders of all the subgroups. TRIUMF has also been the main source for infrastructure support including, at various stages, the design, engineering, electronics, machine shop, and technical support staff. TRIUMF subsidized TWIST's acquisitions of cryogenics for the superconducting solenoid, the detector chamber fabrication and gas costs, beam line improvements, and overheads. The high-quality muon beam that is available at TRIUMF is a crucial ingredient of TWIST's success, and is uniquely suited to the requirements of a polarized muon decay experiment.

4.2.1.2.4.2

Search for New Physics at the TeV Scale via a Measurement of the Proton's Weak Charge: Q_{weak}

Introduction

The standard model of particle physics has been enormously successful, but we know it is incomplete. The search for a fundamental description of nature beyond the standard model (SM) is driven by two complementary experimental strategies. The first is to build increasingly energetic colliders, such as the Large Hadron Collider (LHC) at CERN, to excite matter into a new form. The second strategy is to perform high-precision measurements where an observed discrepancy with the SM would reveal the signature of new forms of matter. The Q_{weak} measurement at Thomas Jefferson National Accelerator Facility at the Jefferson Laboratory (JLab) is an example of the second approach and will lead to an extremely precise determination of the strength of the proton's weak interactions (its weak charge). This measurement will either provide a severe constraint on, or a signature of, new physics. For example, early LHC results might see new physics in the form of directly produced new particles, and the measurement made in the Q_{weak} experiment would constrain their properties. Alternately, the allowed-mass limits for new physics beyond the SM would be significantly raised.

The Q_{weak} collaboration will carry out a precision measurement of parity-violating electron scattering on the proton at very low momentum transfer at Jefferson Laboratory. The experiment will provide the first precision measurement of the proton's weak charge: $Q_{weak} = 1 - 4 \sin^2 \theta_W$. The measured weak charge is screened by clouds of virtual particles in the vacuum, and by taking into account all known particles, SM calculations make firm predictions for what should be seen by the experiment. Any discrepancy between the experimental value and the SM prediction can be used to set limits on as-yet undiscovered new particles and their interactions (*e.g.*, a heavy *Z'* boson, SUSY, and so on). At the planned accuracy of the measurement, the effects of new physics at the TeV scale would be resolvable. The experiment builds on technical advances that have been made in JLab's world-leading parity-violation program and will use the results of earlier measurements to account for finite contributions to the Q_{weak} asymmetry from the proton's structure. The Q_{weak} experiment should achieve a final error bar that is a factor of two more precise than any of the previous measurements of $\sin^2 \theta_W$ away from the *Z* pole.

Description of Dedicated Apparatus

The experiment will measure the parity-violating asymmetry using 1.165 GeV, 85% longitudinally polarized electrons scattered at forward angles (~8°) and very small momentum transfer ($Q^2 = 0.026$ (GeV/c)^2). The forward scat-

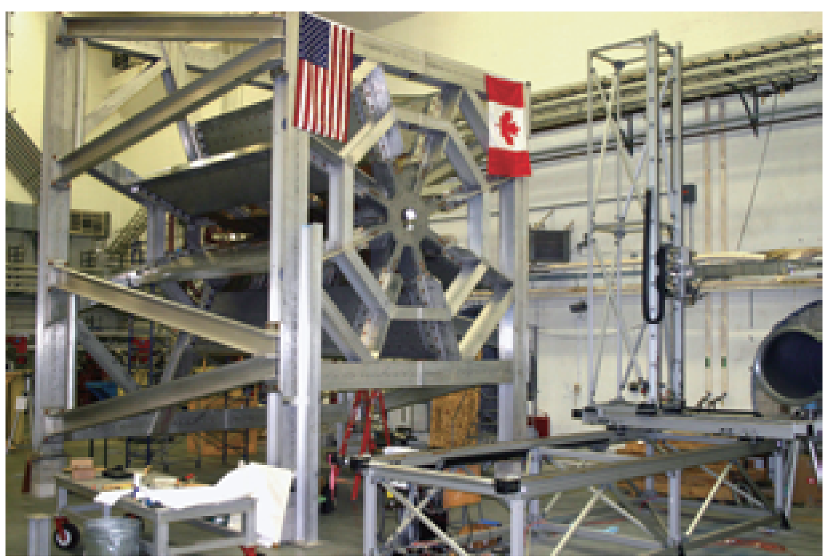


Figure 1: Q_{weak} spectrometer magnet and G0/TRIUMF field mapper at MIT-Bates.

tered electrons will be deflected and focused onto a set of quartz Čerenkov detectors, selected for their radiation hardness and insensitivity to background, by a large toroidal magnetic spectrometer for which TRIUMF supplied crucial project management for the coil construction. The major systems of the experiment include: a 2.5 kW liquid hydrogen cryo-target system; a series of collimators, which define the detector acceptance; an 8-segment toroidal magnet, 8 Čerenkov detectors plus electronics; beam line instrumentation, including precision polarimetry; and the JLab rapid helicity reversing polarized electron source and accelerator. An auxiliary array of tracking detectors will be inserted for calibration runs and used to map the momentum acceptance of the apparatus. Total cost of the installation was estimated at $US 5.12 million in 2003. Canadian contributions totalled $C550 thousand.

Results and Progress

Construction of the experimental apparatus is well underway at participating institutions and JLab, on track for installation at the laboratory in 2009.

The major Canadian contribution to the Q_{weak} apparatus is the magnetic spectrometer "QTOR," shown in Figure 1. This spectrometer, with coil construction funded by NSERC and project management by TRIUMF, is now completely assembled at MIT-Bates. Field mapping will be done in 2008 using a precision field-mapping device developed at TRIUMF and JLab for the G0 experiment.

Canada has also contributed 28 low-noise current mode preamplifiers that have been designed, fabricated and tested at TRIUMF, and funded by JLab for the Q_{weak} experiment. These unique and ultra-sensitive devices will be used in conjunction with TRIUMF-designed and TRIUMF-built digital signal integrators to read out the main detectors and diagnostic luminosity monitors in current mode to achieve the required statistical accuracy for the experiment. Figure 2 shows the layout of an 8-channel digital integrator. The outstanding performance of the TRIUMF electronics system ensures that the electronic

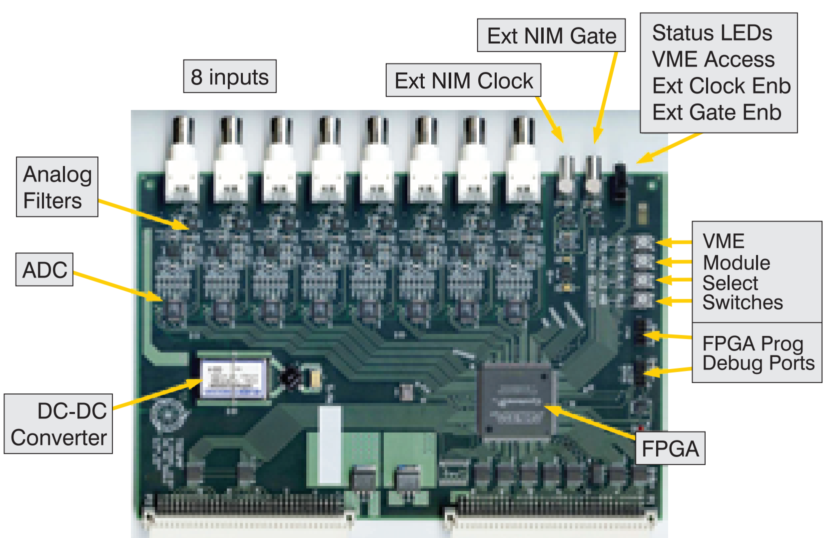


Figure 2: Layout of the TRIUMF VME digital integrator.

noise contributions will be negligible compared to the counting statistics of the high-precision parity-violating asymmetry that they are designed to measure.

Partners

In Canada: University of Manitoba; University of Northern BC; and University of Winnipeg.

International Partners: Armenia (1); Mexico (1); the United States (19); and the United Kingdom (1).

TRIUMF's Role

The QTOR magnet was commercially produced with TRIUMF managing its purchase contract and its construction. The custom electronics were designed and built at TRIUMF. The apparatus (also used for G0) for doing the magnetic field mapping was also designed and built at TRIUMF. Finally, and perhaps most importantly, the project benefited from TRIUMF's expertise acquired performing the TRIUMF proton-proton parity violation experiment (E497).

4.2.1.2.4.3

Experimental Studies of Rare Kaon Decays

Introduction

K mesons or kaons are unstable and can decay in a number of ways. In one important, but very rare decay, a positive kaon decays into a positive pion plus a neutrino and an antineutrino. The standard model predicts that this particular decay should occur only once in every 13 billion decays. However, the decay rate would be influenced by particles and processes that are not included in the standard model (SM). Any discrepancies between the predictions of the model and the experiment would be evidence for new particles and processes beyond the standard model.

A possible hint of evidence for these new particles and processes may have been found by the E949 team using the AGS accelerator at Brookhaven National Laboratory (BNL). The accelerator produces an intense beam of kaons, and the detector is capable of examining 1.6 million decays every second. In particular, the detector can filter the pion-neutrino-antineutrino event from all the other possible decays that the kaon can undergo. The new result, while still consistent with the SM within the uncertainties of the measurement, suggests the rare event could occur once in every 7 billion decays—almost twice the rate predicted by the SM.

One of the conditions necessary to generate the observed dominance of matter over anti-matter in the universe is that the elementary interactions violate charge conjugation symmetry (C) and the combined CP symmetry (where P is parity or left-right symmetry). Although the SM has successfully accounted for all low-energy charge-parity CP-violating phenomena observed so far, it is apparently insufficient as the source of CP violation needed to explain the cosmological baryon asymmetry. Therefore, new sources of CP violation have been sought for many years in particle physics experiments. Prominent among these are the rare decays $K \to \pi\nu\bar{\nu}$, which are sensitive to new physics at mass scales 1-1000 TeV, possibly involving both CP-violating and CP-conserving interactions. TRIUMF has played an important, leading role in the discovery of the long sought ultra-rare reaction $K^+ \to \pi^+\nu\bar{\nu}$ made by BNL experiments 787 and 949. This prominent international effort has developed several new techniques and technologies important in the field of particle physics and for other applications.

Description of Dedicated Apparatus

Figure 1 shows the E949 apparatus. Advanced TRIUMF technologies used in this experiment included approximately 1,000 channels of unique 500 MHz GaAs transient digitizers, a low-mass central drift chamber using inflated cathode foils, beam detector instrumentation, Pb/scintillator photon detectors, and substantial electronics. The large systems of high speed digitizers, the scintillating fibre target, and the development of the world's most efficient detector of radiation are important legacies in current and for future experiments in particle, nuclear, and applied physics.

The TRIUMF group also invented and developed the modern blind analysis methodology used to avoid bias in background predictions and analysis of data. This approach has been adopted by most major high-energy physics groups. TRIUMF's total investment in E949 hardware was ~$C5 million.

For KOPIO (the proposed measurement of $K^0_L \to \pi^0\nu\bar{\nu}$) the TRIUMF rare decay group developed new technologies including a high-efficiency, high-resolution pointing calorimeter for γ-ray detection. This detector system used

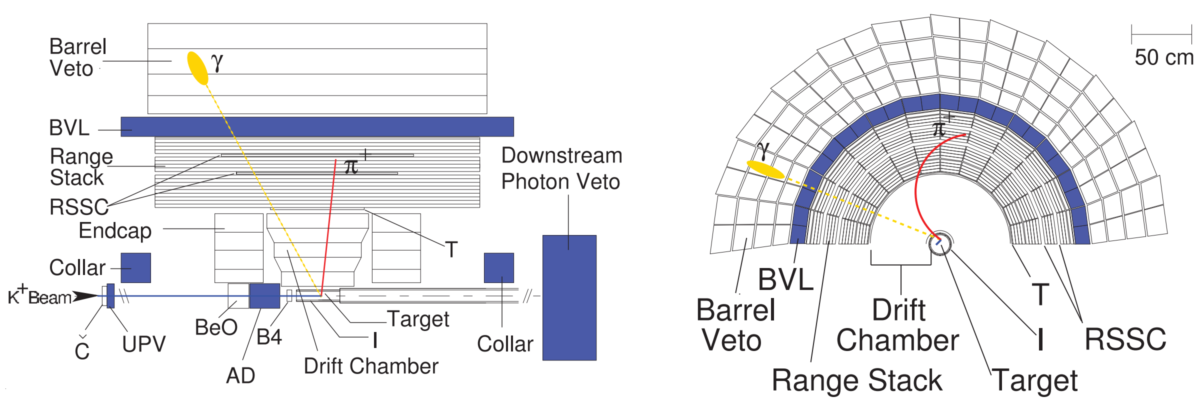


Figure 1: Schematic side (a) and end (b) views of the upper half of the E949 detector. Shown are an incoming K^+ that traverses all the beam instruments, stops in the target, and undergoes the decay $K^+ \to \pi^0\pi^+$ and the outgoing π^+ and one photon from $\pi^0 \to \gamma\gamma$.

extruded scintillator with holes for wavelength shifter fibres. The scintillator system was developed during the 2003–2005 period in conjunction with a local plastics company using a chemical-compound formula for plastic scintillators obtained from Fermilab. Although the calorimeter system was not built, the T2K group at TRIUMF subsequently used the techniques and technology to produce extruded scintillator with holes for the fine-grained detector currently under assembly. Another local company was spurred on by KOPIO to develop the unique capability of manufacturing large area FR4 (fibreglass) panels. KOPIO was also the primary motivation for the development of the CFI-funded Laboratory for Advanced Detector Development (LADD) at TRIUMF and the Université de Montréal, which is now an important infrastructure centre for many TRIUMF detector activities.

Results and Progress

Experiments 787 and 949 discovered the following rare processes: $K^+ \to \pi^+\nu\bar{\nu}$, $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\mu\mu$, $K^+ \to \mu\nu\gamma$ (SD), and $K^+ \to \pi^+\pi^0\gamma$ (DE), where SD refers to structure dependent radiation and DE refers to direct emission. The success of these experiments' techniques in suppressing difficult backgrounds by 10 orders of magnitude leading to observation of poorly defined ultra-rare processes supports the pursuit of future measurements of rare decays at extremely low levels. The initial observation of $K^+ \to \pi^+\nu\bar{\nu}$ at the branching ratio of

$$\mathrm{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89})x10^{-10}$$

was consistent with the precise SM prediction for this second-order weak interaction, $\mathrm{B}(K^+ \to \pi^+\nu\bar{\nu}) = (0.74\pm0.20)x10^{-10}$, although the central experimental value was twice as high.

$\mathrm{B}(K^+ \to \pi^+\nu\bar{\nu})$ is directly related to the real and imaginary parts of $\lambda_t = V^*_{ts}V_{td}$ and Figure 2 shows the region allowed by the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio compared to the regions allowed by other recent measurements with small theoretical uncertainties. The region favoured by other Cabbibo-Kobayashi-Maskawa (CKM) -sensitive measurements is at the edge of the 68% CL region allowed by the $K^+ \to \pi^+\nu\bar{\nu}$ measurement. The other CKM-sensitive results used to produce the confidence level intervals shown are dominated by measurements of *B* meson decays. The possible discrepancy between the λ_t regions allowed by the β-decay measurements and by $\mathrm{B}(K^+ \to \pi^+\nu\bar{\nu})$ could be an indication of physics beyond the SM.

The clean theoretical interpretation of $K^+ \to \pi^+\nu\bar{\nu}$ remains valid in most extensions of the SM in distinct contrast to the β-decay measurements currently used to determine the CKM parameters. Thus, a precise measurement of $\mathrm{B}(K^+ \to \pi^+\nu\bar{\nu})$ would provide an unambiguous consistency test of the flavour sector of the SM. Since $K^+ \to \pi^+\nu\bar{\nu}$ and $K^0_L \to \pi^0\nu\bar{\nu}$ can be precisely calculated in the SM and are highly sensitive to new physics which may contribute in the second-order weak interaction loops, future experiments will pursue data sets with hundreds or thousands of events seeking evidence of a discrepancy or establishing the absence of new effects at mass scales up to 1,000 TeV.

The other processes listed above that were observed for the first time by E787/E949 were mostly radiative reactions of interest in evaluating models of low-energy quantum chromodynamics such as chiral perturbation theory.

Experiments 787/949 also performed the most sensitive searches for the following processes:

$$K^+ \to \pi^+ a,\ K^+ \to \pi^+\gamma,\ K^+ \to \pi^+ H,\ \pi^0 \to \nu\bar{\nu},\ \pi^0 \to \gamma X,\ K^+ \to e\nu\mu\mu\ ,$$
$$\text{and } K^+ \to \pi^0\pi^+\nu\bar{\nu}.$$

Partners

In Canada: The University of Alberta and the University of British Columbia.

International Partners: China (1), Japan (5), Russia (2), and the United States (4).

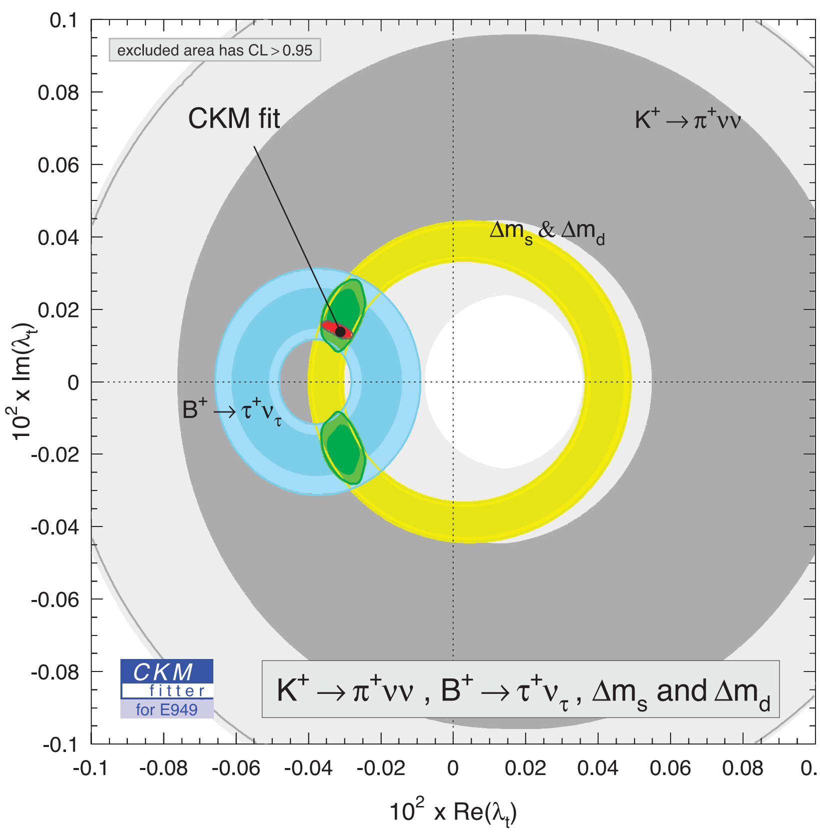


Figure 2: The regions in the λ^t plane allowed by the combined E787's and E949's determination of the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio (gray), $B^+ \to \tau^+\nu$ (blue) and B-mixing measurements (yellow). The regions outside the lighter (darker) shading have CL>0.95 (0.68). The area excluded by $K^+ \to \pi^+\nu\bar{\nu}$ at CL >0.95 is indicated by the gray line. The red-shaded region is allowed by the combination of these measurements, and the small black region denotes the region allowed by all CKM-related measurements.

TRIUMF's Role

TRIUMF was a principal participant in Experiment 787 along with Princeton University and BNL and, in E949, with BNL and others listed above. TRIUMF provided one of the three E949 co-spokespersons, D. Bryman. In addition to developing substantial cutting-edge hardware and leading important aspects of the data acquisition system, TRIUMF led the data analysis of the main $K^+ \rightarrow \pi^+\nu\bar{\nu}$ signal and was the main processing centre for all E949 data. The TRIUMF group also developed and maintained the data analysis framework for the entire E949 collaboration.

TRIUMF and University of British Columbia scientists who developed the concept of using neutral kaon time-of-flight to suppress backgrounds were part of the team that initiated KOPIO. The KOPIO experiment was subsequently cancelled during the planning phase in the US because of unexpected costs associated with the accelerator. Substantial detector research and development was performed at TRIUMF including development of an innovative system for a photon pointing calorimeter using extruded scintillator.

4.2.1.2.4.4

Measurement of the $\pi^+ \rightarrow e^+\nu$ Branching Ratio at TRIUMF: PiENu

Introduction

When a particle decays, it can often decay in one of several different ways. The likelihood of a particle decaying to either an electron or muon is known as its branching ratio for that particular decay mode. In the standard model (SM), electrons and muons have identical electroweak gauge interactions, a hypothesis known as universality, and the only difference between them is mass: a muon is just a heavy electron. The new TRIUMF experiment PIENU, being performed by an international collaboration from Canada, Japan, and the United States, will measure the branching ratio of pion decays to electrons and muons. This challenging experiment will test the hypothesis that the muon is merely a heavy electron while being extremely sensitive to the existence of new particles and interactions hypothesized in many current theories.

The $\pi^+ \rightarrow e^+\nu$ branching ratio

$$R_{e/\mu} = \frac{\Gamma(\pi^+ \rightarrow e^+\nu + \pi^+ \rightarrow e^+\nu\gamma)}{\Gamma(\pi^+ \rightarrow \mu^+\nu + \pi^+ \rightarrow \mu^+\nu\gamma)}$$

provides unique access to hypothetical physics beyond the SM at high-mass scales (up to 1000 TeV) due to the extraordinary precision of its SM prediction and the potential for highly accurate measurements. PIENU uses a compact set up of high-precision crystal detectors, contributed by Brookhaven National Laboratory and Osaka University, to improve the measurement precision an order of magnitude over that of previous studies. The results may signal discovery of unanticipated new physics effects, provide complementary information on directly produced heavy particles at colliders such as the Large Hadronic Collider, or indicate that new physics effects are limited to extremely high-mass scales if the results agree well with the SM prediction.

Description of Dedicated Apparatus

The PIENU experiment involves a refinement of the technique developed in a previous TRIUMF experiment, which produced one of TRIUMF's best-known scientific results. The branching ratio $R_{e/\mu}^{\exp}$ will be obtained from the ratio of positron yields from the $\pi \rightarrow e\nu$ decay and from the $\pi \rightarrow \mu \rightarrow e$ chain decay ($\pi^+ \rightarrow \mu^+\nu_\mu$ followed by $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$). By measuring positrons from the decays $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu \rightarrow e$ in a non-magnetic spectrometer, many normalization factors such as the solid angle of positron detection, cancel to first order, and only small energy-dependent effects like those for multiple Coulomb scattering and positron annihilation, need to be corrected for. Major improvements in precision compared to previous efforts stem from the use of a superior calorimeter, high-speed digitizing of all pulses, Si strip and wire chamber tracking, and higher statistics.

Figure 1 shows the PIENU experimental apparatus, in which B and T indicate beam and telescope plastic scintillation counters, respectively. A 75 MeV/c π^+ beam from the TRIUMF M13 line will be identified by B1 and B2 scintillators and stopped in a target consisting of an array of plastic scintillators, principally a 2-cm diameter, 1-cm thick stopping counter sandwiched by two 2-mm thick counters. Fine tracking near the target will be provided by several sets of single-sided (X,Y) silicon-strip counters located immediately upstream and downstream of the target assembly. The beam rate will be kept low to stop a low background level arising from longer-lived muons in the target region and to minimize potential distortions in the time spectrum due to pulse pile-up. The telescope scintillation counters (T) cover the front side of the large Brookhaven National Laboratory NaI(Tl) crystal (BINA). BINA is a 48-cm diameter x 48-cm long cylindrical single crystal instrument that has shown excellent energy resolution. In the PIENU configuration, energy resolution of $\Delta E / E \approx 2 - 3\%$ at 66 MeV, a factor of 2 better than in the previous TRIUMF measurement, is anticipated. The "Ring" in Figure 1 is a 17-cm thick cylinder, composed of 97 25-cm long pure CsI crystals used to capture shower leakage from BINA. The solid angle acceptance of the system is 25%.

A wire chamber (WC3), located next to the T2 counter, provides information of the positron for evaluation of shower leakage effects and correction of the path length in the T counters for energy loss (*dE/dx*) measurements.

Improvement in statistics will come from using a larger solid angle by an order of magnitude with a longer running period, and from greater precision of the tail correction measurement. With detailed pulse shape information coming from 500 MHz digitizers (supplied by the Japanese group), and reduced background due to pile-up compared to the previous experiment, an improvement factor of 30 or more is expected, and should result in a statistical uncertainty of <0.05% in the branching ratio. The precision of the branching ratio measurement is expect to be <0.08%, which corresponds to <0.04% uncertainty in the ratio of the gauge boson-lepton coupling constants g_e/g_μ used to evaluate the hypothesis of electron-muon universality.

NSERC has provide more than $C1 million for PIENU through 2008. The experiment has also greatly benefited from equipment contributions from the US and Japan with value of ~$US5 million.

Results and Progress

The PIENU experiment is currently under development and expected to begin in 2008. Several beam tests have been carried out to study beam properties and confirm aspects of the techniques to be used. Extensive Monte Carlo calcula-

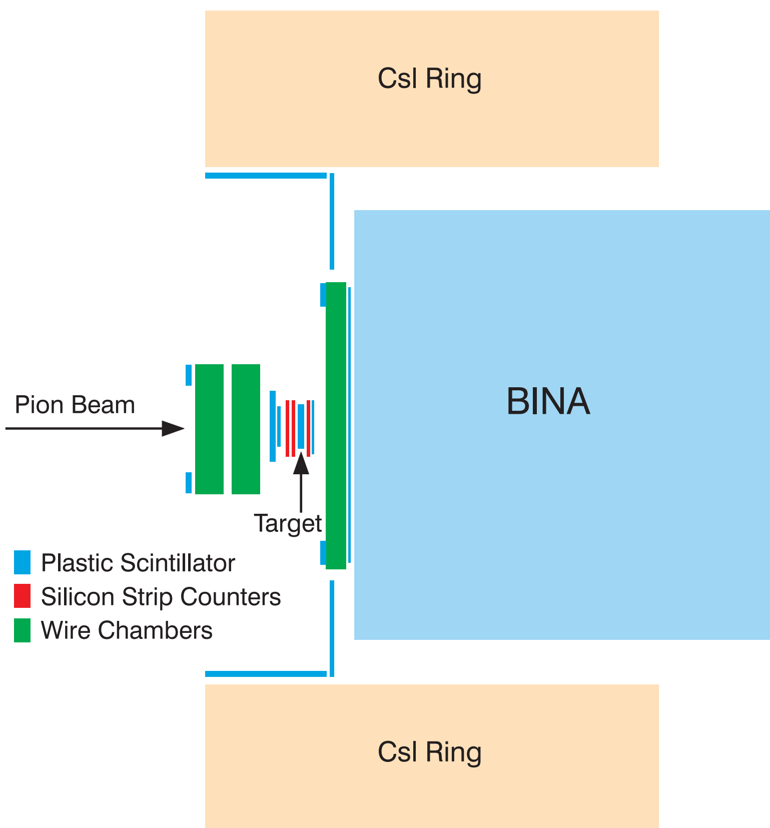


Figure 1: Schematics of the PIENU detector. Red lines near the target denote silicon strip pairs; two pairs are located before the target and one pair after. Colour scheme: scintillators are blue; wire chambers are green; NaI crystal is light blue; CsI crystal array is cream.

tions have been performed to study the beam, the experimental configuration, suppression of backgrounds, and uncertainties in systematic effects. An extension to the M13 beam line will be installed in mid-2008.

Partners

In Canada: The University of British Columbia and the University of Northern BC.

International Partners: Japan (1) and the United States (3).

TRIUMF's Role

TRIUMF provides expert manpower and infrastructure for the PIENU experiment. Personnel from the design, engineering, detector facility, LADD, data acquisition, and beam development groups have made essential contributions. Infrastructure, including data acquisition systems and the counting room, electronics, and the data analysis framework are also provided by TRIUMF. In addition, PIENU has taken full advantage of the TRIUMF LADD facilities for precision machining, advanced electronics design, Si strip detector characterization and testing, and plastic scintillation counter construction. The PIENU experiment was initiated by the TRIUMF group led by D. Bryman (also University of British Columbia) and T. Numao. A world leader in rare decay experiments, this group's previous experimental results in this area are among TRIUMF's most cited.

4.2.1.2.4.5

Antihydrogen Laser Physics Apparatus: ALPHA

Introduction

There is considerable scientific speculation as to why the observable universe is apparently almost entirely matter, whether other places are almost entirely antimatter instead, and what might be possible if antimatter could be harnessed. The apparent asymmetry of matter and antimatter in the visible universe is one of the great, unsolved problems in physics. ALPHA (Antihydrogen Laser Physics Apparatus) is an international project, located at CERN Geneva, whose aim is to achieve the first stable trapping of antihydrogen, the simplest atomic form of neutral antimatter. Trapped antihydrogen would offer a unique opportunity to study anti-atoms, and via comparisons with well-studied hydrogen, provide the possibility of making precision tests of the fundamental symmetries between matter and antimatter.

The assumption that nature is invariant under CPT, the symmetry between left-handed particles and right-handed antiparticles evolving backwards in time, is largely based on the success of quantum field theories. Whether this

CPT symmetry is exactly conserved is an important experimental question. A comparison of the properties of hydrogen and antihydrogen can potentially provide the most stringent test of this symmetry for baryon-leptonic systems. The current precision of a comparison of the charge-to-mass ratio of the proton and antiproton is 9 x 10^{-11} and is limited by our knowledge of the external fields to which they couple. Current measurements of the 1s-2s transition in hydrogen are at the precision of 2 x 10^{-14}, and similar precision can be expected for cold antihydrogen in a trap environment. The CPT-violating energy scale probed by such a measurement could reach beyond the Planck scale (10^{19} GeV), and compete favourably with particle physics measurements such as the $K^0 - \overline{K^0}$ mass difference. Given the importance of CPT symmetry, it should be tested in different particle sectors.

The antiproton decelerator (AD) was built at CERN expressly to study cold antimatter physics, and the ALPHA project is one of its three principal experiments, hence receiving 1/3 of the available beam time/year.

Description of Dedicated Apparatus

Figure 1 shows schematically a cross-sectional view of the ALPHA trap. External and internal superconducting solenoid magnets together with precisely controlled voltages on cylindrical electrodes are used to trap and cool antiprotons ($\bar{p}$), electrons (e^-) and positrons (e^+). The magnetic trap for the antihydrogen consists of a superconducting octupole field for radial confinement and mirror solenoids for axial confinement. The trap is inserted into an external superconducting solenoid. Typical axial fields are shown in the lower panel. A multi-channel plate imaging detector can be inserted on the positron side just out of the external solenoid, and this can be used to image $\bar{p}$, e^+ and e^- plasmas. The positron accumulator (not shown) is positioned to the right.

The value of this apparatus including detectors and electronics is estimated to be $C4 million, of which TRIUMF's contribution is $C0.3 million.

A typical trapping sequence starts with capturing $\bar{p}$, from the AD in a deep electrostatic well within a 3 T magnetic field. They are mixed with e^-, which self-cool from synchrotron radiation and cool the $\bar{p}$, through collisions. Positrons are accumulated and trapped in a well in the right side of the trap.

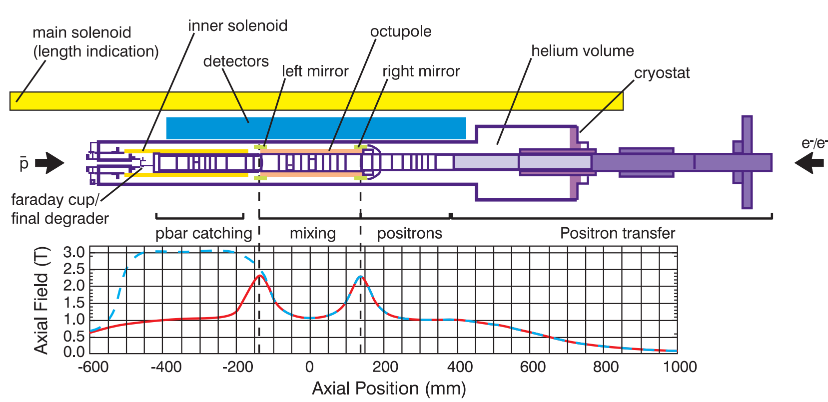


Figure 1: The ALPHA combined charged and neutral particle trap.

Eventually the $\bar{p}$ and e^{+} are moved to wells in the mixing trap with the octupole and mirror coil fields. A spatial overlap between the $\bar{p}$ and e^{+} wells allows the formation of $\bar{H}$. After trap manipulations, the numbers and energy distributions of the $\bar{p}$ remaining in an electrostatic well are measured by directing them to the degrader and measuring the resulting annihilations. $\bar{p}$ losses during manipulations are monitored in the detectors placed near the mixing region. Optimizing these manipulations to produce $\bar{H}$ at sufficiently low energy is the goal of this first phase. Particle detectors play essential roles here for the diagnosis of the plasma processes as well as the identification of antihydrogen trapping.

Results and Progress

The critical components for the experiment have been engineered, constructed, and commissioned. This includes the combined trap, featuring a unique superconducting octupole magnet, published in W. Bertsche *et al.* [Nucl. Instrum. Methods A566, 746 (2006)], and the high-intensity source of low-energy trappable positrons as found in L. Jorgensen *et al.* [Phys. Rev. Lett. 95, 025002 (2005)]. The array of scintillators to monitor antiproton annihilations and to detect antihydrogen production has been constructed and deployed. A novel readout using temperature-stabilized avalanche photodiodes was used because of the difficult magnetic field environment. This was the prime detection system for the 2006–2007 runs. A MIDAS-based data acquisition system able to correlate annihilation signals with the myriad of

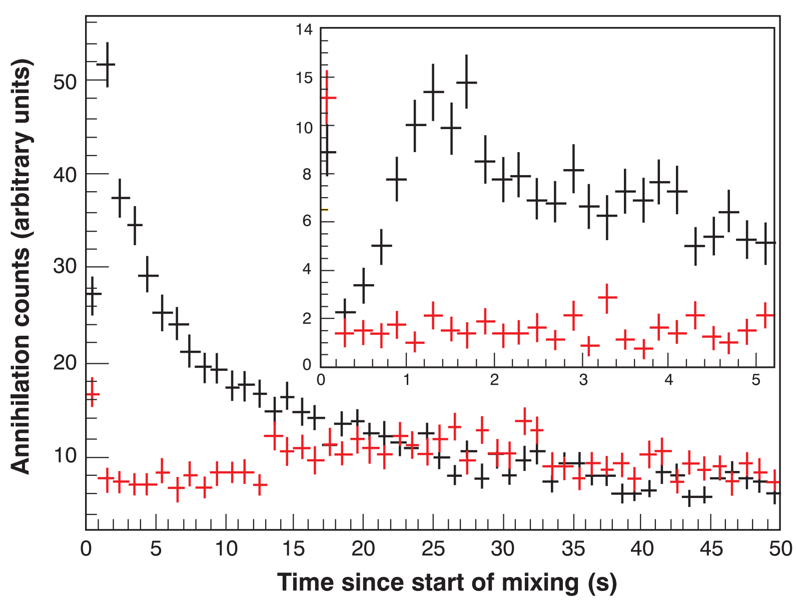


Figure 2: Production of $\bar{H}$ in the ALPHA trap. This figure shows the count rate in the TRIUMF-UBC scintillator system surrounding the mixing region. The start time is when the $\bar{p}$ are introduced in the mixing trap overlapping the e^{+}. Black points are data taken with cold e^{+}, while red points are data where the e^{+} are heated with RF to suppress mixing. When $\bar{H}$ are formed they escape the trap and annihilate on the trap walls.

parameters associated with trap operation and cryogenics has been developed and implemented.

The ALPHA collaboration is developing a powerful three-layer silicon detector for imaging annihilations. Simulation studies for tracking of *pā* annihilation events in the trap have been performed. These simulations were used to design the Si tracking detector. A full simulation code is under development. The readout electronics for the silicon detector use a novel flash ADC unit developed at Université de Montréal. Similar readout electronics were required by ISAC experiments, so there was considerable synergy gained using equipment from the Montreal-TRIUMF Laboratory for Advanced Detector Development (LADD). Prototype boards have been constructed at TRIUMF, and a successful engineering test with 10% of the detector in the trap using *pā* annihilations has been performed at CERN. There have been delays in delivery of the Si from the manufacturer, but deployment of the full array is expected for the 2008 run.

Several milestones towards trapping antihydrogen have already been achieved and published. We have demonstrated that antiprotons and positrons can be stored in the symmetry-breaking octupole field for long enough to produce antihydrogen. Evidence of production of antihydrogen (see Figure 2) in a new ALPHA apparatus with a reduced magnetic field for antihydrogen trapping has been obtained We have demonstrated a technique for radial compression of trapped antiprotons, a key operation for antihydrogen trapping (see Figure 3), and developed a novel antiproton radial diagnostic based on octupole induced ballistic loss. Future prospects using these tools together with the improved Si imaging are quite encouraging.

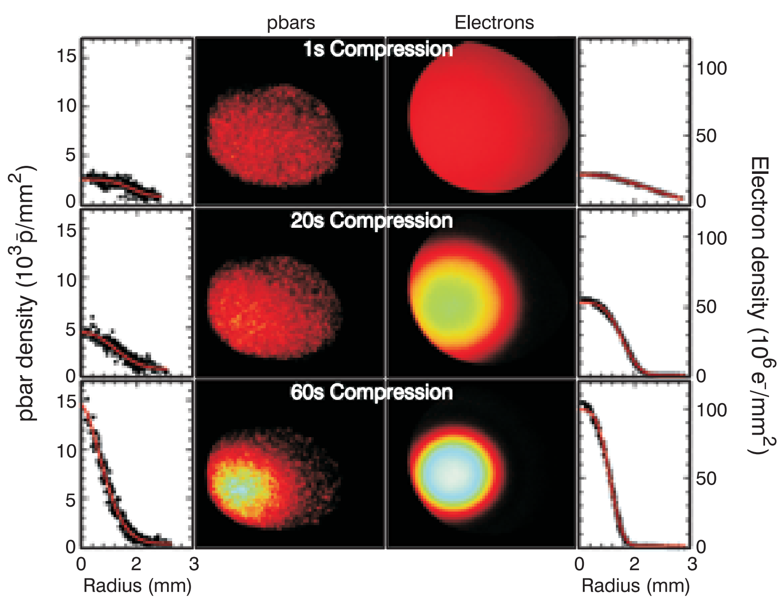


Figure 3: Multi-channel plate images of antiprotons and electrons trapped in a Penning trap demonstrate radial compression of antiprotons, an important step towards antihydrogen trapping.

Partners

In Canada: Simon Fraser University, the University of British Columbia, University of Calgary, l'Université de Montréal, and York University.

International Partners: Brazil (1), Denmark (1), Israel (1), Japan (2), the United Kingdom (2), and the United States (1).

TRIUMF's Role

TRIUMF has taken the lead responsibility for construction of the scintillator array, data acquisition systems, and readout electronics. TRIUMF has also made contributions to the trap design and commissioning of the experimental apparatus. TRIUMF scientists are involved in all aspects of the experiment, from run coordination, to trap construction, to the physics analyses for the ALPHA publications. TRIUMF's contributions have enabled the participation of a diverse group of Canadian physicists in this exciting interdisciplinary project. Canada, because of TRIUMF's efforts, represents 30% of the ALPHA project.

4.2.1.2.5

Hadron Structure

4.2.1.2.5.1

HERMES Experiment

Introduction

The strongest force known in nature is elegantly described by the field theory known as quantum chromodynamics (QCD), one of the intellectual triumphs of the 20th century. QCD describes the interactions between the partons—fractionally charged quarks and electrically neutral gluons—found inside protons and neutrons (nucleons). It is only the “residual leakage” of this force just outside of the nucleons that provides the still-strong binding together of the nucleons in the atomic nucleus; it is this energy that in solar models accounts for the energy produced in the core of the sun and other stars.

One of the key features of QCD is that hard interactions transferring large momenta between partons are much less probable, allowing a simple mathematical “perturbative” treatment to provide quantitative predictions for comparison to observations. Observations are found to be consistent with QCD. On the other hand, it is the much stronger soft interactions that bind partons in the nucleon and determine its internal structure and observable properties. As in many other branches of science, it is found that simple rules can give rise to very complex behaviour. Efforts to calculate nucleon properties from the simple rules of QCD overburden armies of the fastest modern computers. Some properties are expected to be computationally inaccessible for the foreseeable future. Hence, both to test QCD further and to ensure a complete description, measurements related to the structure of the nucleon are highly important.

One of the essential properties of both partons and nucleons is their spin, which is related to their magnetic strength or "moment." Magnetic moments of supposedly elementary particles, such as leptons and quarks, can be predicted from their electric charge and mass, whereas those of composite systems, such as the nucleon, depend on their internal structures. Furthermore, the degree of alignment of the spin orientations of the quarks with that of their parent nucleon is a delicate consequence of the strong force described by QCD, which depends strongly on the relative orientations of the quark spins. Two decades ago, scientists believed that the spin of the nucleon was a sum of the spins of the quarks that it contains. When this alignment of the quark spins came under experimental investigation, it came as a shock to find that the spins of the three quarks inside each nucleon do not combine to form the nucleon spin.

The experimental investigation used virtual photons of polarized light incident on polarized target nucleons, with the spins of both beam and target particles having known orientation with respect to each other. In these deeply inelastic scattering (DIS) measurements, the polarized virtual photons are emitted by a beam of polarized electrons or muons (leptons) incident on the target containing the nucleons. A quark can absorb a virtual photon only if their spins point in opposite directions. The relevant observable here is the difference in the scattering yield caused by reversing the relative orientation of the beam and target spin polarizations from parallel to anti-parallel. The result can be related to the probability that a quark will be found with its spin parallel or antiparallel to that of its parent nucleon. A series of major experiments, of ever increasing precision, at several laboratories in the United States and in Europe, has confirmed that the net contribution of the quarks' intrinsic spins can account for only a fraction of the nucleon's spin. There must be other substantial contributions, possibly from the gluons being exchanged, each of which has an intrinsic spin twice that of a quark, or from the orbital motion of the quarks and gluons about each other.

Description of Dedicated Apparatus

Canada and TRIUMF have played a strong role in the HERMES collaboration working at the Deutsches Elektronen-Synchrotron Laboratory (DESY) in Hamburg, Germany. TRIUMF was one of the 25 founding institutes from 12 nations. This collaboration has provided much of the modern data relevant to the spin structure of the nucleon.

The apparatus (see Figure 1) was based on an approach both advantageous and unique to this field: the combination of a polarized high-energy electron or positron (lepton) beam in a storage ring (HERA at DESY) with undiluted nuclear-polarized atomic gas targets. Furthermore, the magnetic spectrometer that detected the scattered leptons had substantial acceptance and the capability to identify all types of hadrons produced in coincidence with the lepton. An essential component of the spectrometer, the transition-radiation detector (TRD), was designed and built at TRIUMF and has provided essential information to distinguish the leptons from the much more copiously produced hadrons.

Results and Progress

HERMES data have not only greatly improved the precision of existing "inclusive" measurements, in which only the scattered lepton is detected, but more importantly have made pioneering studies of processes that produce more particles in the final state. Over the past decade, these new studies have been typically inspired by dramatic theoretical developments, which showed how such measurements could provide information about the orbital motion of quarks inside the nucleon.

Published results from the five-year period 2003–2008 include the most precise available DIS data for the polarized structure function g_1 of the deuteron, which confirm that the net contribution of quark spins to the spin of the nucleon is a third of the total. The collaboration has also seen the publication of the first data for semi-inclusive DIS where one of the hadrons produced from the struck quark is detected and identified. Interpretation of these data for both longitudinally polarized hydrogen and deuterium targets produced the first information about the alignment with respect to the nucleon spin of the spins of the three lightest flavours of sea quarks. The sea quark polarizations were all found to be small.

Presentation of data has also shed early light on the alignment of the spin of the gluons with that of the nucleon which appears to be small.

Publication of the first data for semi-inclusive DIS on transversely polarized targets addresses two fundamental questions about nucleon spin structure. One relates to the property known as transversity, which differs from those helicity properties discussed above only because the quarks move relativistically inside the nucleon. The new HERMES data were interpreted to indicate that quark transversity is indeed quite different from helicity and differs substantially from the predictions of various models that were constructed to embody

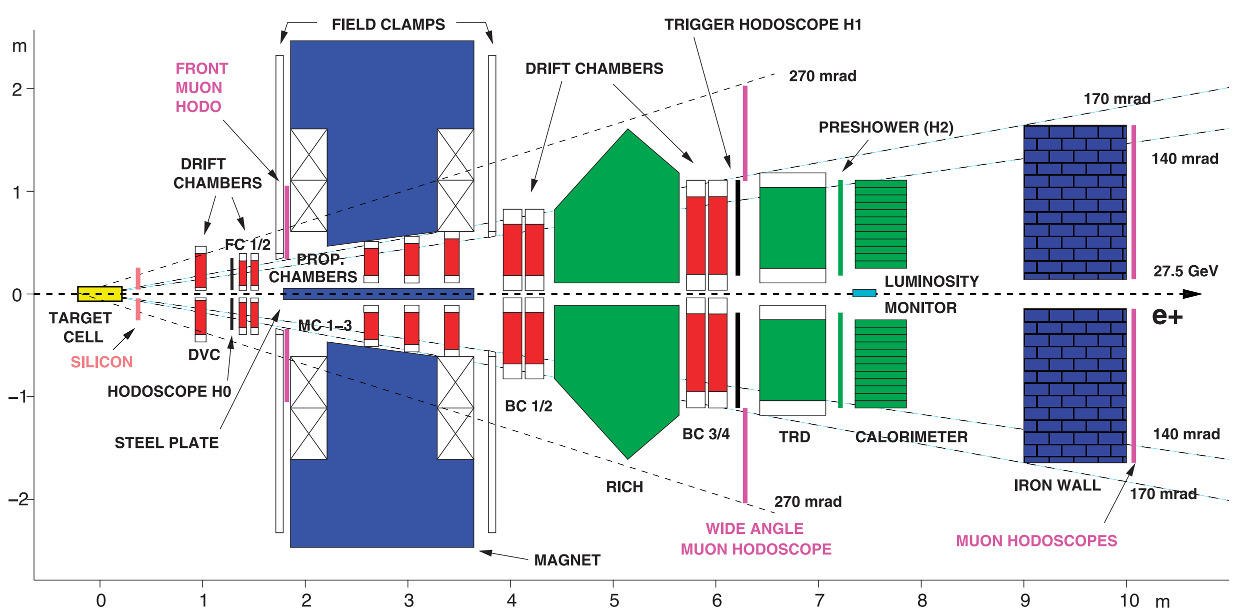


Figure 1: The HERMES apparatus.

certain features of QCD. The other fundamental question addressed by these new data was the orbital motion of partons. Recent theoretical progress led to the realization that this orbital motion is related to a potentially observable correlation between the direction of the transverse motion of quarks and the orientation of the spin of the nucleon in which the quark is found. The new HERMES data have provided strong evidence for this correlation, which was found to be in qualitative agreement with expectations based on the already known contributions of the various quark flavours to the magnetic moment of the nucleon. This finding has given the community confidence in our emerging understanding of this aspect of nucleon spin structure.

HERMES has also published pioneering data for the process of deeply virtual Compton scattering (DVCS), including unique data for both positron and electron beams as well as a transversely polarized target. A theoretical breakthrough about a decade ago revealed that the orbital motion of quarks could be quantitatively probed by the "exclusive" DVCS process in which the struck quark emits an energetic real photon and then is re-absorbed by the target remnant, leaving the nucleon intact. Not only is this process simpler to interpret than other exclusive reactions, but it interferes in a quantum mechanical sense with the well-understood radiative elastic scattering (Bethe-Heitler) process, giving rise to a rich garden of observables that shed light on both the magnitude and phase of the DVCS amplitude. The HERMES DVCS data have served to strongly constrain theoretical models of the nucleon that attempt to describe correlations between the longitudinal momentum and the transverse position of quarks. When the HERMES experiment was conceived, this possibility was not even on the horizon.

In 2007, the HERA accelerator at DESY was decommissioned along with the HERMES experiment. However, the rich trove of recently recorded data is still being analyzed, and further important results are expected to continue to appear.

Partners

International Partners: Armenia (1), Belgium (1), China (2), Germany (4), Italy (4), Japan (1), the Netherlands (2), Poland (1), Russia (4), Scotland (1), and the United States (4).

TRIUMF's Role

TRIUMF scientists have been central to the intellectual life of the HERMES collaboration over the 12 years in which data were analyzed and interpreted. In particular, two TRIUMF research scientists, A. Miller and S. Yen, were heavily involved during the periods 2003–2008 in the data analysis and preparation of papers for publication.

4.2.1.2.5.2

G-Zero (G0) Experiment

Introduction

There are six types of quarks: up, down, charm, strange, top, and bottom. The lightest quarks, called up and down, are permanent residents in the proton, but the next lightest quark, the strange quark, may visit the proton on occasion, popping into and out of existence in the "quark-gluon sea," a seething mass of particles created out of energy from the strong force. It is the gluons, elementary particles that cause quarks to interact, that bind the quarks together in pairs or triplets in the proton and indirectly bind protons and neutrons together in atomic nuclei.

By exploiting a set of unique parity-violation measurements, the G-Zero (G0) experiment intends to determine the contributions from strange quarks to one of the proton's basic properties, its vector form factors, which include its magnetic moment and electric charge distributions. This in turn will shed light on the role of the quark-antiquark "sea" in the proton and neutron, providing valuable insight into the consequences of quantum chromodynamics (QCD) at low energies. Although very little is known about strange quark contributions to the proton's vector form factors, tantalizing evidence from a number of other experiments indicates that strange quarks may play an important role in the structure of the proton and neutron.

Utilizing an alternating right- and left-handed polarized electron beam incident on a proton target at Jefferson Laboratory (JLab), the G0 experiment makes use of a superconducting magnet and detector system to measure the rates and momenta of the scattered electrons or the recoiling protons. Scattering asymmetries, or differences in the scattering reaction rates using the right-handed versus left-handed polarized beams, are observed if "parity," or mirror-reflection symmetry, is violated, and are sensitive to strange quark contributions. The experiment is very challenging due to the small sizes of the typical asymmetries (~5 parts per million) and the high statistical accuracy required (~±5%, ±0.00000025) to achieve adequate sensitivity to the strange quark effects.

Description of Dedicated Apparatus

The G0 experiment aims to measure the parity-violating asymmetries from elastic electron-proton and quasi-elastic electron-deuteron scattering over a range of momentum transfers ($0.1<Q^2<1.0\ (\mathrm{GeV/c})^2$), at both forward (~70˚) and backward (~110˚) angles. To achieve the desired precision in a reasonable amount of time, the experiment is performed at high luminosity and with a large acceptance detector. A 500 W liquid hydrogen cryo-target and a magnetic spectrometer with a large solid angle and momentum acceptance were constructed to carry out the measurements. The spectrometer consists of a toroidal array of eight superconducting coils, with an array of scintillation detectors located at the focal plane of each octant to detect the recoil protons or scattered electrons. In addition, for the G0 second phase (backward-angle mode), a second array of scintillation detectors and a Čerenkov detector are located near the magnet cryostat exit window of each octant (see Figure 1).

The total cost of the G0 installation was ~US$5.6 million, with the Canadian contribution ~C$450,000.

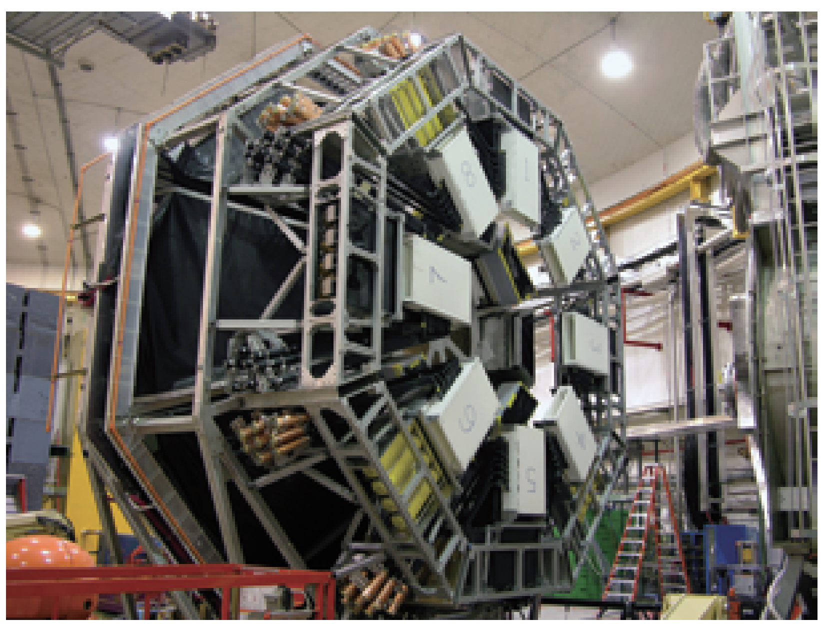


Figure 1: Photograph of the G0 apparatus in the backward-angle configuration with the detector package decoupled and withdrawn from the superconducting toroidal magnet.

PEOPLE

SHELLEY PAGE

Professor of Physics, University of Manitoba

Shelley Page graduated with a B.Sc. in honours physics and a Ph.D. in nuclear physics from Queen's University in 1981 and 1985, respectively. After two years as an NSERC post-doctoral fellow working on fundamental symmetry experiments at TRIUMF, she joined the faculty at the University of Manitoba.

In the 1990s, Dr. Page led an international collaboration which performed a very challenging measurement of parity violation in proton-proton scattering at TRIUMF. She is currently a co-spokesperson for the Q_{weak} experiment at Jefferson Lab, an international collaborative effort to precisely measure the proton's weak charge to test the predicted running of the weak mixing angle with energy scale, a sensitive probe for new physics beyond the standard model. She is also a strong supporter of the proposed Ultra Cold Neutron Facility at TRIUMF.

Shelley and her collaborators maintain strong ties to TRIUMF, which, through the provision of unique technical support in the areas of detector design, fabrication, engineering and project management, has enabled them to make leading contributions to major experiments at international facilities in her field.

Shelley served a term on the NSERC Subatomic Physics Grants Selection Committee including a year as Chair. Subsequently, she co-chaired the 1997-8 NSERC Subatomic Physics Reallocation Steering Committee. At TRIUMF, she served on the subatomic physics EEC and on the Users' Group Executive Committee including one year as Chair, and is currently a member of the Priority and Planning Advisory Committee. She has also served on other advisory panels

CONTINUES ▶

Results and Progress

A blind analysis of the first-phase forward-angle measurement was completed, and the results were revealed on April 15, 2005 and published in a paper featured in the August 25, 2005 issue of *Physical Review Focus* [S.D. Covrig *et al.*, Nucl. Instrum. Methods A551, 218 (2005)]. The G0 experiment itself was also featured in the popular press, in the September 3, 2005 edition of *The Economist* [The Economist, Vol. 376, No. 8443, 72 (Sep. 3-9, 2005)]. While these initial forward-angle results have generated considerable interest, they must ultimately be combined with the second-phase backward-angle results in order to extract the physics quantities of interest, the strange quark components of the proton's vector form factors.

In addition to the above-mentioned primary physics results, other important physics results have also been extracted from the forward-angle data. The analysis of transverse beam spin asymmetry data was recently completed and published; it provides new and important information about two-photon exchange amplitudes, which are needed for interpreting precision electron-scattering data. Also, two instrumentation papers have been published on the G0 cryo-target and electronics subsystems, while work on an instrumentation paper on the overall G0 apparatus is currently underway [nucl-ex/0703026, accepted for publication in Nucl. Instrum. Methods].

Data analysis of the second-phase backward-angle data is presently in progress. It is anticipated that the data will be unblinded toward the latter half of 2008. When this second set of physics results is released, enough information will be available to disentangle the form factors and extract the strange quark contributions.

Partners

In Canada: The University of Northern British Columbia, University of Manitoba, and the University of Winnipeg.

International Partners: Armenia (1), France (2), and the United States (12).

TRIUMF's Role

TRIUMF has played an important role in both phases of the G0 experiment. Not only was the intellectual input of the TRIUMF detector facility needed to design and produce the specialized phototube-base electronics used in all of the G0 scintillation detectors, but also TRIUMF's scintillator and machine shops played crucial roles in the second phase of the experiment. Seventy-five percent of the backward-angle detectors, as well as the support structure, were designed and fabricated at TRIUMF. TRIUMF also designed and constructed 300 phototube bases for the scintillation detectors, Čerenkov detector arrays; the Pion Hall (M11) test beam for Čerenkov detector prototyping, the cryostat-exit scintillation detector arrays, the back-angle detector support structure, customized "parity" electronics, and field mapping apparatus (to be reused by the Q_{weak} experiment).

▼ CONTINUED

including the Jefferson Lab CEBAF Program Advisory Committee and the US Nuclear Science Advisory Committee. Shelley is currently serving as President of the Canadian Association of Physicists.

Enthusiastic about communicating the excitement of physics to a wide audience, Shelley enjoyed a term as physics columnist for CBC's *Quirks and Quarks* radio program in 2000.

4.2.1.2.5.3

NPDGamma Experiment at Los Alamos

Introduction

Parity conservation in quantum mechanics means that two physical systems, one of which is a mirror image of the other, must behave in identical fashion. Parity conservation implies that nature is symmetrical and makes no distinction between right- and left-handedness. For example, two otherwise identical radioactive particles spinning in opposite directions about a vertical axis should emit their decay products with the same intensity upwards and downwards.

Experiments on parity conservation have shown that parity is not conserved in all types of interactions. Three of the four known physical forces, gravity, electromagnetic, and strong, conserve parity; the fourth force, the weak force, does not. This knowledge has cleared the way for physicists to reconsider physical theories and has led to new and far-reaching discoveries regarding the nature of matter and the universe.

The NPDGamma experiment measures the very small, parity-violating, up-down, γ-ray asymmetry in the capture of vertically polarized cold neutrons on liquid para-hydrogen ($n + p \rightarrow d + \gamma$). This parity-violating asymmetry, A_γ, is proportional to the weak pion nucleon coupling constant, f_π^1. Attempts to measure the value of f_π^1 from measurements in finite nuclei such as ^{18}F and ^{133}Cs have produced inconsistent results. Because the NPDGamma experiment is based on the simple *np* system without complex many-body dynamics, we expect it to produce a definitive result. Such a result is important, for without it, one can argue that we still have no clear experimental evidence for hadronic weak neutral currents.

Description of Dedicated Apparatus

The $np \rightarrow d\gamma$ experiment is pictured in Figure 1. A 20 Hz pulsed beam of cold neutrons is transported to the experiment through a supermirror neutron guide entering the experimental cave on the left of the picture. The neutrons are polarized by a ^3He spin filter in a uniform 10 g vertical guide field, which is constant over the entire experiment. The vertically polarized neutrons are then captured in liquid hydrogen, forming deuterium with the emission of 2.2 MeV γ-rays. The 100 kPa, 17 K liquid hydrogen target achieves an equilibrium composition of 99.8% para-hydrogen, which prevents spin flip scattering and the consequent neutron depolarization that would occur with ortho-hydrogen. To reduce systematic errors, an RF spin flipper reverses the neutron spins at the 20 Hz neutron-pulse rate. Capture gammas are detected in an array of 48 CsI(Tl) crystals. Three beam monitors, provided by the University of Manitoba group, are used to determine the neutron polarization and to monitor the para/ortho hydrogen ratio in the target. To calibrate the detector positions and offsets, TRIUMF designed and built a computer controlled stand and motion system that is able

Figure 1: From left to right: the pipe containing the neutron guide, the blue cube of the ^3He polarizer, the cylindrical RF spin flipper, and the array of 48 CsI(Tl) crystals surrounding the liquid hydrogen target. Not visible are beam monitors before and after the ^3He polarizer and downstream of the detector array.

to move the whole 1000 kg detector array in the horizontal and vertical directions over ±10 mm with a precision of 0.025 mm (see Figure 1).

TRIUMF also designed and built a set of VME-based gain control modules each providing 8 amplifiers that could be set independently to a gain of 0.8 to 1.2 via the VME interface. These modules were used to match the signals of all the CsI crystals.

Cost of apparatus: Beam line ~$C2 million; experiment ~$C2.6 million. Canadian contributions from NSERC are ~$C15,000.

Results and Progress

Results of the solid target runs in 2004 and 2005 have been published. During the LH_2 production runs in the latter half of 2006, sufficient data were taken to determine the $n + p \rightarrow d + \gamma$ asymmetry, A_γ, to $\approx 2 \times 10^{-7}$, a level comparable with the previous world limit. The experiment was moved to the Spallation Neutron Source at Oak Ridge National Laboratory in 2007. Once the apparatus is commissioned there, it should be possible to measure A_γ to a statistical precision of $\pm 1 \times 10^{-8}$ in 4,000 hours at the design power of 1.4 MW. The mid-range theoretical prediction for A_γ is -5×10^{-8}.

Partners

In Canada: The University of Manitoba and the University of Winnipeg.

International Partners: India (1), Japan (1), Russia (1), and the United States (15).

TRIUMF's Role

TRIUMF played a major role in the design and construction of a precision computer-controlled detector movement system as well as the design and construction of VME-based gain control electronics. TRIUMF's invaluable intellectual input was based on experience from parity-violation experiments at TRIUMF and Thomas Jefferson National Accelerator Facility.

4.2.1.3

Particle and Nuclear Physics Theory

Introduction

These are exciting times for subatomic physics. Major new developments are taking place across the discipline. In low-energy nuclear physics, the understanding of nuclear structure is undergoing a profound change using the idea that interactions depend on the resolution with which they are studied. This new understanding leads to effective field theory and renormalization group interactions. These new theoretical understandings, coupled to increased computational power, have greatly increased the ability of nuclear theorists to make reliable calculations. Moving from low-energy nuclear physics to the next higher energy scale, the understanding of the structure of the constituents of the nucleus, the proton and neutron, is advancing through the use of numerical techniques known as lattice quantum chromodynamics (QCD). With ATLAS and T2K experiments taking data from 2010 to 2015, the future of high-energy physics is bright as well.

The TRIUMF Theory Group provides a focus for theoretical research at the laboratory and, as part of the international theoretical community, helps connect the laboratory to the exciting developments mentioned. This active group of researchers undertakes high quality research in areas relevant not only to the

ACHIM SCHWENK

TRIUMF Research Scientist
Deputy Theory Group Leader

Achim Schwenk was an undergraduate student for three years at the University of Heidelberg, Germany. He then moved for his Ph.D. research to Stony Brook, NY, from 1998-2002, where he was a Fulbright Fellow and a Scholar of the Germanistic Society of America. His thesis on the "Renormalization Group Approach to Nuclear Forces and the Nuclear Many-Body Problem" won the Max Dresden Prize for Outstanding Theoretical Thesis. From 2002-2006, he was a University Postdoctoral Fellow at The Ohio State University, Assistant Research Scientist at Indiana University, and a Senior Fellow at the University of Washington.

Dr. Schwenk is currently an Affiliate Assistant Professor at the University of Washington, a member of the Pacific Institute of Theoretical Physics at the University of British Columbia, a member of the US Joint Institute for Nuclear Astrophysics, and an international collaborator in the US SciDAC UNEDF effort to develop a Universal Nuclear Energy Density Functional. His research activities focus on understanding and predicting the structure of strongly interacting matter in laboratory nuclei and the cosmos.

Dr. Schwenk is internationally recognized for the development of the renormalization group in nuclear physics, which has led to universal interactions for nuclei and nuclear astrophysics. His work on three-nucleon interactions has become crucial for ab-initio calculations of nuclear structure and towards the extremes investigated at ISAC. He has developed new systematic approaches to nucleonic matter, with applications ranging from superfluidity in neutron stars to the properties of matter and neutrino

CONTINUES ▶

physics program at TRIUMF but also to the interests of the subatomic physics community across Canada. The Group provides support for the TRIUMF experimental program and like the experimental program, the theoretical research program covers a wide range of topics in nuclear and particle physics with emphasis on ISAC science and the work of TRIUMF's scientists at other laboratories and institutions in Canada and around the world.

The Group's research involves working directly with experimentalists in support of particular experiments, providing a more general background to the experimental program, dealing with fundamental areas not currently directly related to the experimental program.

The Theory Group currently consists of four permanent members: B.K. Jennings, J.N. Ng, A. Schwenk, and R.M. Woloshyn, two emeritus researchers H.W. Fearing and E.W. Vogt, eight research associates and a number of students. A new permanent member, D. E. Morrissey, will be joining the group 2009. A sixth member is expected to be added in 2009.

Recent Developments

Nuclear Physics

The physics of strong nuclear interactions extends over extremes of density, neutron-to-proton ratios, and temperatures, ranging from universal properties in ultracold atoms, new forms of matter in laboratory nuclei, to neutron stars and supernovae in the cosmos. This is an exciting era for nuclear theory: trying to understand the nuclei across the range of environments mentioned above. There are advances on many fronts, and a coherent effort to understand and predict the structure of nuclear systems based on effective field theory (EFT) and renormalization group (RG) interactions is underway. These EFT and RG interactions have become the top workhorses in nuclear theory.

Nuclear forces depend on the resolution scale and the scale-dependent two-nucleon (NN) and corresponding many-nucleon interactions are determined in the context of effective field theory. At very low momenta, $Q < m_\pi \approx 140$ MeV, the details of pion exchanges are not resolved, and nuclear forces can be systematically expanded in contact interactions and their derivatives. The corresponding pionless EFT is extremely successful for the capture of universal large-scattering-length physics (with improvements by including effective range and higher-order operators) in loosely bound or halo nuclei, to predict new Borromean states for ^{6}Li and ^{40}K fermionic atoms, and for the equation of state and superfluid properties of low-density neutron matter.

For most nuclei, the typical Fermi momenta are $Q < m_\pi$, and therefore pion exchanges have to be included explicitly in chiral EFT, which makes a direct connection to the underlying theory of QCD. One of our highlights was the application of the RG to nuclear forces by integrating out high momenta through RG equations or equivalent unitary transformations. The resulting low-momentum interactions, generically known as "$V_{\text{low k}}$", become universal at lower cut-offs (see Figure 1), show great promise for few- and many-body calculations, and provide a basis for model-independent predictions of phenomena in nuclei and astrophysics.

Changing the cut-offs or equivalently the resolution scale, by construction, leaves observables unchanged but shifts contributions between the interaction strengths and the sums over intermediate states in loop integrals. These shifts can weaken or largely eliminate sources of non-perturbative behaviour such as strong short-range repulsion and short-range tensor forces. We have found rapid convergence for low-momentum interactions with smooth regulators and for similarity RG (SRG) interactions. The evolution of chiral EFT interactions to lower resolution is beneficial and leads to direct convergence for nuclear structure applications, demonstrated in the *ab-initio* no-core shell model.

Three-nucleon (3N) interactions are a frontier in the physics of nuclei. They are crucial for the prediction of masses, play a central role for spin orbit and spin dependences, for neutron- and proton-rich systems, and for driving the density dependence of nucleonic matter. The latter are pivotal for extrapolations to the extremes of astrophysics. When 3N interactions are neglected, we obtain a universal correlation between three- and four-body binding energies (empirically known as the Tjon-line). We have shown that 3N interactions corresponding to $V_{\text{low k}}$ are perturbative in light nuclei and thus tractable. As a result, we are able to perform the very first calculations for intermediate-mass nuclei with microscopic 3N interactions.

The cut-off variation can provide lower bounds for theoretical uncertainties due to neglected many-body interactions or an incomplete many-body treatment. This is a powerful and practical tool, particularly for matrix elements needed in fundamental symmetry tests such as double-beta decay and isospin-violating corrections for superallowed Fermi beta decays.

Coupled-cluster theory combined with rapid convergence for low-momentum interactions pushes the limits of accurate calculations to medium-mass nuclei and sets new benchmarks for ^{16}O and ^{40}Ca. First coupled-cluster results with 3N forces show that low-momentum 3N interactions are accurately treated as effective zero-, one- and two-body terms, and that residual 3N interactions can be neglected. This finding is very promising and supports the idea that phenomenological monopole shifts in shell model interactions are due to 3N contributions. This would link understanding the shell model and the drip lines to 3N forces, and systematic investigations in this direction are progressing. Finally, low-momentum interactions offer the possibility of perturbative

▼ CONTINUED

interactions in supernovae. In the past five years, he has published 28 articles, organized nine workshops, and given over 100 invited talks and seminars on these topics.

In 2005, TRIUMF recruited Dr. Schwenk to enhance and help lead the Theory Group. ■

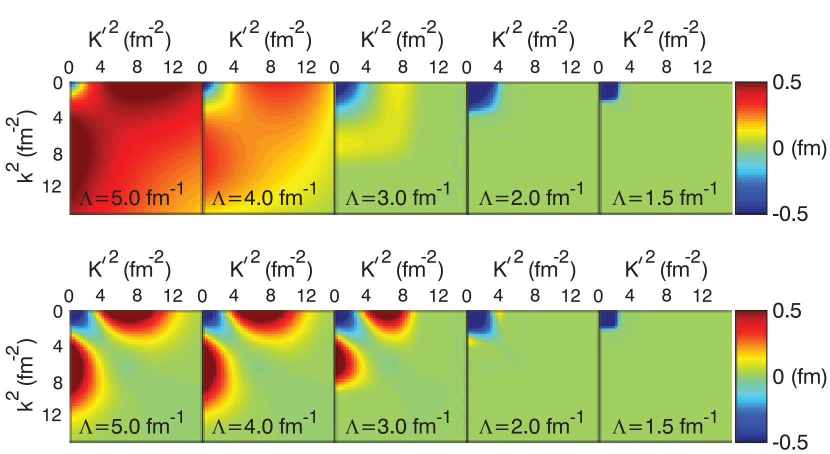


Figure 1: Evolution of two different NN potentials to low-momentum interactions $V_{\text{low k}}$ (with Λ = 5, 4, 3, 2 and 1.5 fm^{-1}) that become universal at low cut-offs.

nuclear and neutron matter, which provides key guidance to develop a universal density functional based on microscopic interactions.

We have developed a non-perturbative RG method for nucleonic matter. For neutron matter, it shows that induced interactions (generated by integrating out modes away from the Fermi surface) deplete *S*-wave superfluidity in the crust of neutron stars, compared to the Bardeen-Cooper-Schrieffer level. In addition, we have investigated the effects of tensor- and spin-orbit interactions in nucleonic matter. In many-body systems, such non-central interactions lead to remarkable phenomena, for instance the differences observed in the A and B phases of liquid ^{3}He. Our work is the first complete study of the spin structure of induced interactions. TRIUMF theorists showed that neutron *P*-wave superfluidity in the interior of neutron stars may be reduced considerably below earlier estimates, and that novel tensor and spin non-conserving interactions are generated in matter. These results for neutron *S*- and *P*-wave superfluidity are discussed in all modern neutron star cooling simulations and imply that low-mass neutron stars cool slowly.

The proposed virial equation of state presents a benchmark description of low-density nuclear matter (composed of neutrons, protons, and light nuclei) based on the virial expansion. The virial approach systematically takes into account contributions from bound nuclei and the scattering continuum, and provides a framework to include strong-interaction corrections to nuclear statistical equilibrium models commonly used in astrophysics. The virial equation of state makes model-independent predictions for a variety of properties of nuclear matter over a range of densities, temperatures, and compositions, for the consistent neutrino response, and constrains the physics of the neutrinosphere (surface of last neutrino scattering) in supernovae. The resulting alpha particle concentration differs from all equations of state currently used in supernova simulations, and the predicted symmetry energy at low densities was recently confirmed in near-Fermi-energy heavy-ion collisions. While the mass fraction in light elements is of order 10% for typical conditions in supernovae, they have significant effects on the neutrino absorption and therefore on the neutrino spectra.

The shell model solves the nuclear many-body problem in a restricted model space and takes into account the restricted nature of the space by using effective interactions and operators. Two different methods for generating the effective interactions have been considered. One is based on a partial solution of the Schrodinger equation (Bloch-Horowitz or the Feshbach projection formalism) and the other on linear algebra (Lee-Suzuki). The two methods have been derived in a parallel manner so that the difference and similarities become apparent. The Bloch-Horowitz method deals with one state at a time and has energy dependent effective interactions and operators. It can describe any state with a non-zero overlap with the model space. The Lee-Suzuki method deals with a set of wave functions, a set with the same dimension as the model space. It can describe only those states in that set. The effective interactions and operators are energy independent.

The no-core shell model and the effective interaction, $V_{\text{low k}}$ can both be derived using the Lee-Suzuki projection operator formalism. The main difference between the two is the choice of basis states that define the model space. The effective interaction, $V_{\text{low k}}$, can also be derived using the renormalization group. That renormalization group derivation can be extended in a straightforward manner to also include the no-core shell model. In the nuclear matter limit, the no-core shell model effective interaction in the two-body approximation reduces identically to $V_{\text{low k}}$. The same considerations apply to the Bloch-Horowitz version of the shell model and an alternate renormalization group treatment of two-body scattering.

Chiral Perturbation Theory

The group has considered two main aspects of chiral perturbation theory (ChPT). The first deals with more basic or technical issues such as the analysis of different renormalization schemes and the extension of the ChPT Lagrangians to include higher orders and new degrees of freedom like photons. The second is more practical and deals with applications of these ideas to specific processes such as muon capture, radiative muon capture, radiative corrections to beta decays, and few nucleon weak processes.

One of the major problems considered on the technical side deals with techniques for renormalization when one extends ChPT to the relativistic realm. Relativistic chiral perturbation theory presents some problems not present in non-relativistic approaches because of the non-zero baryon masses in the chiral limit. In particular, it is hard to obtain a systematic expansion scheme in the relativistic theory. A new renormalization scheme for relativistic ChPT with nucleons was proposed by Becher and Leutwyler and modifications of the approach have been intensively studied by Fuchs and others. These approaches seemingly correct the analytic structure of the amplitudes and, in the case of Fuchs, generate a systematic counting procedure that reproduces the results of heavy baryon chiral perturbation theory. We have analyzed these new approaches to understand the pros and cons of each and the way they can be applied to practical calculations.

Another interesting problem is that of extending the usual ChPT Lagrangian to include lepton fields, as well as photons, as explicit degrees of freedom. We have constructed the hermitian Lagrangian built from pions and nucleons, external scalar, pseudoscalar, vector, and axial-vector fields, virtual photons, and leptons, which are parametrized in terms of $J_\mu{}^w = l\gamma_\mu (1 - \gamma_5)\nu_l$. We consider only terms quadratic in the lepton fields and at most linear in GF. Such a Lagrangian is necessary for leptonic processes involving internal photons, *i.e.* radiative corrections.

These more general investigations have then been applied to specific problems of practical interest. We looked at ordinary muon capture in a relativistic ChPT and used what we had learned about the new renormalization schemes to obtain the observables in terms of the low-energy constants (LECs) of the theory and to evaluate these LECs. Those results are now being used in a calculation in progress of radiative muon capture in the same approach.

In addition, on the practical side, we calculated neutron beta-decay, rate and correlations, in an effective field theory including radiative corrections. The radiative corrections were first included only in terms of some phenomenological constants. This restriction was the main motivation for our work on the ChPT Lagrangian including photons as explicit degrees of freedom. With our new Lagrangian, we will be able to express these radiative corrections explicitly in terms of the LECs of the Lagrangian, which in principle are determinable from other processes. Such a calculation is now in progress.

The TRIUMF Theory Group has also been involved in a number of other projects. An article surveying what is known, mainly from muon capture, about the induced pseudoscalar coupling constant and how it compares with the very well-determined predictions of chiral symmetry was written for the *Review of Modern Physics* (see the comprehensive list of publications in Appendix A). The group was also involved in calculations of solar neutrino reactions on the deuteron in an effective-field thery, in a calculation of axial form factors of the nucleon in ChPT including axial vector mesons, and in a calculation of $\pi p \rightarrow ne^{+}e^{-}$ in heavy baryon chiral perturbation theory.

Lattice QCD

During the past five years, calculations with lattice QCD have evolved to the stage where precision of a few percent is within reach. To get to this level of precision two conditions are crucial: full dynamical simulations are required and light (up/down) quark masses have to be sufficiently small so that a meaningful extrapolation (aided by chiral effective theory) can be made to the physical mass region. The lattice QCD work done at TRIUMF can be divided into two parts: one deals with technical and computational aspects of lattice field theory aimed at understanding how to achieve the above conditions, the second looks at applications of lattice QCD to specific problems in hadronic physics.

Within the realm of technical studies, most of our recent efforts have been devoted to twisted mass QCD. This is a variation of the Wilson fermion scheme, which allows for a chiral rotation of the mass term that can be tuned to offset the error induced by the so-called Wilson term. The feature of this lattice QCD formulation is that it allows stable numerical lattice simulations to be done at quark masses corresponding to pions well below 300 MeV/c^2. This is a big advantage for chiral extrapolation. However, to achieve stable results, tuning of the chiral rotation (or twist) is crucial. In collaboration with the University of Regina group, the first contribution that we made to twisted mass QCD was to suggest an alternate scheme for tuning to so-called maximal twist. This was able to remove some problems in earlier calculations and resulted in a more reliable small-quark-mass behaviour, at least for pseudoscalar mesons. To do realistic dynamical simulations requires that the strange quark vacuum polarization effects be included, a challenge for twisted mass QCD, which naturally deals with quarks in flavour doublets. Our second contribution to twisted mass QCD was to elucidate some issues such as flavour symmetry violation and parity mixing that arise when trying to include a strange quark in the simulation.

Doing calculations at small-quark masses is necessary for chiral extrapolation, but the downside is that statistical fluctuations grow as quark masses decrease. A strategy to counter this effect is to try to construct operators that can propagate with optimal efficiency the hadron states that one is interested in studying. Our final contribution to twisted mass QCD was a study of how operators for mesons could be constructed in twisted mass QCD, which allows for optimal isolation of different spin and parity channels.

A technical problem that our group addressed was that of dynamical simulation using highly improved, staggered fermions. This fermion action allows simulation at small quark masses and, by aggressive improvements to remove lattice spacing errors, can also be used for heavier quarks (up to charm). In collaboration with K. Y. Wong from the University of Glasgow, we developed and tested a scheme for doing dynamical simulations with this action.

The major recent lattice QCD application undertaken at TRIUMF was the calculation of masses of heavy baryons, or baryons whose quark content includes one or more charm or bottom quarks. A number of years ago, we completed a systematic study of such systems within the framework of quenched lattice QCD and were able to predict masses for many heavy baryon states. Since then, four new heavy baryons have been observed. Our earlier predictions are holding quite well, but full dynamical simulations are called for. These simulations have been started for the *b*-quark sector using dynamical gauge field configurations generated in Japan by the JLQCD (Japanese Lattice QCD) Collaboration. Results are being analyzed, and a paper is in preparation.

Particle Physics Phenomenology

It is now generally accepted that the three active light neutrinos of the standard model (SM) have small masses. However, the origin of the masses is still not understood. The conventional view is that they result from the seesaw mechanism, which invokes the existence of at least two very massive right-handed SM singlet neutrinos. While the mechanism can be elegantly tied to Grand Unified Theories, it remains very difficult to test directly. Recently, we have taken the unconventional approach that the light neutrinos get masses from quantum effects without invoking the existence of very massive SM singlets. We extended the Higgs sector to include a triplet and a singlet complex scalar field. We hypothesize that the lepton number violating interactions reside only in the scalar potential while the Yukawa and gauge interactions all conserve lepton number. As a result, the active neutrinos acquire masses at the two-loop level and thus are naturally small. We predict a normal hierarchy for neutrino masses. The additional scalars are all found to be in the TeV range or the theory to be predictive. This makes the model directly testable at the Large Hadron Collider (LHC). We have calculated the production rate and the decay signature of the doubly charged Higgs, which is predicted to exist within reach of the LHC.

We have also performed an EFT study of low-energy precision measurements. We used measurements of muon decay parameters and π- and K-meson decays to constrain the four Fermi operators allowed by the SM symmetry. This set is different from the larger set that respect only U(1) electromagnetic gauge invariance. The allowed operators also depend on whether the active neutrinos are Dirac or Majorana particles. Effects on other precision measurements such as polarized Moller scattering are now underway.

Building on our previous study of split fermions in flat extra dimensions, we are now carrying the study to the case of the Randall-Sundrum model. The model has a natural solution to the hierarchy problem, and we find that it is a good framework to study the flavour problem of the SM. It is a very active area of research, and we expect many new results to emerge.

Philosophy of Science

The nature of the scientific method is controversial, with claims that a single scientific method does not even exist. However, the scientific method does exist. It is observationally constrained model building not induction, falsification not methodological naturalism. The observations must be carefully done and be reproducible [B.K. Jennings, Physics in Canada, 63 (2007) 7]. The models must be logical, internally consistent, predictive, and as simple as possible. Both observations and models should be peer reviewed for error control. The goal of science is to construct models that make the maximum number of correct post-dictions and predictions with the minimum number of assumptions. Supernatural explanations are rejected not *a priori* but when, as is usually the case, they lead to no testable predictions for future observations. In general, if you want your model to be accepted you must show that it makes more correct, precise predictions with fewer assumptions than competing models. There is a surfeit of models that make fewer predictions. As models are improved, their predictive powers increase. We see progress with time; the models become less wrong, probably not absolutely right, but less wrong. There appears to be convergence toward the probably unreachable goal of a model of everything.

The same cannot be said for the philosophical and metaphysical implications of the models. Here there is no obvious convergence or at least the convergence is much slower. There is no overwhelming reason to believe the philosophical and metaphysical implications of presently accepted models. They will probably change in unpredictable ways when new, improved models come along. The only important, enduring property of a model is its predictions for observations. Thus, the metaphysical baggage—the action at a distance, the ether, the caloric, the many worlds, and the objective reality—should not be taken too seriously. However, they frequently play a useful pedagogical role.

The model building understanding of science has implications on how quantum mechanics is interpreted. In analogy with classical probabilities, the quantum mechanical wave function is a property of the combined observer-quantum system and not of the quantum system alone. This means that probability in the quantum world is observer dependent just as in the classical world. Thus, this approach respects the correspondence principle unlike variants of the Copenhagen and many-worlds interpretations of quantum mechanics. Moreover, this approach eliminates the need for action-at-distance or consciousness. It also rejects what is frequently called realism.

Partners

In Canada: McGill University, Simon Fraser University, University of the Fraser Valley, University of Prince Edward Island, University of Regina, and York University.

International Partners: Belgium (1), Denmark (1), France (2), Germany (4), India (1), Israel (2), Italy (2), Japan (2), the Netherlands (1), the United Kingdom (2), and the United States (17).

TRIUMF's Role

TRIUMF supports five permanent members of the TRIUMF Theory Group and five research associates. In addition, it provides resources for the Theory Group Visitor and Theory Group Workshop programs.

4.2.2

Life Sciences and Nuclear Medicine

4.2.2

Life Sciences and Nuclear Medicine

The Life Sciences program includes several primary thrusts: neuroscience research in collaboration with the University of British Columbia (UBC), UBC Hospital, and the Pacific Parkinson's Research Centre; oncology research in collaboration with UBC, the BC Cancer Agency (BCCA), and BC Children's Hospital; general research to advance positron-emission tomography (PET) imaging and research; and proton-beam treatment of ocular cancers.

The historical focus of TRIUMF's research has been in accelerator-based subatomic physics and the related accelerator, detector, and isotope-production technology. For more than 20 years, the skills and techniques developed in this pursuit have been applied to the life sciences. Not only can critical isotopes used for medical imaging and treatment be produced with TRIUMF cyclotrons, but the techniques used by subatomic physicists to peer "inside" the atom can be used to image and trace these agents inside the body to study human health and disease. At TRIUMF, this work typically falls within the research field known as nuclear medicine.

The core of the TRIUMF nuclear medicine program is PET imaging, a technique whereby tiny amounts of radioactive nuclei known as radioisotopes are combined with certain biomolecules and injected into the body. The biomolecules can be "traced" by imaging the decay products (two photons produced by the decay of the radioactive nucleus via the emission of a positron) outside the body. PET allows the concentration of positron-labeled compounds to be determined quantitatively in space and time within the living body. PET is more sensitive than any other human imaging method, such as MRI or CT, and has now become the "gold standard" for the detection of cancer.

Traditional imaging techniques such as CT and MRI are widely used to monitor human disease. Many diseases, however, do not cause disruption of macroscopic physical structure, but alter functional relationships within and between organ systems. Functional molecular imaging enables metabolic change to be visualized. The most sensitive approach for acquiring functional images is to use biologically active molecules that are labeled with radioisotopes. The development of positron-emission tomography in the 1970s and the use of a sugar molecule labeled with ^{18}F enabled researchers to measure glucose metabolic rates in the living human brain for the first time. The use of ^{18}F-glucose as a biomarker is, however, relatively non-specific and has a limited ability to define metabolic changes associated with disease conditions. The dramatic advances in the detailed understanding of the molecular basis for many diseases offers the opportunity to design targeted functional imaging agents that will revolutionize the specificity/selectivity of disease diagnosis and aid in the direction of therapeutic interventions.

TRIUMF's life sciences program is literally saving lives every day through its scientific projects. A critical diagnostic imaging drug (FDG) is sent to BCCA each day to diagnose cancer, determine treatment regimes, and follow treatment efficacy. Several thousand British Columbians have been helped with this TRIUMF-BCCA program. In another program, over a hundred patients suffering from ocular melanoma have been successfully treated and cured by the proton irradiation facility at TRIUMF.

Other basic research projects include the development of PET radiopharmaceuticals that act as enzyme inactivators to follow the course of enzyme replacement therapy used in children's diseases such as Guacher's disease. TRIUMF is also working on the development of radiometal-based radiopharmaceuticals for use as possible cancer imaging and therapy agents. With the acquisition of the microPET small-animal scanner, the PET group has broadened its research to include other diseases such as cancer and diabetes.

TRIUMF has provided considerable expertise and advice to other PET centres across Canada. TRIUMF's PET chemistry group has provided both the Edmonton Cross Cancer PET facility and BCAA with ^{18}F before the installation of their own cyclotrons.

The increased emphasis on PET has brought significant commercial interest in the development and production of enriched target material, automated chemistry devices, and other systems to carry out the synthesis of PET radiopharmaceuticals. TRIUMF has world-leading expertise in creating the initial quantities of radioisotopes and in combining them with biologically active molecules and compounds. Through partnerships with other researchers and clinicians in British Columbia and across Canada, TRIUMF scientists contribute to the overall understanding of human health.

4.2.2.1

Neurology

TRIUMF and UBC have developed a joint program with the Pacific Parkinson's Research Centre (PPRC) that is committed to the study of central nervous system disorders. Approximately 80% of the studies are related to Parkinson's disease (PD), and the remainder are related to mood disorders and Alzheimer's disease. In addition to shared equipment and methodology, this joint approach fosters a greater collaboration between the disciplines and permits researchers to explore problems of major importance, such as depression in PD, in more effective ways. The program has a long record of exploring the origins, progression, and therapies of the disease as well as the complications arising from therapy using molecular imaging as the primary tool.

The focus of the program has been to investigate the origins, progression, therapy, and complications of therapy of PD. Recent research results indicate that PD is probably caused by a small number of "insults" to the neurons that control movement, damaging some neurons and killing others. The disease's progression is the result of damaged neurons dying prematurely. Recent TRIUMF-PPRC research results have also shown that PD patients produce dopamine in response to the expectation of receiving a therapeutic drug. This result has implications for future directions in that successful therapy could involve a combination of placebo and bona fide drugs.

The majority of the neuroscience work is conducted under the auspices of UBC, the Vancouver Coastal Health Authority or Vancouver General Hospital (VGH), and TRIUMF. UBC provides support in the form of full-time salaries for Drs. D. Doudet, M. McKeown, A. Phillips, and L. Yatham. In addition, Drs. V. Sossi and J. Stoessl have career awards that are backed by grant-funded tenure positions. TRIUMF covers base salaries for Drs. M. Adam and T. Ruth as well as one project engineer and two cyclotron operators for the PET program. The hospital and university provide space for all operations, including the clinical program, and VGH offsets some of the expenses of the clinical program with funding for one nurse coordinator as well as partial secretarial support.

Description of Facilities

The PET program facilities at TRIUMF include cyclotron systems for the production of radioisotopes and chemistry labs for the synthesis of radiopharmaceuticals (see Figure 1). TRIUMF currently uses the TR-13 cyclotron and target systems for the production of ^{18}F, ^{11}C, and ^{13}N. Radiopharmaceutical production facilities include the small modular clean room at the cyclotron for the synthesis of FDG for BCCA as well as three chemistry-annex labs for production and development of radiopharmaceuticals used in brain research and other programs at UBC. In addition, another lab room has equipment to carry out quality control tests on all PET radiopharmaceuticals used in humans and animals.

The small clean room area located beside the cyclotron contains a lead shielded hot cell, which houses a commercial GE, FDG synthesis module, and a laminar flow hood. Most of the radiopharmaceutical production and development is carried out in the two labs, each containing one lead shielded hot cell and a total of ten fume hoods and other instrumentation and chemistry apparatus. Synthesis units housed inside the two hot cells were designed and built in-house. The third lab contains the pneumatic send station that is located at the TRIUMF end of the 2.5-km line used to transport the radiopharmaceuticals to the UBC Hospital.

Figure 1: Radiochemist preparing radiopharmaceuticals at TRIUMF.

Results and Progress

In 2004, a method to carry out the radiolabelling in a small diameter quartz tube with ^{11}C methyl iodide in the gas phase was developed and used for the routine production of the ^{11}C-labeled compounds. In collaboration with the chemistry department at UBC, a unique method to label larger biomolecules with ^{18}F by using boron-containing intermediates was developed [R. Ting, *et al.*, JACS 127, 13094, 2005].

A large team of investigators has worked as members of a Canadian Institutes of Health Research Team. Since 2003, team investigators have produced more than 200 PubMed listings, of which more than 70 represent collaborative work within the team. Funding for this team is based on 11 project and 4 core grants. This research team takes advantage of a wealth of clinical material. The Movement Disorders Clinic conducts approximately 3,500 patient visits and annually sees 1,100 patients with typical PD. In recent years, it has become increasingly apparent that PD is probably not a single disease, but rather a syndrome characterized by bradykinesia and rigidity, commonly asymmetric, and commonly associated with tremor [D.B Calne, *et al.*, Parkinsonism Relat. Disord., 10(5):319-322, 2004].

The team has previously demonstrated evidence of compensatory changes in the nigrostriatal dopamine systems of patients with PD, with up-regulation of decarboxylase activity and down-regulation of the membrane dopamine transporter, as well as evidence of early increases in dopamine turnover. Based on the team's observations in asymptomatic carriers of LRRK2 mutations (Project 1 of the Team grant), there is evidence that such changes are seen prior to clinical expression of disease.

Some significant accomplishments during this period include the recent discovery of the LRRK2 mutation [A. Zimprich *et al.*, Neuron 44, 601-607, 2004], led by groups working in collaboration at the Mayo Clinic Jacksonville, Tübingen, and Munich. UBC investigators participated in this work by contributing and characterizing one of the larger pedigrees and have recently published detailed imaging findings in two of the families [J. Adams *et al.*, Brain 128, 2777-2785, 2005]. The team has published papers describing workplace "clusters" of Parkinson's [N. Kumar *et al.*, Arch. Neurol. 61: 762-766, 2004] and lack of regional heterogeneity during disease progression (as opposed to earlier disease stages) [C.S. Lee *et al.*, Arch. Neurol. 61, 1920-1925, 2004]. Functional MRI and Independent Component Analysis were used to differentiate anterior cingulate activation during sustained attention and pain [C.W. Buffington *et al.*, Pain 2005]. This work was the subject of an editorial in the same issue.

1. A theoretical model outlining the presynaptic basis for motor fluctuations in PD [R. de la Fuente-Fernandez *et al.*, Brain 127: 888-899, 2004] and work describing changes in the temporal pattern of dopamine release in PD with motor complications [R. de la Fuente-Fernandez *et al.*, Brain 127: 247-2754, 2004] were published.

2. Changes in dopamine turnover with disease progression in PD were described [V. Sossi *et al.*, JCBFM 24: 869-876, 2004], based on methodology developed at this centre.

3. The effects of ECT [E. Strome, C. Clark , A. Zis , and D. Doudet, Biol. Psychiatry 57: 1004-1010, 2005] and of retinal pigmented epithelial cell implants [D. Doudet *et al.*, Exp. Neurol. 189: 361-268, 2004] in primates were described.

4. Further development of *in vivo* Scatchard methods to differentiate changes in binding affinity and density were applied to study the effects of pharmacological challenges [D. Doudet *et al.*, JCBFM 26: 28-37, 2005] and quantitative phosphor imaging was applied to studies with PET tracers [E. Strome *et al.*, J. Neurosci. Methods, 141: 143-154, 2005].

5. The effects of negative contrast using different concentrations of sucrose on behaviour and dopamine release were described [R.F. Genn *et al.*, Behav. Neurosci. 118: 869-873, 2004]. The relationship between medial prefrontal cortical dopamine release and performance on a working memory task was described [A.G. Phillips *et al.*, J. Neurosci. 24:547-553, 2004].

Partners

In Canada: University of British Columbia and Vancouver Coastal Health Authority.

TRIUMF's Role

TRIUMF provides five key people in the PET chemistry program. It has provided infrastructure support including design, engineering, electronics, the machine shop, and other technical support. TRIUMF's support ensures that the TR-13 cyclotron, the chemistry systems, and the imaging tomographs remain operational so that the imaging program can continue to function. Two TRIUMF research scientists are routinely involved in the design of the studies.

4.2.2.2

Oncology

Ever since the initial studies using microPET, the BCCA has aggressively pursued molecular imaging. The agency has acquired a PET/CT system and plans to have a dedicated research scanner as part of their Phase B Functional Imaging Program. In addition, they have received a Leading Edge Endowment Fund (LEEF) award, with which they have created a chair in molecular imaging. Led by this LEEF BC Leadership Chair in Molecular Imaging, BCCA, in conjunction with the UBC-TRIUMF PET Program, will draw together a unique set of expertise to create a fully integrated radiotracer development and functional imaging program. This program will position BC as a world leader in biomarker development and molecular imaging.

Description of Facilities

The Functional Imaging Program at the BCCA is a collaboration among the agency, TRIUMF, UBC, and the BC Children's Hospital. Capital acquired through the BC Provincial Health Services Authority Emerging Technologies Fund allowed purchase of the province's first hybrid PET/CT scanner in 2004. The clinical PET/CT program, located at BCCA's Vancouver Centre, was enabled by TRIUMF supplying ^{18}F, the positron emitting radionuclide used in production of ^{18}F-fluorodeoxyglucose (FDG). FDG, as a marker of glucose metabolism, is the tracer used in oncologic PET imaging, a diagnostic study which has become a standard of care in the management of many cancer types. A small clean room and shielded chemistry system were installed at the TR-13 cyclotron to produce FDG for the clinical program (see Figure 1). ^{18}F is delivered to the automated chemistry box in the shielded clean room, and BCCA staff members produce FDG in the box. Two shipments a day are sent to the BCCA PET facility to scan up to 16 patients with various forms of cancer.

Expanding on early pilot studies carried out with the small animal PET purchased through a previous Canada Foundation for Innovation (CFI) grant, the TRIUMF/UBC team with BCCA is now aggressively pursuing functional imaging as its major research tool to achieve a fully integrated cancer imaging program. This program will address basic biological questions and clinical

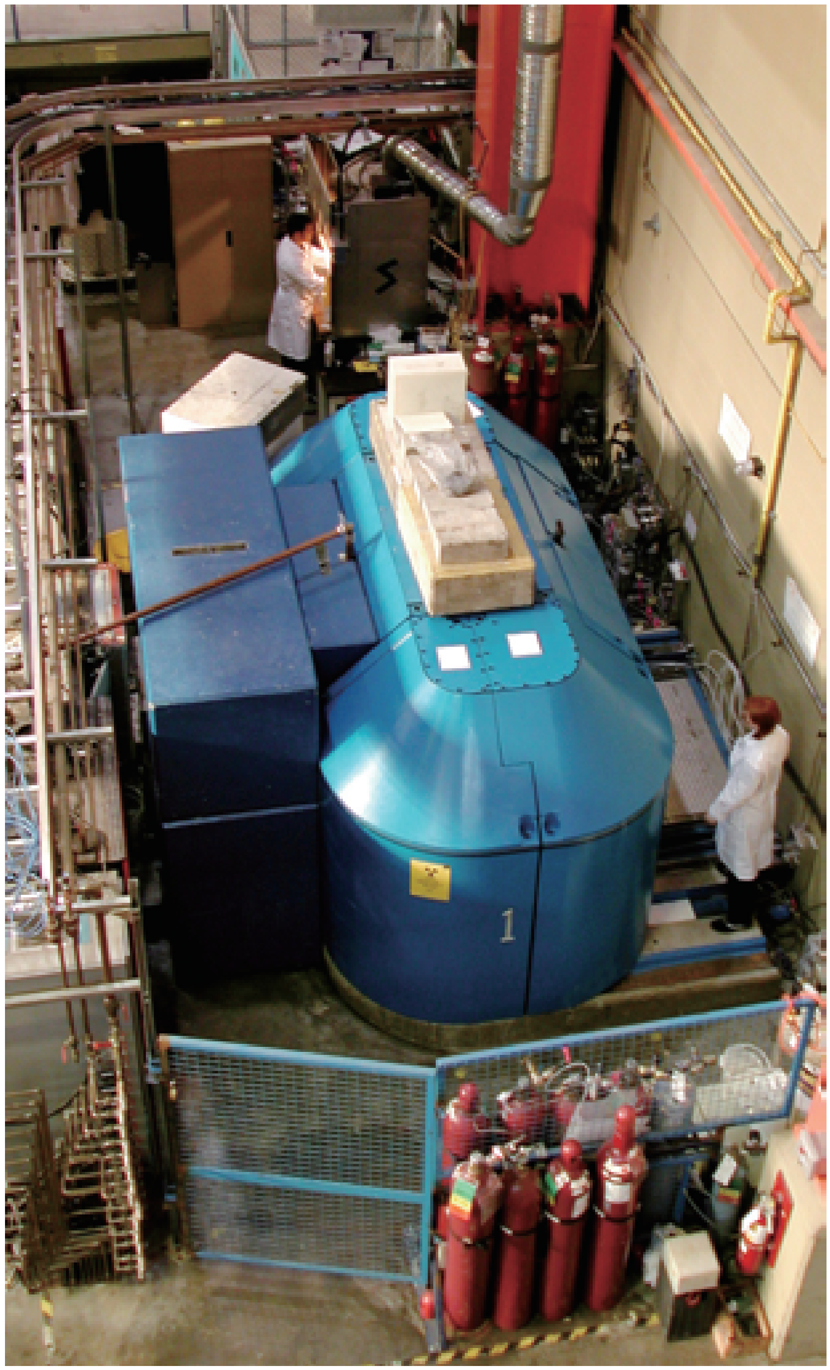


Figure 1: Overhead view of the TRIUMF TR-13 cyclotron.

problems in oncology using functional imaging. Central to all aspects of the BC Functional Cancer Imaging Group will be the development of an interdisciplinary radiotracer research program in conjunction with TRIUMF, basic and clinical researchers at UBC and BCCA, and corporate partners that include Advanced Cyclotron Systems, MDS Nordion, AMI (Quebec), Bristol Meyers Squibb, and Siemens, Canada. The expertise attracted to BC by the establishment of the LEEF Chair will enable the province to enhance its leadership position in the areas of radioisotope production, and radiopharmacy, in addition to paving the way for new research in genomics, biophysics, biochemistry, *in vivo* pharmacokinetics, computational biology, bioinformatics, and clinical oncology using radiotracers as biomarkers.

Results and Progress

Clinical operations began on June 28, 2005, and as of November 15, 2007, 4,769 adult and 275 pediatric oncology patients have been scanned. Referrals to this publically funded program are accepted from physicians across the province with reference to Provincial Tumour Group-approved, evidence-based guidelines for the use of PET/CT in oncology. All PET/CT scans at the Vancouver Centre are performed under Clinical Trials Agreements with Health Canada. The largest groups of patients studied are those with potentially operable non-small cell lung carcinoma (31%), colorectal carcinoma (19%), and lymphoma (14%). Specific approved indications for both adult and pediatric populations are listed on the BCCA's website and include some gynecologic and testicular cancers as well as melanoma and sarcoma. Analysis of the data obtained from referring physicians indicates that PET/CT scan results have led to improved clinical decision making in over 90% of patients and in many cases have led to significant changes in treatment.

A planned physical expansion of the BCCA Vancouver Centre will house a 19 MeV cyclotron, FDG production, and radiochemistry research facilities. Construction began early in 2008, with completion anticipated by early 2009. A small animal PET scanner will be purchased in 2008 and located in the BC Cancer Research Centre, across the street from the Vancouver clinic. Dr. François Benard was recruited as the LEEF BC Leadership Chair in Molecular Imaging and assumed this BCCA/UBC appointment in March 2008.

Partners

In Canada: UBC, BC Cancer Agency, and BC Children's Hospital.

TRIUMF's Role

TRIUMF plays a dual role in the regional partnership for oncology research. All of the radioisotopes used in the imaging studies are produced using TRIUMF's accelerators and technical expertise. TRIUMF has the expertise key to combining the radioisotopes with the biomolecules to be used. In addition to this technical contribution, TRIUMF scientists T. Ruth and M. Adam collaborate on a peer-to-peer level with the clinical research programs of the partnering institutions.

4.2.2.3

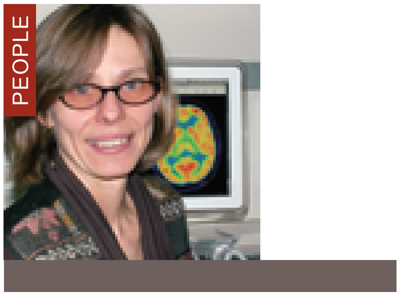
PET Centre

The PET Program in Vancouver was established in 1980 as a collaboration of several departments within the Faculty of Medicine at the University of British Columbia and with TRIUMF. The program is dedicated to basic research in neurology and psychiatry. The program has been funded continuously for over 25 years. Within the United States, where statistics are more available, it is estimated that there are 20 million nuclear medicine procedures performed annually. PET is becoming an increasingly important imaging technique with 1.4 million PET studies carried out in the US in 2006 along with 240 PET/CT scanners sold in the same year.

Description of Facilities

The major resources include the TRIUMF-designed TR-13 cyclotron, which delivers 13 MeV protons, and the ECAT 953B PET scanner to detect the tracers. Two previous CFI-funded projects enabled the Pacific Parkinson's Research Centre (PPRC) to acquire the state-of-the-art human brain scanner, the high-resolution research tomograph (HRRT), and to purchase a microPET small animal scanner to establish a functional imaging program for basic biomedical research, with a focus on neuroscience and cancer. A 2.5 km underground pneumatic tube quickly transports the short-lived tracers from TRIUMF to the UBC hospital where two human scanners reside.

The nuclear medicine facilities that support the research program can be segmented into two major portions, those associated with production of the scanning agents—cyclotron and hot cells—and the scanning instruments themselves. TRIUMF has four scanners: three for studies using human subjects, and one dedicated to small animal experiments. This equipment is described below.



VESNA SOSSI

Associate Professor, UBC

Vesna Sossi completed her Ph.D. at the University of British Columbia in 1991. She performed her thesis research at TRIUMF where she studied pion-induced pion production on deuterium. After graduation she joined the UBC/TRIUMF Positron Emission Tomography (PET) imaging group and in 2001 the UBC Physics and Astronomy Department.

Vesna's current research bridges PET imaging techniques with the investigation of neurodegeneration as manifested in Parkinson's disease in humans and animal models.

Dr. Sossi is the recipient of the NSERC University Faculty Award, a Michael Smith Scholar Award, and a Michael Smith Senior Scholar award. ■

Cyclotron and Hot Cells

The production of the radiotracers used in studying disorders of the monoaminergic pathways relies on the production of specific radionuclides, the conversion of these radionuclides into a useful form, and labelling a biologically active molecule or radiotracer that can be used to probe the system. The production of the radionuclides is performed on the TR-13 cyclotron with gas and liquid targets.

The TR-13 cyclotron is a negative ion cyclotron capable of accelerating two H^- beams simultaneously to 13 MeV where they are extracted into targets containing the appropriate material for the production of ^{11}C as methane and ^{18}F as fluoride or F_2. TRIUMF, in collaboration with Ebco Technologies, designed and built the cyclotron. TRIUMF also designed and built the target systems.

The actual chemistry for producing the radiotracers occurs in lead shielding containers called hot cells. The program has two such hot cells, one dedicated to ^{18}F radiotracers and one dedicated to ^{11}C radiotracers. Development work is performed in fume hoods with lead bricks for shielding, and there is a lab dedicated to quality control measurements for testing the radiotracers before they are released for injection into human subjects.

Once a radiotracer is prepared, it is sent via a pneumatic pipeline the 2.5 km separating the TRIUMF site and the UBC Hospital where the scanners are located (see Figure 1). TRIUMF personnel maintain the pipeline.

Scanning Instruments

The Siemens ECAT 953B is a brain-only scanner. The scanner is composed of 16 rings of detectors for a total of 6,144 single crystal elements, yielding 31 image planes that cover an axial field of view of 10.8 cm. The detector material is bismuth germinate (BGO).

This scanner was one of the pioneer instruments in the transition from 2D to 3D acquisition mode, the latter characterized by the additional acceptance of those positron annihilation events where the two emitted gamma rays travel at an oblique angle with respect to the scanner axis. In using 3D acquisition mode, the resulting radiotracer detection sensitivity increased by a factor of 6, from 0.5% to 2%, providing images with better statistical properties. The ability to acquire data in 3D prompted a large increase in the development of suitable image reconstruction and data quantification algorithms, which were aided by the rapid development in computing power and data storage devices. The scanner is capable of a spatial resolution of 5.5 x 5.6 x 6 mm^3; in practice, when reconstructing human data sets, smoothing filters are introduced to minimize the impact of statistical noise leading to an effective resolution of approximately 9 x 9 x 6 mm^3.

The ECAT has been the workhorse for the UBC-TRIUMF PET group for almost two decades and has been used for several pioneering studies, including a study of Parkinson's disease (PD) etiology and progression, where approximately sixty patients were scanned three times at four-year intervals with three different dopaminergic tracers. This unique data set provided insights into early disease regulatory changes and is currently being completed to provide the full longitudinal data set.

Members of families with PD-associated gene mutation (LRKK2) are being examined on this scanner at UBC in collaboration with the Jacksonville Mayo Clinic. In addition to providing a glimpse into the preclinical stage of PD, this study demonstrates that the neurochemical changes identified in this group are identical to those observed in sporadic PD. Dopamine release associated with the placebo effect was first demonstrated with data acquired on this scanner. Likewise, studies investigating the role of dopamine turnover in PD were first performed on this scanner. Over the course of the years, the ECAT has proved to be very stable and reliable.

The high-resolution research tomograph (HRRT) from Siemens is a double layer LSO/LYSO scanner, currently the most complex brain scanner, which is available in only 17 PET centres worldwide (see Figure 2). The double layer architecture is designed to increase the resolution uniformity across the field of view. The spatial resolution achievable with the scanner is approximately (2.5 mm)^3, the detection sensitivity is approximately 6%, and the axial field of view is 25 cm. Due to its hardware complexity (119,800 crystals), there are several challenging aspects to this scanner. For instance, data sets are very large, of the order of several GBytes, thus rendering data storage and reconstruction is demanding from the computational point of view. Frequent hardware calibrations are required, and the impact of patient motion on data accuracy cannot be ignored.

Addressing these challenges contributed to a rapid development of reconstruction and data quantification algorithms, which will not be limited to the HRRT but will ultimately benefit the PET field in general. In spite of its complexity, the HRRT provides data that could not be easily, achievable, if at all, with any other scanner. In particular, a large part of the UBC-TRIUMF PET group research being planned involves the quantification of tracer binding/uptake in the ventral striatum, which is involved in expectation/reward/addiction mechanism. There, the HRRT provides the necessary resolution to avoid

Figure 1: Dr. T. Ruth discussing a PET scanning procedure in the medical-imaging suite

partial volume effects for this small structure. Detailed studies investigating the mechanism of placebo effect, psychiatric complication in PD, such as depression and compulsive behaviour, as well as psychiatric manic behaviour will be performed in the HRRT in the next five years.

The recently acquired Advance NXi GEHC PET Scanner is a whole body BGO scanner with a 16 cm axial field of view that has proved to be very reliable and stable. It is meant to be a replacement for the Siemens ECAT scanner, which is showing signs of aging; currently there are no commercial dedicated brain scanners available. The Advance intrinsic resolution in 3D mode is approximately 5 mm in all three directions in the centre and degrades by approximately 50% at 20 cm off centre, while the sensitivity is approximately 2%. Studies that do not require the high resolution provided by the HRRT will be performed on the Advance. In particular, the longitudinal studies started on the ECAT will continue on the Advance after appropriate calibration between the two scanners is performed.

The Siemens microPET Focus 120 is a dedicated rodent LSO tomograph with a 10 cm axial field of view, a resolution of 1.8 mm^3 at the center of the field of view and a sensitivity of 6%. The majority of the studies currently performed on the scanner are dedicated to the investigation of the dopaminergic system in the 6-hydroxydopamine-lesion model of Parkinson's disease and survival of retinal cell transplantation as treatment for PD. A pioneer study, which investigated pancreatic islet survival following transplantation, has also been performed on this scanner together with the investigation of hypoxia in tumour mice models. Several pilot studies have been performed to assess the availability of large molecules such as antibodies to the brain. Future planned studies involve the investigation of transgenic mice models of PD and overlap syndrome disease such as PD and dementia.

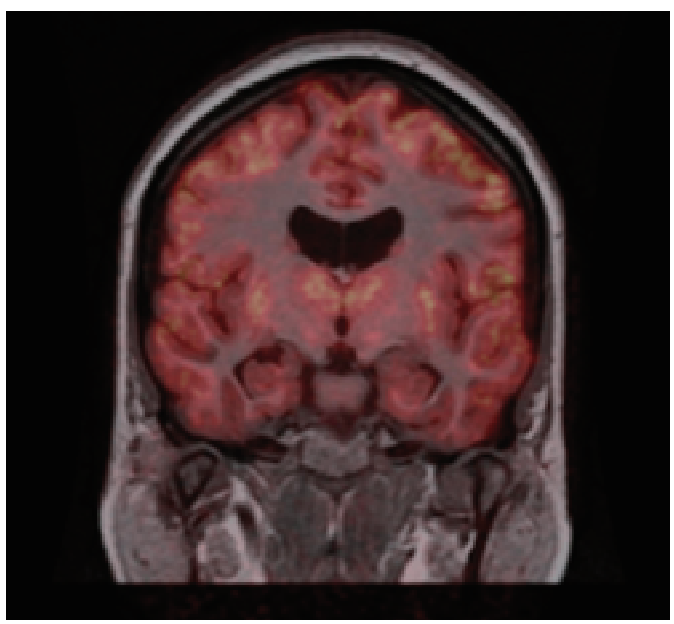


Figure 2: A high-resolution PET scan of the brain combined with an image from MRI.

Results and Progress

TRIUMF's PET program has taken the lead in promoting and assisting other PET centres in Canada. Besides its expert advice, TRIUMF's PET chemistry group provided both the Edmonton Cross Cancer PET Facility and the BCCA with ^{18}F prior to the installation of their own cyclotrons. With the acquisition of the microPET small animal scanner, the PET group has broadened its research to include other diseases such as cancer and diabetes. However, significant improvements and upgrades to the life sciences infrastructure at TRIUMF need to be made if the PET program is to continue its leadership position and continue broadening the imaging research program into other diseases.

The program has been funded continuously for over 25 years. Currently, the major resources include the TRIUMF designed TR-13 cyclotron and the ECAT 953B PET scanner to detect the tracer. In addition, the PET group has acquired two relatively new PET scanners: the high resolution research tomograph (HRRT) for human brain studies and the Focus-microPET© small animal scanner. A 2.5 km underground pneumatic tube quickly transports the rapidly decaying tracers from TRIUMF to the UBC hospital where the human and animal scanners reside. The Neurology group is now planning to add another used whole body PET scanner as a backup to the aging ECAT tomograph. In addition to this hardware, the PET chemistry group has three labs in the Chemistry Annex at TRIUMF (rooms 005, 007, and 110) as well as a small quality-control lab (room 103). These labs were all constructed in 1980 and have not been renovated.

A program to develop new imaging agents for the diagnosis and monitoring of enzyme treatments for two lysosomal storage diseases, namely Mucopolysacchridosis I (MPS I) and Gaucher, will be carried out in collaboration with Dr. S. Withers in the UBC Department of Chemistry. These diseases are caused by mutation of genes encoding for the enzymes iduronidase and glucocerebrosidase, respectively. Studies utilizing the small animal PET scanner are proposed to assess the *in vivo* potential of these new tracers in rats or mice. In parallel, they also plan to develop chemical chaperone therapies for these genetic diseases. Dr. C. McIntosh (UBC) has been examining the use of PET coupled with the reporter gene approach developed by Dr. Gambhir to establish an *in vivo* imaging approach to monitor the survival of transplanted pancreatic islets. Based on preliminary results, Dr. McIntosh wishes to pursue this approach in other animal models to ultimately monitor islet transplantation in humans.

Through the PET Centre, TRIUMF and UBC have partnerships with a variety of other research groups to develop PET-based imaging techniques specific to their research problems. PET isotopes are used by other UBC departments including: Botany (for fertilizers, protein enrichment of rice), Chemical Engineering (multiphase fluid dynamics for the pulp and paper industry), Zoology (imaging animal models of physiological systems), and Oceanography (CO_2 sequestering via copper catalyzed reactions).

Together with its partners, TRIUMF is uniquely poised to fast-track the establishment of a fully integrated radiotracer program by mobilizing, coordinating, and expanding on resources that currently exist within the biomedical and basic research communities. The region has outstanding programs of research in nuclear physics, engineering, physics, biophysics, chemistry, biochemistry, radiochemistry, radiopharmacy, mathematics, genome sciences, bio-informatics, epidemiology, radiology, clinical oncology, and clinical imaging.

Partners

In Canada: BC Cancer Agency, Pacific Parkinson's Research Centre, Simon Fraser University, UBC, UBC Hospital, and University of Victoria.

TRIUMF's Role

TRIUMF is one of the founding partners of the PET Program and TRIUMF scientists play a key role in the intellectual guidance of the program. TRIUMF contributes the technical capability for producing and tailoring the radioisotope compounds for a wide variety of uses. By training students and other scientists in these techniques, TRIUMF has an even broader impact.

4.2.2.4

Proton Eye Therapy

The Proton Therapy Facility at TRIUMF uses 74 MeV protons extracted from the main cyclotron for the treatment of ocular melanoma. The proton therapy equipment was developed as a collaborative project between TRIUMF scientists, medical physicists and oncologists from the BC Cancer Agency and opthalmologists from the UBC Eye Care Centre.

Description of Facilities

Choroidal or uveal melanoma is life-threatening but relatively rare disease (about six cases per year per one million population) and can be treated with radioactive plaques or charged-particle therapy. The physicians and medical physicists responsible for proton therapy at TRIUMF also carry out ^{198}Au plaque therapy, and patients are referred for proton therapy based on tumour size and/or location. Plaque therapy gives excellent results for smaller and favourably placed tumours while protons are used for larger tumours and those located near the back of the eye. A third treatment is enucleation, or removal of the eye, which is the only alternative to proton therapy for medium and large-sized tumors. Of the patients treated to date with protons, the local control rate is about 95%, with the complications rate similar to those observed elsewhere (*cf.*, E. Egger, L. Zografos, A. Schalenbourg, D. Beati, T. Bhringer, L. Chamot, G. Goitein, "Eye retention after proton beam radiotherapy for uveal melanoma," International Journal of Radiation Oncology, Biology, Physics, 55:4, 867-880).Visual acuity is maintained in cases where the vision is good before treatment and where the tumour is away from the optic disc and macula.

Before proton treatment became available at TRIUMF, the usual course of action for Canadian patients with large tumours or ones at the back of the eye was to remove the eye entirely. For smaller tumours, the preferred treatment is still to implant a radioactive disk for a few days. Occasionally it is possible to remove small tumours surgically, but this can be difficult. Any of these alternatives could damage other sensitive parts of the eye and result in some loss of vision. Proton therapy offers the possibility of having the tumours stabilized, the eyes preserved and, depending on the location of the tumour, the vision intact. Iris tumours and benign tumours of the eye called hemangiomas, both even rarer than choroidal melaonoma, are also treated using protons at TRIUMF.

A session of proton therapy is scheduled once per month while the cyclotron is operating. Patients, usually from Western Canada, are referred to the BC Cancer Agency and UBC Eye Care Centre and scheduled for proton treatment if that is deemed the best treatment modality. The tumour size is determined by ultrasound and tantalum markers are surgically implanted by the ophthalmologist to define the location of the tumour. The tantalum clips are visible relative to the beam alignment cross-hairs using X-rays. At TRIUMF a patient mask and bite-block are prepared for each patient and X-rays taken for treatment planning (see Figure 1). Medical physicists determine the optimum eye position and proton beam parameters for treatment.

The 74 MeV proton beam is modified by range modulation, scattering and collimation to provide a uniform dose over the volume of the tumour while sparing, if possible, the critical structures such as the lens and optic nerve. The patient positioning chair, which has six motorized degrees of freedom, the

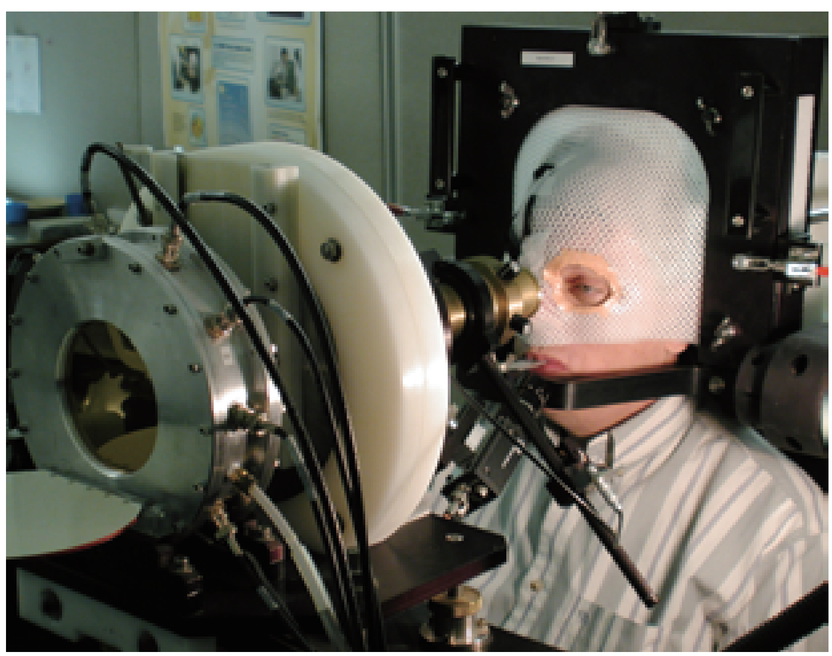


Figure 1: A patient being readied for proton therapy. The mask and headrest keep the patient still during the treatment.

patient mask and bite-block, and the X-ray verification system ensure sub-millimeter positioning accuracy. During treatment the patient stares at the blinking light to align the tumour to the beam. The treatment dose of 50 proton-Gy is delivered in four daily fractions, each treatment taking about two minutes.

Results and Progress

Since 1995, TRIUMF has housed Canada's only clinical proton therapy centre for the treatment of choroidal melanoma, a type of eye cancer. The Proton Eye Therapy Facility is unique in Canada and therefore fills a clinical gap for the treatment of certain eye cancers. Proton therapy continues to save vision in patients. Since the inception of the program, 130 patients have been successfully treated at TRIUMF. About half of the patients are from British Columbia; the other half primarily from the other Western provinces.

The availability of proton and charged-particle therapy is increasing worldwide with several hospital-based facilities operating in the United States and more in Europe and Japan. While ocular melanoma is the most frequently treated cancer with protons, other well-localized cancers near critical structures are particularly suitable for proton therapy.

Partners

In Canada: BC Cancer Agency and the UBC Eye Care Centre.

TRIUMF's Role

Without TRIUMF's specialized proton beams, this program would not be possible. TRIUMF's capabilities make the program unique in Canada.

4.2.3

Molecular and Materials Science

4.2.3.1

Centre for Molecular and Materials Science: CMMS

Introduction

CMMS is the acronym for the Centre for Molecular and Materials Science at TRIUMF. This TRIUMF facility enables an international community of chemists, condensed matter physicists and materials scientists to utilize the powerful experimental capabilities of the muon and polarized nuclei as atomic-scale local probes of matter (please see Figure 1). The research program is multi-faceted, from a broad range of fundamental studies in systems of ever-increasing complexity and sophistication, to the characterization of modern materials and industrial processes. TRIUMF is the sole provider of muon beams in the Americas and one of only four institutions in the world to provide similar experimental capabilities. The three other muon production institutions are RAL (UK), KEK-J-PARC (Japan), which is due to come online in 2010, and PSI (Switzerland). Of these, RAL and J-PARC provide pulsed beams whereas PSI delivers a CW beam similar to that provided by TRIUMF.

The historical core of the CMMS research program utilizes muon spin rotation, relaxation and resonance (μSR) techniques based on the unmatched capability of the positive muon (μ^+) to detect the magnetic field at its microscopic location. It is now well recognized that this capability enables μSR to provide unique information over a very wide range of disciplines. Specifically, μSR has been applied to the study of magnetism, superconductivity, semiconductors and semi-metals, quantum diffusion, molecular bonding states, and fundamental and complex chemical reactions. A recent subset of this work, broadly summarized in Figure 2, is highlighted in this report.

Muons "out of the TRIUMF beam pipe" distribute themselves into condensed matter samples over a depth scale of one half to several millimetres; thus they are a bulk probe and cannot be used in the study of nanoscale structures. Unlike PSI (the Paul Scherrer Institut), with its order-of-magnitude higher proton current, TRIUMF does not have the capability to produce low-energy muon beams of sufficient intensity for a μSR-based nanoscience

Facilities:

	Current	2010 - 2015
Beam lines:	3 Muon (40 wks) + 2 Rib (3 wks)	5 Muon (40 wks) + 2 Rib (12 wks)
Personnel	5 fte/MFA grant + 2 fte/TRIUMF	7 fte/MRS grant + 3 fte/TRIUMF
Spectrometers	5 General Purpose + 5 Specialized	7 General Purpose + 6 Specialized
Dedicated equipment	$4 million	$5 million

Users:

Nationality/Region	# Users	Institutions
Canada	94	16
USA	59	25
Japan	113	23
Europe	52	19
South America	5	2
Total	**286**	**85**

Experiments

January 2004 - December 2007: 110

Publications

January 2004 - April 2009: 219

PRL / Nature / JCP etc: 29

Figure 1: An Overview of the CMMS Facility, its user community, number of experiments and publications.

program. On the other hand, radioactive nuclei from TRIUMF's ISAC-I can be used to probe materials from 5 – 400 nm below the surface, using the techniques of β-NMR (beta-detected nuclear magnetic resonance) and β-NQR (beta-detected nuclear quadrupolar resonance). The CMMS program now encompasses these techniques. To date, β-NMQR experiments have been successfully carried out on surface and interface proximity effects in normal metals, superconductors, systems with structural and quantum phase transitions, and on the properties of magnetic multi- and monolayers.

Very recently, the β-NMQR infrastructure has been completed, and work is proceeding on rebuilding M9A into a very high luminosity, muons on request (MORE)-enabled, state-of-the-art μSR beam line. However, even with this very welcome additional to TRIUMF's μSR capacity the CMMS was still substantially unable to meet the demands of the growing user community. Therefore, in February 2006, Simon Fraser University (with Dr. P. Percival as Principal Investigator) submitted a proposal to the Canada Foundation for Innovation's (CFI) New Initiatives Fund. TRIUMF and 15 other Canadian universities supported the proposal. CFI approved the proposal in November 2006 and will fund 40% of the $C6 million M20 project (see Figure 3) which will add a second channel, enable the MORE mode, and significantly upgrade the overall beam quality.

In July 2007, it was announced that the British Columbia Knowledge Development Fund (BCKDF) would provide matching funds, and TRIUMF would provide an in-kind contribution equivalent to 20%. The final budget claim for the project was submitted to CFI by SFU in April 2008. TRIUMF and the

Scientific Scope:

High temperature superconductivity (HTSC), definitive measurements & tests:
- Vortex core structure in type-II superconductors
- Generic magnetic phase diagram of HTSC and hidden order

Physical, green and materials design chemistry:
- Reaction kinetics and organic free radicals under hydrothermal conditions
- Catalysis of organic reactions in zeolites
- Ionic liquids, carbenes and related muoniated radicals
- Fundamental molecular reaction rates
- Designing molecular polymer magnets

Exotic magnetism, strongly correlated systems, quantum phase transitions:
- Quantum phase transitions, criticality and dynamics in itinerant heli/ferromagnets
- Magnetism in non-fermi-liquid metals
- Heavy fermion (HF) systems & unconventional (non-HT) superconductivity
- SC pair breaking mechanisms via radiation induced defects
- Lack of magnetic ordering in Pu metal
- Multipole ordering in f-electron systems
- Geometric frustration and surface effects
- Magnetic polarons

Hydrogen-materials interactions:
- Semiconductors
- Hydrogen storage materials

Industrial basic research for automobile technology

β-NMQR: Probing the interface:
- Monolayer molecular magnets
- Vortex core size in type-II superconductor
- Thin metal films
- Phase transition probe

Nuclear quantum electrodynamics

Figure 2: A subset of the scope of CMMS research activities as highlighted in this Report.

CMMS plan to have the beam line installed and operational by April 2011.

This award is an important precedent for TRIUMF. It is the first time a broadly based outside funding agency has committed funding for a major capital component required for development of beam line infrastructure on site. For the CMMS, the national character of the CFI decision marks a watershed because it conveys the clear message that this TRIUMF program is considered, by its peer community, to be one of national importance.

Description of Dedicated Apparatus

Beam Lines

Muon Beam Lines in the Meson Hall

Two dedicated surface muon (29.5 MeV/c) beam lines are in operation. Both M15 and M20 are capable of delivering a separated and/or spin polarization rotated beam via the crossed electric and magnetic field Wien filter/spin rotators. M15 features a modern optical design, invented at TRIUMF, with dual spin rotators separated by a triplet to remove achromatic distortions for efficient beam transport. The older M20 does not have this feature and, when operated in its 90° spin rotated mode, over 50% of the beam is lost. These beam lines are used for condensed matter samples that do not require significant confinement.

For materials that require confinement, *i.e.*, high-pressure studies, the muon decay channel M9B is available, providing muon momenta throughout the range 40–110 MeV/c. The unique feature of this beam line is that it is the sole decay muon channel in the world that provides beams of high transverse spin polarization.

M9A is a new high luminosity beam line, with modern optical design (dual spin rotators), that is currently under construction. This beam line will have a new generation of spin rotators, see Figure 4, which allow for extremely stable high voltage operations. This enhanced feature is accomplished by means of a very innovative electrode design around the edges of the electrostatic plates. The beam line will also feature a fast electrostatic kicker to allow it to be run in the "muons on request" (MORE) mode.

β-NMR and β-NQR Beam Lines in ISAC-I

Polarized beams of β-emitting unstable light nuclear isotopes can be produced in ISAC-I for transport into its low-energy experimental area and delivered into its condensed matter research facilities. The potentially useful nuclei are ^{8}Li, ^{11}Be, ^{12}O, and ^{17}Ne, but to date only ^{8}Li, with a nominal energy of 28 keV

Simon Fraser University

New Initiatives Fund / Fonds des initiatives nouvelles	
Muon Beam Line for Molecular and Materials Science at TRIUMF	$2,405,525
1 project / projet	**$2,405,525**

Figure 3: The CFI award notification published in Nov. 2006 representing its 40% contribution toward CMMS M20 Beam Line rebuild project at TRIUMF.

and a flux to 10^7/s, has been delivered. A fast kicker front-end multiplexer then switches the beam to either the β-NMR or β-NQR arms allowing for quasi-simultaneous operation and increased utilization efficiency of the available beams. Each spectrometer is mounted on an isolated HV platform which confers the capability to decelerate the beam to as low as 0.1 keV. The bi-polar β-NMR HV platform can also accelerate the beam to 80 keV. Both beam lines incorporate *in situ* optical imaging of the beam spot for the assessment of their focusing mechanism. The final beam line stages and cryostats operate in a UHV environment that is time consuming to prepare. To that end, sample load locks and an in situ system, in which a multi-sample holder can be placed in the high voltage, have greatly reduced the turnaround time for sample changes.

New CMMS Devices in the Last Five Years

- A novel μSR high field (5 T) high timing resolution (250 ps) front-end detector array for use in the CMMS dilution refrigerator (base temperature 15 mK) delivers an unprecedented B/T range for μSR studies. Figure 5 illustrates the detector design.
- A general-purpose, extremely flexible spectrometer, OMNI', for use in the M9B decay channel has been commissioned.
- Standardized universal mounting systems for all μSR spectrometers deployed.
- Compact data acquisition electronics for integral μSR designed and implemented.

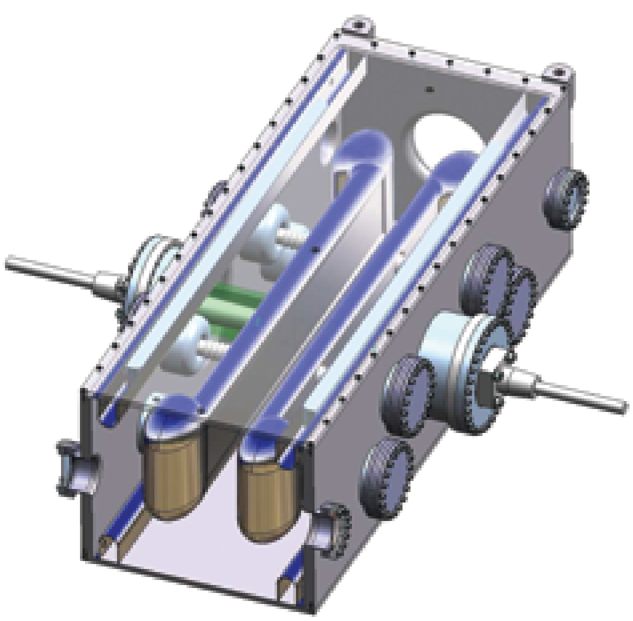


Figure 4: A rendering of the vacuum tank, electrostatic plates and high-voltage feedthroughs of the Wien filter / spin rotator being fabricated by Bruker Biospin for the TRIUMF M9A beam line. The design should offer unprecedented stability for the +/- 275 kV operating plate voltages.

- Ceramic temperature stable (2–450 K) 0.8–2.5 GHz microwave resonant cavity for Mu studies designed and implemented.
- High-pressure/temperature apparatus designed and built for supercritical studies.
- High-pressure 2.5 GP piston pressure cells designed and utilized in OMNI'. Figure 6 shows a 3rd generation design which will be used for even higher pressures.
- Cryogenic OMNI' insert designed and built specifically for optimizing muon polarization in high-pressure cell above.
- Advanced firmware modules for β-NMQR (shown in Figure 7) have been developed to allow random frequency sweeping and complex rf-pulse modulation of capabilities.
- Athermal excitation (optical, electrical, and strain) capabilities have been added to selected experimental configurations.

Catalogue of Equipment

The equipment belonging to, or available to, the CMMS is includes spectrometers—magnets plus detectors (see Table 1); sample environment control devices—cryostats, ovens, and so on; and ancillary supporting equipment.

Spectrometers

A spectrometer for the CMMS is a magnet (or magnets) plus an array of counters to detect incoming particles and outgoing electrons/positrons after β-decay. Some spectrometers move from beam line to beam line, some are only used on a specific beam line, and the ISAC-deployed units (β-NMR, β-NQR) are permanently attached to a particular beam line.

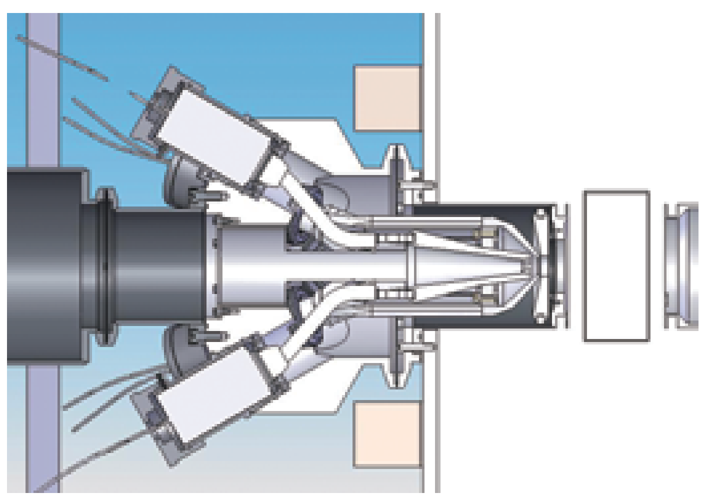


Figure 5: Schematic diagram of the scintillators, light guides and photomultiplier arrays in the beam line vacuum that compose the muon CMMS DR front-end detector. The dense design is made possible by the use of wave-shifting scintillators to efficiently bend light around corners.

The magnets are of various types—Helmholtz, solenoid, or solid pole electromagnet, superconducting or normal—and most spectrometers have more than one magnet. The main magnet of a spectrometer is usually oriented so the field is along the beam axis that allows the beam to enter the sample without being turned away. Other coils provide weaker fields in perpendicular directions either for zeroing the field or for applying weak fields (<10 mT) transversely to the beam direction.

Most of the counter systems are movable in various ways, and many follow a general-purpose design of multi-counter modules mounted on tracks on tables attached to the spectrometer. Other counters are fixed components of the spectrometer or sample-holding inserts.

The spectrometer provides the magnetic field, but other experimentally relevant conditions are typically controlled. Temperature is the most important, and samples are usually held within a cryostat or oven. Other variables are pressure, RF/microwave excitation, and electric field.

Results and Progress

CMMS has contributed to and enabled a number of key advances in molecular and materials science, namely: high-temperature superconductivity; physical, "green," and materials design chemistry; exotic magnetism, strongly correlated systems, and quantum phase transitions; hydrogen-materials interactions; industrial basic research for automobile technology; β-NMQR; and nuclear quantum electrodynamics. Each of these advances is described separately below.

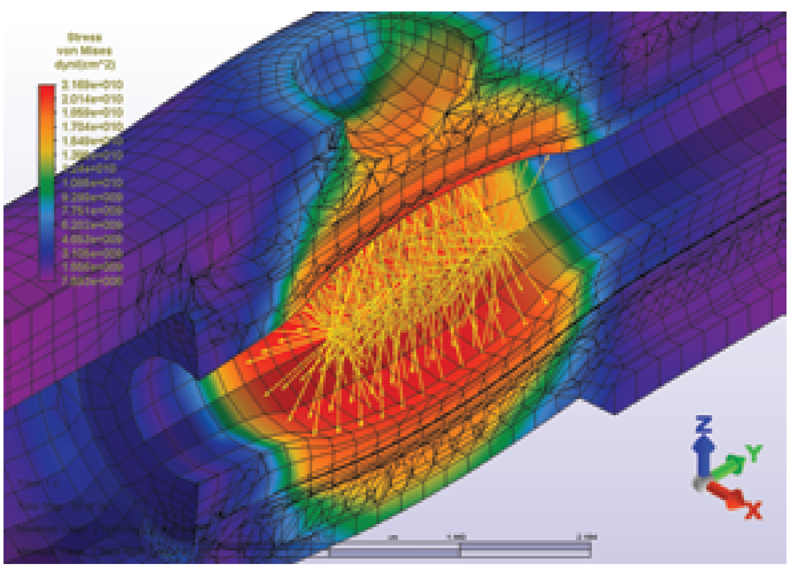


Figure 6: A preliminary analysis (T. Ries, TRIUMF) of the stress vs. strain in a double walled pressure cell specifically designed for μSR studies at 3.5GPa. The top dimple reduces the mass density along the muon's path to mitigate multiple scattering and enhance the probability that it will stop in the central target volume.

High-Temperature Superconductivity: Definitive Measurements & Tests

High-temperature superconductivity (HTSC) has the potential to factor into future energy-saving technologies. μSR has played a prominent role in our current understanding of HTSC, with studies at TRIUMF accounting for the most recognized μSR contributions to this field. Since the discovery of high-T_c cuprates in 1987, μSR has been used to map out significant pieces of their generic phase diagram by exploiting the technique's unique sensitivity to disordered static magnetism, short-range magnetic order, and magnetic phase separation. μSR has also been used to probe low-energy excitations, to establish a definitive relationship between the superconducting carrier density and T_c (the so-called "Uemura plot"), and to provide one of the earliest pieces of evidence for d-wave superconductivity in the bulk. μSR studies on high-T_c cuprates at TRIUMF have provided strong evidence for the existence of a state closely competing with superconductivity, beginning with the reported finding of weak anomalous magnetism [Science 292, 1692 (2001)], and including more recent experiments showing unusual magnetic field-induced effects in the superconducting and normal states. The prominence of μSR in the study of

Name	Magnet Type	Purpose & Notes
Helios	Superconducting 6 T	General purpose beam
DR	Superconducting 5 T	Low temperatures (see DR sample environment)
Hi-time	Superconducting 8 T	High field, high frequency
OMNI'	Conventional 0.3 T	Energetic muon beam, thick targets (high pressure)
LAMPF	Conventional 0.3 T	Low-field, general purpose
SFUmu	Conventional 0.45 T	General purpose and energetic beam
β-NMR	Superconducting 7 T	β-NMR studies
β-NQR	Conventional 0.01 T	Low-field β-NQR studies
Gas cart	Conventional 0.03 T	Very large samples
Varian	Conventional 1 T	Energetic beam transverse field. Deprecated since transverse muon polarization developed on M9b beam line
OMNI	Conventional 0.2 T	General purpose, deprecated

Table 1. Magnets and detectors and their uses.

HTSC and other unconventional superconducting materials is predominantly due to: (i) the availability of extremely high quality samples from collaborators at UBC; (ii) CMMS spectrometers, which boast unique measurement capabilities not available elsewhere; and (iii) the quality of the research groups involved.

Vortex Core Structure in Type-II Superconductors

μSR has become the leading experimental probe of the effective size of magnetic vortices in type-II superconductors. The core size and shape (see Figure 8) is a fundamental property of type-II superconductivity that has proven difficult to measure by other methods. The cumulative results, which include studies over the past five years [Physical Review Letters 93, 017002 (2004); Physical Review Letters 95, 197001 (2005); Physical Review B 74, 024513 (2006); Physical Review B 74, 054511 (2006); Physical Review B 76, 134518 (2007), Reports on Progress in Physics 70, 1717 (2007)], have served as a primary motivation for recent advances in the development of a complete microscopic theory of the electronic and magnetic structure of the vortex state in single-band and multi-band superconductors. Recently, the effects of multi-band superconductivity on the vortex core size have been demonstrated in the high-T_c superconductor $YBa_2Cu_3O_y$ [Physical Review B 76, 134518 (2007); Physical Review B 77, 024514 (2008)].

Generic Magnetic Phase Diagram of HTSC and Hidden Order

Within this five year time span, μSR studies at TRIUMF have continued to considerably add to our understanding of the generic magnetic phase diagram of cuprates, which serves as the primary motivation for theoretical ideas on the

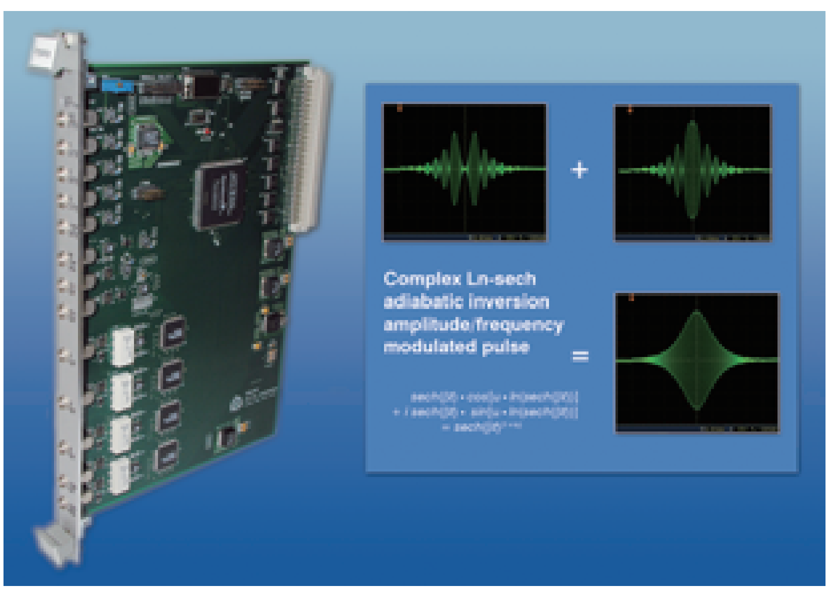


Figure 7: The β-NMQR rf generator, which contains digital FPGA based DSPs to generate complex modulated pulse shapes to produce sophisticated frequency swept pulses which can be designed to irradiate any discrete set of frequency slices in the spectrum.

microscopic origin of HTSC. The complexity and fragility of HTSC is believed by many to be due to the presence of a hidden order that competes with superconductivity. Zero-field (ZF) μSR is an extremely sensitive probe of weak magnetism associated with a competing state. Very recently, the earlier finding of anomalous weak magnetism in $YBa_2Cu_3O_y$ by ZF-μSR [Science 292, 1692 (2001)] was independently confirmed [Xia *et al.* submitted to Physical Review Letters]. This and new findings from neutron scattering have sparked considerable interest and are driving demand for new μSR measurements. The first new ZF-μSR study of this kind has recently been completed [G.J. MacDougall *et al.* submitted to Physical Review Letters].

High-T_c superconductors are achieved by doping an antiferromagnetic insulator with charges or holes. ZF-μSR studies, including recent work near the insulator-to-superconductor boundary [Physical Review B 73, 144509 (2006)] indicate that superconductivity struggles against remnants of the magnetic parent compound. In 2003, it was shown for the first time by μSR that local suppression of superconductivity in an electron-doped high-T_c cuprate by a weak magnetic field results in the appearance of magnetic order [Physical Review Letters 91, 147002 (2003)]. Field-induced effects in hole-doped cuprates were further studied by transverse-field (TF) μSR [Physical Review Letters 95, 157001 (2005); Physical Review B 75, 054511 (2007)], and it was shown for the first time that an applied field induces static spin-glass magnetism in the superconducting phase immediately below the critical doping for the so-called "normal-state metal-to-insulator crossover (MIC)" [Physical Review B 76 064522 (2007)]. This discovery identifies the precise location of a hidden quantum phase transition to a state of coexisting superconducting and magnetic orders, and also supports the theoretically predicted occurrence of an "avoided" quantum critical point (QCP) in the HTSC phase diagram. This is the first experimentally established example of an "avoided" QCP in a three-dimensional bulk system.

Recently, an anomalous inhomogeneous magnetic-field response has been observed by TF-μSR above the bulk superconducting transition temperature T_c that tracks the magnetic response of the superconducting state [J.E. Sonier *et al.*, submitted to Physical Review Letters]. The experimental results, shown in Figure 9, are explained by the occurrence of superconducting domains at temperatures extending well above T_c. Remarkably, spatial field inhomogene-

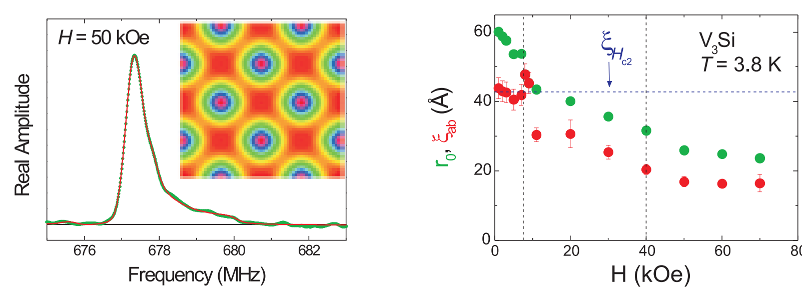


Figure 8: Internal magnetic field distribution in the vortex state of superconducting V_3Si (left panel), and the magnetic field dependence of the vortex core size (right panel) due to the delocalisation of bound quasiparticle core states. From [J.E. Sonier et al. Phys. Rev. Lett. 93, 017002 (2004)].

ity above T_c is observed even in ortho-II $YBa_2Cu_3O_6\overline{H}_{50}$, which has highly ordered doping. Hence, the spatial field inhomogeneity above T_c does not appear to be due to local disorder introduced by the chemical dopants but is suggestive of a reorganization of the electronic structure brought about by a closely competing state. The observation of superconducting signatures far above T_c raises the prospect of one day creating a room-temperature superconductor, and future μSR investigations are expected to play a prominent role in elucidating the reason why the bulk superconducting state breaks up into domains above T_c.

Physical, Green, and Materials Design Chemistry

In contrast to the work described in the previous section, which depends on the use of the muon as a microscopic probe of magnetism, applications of μSR to chemistry emphasize the role of the muon as nucleus of the muonium atom (Mu), a spin-labeled light isotope of hydrogen (H). The μSR signature of Mu atoms is very distinct and allows unambiguous measurements of hydrogen atom reactivity and environmental interactions. In some applications, emphasis is on comparison of the behaviour of Mu and H, *i.e.*, isotope effects; others utilize Mu as a substitute for H, to permit studies under conditions where H atom experiments are not possible or the signals cannot be distinguished from background. Incorporation of Mu into a molecule with an unpaired electron (*i.e.*, a free radical) modifies the μSR signature in a manner that provides information on the unpaired electron spin density at the muon location in the molecule. Further aspects of the unpaired spin distribution can be learned by applying another type of muon spin spectroscopy, avoided level-crossing resonance (MuLCR).

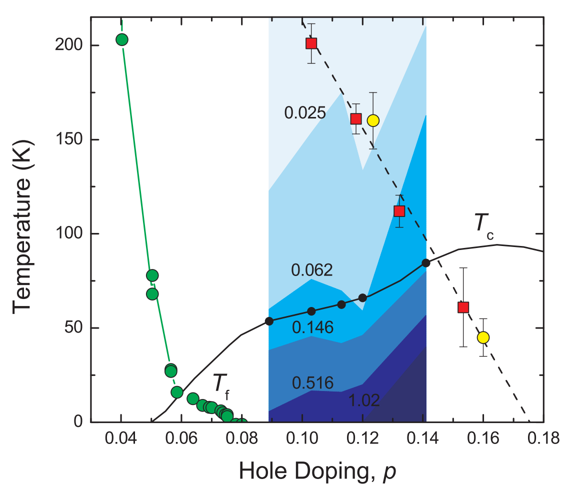


Figure 9: The inhomogeneous superconducting behaviour in YBCO at H = 7 T is shown as coloured bands which displays the additional induced relaxation L - L_{Ag}. Also shown is the extended spin freezing transition T_f and the onset of magnetic order (yellow circles) determined by ZF-μSR in previous TRIUMF work. From [J.E. Sonier et al., submitted to Physical Review Letters].

PEOPLE

JUN SUGIYAMA

Principal Research Scientist

Jun Sugiyama received a B.Sc. in Chemistry and a M.Sc. in Applied Physics from Nagoya University in 1979 and 1982, respectively. After graduation, he joined the sensor group of Toyota Central R&D Labs (TCRDL), where his work ranged from magnetic sensors to surface acoustic wave devices. From 1989–1993, Jun worked with the materials group of Superconductivity Research Laboratory in Tokyo. He completed his Ph.D. thesis, "Substitution effect on magnetism and superconductivity in Nd2CuO4," in 1992 at Nagoya University.

Dr. Sugiyama returned to the materials division of TCRDL in 1993 to lead the research effort focused on battery-related thermoelectric materials. Emphasis focused on the layered cobalt dioxides which had excellent thermoelectric properties. To that end, Jun has been using TRIUMF's μSR facilities to probe and understand the magnetic character of the complex phases found in these materials.

Jun is currently the leader of the particle beam analysis group of TCRDL. This effort is focused on the development of new materials that have potential applications for future automotive technologies. As a case in point, recent initiatives encompass studies of hydrogen storage materials that promise a means to use clean-burning hydrogen for fuel cell vehicles and other instruments pertinent to a sustainable future "hydrogen economy."

In 1991, Jun received the SRL Technical Research Award. In 2004, he was the co-recipient of a World Young Fellow Meeting Presentation Award presented by the Ceramic Society of Japan, and the recipient of TCRDL's Most Excellent Research Award.

In recent years, many of the muonium chemistry projects at TRIUMF have explored problems in reaction kinetics and free radical chemistry which have applications of environmental relevance, for example, the destruction of toxic waste and the development of environmentally friendly industrial processes, or so-called "green chemistry". This Canadian-dominated research effort, from P. Percival (SFU), J. Clyburne (Saint Mary's University), K. Ghandi (Mount Allison University), and D. Fleming (UBC), is the focus of the work reported below.

Reaction Kinetics and Organic Free Radicals under Hydrothermal Conditions

Developing an understanding of transient free radical reaction dynamics in superheated aqueous solutions is motivated by their relevance and applicability to geochemical production of fossil fuels, biology of submarine volcanic vents, corrosion in pressurized water reactors, the destruction of chemical weapons, and utilization in green industrial processes. However, direct experimental access to the H atom chemistry under these extreme conditions is very difficult, and the use of Mu substitution has provided the experimental means to extract much information of significance.

Measurements of kinetic data for hydrogen atom abstraction and electron transfer reactions in sub- and supercritical water have led to an improved model for the reactions of key intermediates involved in the radiolysis of water in the cooling cycle of nuclear reactors [J. Phys. Chem. A 107: 3005–3008 (2003) "Prediction of Rate Constants for Reactions of the Hydroxyl Radical in Water at High Temperatures and Pressures"]. The data are also relevant to the chemistry involved in the supercritical water oxidation scheme for the destruction of toxic waste [Physica B 326: 55-60 (2003) "Muonium kinetics in sub- and supercritical water"; Rad. Phys. Chem. 76: 1231-1235 (2007) "H atom kinetics in superheated water studied by muon spin spectroscopy"].

Organic free radicals are usually characterized by electron spin resonance (ESR) but this technique is not possible for radicals in superheated water. Thus information gained in the study of muoniated radicals is unique [J. Am. Chem. Soc. 127: 13714-13719 (2005) "Organic Free Radicals in Superheated Water Studied by Muon Spin Spectroscopy"]. An example is the investigation of the equilibrium between keto and enol forms of acetone, where it was found that high temperatures favour the enol, which is only present in minute quantities at room temperature [J. Am. Chem. Soc. 125: 9594-9595 (2003) "Enolization of Acetone in Superheated Water Detected via Radical Formation"].

To carry out these studies on Mu and free radicals in superheated water, specialized apparatus was designed and fabricated to permit μSR and MuLCR measurements under conditions (up to 400°C and 400 bar) not previously attained [Physica B 374-375: 314-316 (2006)].

Catalysis of Organic Reactions in Zeolites

The use of zeolites as heterogeneous catalysts is ubiquitous, particularly in the petrochemical industry, yet there is still relatively little understanding of the mechanisms involved at the microscopic level, and in particular the roles played by neutral free radicals. Mu easily substitutes in the known organic processing precursors (C_6H_6 and C_2H_4), forming the radical, which can be detected via the MuLCR technique. The positions, widths, temperatures, and molecular coverage dependencies of the resulting spectra deliver information concerning the binding sites and the dynamics of intra- and inter-site motions of the radicals under study [Physica B 326: 64-67 (2003) "Observation of Muonium in Zeolites"; J. Phys. Chem. C 111: 9779-9793 (2007) "The Interaction and Hyperfine Coupling Constants of the Mu-Ethyl Radical in Faujasites: NaY, HY and USY"; Phys Chem/Chem Phys (2008) "Hyperfine Interactions and Molecular Dynamics of the Mu-cyclohexadienyl Radical in Y-Zeolites"].

Ionic Liquids, Carbenes and Related Muoniated Radicals

Ionic liquids have attracted significant interest as environmentally friendly solvents. They perform well as acidic reaction media and have very low volatility. One significant aspect of the chemistry of the imidazolium-based ionic liquid is its binary reaction into a pair of carbene molecules, entities with two proximally coordinated unpaired electrons. Until recently, carbenes were considered undetectable due their extreme reactivity, but carbenes incorporating an imidazole ring are relatively stable, and their H atom adducts can be investigated by means of the Mu analogues [J. Am. Chem. Soc. *125:* 11565-1157 (2003) "The Reactions of Imidazol-2-ylidenes with the Hydrogen Atom: A Theoretical Study and Experimental Confirmation with Muonium"; Chem. Comm. DOI:10.1039/ b512462j (2006) "From the reactivity of N-heterocyclic carbenes to new chemistry in ionic liquids"]. Since that initial work, the idea has been extended to study muonium in addition to the even more exotic silylenes and germylenes. H analogues of the ensuing silyl and germyl radicals have not been detected, so the information obtained on their structure and reactivity via μSR is unique, with relevance to the chemical processes used to prepare thin films of silicon and germanium for the semiconductor industry.

Fundamental Molecular Reaction Rates

The study of the reaction rates of the Mu atom provides for a uniquely sensitive measure of quantum mass effects in chemical reactivity, thereby providing a stringent test of any reaction rate theory describing the process. A good example is the recent study of the Mu+CO reaction, which, in comparison with its isotopic HCO analog, provided an important test of the rates, predicted by the "Isolated Resonance Model". The utility of Mu is due to the enhanced zero-point energy of MuCO, which reduces its density of resonant states by a factor of 30 when compared with HCO [J. Chem. Phys. 125, 014307-13 (2006) "Termolecular kinetics for the Mu+CO+M recombination reaction: A unique test of quantum rate theory"].

Designing Molecular Polymer Magnets

The intense interest in coordination polymer research can be attributed to the potential to design functional materials by utilizing judiciously chosen building blocks to generate specific structural motifs with targeted physical properties. The group headed by Leznoff (SFU) has been examining metal-cyanide coordination polymers, particularly those based on the dicyanoaurate building blocks. These materials have a wide variety of potential applications as magnetic sensors, birefringent components and gas storage matrices. Recently, a new series of isostructural polymers of the form $M(\mu\text{-}OH_2)_2[Au(CN)_2]_2$ (M = Cu, Ni, Co, Fe, Mn) has been prepared. The $M(\mu\text{-}OH_2)_2M$ aqua-bridged chain motif found in these polymers is unique in cyanometallate materials and is rare in aqueous coordination chemistry. An illustration of the structure, in an aqueous environment and subject to a muon beam, is illustrated in Figure 10. Such new structural motifs are significant as they form the basis for further modification of polymer properties. Utilizing mSR and squid magnetometry, the magnetic properties of these systems were studied as a function of transition-metal moment. A variety of magnetic behaviour, from ferromagnetic to spin-glass meta-magnetic, was found. These results were interpreted in light of the unprecedented structural motif, which features a $M(\mu\text{-}H_2O)_2M$ chain and $H_2O/Au(CN)_2$ hydrogen bonding and will assist in the future design of molecule-based magnetic materials [Chem. Eur. J., 2006, 12, 6748-6761 "A New Basic Motif in Cyanometallate Coordination Polymers: Structural and Magnetic Properties of $M(\mu\text{-}OH_2)_2[Au(CN)_2]_2$ (M = Cu, Ni)"].

Exotic Magnetism, Strongly Correlated (SC) Systems, Quantum Phase Transitions

The study of the interplay and competition between the ordering and disordering mechanism in strongly correlated systems at low temperatures is not

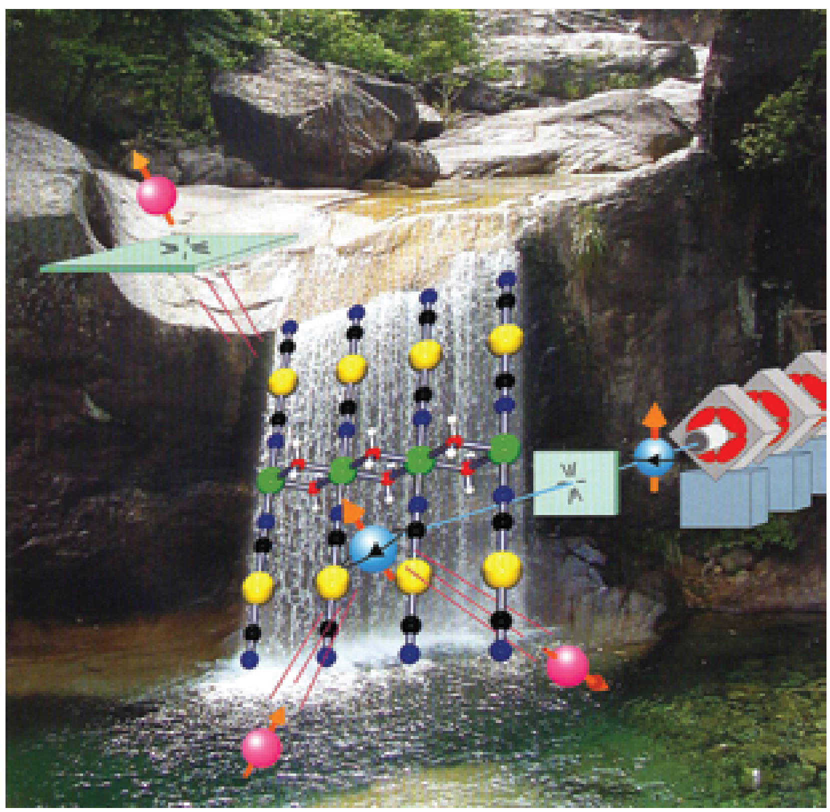


Figure 10: Watery bridges play the key role in a new basic structural motif exhibited by $M(\mu\text{-}OH_2)_2[Au(CN)_2]_2$ (M = Cu, Ni, Co, Fe, Mn); a 1D chain propagated by double aqua-bridges. These metal-water chains, shown here cascading down a rock-studded waterfall, aggregate through hydrogen bonds to form stacked ribbons in 3D.

limited to HTSC. Itinerant non-local magnetism, non-Fermi liquid (NFL) magnetism, heavy fermion systems with complex SC and magnetic properties, organic high-pressure SC/antiferromagnetic materials, systems in which geometrical frustration suppresses spin freezing at $T = 0$ due to degeneracy, all can be considered within this general theme. The study of such magnetic systems is the "natural" province of μSR. The muon's magnetic sensitivity, coupled with the capability to conduct experiments from zero to large applied (decoupling) fields, yields an enormously powerful tool to microscopically characterize the statics and dynamics of such complex magnetic behaviour. Only a small sample of what is traditionally the most heavily represented field of study in mSR can be alluded to in the following.

Quantum Phase Transitions, Criticality and Dynamics in Itinerant Heli/Ferromagnets

It has been demonstrated that in two itinerant ferromagnetic systems, MnSi and $Sr_{1-x}Ca_xRuO_3$, the quantum phase transition from the ferromagnetic state to the paramagnetic state is first order. The magnetic and non-magnetic phases compete for volume fraction near the transition where the ordered magnetic phase is driven to zero temperature, either by pressure (MnSi) or by substitution ($Sr_{1-x}Ca_xRuO_3$). The results suggest that many such quantum phase transitions are first-order, and that nature wants to avoid an actual quantum critical point [Nature Physics 3, 29-35 (2007) "Phase Separation and Suppression of Critical Dynamics at Quantum Transitions of Itinerant Magnets: MnSi and $(Sr_{1-x}Ca_x)RuO_3$"].

Magnetism in Non-Fermi-Liquid Metals

μSR experiments show that structural disorder is important in many non-Fermi-liquid (NFL) systems. Disorder-driven mechanisms for NFL behaviour are suggested by the observed broad and strongly temperature-dependent μSR (and NMR) linewidths in several NFL compounds and alloys. Local disorder-driven theories are, however, not capable of describing the time-field scaling seen in muon spin relaxation experiments, which suggest cooperative and critical spin fluctuations rather than a distribution of local fluctuation rates. A strong empirical correlation is established between electronic disorder and slow spin fluctuations in NFL materials [J. Phys.: Condens. Matter 16, S4479 (2004) "Disorder, Inhomogeneity and Spin Dynamics in f-electron Non-Fermi Liquid Systems"].

Heavy Fermion Systems & Unconventional (non-HT) Superconductivity

In strongly correlated electron systems, *s*-wave pairing is difficult to realize, and the study of anisotropic superconductivity is a central feature of such systems. Such systems can further sustain superconducting electron pairing, which are spin-singlet (even-parity) or spin-triplet (odd-parity), the unconventionality of which motivates their extensive study. $PrOs_4Sb_{12}$ is the first known unconventional heavy-fermion SC with a postulated pairing mechanism driven by quadrupole fluctuations. μSR experiments in this material indicate the presence of a small internal field in the SC state along with spin-triplet pairing, a first for a 4f-electron system [Phys. Rev. B 75 020510-1-4 (2007) "Spin-Triplet Superconductivity in $PrOs_4Sb_{12}$ Probed by Muon Knight Shift"].

A natural companion to such work is the investigation of the alloy series $Pr(Os_{1-x}Ru_x)_4Sb_{12}$ and $Pr_{1-y}La_yOs_4Sb_{12}$ in which anomalous dynamic muon spin relaxation has been identified as resulting from the interaction with the enhanced spin of the ^{141}Pr nuclei, which is itself caused by the Pr nuclear hyperfine interaction (Bleaney 1973) derived from a Van Vleck-like admixture of magnetic Pr^{3+} crystalline-electric-field-split excited states into the nonmagnetic singlet ground state. The results, therefore, indicate that the electronic spin fluctuations are not directly involved in the dynamic muon spin relaxation [Phys. Rev. B 76, 015427 (2007) "Muon Spin Relaxation and Hyperfine-Enhanced ^{141}Pr Nuclear Spin Dynamics in $Pr(Os,Ru)_4Sb_{12}$ and $(Pr,La)Os_4Sb_{12}$"].

The two-fluid model of heavy-fermion formation introduced by Nakatsuji *et al.* has been tested with experiments performed in the heavy fermion material $(Ce,La)_2IrIn_8$. Good agreement was found. A similar analysis of previous data in UBe_{13} was also successfully performed [J. Phys. Chem. Solids, to be published "Study of the Effects of Ce Dilution on the Development of the Heavy-Fermion State in $(Ce,La)_2IrIn_8$,"; J. Magn. Magn. Mat. 310, *e6* (2007) "Two-Fluid Model of Heavy Fermion Formation and μSR Knight Shift Measurements in UBe_{13}"].

In superconducting systems, *i.e.*, $CePt_3Si$, Li_2Pt_3B, Li_2Pd_3B, Uir, without unit cell inversion symmetry, Cooper pairs can have mixed parity, *i.e.*, with an admixture of spin-singlet and triplet amplitudes. Establishing the symmetry of the SC order parameter is therefore an important aspect in the understanding of SC phenomena in such low symmetry materials. μSR Knight shift studies in $CePt_3Si$ shows no temperature dependence below 1K and therefore do not substantiate the theoretical predictions for either spin-singlet or spin-triplet pairing for such systems [J. Phys. Soc. Japan 75, 180 (2006) Supplement "Magnetism and Superconductivity in $CePt_3Si$ Probed by Muon Spin Relaxation"].

SC Pair Breaking Mechanisms via Radiation-Induced Defects

The effects of radioactive pair breaking on the superconducting properties of $PuCoGa_5$ were investigated through μSR studies on a single crystal sample 25 days after preparation (*i.e.*, fresh) and then 400 days after preparation, allowing radiation damage to accumulate at room temperature. The measured temperature dependence and magnitude of the superfluid density in both samples was compared with a state-of-the-art theory performed as part of the collaboration. It was found that both the fresh and aged samples were consistent with *d*-wave pairing, but that the extreme suppression of the superfluid density in the aged sample is inconsistent with the usual Abrikosov-Gor'kov pair-breaking theory, in which the order parameter is averaged over the defect sites. It was concluded that the aged material is in the limit of a short superconducting coherence length material, consistent with an inhomogeneous order parameter that is suppressed in the region of the defects, similar to the cuprate superconductor YBCO. In order to explain the data, the work extended the theory of inhomogeneous pair breaking to finite temperatures [Phys. Rev. B 76, 064504 (2007) "Muon Spin Rotation Measurements of the Superfluid Density in Fresh and Aged Superconducting $PuCoGa_5$"; J. Phys. Soc. Japan 75, 14 (2006) Supplement "μSR studies of Pu metal and the Pu-based Superconductor $PuCoGa_5$"; J. Phys. Soc. Japan 75, 53 (2006) Supplement "Flux-Line Lattice State in $PuCoGa_5$ Probed by Muon Spin Rotation"].

Lack of Magnetic Ordering in Pu Metal

Experiments in two alloys of Pu metal (α-Pu and δ-Pu) unambiguously demonstrate that no ordered magnetism exists in these materials down to a temperature near 2 K. The results have contradicted previous theoretical predictions of ordered moments in δ-Pu, leading to new physics concerning the configuration of the 5 5-f electrons in Pu [Phys. Rev. B73 094453 (2006) “Limits for ordered magnetism in Pu from muon spin rotation spectroscopy”; J. Alloys and Compounds 444-445, 80-83, 2007 “The Search for Magnetic Order in δ-Pu Metal Using Muon Spin Relaxation”].

Multipole Ordering in *f*-electron Systems

Due to the compactness of the f shells, spin and orbital components of the f-electron are strongly coupled, and the relevant degrees of freedom are described by using multipole moments in the localized limit. Early research concentrated on quadrupolar ordering, but it is now recognized that higher multipole ordering can occur. μSR has been utilized to characterize these orderings in, for example, the intermetallic binary compound $PrPb_3$, which has a non-magnetic ground state with quadrupole and octupole degrees of freedom and is considered to quadrupole order at 0.4 K. ZF-μSR results suggest a possible contribution from an octupole magnetic moment but TF-μSR rules this out from symmetry arguments. The results therefore cannot be explained only by the multipole degrees of freedom in the cubic effective field (CEF) ground state and this suggests the importance of excited CEF states [J. Mag. Mag. Mater. 310 743-745 (2007) “Muon Knight Shift Measurements on $PrPb_3$ in Paraquadrupolar State”].

The multipole ordering of $SmRu_4P_{12}$ below its 16.5 K metal to insulator transition (T_{MI}) has also been studied indicating that a magnetic dipole and/or octupole ordering occurs at T_{MI}. Observed large amplitude fluctuations in the ordered state indicate low-energy excitations of the ordered octupole moment [J. Phys. Soc. Jpn. 76 (2007) 05370 “Evolution of Local Magnetic State in $SmRu_4P_{12}$ Pobed by Muon Spin Relaxation”].

Geometric Frustration and Surface Effects

In the study of competing ordering and disordering mechanisms, canonical system behaviour is provided by the existence of geometric frustration and spatial inhomogeneity of the underlying ordering interaction. The phenomena of macroscopic quantum ground state degeneracy, *i.e.*, T=0 fluctuating spin states, is a theoretically rich, controversial, and very active field of research which is exquisitely experimentally accessible using zero field μSR. This technique delivers detailed signatures of the static and dynamic nature of the low temperature states in the plethora of possibly co-existing ordered, disordered, and/or fluctuating degenerate states that may be present. The capability extends equally well to powder samples for which alternate techniques, like neutron diffraction, may not be available [J. Magn. Magn. Mater. 310, 1288 (2007) “Co-existence of long range order and spin fluctuation in a new geometric frustration series $M_2Cl(OH)_3$;” Phys. Rev. Lett. 97, 247204 (2006) “Coexisting ferromagnetic order and disorder in a uniform system of hydroxyhalide $Co_2(OH)_3Cl$;” Phys. Rev. Lett. 95, 057201 1-4 (2005) “Coexistence of long-range order and spin fluctuation in geometrically frustrated clinoatacamite $Cu_2Cl(OH)_3$;” Phys. Rev. B 72, 014468 1-8 (2005) “Finite-size effect

YASUTOMO UEMURA

Professor, Columbia University

Yasutomo (Tomo) Uemura obtained his M.Sc. and D.Sc. from the University of Tokyo, in 1979 and 1982, respectively. His thesis entitled "Muon Spin Relaxtion Studies of CuMn and AuFe Spin Glasses" was supervised by Prof. Yamazaki and the work performed at TRIUMF.

Professor Uemura has performed pioneering μSR experiments on various novel magnetic systems. His studies of spin glasses, and the development of phenomenological models for the relaxation functions in these systems, are now considered standards. More recently, he has performed work systemizing μSR penetration-depth data in a wide range of superconductors. He has profoundly demonstrated the value of μSR to the wider condensed matter physics communities. Much of this work has been carried out at TRIUMF.

Between 1983–88, Dr. Uemura worked at Brookhaven National Laboratory with the neutron scattering group, and, in 1988, he joined the Department of Physics at Columbia University.

Tomo is the recipient of the Packard Fellowship and is a Fellow of the American Physical Society. In 2005, he won the first Yamazaki Prize from the International Society for μSR. ■

on Néel temperature in antiferromagnetic nanoparticles"; Phys. Rev. B 69, 214415 (2004) "Random spin freezing in Ce_2MIn_8, M = Co, Rh, Ir heavy fermion materials"].

Magnetic Polarons

Semiconductor electronics to date is based on the quantum transport of charge carriers, while information storage relies mainly on the collective interactions (magnetism) of spins. The promise of new technologies for computational devices motivates the discipline of "spintronics," which proposes to exploit the strong mutual influence of magnetic and electrical properties found in magnetic semiconductors. The mechanism for such phenomena relies on the magnetic polaron, a microscopic cloud of magnetization composed of charge carriers and neighbouring magnetic ions that determines most of the electrical, magnetic, and optical properties of the material. In spite of the importance of this quasiparticle, it has eluded direct observation using more standard techniques. Using the μ^+ in EuS as both a donor centre and a local magnetic probe, the magnetic polaron has been generated and detected. Size and magnetic moment determinations have been made [Physica B 374-375, 430-432 (2006) "Room temperature ferromagnetism in III-V and II-IV-V_2 dilute magnetic semiconductors"].

Hydrogen–Materials Interactions

The applicability of μSR when muons chemically adopt the role of hydrogen is not limited to its use in chemistry but has equal utility in the study of many aspects of hydrogen-materials interactions. In semiconductors, muons exist in a variety of electronic states and site locations, which undergo complex cycles of charge state reactions and/or site migrations. In materials that can accommodate large volumes of hydrogen, muons characterize *in situ*, *i.e.*, as a function of H loading sites, mobility, and host interactions.

Semiconductors

H is a highly mobile, often unintentional, interstitial impurity in semiconductors. It rapidly forms complexes with, and passivates, other defects and dopants, resulting in dramatic modifications of the electrical and optical properties of the material. Its high diffusivity and reactivity greatly restrict direct measurements on the isolated states of H or the specifics of the passivation reaction. In keeping with the general theme underlying the surrogate utility of Mu, an understanding of the charged states of H can be indirectly obtained via μSR, which many consider to be the main source of information on isolated H in semiconductors.

Utilization of athermal excitation (optical, electric, and uniaxial stress) with μSR leads to powerful ways of studying Mu (H). Significant progress along these directions has been made in GaAs and Si [Physical Review B 72, 33201 (2005) "Nature of Charged Muonium in GaAs with an Applied Electric Field;" Physical Review B 73, 113202 (2006) "Demonstration of the effect of uniaxial stress on the electronic structure of bond-centred muonium in Si;" Physical Review B, submitted (2007) "Optically induced dynamics of muonium centre in Si studied via their precession signatures"].

The discovery of a Mu centre with a very small central hyperfine interaction in GaN suggests that H may also act as an effective shallow donor in this important semiconductor used for optoelectronics [Physical Review Letters 92, 135505 (2004) "Muonium as a shallow centre in GaN"].

The first detailed structural characterization for isolated H^+ or Mu^+ in any semiconductor with direct confirmation of bond-centre occupancy was conducted with TRIUMF [Physical Review Letters 95, 086404-1 to 4 (2005) "Detailed local structure of isolated positively charged muonium, as an analog for the hydrogen ion, in *p*-type GaAs"].

An extensive effort in a series of semiconductor materials (Si, Ge, GaAs, GaP, 6H-SiC, and SiGe alloys) systematically established the energy of the thermodynamic levels associated with a change in the equilibrium charge-state for the Mu analogs of isolated H. Utilization of RF and μwave muon resonance was critical to quantify the final states. The accumulated data support the theoretical claim in that the midpoint between the acceptor and donor levels for the Mu (H) lies at a constant energy independent of host, except that the experimental value is 0.5 eV above the prediction [Physical Review B 76, 045221_1-5 (2007) "Donor and Acceptor Energies for Muonium in GaAs" is a typical work in the series of 4 publications].

Hydrogen Storage Materials

Complex hydrides, like the alanate $NaAlH_4$, are one of the most promising hydrogen storage materials to have emerged in recent years. Until recently, slow-cycling kinetics precluded these from consideration as practical onboard hydrogen carriers until Bogdanović's discovery of the remarkable acceleration effects of transition metal dopants, thereby opening the door for new classes of potential H-storage materials. In a seminal work, Kadono and Jensen *et al.* have shown the utility of implanted muons to emulate the Ti catalyzed H dynamics in this material, thereby allowing μSR a definitive role in what will soon be a very active field of research [Phys. Rev. Lett. 100, 026401 (2008) "Hydrogen Bonding in Sodium Alanate: A Muon Spin Rotation Study"].

Industrial Basic Research for Automobile Technology

Some layered cobalt dioxides A_xCoO_2 (A = Li, Na and K) exhibit excellent thermoelectric (TE) properties: they can be used to convert heat directly into electrical power. This unusual property attracted the interest of Jun Sugiyama of Toyota Central R&D Labs to spearhead a vigorous research program at the TRIUMF CMMS. Sugiyama's contention is that the unconventional magnetic properties of Na_xCoO_2 (NCO) are critical to understand its thermoelectric efficiency, and that the positive muon's unique sensitivity as a probe is key to understanding these magnetic properties. Over the past few years, this strategy has paid off, as a number of remarkable properties of NCO have been revealed: with $x \sim 0.75$, it is an antiferromagnet (AF); with $x \sim 0.7$, NCO is a superb TE; with $x = 0.5$ it is an AF with a charge-ordering transition; and with $x = 0.35$ and absorbed water, it is a superconductor. Sugiyama's CMMS research defines the leading edge of worldwide efforts to understand the phase diagram of NCO and its related compounds with A = Li and K. All are examples of highly correlated electron systems, akin to the HTc-SC cuprates. Recently, this group's CMMS based research initiative has broadened to encompass hydrogen storage materials, with their well-known impact for modern environmental issues [Phys. Rev. Lett. 92, 017602 (2004) "Dome-shaped magnetic phase diagram of thermoelectric layered cobaltites;" Phys. Rev. Lett. 96, 037206 (2006) "Static magnetic order in metallic $K_0\overline{H}_{49}CoO_2$;" Phys. Rev. Lett. 96, 197206 (2004) "Evidence of two-dimensionality in quasi-one-dimensional cobalt oxides;" Phys. Rev. Lett. 96, 197206 (2004) "Magnetic phase diagram of layered cobalt dioxide Li_xCoO_2" plus 12 additional full journal publications 2003-2007].

β-NMQR: Probing the Interface

The TRIUMF low-energy ISAC-I facility produces and delivers an intense (~10^7/s) beam of highly polarized variable energy 28 keV $^8Li^+$ nuclei to the two platforms dedicated for condensed matter physics. The capability to decelerate the beam just prior to implantation allows the ^{8}Li nuclei to be ranged into surfaces over a depth profile from 5–400 nm. The combination of high nuclear polarization, 0.84 s half-life, 0.63 kHz/G magnetic moment, spin 2 with a +32 mb electric quadrupole moment; and RF irradiation capabilities of up to 50 MHz dictate that ^{8}Li magnetic and quadrupole resonances will be directly sensitive to field fluctuations within the range of 0.1–10^5 Hz coupled with capability to carry out measurement in a magnetic field of up to 9 Tesla.

Over the past several years, the art of β-NMQR has been significantly refined at TRIUMF. Capabilities to control the depth of implantation allow for selective layer implantation where the ^{8}Li nuclei may be placed in a benign host layer adjacent to the material of interest. RF pulse shaping and random frequency irradiation technology allow for excitation of discrete slices of the spectrum and the elimination of the spectral sweep distortions. The availability of both zero- or low-field β-NQR, and high-field β-NMR, allows for the flexibility to utilize or mitigate the effects of local fluctuating electric fields in non-cubic sites. These and future capabilities, *i.e.*, transverse counters to allow spin echo measurements, bode well for the vigour of the program.

Monolayer Molecular Magnets

Monodispersed, individually addressable nanoscale magnets are a requirement for technological applications (information storage, quantum computing). With the recent advent of monolayer deposition of single-molecule magnets (SMM), such systems become feasible. Low temperature quantum effects, *i.e.*, magnetization tunnelling, phase interference, and quantum coherence, dramatically affect macroscopic magnetic properties. The small quantity of magnetic material present in a monolayer is well suited for study by β-NMR techniques [Nano Letters 7, 1551 (2007) "Local Magnetic Properties of a Monolayer of Mn_{12} Single Molecule Magnets"].

Vortex Core Size in Type-II Superconductor

Understanding the size and dynamics of type-II superconductor vortex lattices is a central theme in not only in HTc material but also for normal metal type-II materials. This work examines the vortex size near the surface of the well-studied, multi-band $NbSe_2$ to find that at low fields the vortex cores are anomalously large [Phys. Rev. Lett. 98, 167001 (2007) "Magnetic-field Effects on the Size of Vortices below the Surface of $NbSe_2$"].

Thin-Metal Films

The β-NMR study of isolated ^{8}Li on the surface of nearly ferromagnetic Pd indicates a large negative shift, which scales with the bulk susceptibility above 100K. Below this temperature effects attributed to the Li defect are observed [Phys. Rev. Lett. 98, 047601 (2007) "ß-NMR of isolated lithium in nearly ferromagnetic palladium"].

Knight shift and relaxation data in 5 keV depth-controlled $^{8}Li^{+}$ in 50nm of Ag on $SrTiO_3$ using a 5 keV show a thermally activated transition from an octahedral (O) interstitial to a substitutional (S) site at 100 K. Similar work using 30 keV $^{8}Li^{+}$ in 100 nm Cu film on MgO indicate both O and S are occupied at low temperature with a similar transition to S above 100 K. In both materials, high temperatures data, *i.e.*, 100% S occupancy, are consistent with the Korringa law for a simple metal [Phys. Rev. Lett. 93, 157601 (2004) "Beta detected NMR of Implanted 8Li in a Thin Silver Film;" Phys. Rev. B. 75, 073405 (2007) "ß-NMR of isolated $^{8}Li^{+}$ implanted into a thin copper film"].

Phase Transition Probe

Structural phase transitions near a surface invariably exhibit broken symmetry in the underlying driving mechanism. As such it is expected that the onset and nature of the transition near the surface will vary from that found in the bulk. The zero field β-NQR study of ^{8}Li near the surface of the well-known $SrTiO_3$ second-order structural phase transition presents a textbook case of the utility of this probe. At temperature >150 K, the three ^{8}L sites have cubic symmetry and hence no efg (electric field gradient) is present with consequently no spin precession and no strong loss of polarization. As the temperature is lowered and the lattice distortion sets in, two of the three sites develop an efg, and the resulting spin precession destroys that fraction of the polarization. The resulting loss of polarization is closely related to the distortion's temperature dependent distribution profile away from the surface, a distribution probed by the depth profile of the implanted beam. These measurements also emphasize that the rather small quadrupole moment of ^{8}Li is not a barrier to using it for β-NQR studies [Phys. Rev. Lett. 96, 147601 (2006) "Near-Surface Structural Phase Transition of $SrTiO_3$ Studied with Zero-Field ß-Detected Nuclear Spin Relaxation and Resonance"].

Nuclear Quantum Electrodynamics

Using the unique capacity of the M9A decay channel to provide μ^- with substantial spin polarization, spin precession measurements were carried out on series of muonic nuclei ranging from ^{12}C to ^{207}Pb in fields as high as 2.4 T. These fields, more than twice the previous standard, facilitated the measurement of the relativistic shifts of μ^- g-factors in very high Coulomb fields (*i.e.*, bound to nuclei of intermediate and high atomic number Z) to unprecedented precision. These results promise a new testing ground for quantum electrodynamics under extreme conditions [Phys. Rev. A Brief Rep. 72, 022504-022507 (2005) "Relativistic shifts of bound negative muon precession frequencies"].

Partners

In Canada: AECL Chalk River, Brock University, Dalhousie University, McMaster University, Mount Allison University, Saint Mary's University, Simon Fraser University, Trent University, University of Alberta, University of British Columbia, University of Saskatchewan, University of Sherbrooke, University of Toronto, and the University of Waterloo.

International Partners: Argentina (2), Austria (1), France (1), Germany (5), Israel (1), Italy (1), Japan (23); Portugal (1), Russia (3), Scotland (1), Sweden (1), Switzerland (2), Turkey (1), United Kingdom (1), and the United States (25)

TRIUMF's Role

The impact of the CMMS program at TRIUMF is now thoroughly distributed over a variety of pure and applied fields of research. The program has hosted cutting-edge and unique contributions into the underlying aspects of high temperature superconductivity, reactions relevant to environmental and industrial processes, new technological materials, nano-scale interface physics while providing fundamental data to test theories ranging from chemical reaction rates to quantum phase transitions, and even quantum electrodynamics. What was once an esoteric and specialized technique is now a tool sought out by an ever-increasing community of users from across disciplinary boundaries.

In recognition of this fact, TRIUMF, CFI and BCKDF have funded an expansion of CMMS infrastructure to facilitate and more readily distribute the research capabilities supported by this program.

To this end TRIUMF's most notable CMMS infrastructure initiatives have been the development of the nascent β-NMQR experimental platforms and the use and redevelopment of its M9A channel into one dedicated solely for μSR. This latter contribution was no doubt a key indicator leading to the M20 upgrade award by CFI/BCKDF. In addition to such very visible "large scale" measures, TRIUMF's tacit support for the program encompasses the provision of outstanding technical facilities, *i.e.*, engineering, machine shop and detector fabrication resources, budget support for CMMS facility R&D and, more recently, a full-time facility scientist position.

In summary, TRIUMF, CFI and BCKDF have funded an expansion of CMMS infrastructure to facilitate and more readily distribute the research capabilities supported by this program. Together with NSERC, which clearly continues its strong commitment to CMMS involved research groups, this program is poised to further expand its impact on the international Molecular and Materials Science community.

4.2.3.2

Proton Irradiation Effects in Advanced Semiconductor Technologies

Introduction

Energetic protons in space can cause the degradation of semiconductor devices by several mechanisms, including total dose effects and single-event effects (SEEs). Total dose effects are due to the buildup of charge in oxides induced by the holes and electrons generated as protons lose energy by ionization. Typical effects of this charge buildup in integrated circuits (ICs) are large increases in leakage current and functional failure. Total dose effects are often permanent. SEEs occur as a single proton impinges on a material, generating secondary particles. These secondary particles can deposit sufficient energy per unit depth by ionization to change the state of circuit nodes in a memory circuit and cause false information to be stored as a single-event upset (SEU). A SEU can be corrected by reprogramming the circuit into its correct logic state, but if the error rate is too large, it can result in performance degradation of a system and potentially mission failure. Another class of SEEs, which is not correctable by reprogramming, is termed a hard error. Hard errors include single-event latchups (SELs) and gate ruptures (SEGRs). If a hard error occurs, a circuit element may suffer permanent physical damage.

As IC technology advances, devices become more vulnerable to SEEs. To ensure space system functionality and survivability, it is essential that reliable hardness assurance test protocols and radiation-hardened device technologies are available. Both of these require a sound understanding of the basic mechanisms for proton-induced radiation effects.

Future work will continue to explore new issues as semiconductor technologies advance. For example, IC dimensions are becoming so small that there is now evidence that protons can induce SEEs by direct ionization, which can greatly increase SEU error rates and could make traditional hardening approaches obsolete. New technologies (both electronic and optoelectronic) are also introducing new failure mechanisms. These issues greatly exacerbate problems in developing reliable hardness test protocols and will require continued work to identify the mechanisms for proton radiation effects in these new and advanced technologies.

Results and Progress

We have made significant advances in the understanding of the mechanisms for proton radiation effects in numerous areas. For example, by combining our work at TRIUMF with high-energy transport calculations, we showed that proton interactions with the high-Z materials used in advanced IC technologies could generate secondary particles that can deposit high levels of charge, making some ICs more prone to SEL. The cross section for these interactions increases at high proton energies. Because of this, we were able to demonstrate the importance of performing SEL proton testing at high proton energies. Other work showed that the circuit designs used for some advanced ICs can lead to considerably higher SEU error rates during space flight due to the effects of total dose exposure.

Advances were also made in the basic understanding of charge collection and propagation characteristics of transient signals generated by secondary particles created by proton/material interactions. These results were correlated to device technology features, thereby providing insight that can be used to fabricate improved radiation-hardened devices.

Based on these results and other results at TRIUMF, we have written a new comprehensive hardness assurance test procedure for proton testing for SEE based on the mechanisms for proton-induced SEE. In other work, we determined that secondary particles generated by proton/silicon interactions can deposit high levels of localized charge in the oxides of power MOSFETs (known as microdose effects), leading to device degradation at extremely low total dose levels. This result has important implications for power MOSFET operation in space environments.

In the area of optoelectronics, we were able to identify point defect mechanisms in optical fibres under proton irradiation. The importance of this research is indicated by the fact these works have led to two Outstanding Paper Awards and two Meritorious Paper Awards at the Nuclear and Space Radiation Effects Conference, out of ~100 papers presented each year.

Partners

International Partners: France (1) and the United States (1).

TRIUMF's Role

The TRIUMF spectrum covers almost the entire energy spectrum of trapped protons encountered in near-earth space orbits, and therefore it is an ideal facility for exhaustively characterizing semiconductor devices for space applications. No facility in the United States covers the wide proton energy spectrum covered by TRIUMF. Research Scientist Ewart Blackmore has also provided significant technical support enabling the success of these experiments.

4.2.4

Accelerator Physics

The TRIUMF Accelerator Research Group was formed in October 2004 and given the mandate to provide operational support for the cyclotrons and ISAC, to develop beam physics for higher intensity in the cyclotron, to develop primary and secondary ISAC beam line optics and optics for spectrometers, to undertake beam studies for external projects, and to develop new initiatives such as fixed field alternating gradient (FFAG) accelerators and beta beams.

The Group ensures that the beams required to satisfy the demands of the TRIUMF science program are delivered. The priorities of the Group can be divided into three broad classes: (1) support for operation and development of TRIUMF accelerators and beam lines: (2) support for approved collaborations with other accelerator-based laboratories: and, (3) research in theoretical aspects of accelerator physics. One important activity not captured in this section is the ongoing support for operation. This support includes help with tuning accelerators, beam lines and the ISAC mass separator, development of software to facilitate tuning by operations, and training operators to understand and operate beam line and accelerator components.

The Accelerator Research Group consists of the following scientists: R.A. Baartman, theory, optics, and collective effects; M.K. Craddock, accelerator design; J. Doornbos, secondary channel design; F.W. Jones, multi-particle simulations and parallel computing; S.R. Koscielniak, theory, novel accelerators, and collective effects; Y.-N. Rao, cyclotron and beam line modeling; and L.W. Ro, cyclotron modeling, development, and choppers. Figure 1 summarizes the group's activities.

TRIUMF activities in the operation and development of accelerators and beam lines are discussed next.

High Current Beam Development for TRIUMF

Introduction

TRIUMF is pursuing a high current beam development program aimed at increasing the extracted current from its pre-ISAC level of about 200 μA to 300-400 μA. This level is required to operate the ISAC beam lines at maximum intensity without having to lower the current to non-ISAC users.

Results and Progress

Since 2000, a large fraction of TRIUMF's one-day-per-month beam development shifts has been devoted to using TRIUMF's low- and high-energy probes to measure beam quality and to develop high current/low spill tunes. In 2005, centre region re-alignment work, and the installation of a water-cooled beam stopper on the first turn to prevent overheating of the centre region components, enabled TRIUMF to extract, without incident, an average current of 298 μA for 2.4 hours. This was followed by a week of beam production in 2006 during which 270 μA was extracted without incident. Although the existing beam lines only have a current capacity of 300 μA, in 2003 a peak current of 420 μA at 25 % duty cycle with good transmission was extracted, thus confirming that 400 μA is within the TRIUMF cyclotron's space-charge limit.

Although TRIUMF's high-current ion source I3, which has been dormant for many years, will resume operation in 2009, users won't be able to extract average currents greater than 300 μA until there is more beam dump capacity, improved centre region/ISIS cooling, and perhaps an ISIS vacuum upgrade. In the meantime, 300 μA will be enough to satisfy all of the existing users' requirements, and TRIUMF will continue improving this tune and studying the 400 μA tune at reduced duty cycle.

Release of ^{7}Be from Stripping Foils

Introduction

The recent improvement in cyclotron beam quality has resulted in a denser beam on the carbon foil used to strip the H^- ions and extract them from the cyclotron. As a result, at the highest extracted current the foil is sufficiently hot that the ^{7}Be created by nuclear interactions is released rather than remaining conveniently contained in the foil. This release adds to cleanup time during shutdown. We assigned the task of modeling the heating to a visitor from the Paul Scherrer Institut. The results are clear, but need testing. The testing is ongoing and the activation near the stripper is measured during each shutdown.

Results and Progress

Most of the foil heating is due to the stripped 270 keV electrons. These travel in spirals along the magnetic field lines, repeatedly traveling through the foil until either they are lost or completely lose their energy through straggling. A new result is that the multiple Coulomb scattering during each foil passage makes thinner foils preferred because, although the scattering angle is smaller for thinner foils, it is a square root effect, not a linear one. This means that for thinner foils the probability is higher that the electron scatters off the foil before it ranges out. The standard foil has been 5 mg/cm^2. We are now testing foils down to 1 mg/cm^2, and looking for lower activation levels when the lid is raised during shutdown.

Project	Start - End	Principal	Collaborating Laboratories
High current beam development for TRIUMF	2000 - 2013	Root/Baartman/Rao	
Release of ^{7}Be from stripping foils	2007 - 2009	Baartman/Rao	
New spiral inflector for TRIUMF	2007 - 2009	Root	
Redesign of muon beam lines at TRIUMF	2006 - 2010	Doornbos	
TRIUMF cyclotron extraction and beam line optics	2004 - 2005	Rao/Baartman	
TRIUMF injection line optics	2003 - 2008	Baartman/Rao	
Cyclotron computer code development	2003 - 2007	Rao	CIAE, Thales, D-Pace
Radioactive ion storage ring	2003 - 2003	Craddock	
Large scale simulations for the CERN LHC using distributed computing	2005 - 2007	Kaltchev	CERN
LHC collimation system	1997 - 2004	Kaltchev	CERN
LHC beam-beam effects and parallel codes	1997 - 2008	Jones	CERN
EURISOL betabeam	2005 - 2008+	Jones	CERN
T2K experiment at J-PARC	2000 - 2005	Doornbos	KEK, JAERI
Charged kaon beams at J-PARC	2005 - 2007	Doornbos	KEK, JAERI
Pellet-beam interactions at HESR	2003 - 2004	Rao	GSI
Microbunching for KOPIO	1997 - 2005	Koscielniak	BNL
Impedance and collective-effects at JPARC	2002 - 2004	Koscielniak	KEK, JAERI
GEANT4	2003 - 2008+	Jones	Int'l GEANT4 Collaboration
Development and support activities for ACCSIM	1986 - 2008+	Jones	CERN, LANL, KEK, JAERI, BNL, ORNL
Space charge simulation codes	2003 - 2005	Jones	
60 GeV/c RF separated kaon beam	2006 - 2006	Doornbos	FNAL, BNL, CERN
FFAG studies	2003 - 2009+	Koscielniak	Int'l Muon Collider Collaboration
Intensity limitations in cyclotrons	2006 - 2008	Baartman	
Fringe fields	2007 - 2009+	Baartman	
Nonlinear transfer maps for charged particle beam transport	2004 - 2008+	Kaltchev	University of Maryland

Figure 1: Activities of the TRIUMF Accelerator Research Group showing the extensive and international research program.

A New Spiral Inflector for TRIUMF

Introduction

TRIUMF's spiral inflector bends the 300 keV H^- axially injected beam coming from the ion source onto the median plane and centres the beam for injection into the magnet dees. It consists of a pair of 12 in. high spiral-shaped electrodes with a 1 in. gap operating with voltages of 28.7 keV. Although the existing inflector has performed well for over 30 years, the new one will allow TRIUMF to have the old one as a spare, be better engineered mechanically, and perform better because its design will be based on improved magnetic field measurements. As well, with modern CNC machining techniques, construction of the spares is cost effective. This work started in 2007, and installation is planned for the beginning of 2009.

Results and Progress

TRIUMF's inflector is a non-analytic version of Belmont and Pabot's original Grenoble design. It was designed using AXORB, a TRIUMF computer code, which used a modified version of Belmont and Pabot's electric field and took into account TRIUMF's magnetic field, which varies between 0.5 kG and 3 kG along the inflector's central trajectory.

Due to time constraints, the calculations for the existing TRIUMF inflector were based on magnetic field measurements made on a 10:1 scale model of the magnet. After the inflector was constructed, more accurate axial magnetic field measurements were made on the main magnet. In early 2007, AXORB, which had been dormant for 30 years, was re-written so that it would run on TRIUMF's newer computers. Improved electrode shapes were calculated using the main magnet measurements. The improved electrode shape should increase the spiral inflector's acceptance by 5 to 10%.

The inflector electrodes are routinely removed for maintenance. Mechanical engineering studies are being carried out and are aimed at improving the electrode mounts so that the required mechanical tolerances can more easily be achieved when the electrodes are re-installed after maintenance.

Re-design of Muon Beam Lines at TRIUMF

Introduction

The new M9A and M20 are both surface muon beam lines for μSR studies. Surface muons are so-called because the muons result from the decay of pions that have stopped near the surface edge of the pion production target. Only positive muons can be obtained in this way. The maximum momentum is 29.8 MeV/c. The muon polarization is almost 100% longitudinally. They have a well-defined source location unlike muons from the decay of pions in flight. This makes it possible to obtain a small beam spot with high luminosity at the end of the beam.

In 2006 and 2007, the Group completed new designs for M9A and M20 and designed an extension for M13. The M13 extension will be installed in 2008, M9A in 2009, and M20 in 2010.

Results and Progress

The newly designed M9A and M20 beam lines will be equipped with spin rotators, basically crossed electric and magnetic fields, which can rotate the spin in a direction transverse to the direction of motion. In M9A, the spin will be horizontally transverse. In M20, the spin will be vertically transverse. The spin rotator systems are achromatic, which makes a high momentum acceptance possible. The achromaticity is achieved by using two spin rotators, each rotating the spin through 45° and placing a quadrupole triplet between them. At present, the TRIUMF beam line M15 is the only beam line in the world that has this feature.

An important aspect of both the M9A and M20 beam lines is the Muons On REquest (MORE) feature invented at TRIUMF. As soon as a muon enters the experimental target, the beam is switched away by using a fast electrostatic kicker. In M9A, the beam is discarded. In the case of M20, the beam is directed to another leg. This switching means that two experiments can run simultaneously on M20. The optics in both beams have been designed to give a small beam spot and a high luminosity, which is important because advanced modern experiments are done on small samples, of the order of 1.0 or 2.0 cm diameter. Several slit arrangements in both beams make it possible to limit the background effects.

The extension of M13 was proposed by the Accelerator Research Group to decrease the background of positrons in the PIENU experiment, which intends to very accurately measure the decay of a positive pion into a positron and a neutrino. The extension consists of a 70º bending magnet and a quadrupole triplet.

Extraction of the Cyclotron Beam and Beam Line Optics

Introduction

Because extraction is by H^- stripping, the TRIUMF cyclotron is able to supply multiple beams continuously for multiple experiments. Typically, a 50 kW beam is extracted into a beam line and the beam can be focused to a spot smaller than 2 mm diameter. This gives a sufficiently high energy density to damage the carefully prepared targets. It is therefore essential to accurately characterize the extracted beam and its spot size to avoid target damage.

Work on improving the agreement between calculated and measured beam sizes began at the end of 2004, because beam power on ISAC targets had reached 20 kW and management of the size of the beam spot became essential. New tunes were developed and successfully used in 2005. At the present time, not all aspects of the various modes of operation are understood down to the 1 part in 10^5 level necessary for running without the spill monitors in beam line 2A tripping the beam off. The Group continues to make the refinements needed for the new mode of operation, where the beam is swept across the ISAC target with AC steering magnets. A good understanding is also needed so that we can optimize the design of the new beam line 4.

Results and Progress

In 2004, because of target damage from over-dense beams, the Group re-investigated the coding of the equations of motion in the computer program used to track particles from the stripping foil to the beam line. We discovered an error that had existed for 30 years. As a result of this work, for the first time, we have an accurate description of these beam lines. We have obtained agreement of better than 15% everywhere between calculated and measured beam sizes in the beam lines, so we can confidently change the beam spot size to what is required by the target designers. We are currently using GEANT4 to try to understand the beam distribution halo to the level of 10 ppm of the core.

TRIUMF Injection Line Optics

Introduction

The space-charge effect is important in the TRIUMF injection line because it strongly affects the fraction of beam that can be accepted by the cyclotron centre region as well as the amount of beam halos that can possibly spill in the cyclotron and beam lines. Research in this area will be used to help design replacement optics needed for future upgrades to > 400 μA extracted from the cyclotron. A series of experiments was performed in 2003–2004 to measure the beam emittance and space-charge neutralization level. Further experiments will be performed in 2008.

Results and Progress

To achieve improved understanding and also to allow accurate modeling of the 300 keV injection line, we measured important beam parameters such as space-charge neutralization and emittance. This work prepared us for future development and exploration of the injection line for high-current operation, which aims to reach an extracted current of > 400 μA from the cyclotron.

Using software developed at TRIUMF, the Group performed transport calculations in six-dimensional phase space with the linear space-charge force included. Good agreement was achieved between the measured and calculated transverse sizes of the 300 keV beam in the injection line. The emittance is ~0.13 om (normalized) at a dc current of 575 μA. Matching to the periodic sections appears good in the horizontal section, but not good in the vertical section where there are fewer diagnostics and beam-size restraining collimators. With bunching, the local current reaches >3 mA at cyclotron injection; the space-charge effect becomes increasingly dominant as the beam travels along the injection line. For injection line currents above 500 μA, the fraction of beam that can be accepted by the cyclotron centre region begins to fall despite adjustments to the existing bunchers. This could be corrected by introducing an additional first harmonic buncher in the vertical section at ~2.5 m upstream of the inflector. Or, this effect could be partially compensated by increasing the RF dee voltage, thereby increasing the longitudinal cyclotron phase acceptance. Alternatively, injection with dc beam current 5 mA is contemplated.

The choice of the final configuration for 450 μA extracted will be made based on this research and will largely depend on reliability, reproducibility, and stability issues, including the ion source.

Cyclotron Computer Code Development

Introduction

Cyclotron FFAG orbit dynamics are different in nature than those of most other accelerators because the model of separated elements (drifts, dipoles, focusing, and so on) is not a good one, and because there is no given reference orbit. Instead, particles must be tracked through varying fields and reference orbits found for each energy by an iterative technique.

From 2003 to 2005, updates were implemented in the orbit codes porting them from obsolete operating systems to the Linux OS. In 2007, modifications were made to enable FFAG lattice studies.

Results and Progress

Over the years, TRIUMF developed a series of computer codes for cyclotron orbit dynamics research. This is one of the important contributions of TRIUMF to the cyclotron development. These codes are essential for cyclotron design and research and maintaining optimal beam tune. From time to time, TRIUMF receives requests from other laboratories to use these codes for the design of new machines. Maintaining these codes is therefore an ongoing activity

Partners

In Canada: MDS-Nordion, D-Pace.

Internatioal Partners: Chinese Institute of Atomic Energy, Thales (France).

TRIUMF's Role

TRIUMF played a leading role in the collaborations with CIAE and D-Pace/Thales in providing intellectual guidance to the cyclotron design and development: to the understanding and optimization of the magnetic field; to the approach of beam probe design; to the consideration and modeling of extraction optics.

Radioactive Ion Storage Ring

Introduction

The Accelerator Research Group has studied the design of a storage ring to be fed by radioactive ions from ISAC-II. The low intensities of beams of unstable isotopes make it vital to use them efficiently. Their collection in a storage ring would open up a number of possibilities: 40,000 times higher beam intensities (depending on half-lives and loss mechanisms in the ring), enabling better suppression of background and more accurate measurement of isotopic and ionic properties; higher luminosities, by the use of beam cooling and internal targets; acceleration to higher energies; quasi-simultaneous operation with fixed-target experiments; and colliding- or merging-beam experiments with protons, electrons, muons, etc.

This work was carried out in 2003 but discontinued when it became apparent that TRIUMF's highest priority for RI beam development was the provision of additional targets and beams. When these immediate aims are accomplished, however, a storage ring remains a potentially powerful tool for TRIUMF's further development.

Results and Progress

There were two main aspects to this study: estimating by what factor the ISAC beam intensity could be amplified by storage, and designing the magnet lattice for the ring itself. For injection of ions with short lifetimes, it was clear that stripping is preferable to multi-turn stacking. Stripping also increases the ions' average charge state, thus lowering the magnet strengths required in the ring, and reduces the fractional width of the charge-state distribution, thus enabling a greater fraction of the beam to be contained. A stripping foil also presents an obstacle to the circulating ions, but it was found that "painting" the incoming beam could reduce the frequency of interceptions to an acceptable once in 400 turns. Moreover, it was found that the ion losses per foil traversal could be kept to 1% provided the charge/momentum acceptance of the ring was at least ~4%. With continuous injection, the stored beam intensity should be maintainable at 40,000 times that delivered by ISAC. Alternatively, pulsed operation could provide a 25,000 times improvement while allowing the beam to be shared with ISAC-I or ISAC-II.

To obtain a ring with large charge/momentum acceptance, low dispersion and low horizontal beta function, a double-bend achromat lattice was chosen. The ring is four-sided, with a diameter of 15 m and the long straights assigned to injection, cooling, acceleration and experiment (or extraction). With a bending power of 2.6 T-m, light ions such as carbon can be accelerated to 80 MeV/u and heavier ones such as the rare earths to 35 MeV/u. Initial tracking studies showed good behaviour for charge or momentum excursions up to about 4%, as required.

TRIUMF's collaborations with other laboratories on accelerator science and technology projects are presented here.

Large-Scale Simulations for the CERN LHC Using Distributed Computing

Introduction

In the final design phase of the Large Hadron Collider (LHC), it will be necessary to verify the long-term stability, particularly in the presence of the beam-beam forces that will eventually limit the LHC performance. Due to the very non-linear nature of motion in the LHC, only a detailed numerical simulation can reliably predict the long-term behaviour of the particles.

In 2004, the CERN IT Department developed the LHC@home system based on the Berkeley Open Infrastructure for Network Computing (BOINC). This system provided access to more than 60,000 home computers, donated by more than 30,000 volunteers worldwide. The computing power provided by LHC@home allows experimenters to evaluate the parameter space with maximum accuracy and to find possible problems, which could be missed by a less detailed analysis.

Results and Progress

The Accelerator Research Group extended the CERN-based automatic procedures for launching tracking jobs with our own tools that automatically process large volumes of tracking data in order to extract information about long-term stability such as dynamic aperture and border of chaos. In 2005–2006, tracking jobs launched from TRIUMF, totalling an estimated 6 million CPU hours, were used by CERN to make the final choice of the LHC crossing scheme, *i.e.*, the plane in which the two beams collide and the LHC working point on the tune diagram, and also to analyze the effect of multipole errors in the interaction point (IP) quadrupoles. In 2007, a similar study was performed, but in conditions corresponding to LHC start-up at injection energy. There is a strong request from CERN for TRIUMF to continue the BOINC-tracking studies.

Partners

International Partners: CERN, Queen Mary University of London, Niels Bohr Institute and University of Copenhagen, and Helsinki Institute of Physics.

TRIUMF's Role

Since late 2005, because of our knowledge of the LHC lattice optics, optical databases, and tracking codes, nearly all BOINC-tracking runs have been launched from TRIUMF, following directions for machine studies coordinated with CERN. During 2005–2006, these runs led to the present set of LHC parameters and enabled our CERN colleagues to test additional configurations and to define strategies for the start of the collider

LHC Collimation System

Introduction

Even a tiny release of the energy stored in the LHC beam would lead to a serious damage of equipment, hence the importance of the system of collimators whose function is to cut off the amplitudes of the circulating particles at 8 sigma at injection energy and 6 sigma at collision. TRIUMF has played an important role in the design of lattice optics for the betatron- and momentum-collimation sections of the LHC and in the optimization of collimator parameters. Work on collimation continued in 2003; since then a new constraint—impedance—was introduced. The collimation will be first used during LHC commissioning in May 2008.

Results and Progress

The main objectives were to maximize the beam size at the collimators (and so decrease their contribution to the ring impedance) and generate additional space for longer collimators.

By following the original design approach, by the end of 2003 a new arrangement of collimators was found and implemented in the LHC sequence. The final solution preserved the number of collimators, warm quadrupoles and maximum voltage of the power supplies. It provided a wider domain of betatron phases at intermediate locations, making it possible to position the collimators where the beam envelope is larger. A good cleaning efficiency was simultaneously maintained.

Partner

CERN.

TRIUMF's Role

For a number of years, in an extensive collaboration with the LHC team, TRIUMF has been responsible for the software that optimizes collimator parameters and for the design and maintenance of the optics (quadrupole parameters) of the betatron- and momentum-collimation insertions.

LHC Beam-Beam Effects and Parallel Codes

Introduction

As part of the Canadian contribution to the LHC, the Accelerator Group has collaborated with CERN on studies of coherent beam-beam effects, which pose limitations to the performance of existing colliders and will play a role in the operation and performance of the LHC.

The first collaborations occurred prior to 2003 and applied TRIUMF-developed space-charge techniques to a prototype beam-beam code. The first 3D parallel code was developed in 2003–2004. The parallel multi-bunch multi-IP code was developed in 2006–2007, with further work on fast-multipole field computation to be done in 2008.

Results and Progress

Using routines developed by TRIUMF originally for space-charge simulation, TRIUMF and CERN have co-developed the first application of fast multipole methods to beam-beam effects. The availability of parallel computing facilities at the University of Alberta, and later at the Westgrid facilities in Calgary and Vancouver, prompted the collaboration to extend this 2D code to 3D by implementing parallel algorithms to treat the interactions of longitudinal bunch segments as they approach and leave the crossing point of the counter-rotating beams in the LHC. The resulting code BEAMX was among the first of its type to be able to exhibit and estimate longitudinal beam-beam effects such as the crossing angle and the frequency sidebands due to synchrotron motion.

More recently, further advances in the high-speed communications architecture of computing clusters have allowed us to pursue a more ambitious simulation. In the LHC, the two beams consist of trains of thousands of distinct bunches of protons, and these bunches approach and collide with each other at four IPs where the four LHC experiments are sited, whereas existing beam-beam simulation codes were limited to a single pair of bunches and a single IP. For operational reasons the bunch trains have gaps in them and, in general, the two beams do not have exactly the same gap structure.

In the LHC and other collider communities, there is strong interest in being able to simulate the full complexity of collision patterns that arise from gaps and differences in the beam. Our Group formulated plans for a new parallel simulation code that would track multiple bunches through multiple IPs. This project was approved for access to high-performance computing systems at École Polytechnique Fédérale de Lausanne: a MYRINET-based commodity cluster on which development, benchmarking, and production were done, and an IBM Blue Gene supercomputer where very large-scale performance tests could be done. The first production version of the code was completed and showed good parallel efficiency and excellent scaling properties. The code input and parallel communications scheme have been designed in a very general way, allowing arbitrary bunch patterns and extension to arbitrary numbers of bunches and IPs, limited only by the number of processors available in the computing cluster. Further enhancements of the simulation options and the field solution methods are planned.

Partners

International Partners: CERN, École Polytechnique Fédérale de Lausanne.

TRIUMF's Role

TRIUMF provides knowledge and expertise in accelerator simulation, and undertakes the software conceptual design, application of numerical methods, parallel programming, testing and debugging, and collaborates on the production and analysis of results.

EURISOL Betabeam

Introduction

The Sixth Framework Programme of the European Union funds the EURISOL Design Study. Its mandate is to define a next-generation ISOL-based radioactive beam facility to be sited in Europe and to support a large and diverse research program. As a high-intensity source of radioactive ions, the EURISOL facility may act as the first stage of a neutrino factory based on the acceleration of these ions to high energies and their accumulation in a large racetrack-shaped storage ring where they emit neutrinos through the beta decay process.

Betabeam is a potential key to future long baseline neutrino experiments because it relies on known technology and is able to produce a neutrino beam of precise timing, low divergence, and low-energy spread, as opposed to the technical challenges and high costs associated with the beam production and beam cooling in muon-based facilities. TRIUMF participates in the Betabeam task of the EURISOL study, which will produce a conceptual design study incorporating all aspects of the Betabeam accelerator complex and its operation.

Results and Progress

Our beam dynamics group was invited to collaborate with Betabeam study members who had noted that the code ACCSIM was a good candidate for a platform on which to build a comprehensive simulation of the decay ring, incorporating ion injection, RF capture, tracking, decay, and detection and quantification of losses of the decay products.

At early Betabeam meetings, TRIUMF presented a survey of the available computing tools and methods, and a plan for the software developments needed to meet the simulation requirements. Initially, we worked with CEA Saclay personnel, who were designing the optics and magnet lattice of the decay ring. Together, we worked to establish the parameters and operating conditions of the ring and determine how they would be imported into the simulation, and how simulation results could be folded back into their optimization process for the ring design. We also worked with CERN members to specify the simulation parameters for the injection, RF system, and stacking mechanisms that were envisaged for accumulation of radioactive ions in the decay ring.

This definition stage was followed by work on a three-part upgrade package for ACCSIM, comprising: (1) generalization of tracking and acceleration for arbitrary ions; (2) physics and tracking model for ion decay process; and (3) accurate tracking and loss detection of secondary ions. In the latter task, we developed some new tracking techniques that involved transfer matrix scaling and direct computation of dipole trajectories.

With this package complete, the application to the decay ring was pursued as a joint TRIUMF-CERN project in which data sets of secondary ion losses were produced by ACCSIM runs and then were post-processed by the FLUKA code to account for ion interactions with the accelerator components, in particular the superconducting dipoles. The publication of these results represents a first look at Betabeam decay-ring operation from the point of view of ion losses, radiation exposure of ring hardware, and especially the heat deposition in the dipoles that may result in magnet quenching. The latter result has led to a new design effort to specify an open-coil dipole that will be resistant to quenching via ion losses.

The new ACCSIM version has also been distributed to other Betabeam members who are using it to estimate losses and space-charge effects in the post-ISOL accelerators (CERN PS and SPS in the baseline scenario).

Partners

International Partners: CERN, CEA Saclay (France).

TRIUMF's Role

TRIUMF provides the design and programming of simulation tools needed for Betabeam studies, configuration for current lattice and operational parameters, and streamlining of simulation data flow to post-processing applications.

T2K Experiment at J-PARC

Introduction

The T2K (Tokai to Kamioka) experiment needs a fast extracted proton beam from the 50 GeV J-PARC (Japan Proton Accelerator Research Complex) accelerator. The design work was finished in 2005. The J-PARC 50 GeV ring is under construction.

Results and Progress

The beam line bends the beam through 90^o. It consists of an arc of superconducting combined-function magnets, which combine quadrupole and dipole fields. The arc is preceded by a normal conducting preparation section, and followed by a normal conducting targeting section. Extreme care had to be taken to prevent the proton beam triggering the quenching of the magnets in the arc. The beam line is presently being built at J-PARC.

Partners

International Partners: KEK, JAERI.

TRIUMF's Role

TRIUMF was the main designer of the optics for the 200 m long transfer line between the accelerator and the target where the neutrinos are produced. The design work was finished in 2005. The J-PARC 50 GeV ring is under construction.

Charged Kaon Beams at J-PARC

Introduction

In 2006 and 2007, the J-PARC Physics Advisory Committee asked TRIUMF to perform an extensive external review of the designs for the proposed 1.8 GeV/c and 1.1 GeV/c kaon beams. These are clean kaon beams where the intensities of the various background particles, mainly pions and muons, are reduced by a factor of several thousands by two stages of separation using DC separators. The very delicate and critical second- and third-order optics are corrected with sextupoles and octupoles. The beams will be used for the study of hyper-nuclear physics.

Results and Progress

TRIUMF's expertise in the design of clean kaon beams continues to be called upon. An example of that expertise was the beam line built at Brookhaven National Laboratory [J. Doornbos *et al.*, Nucl. Instrum. Methods A444, 546-556, (2000)]. TRIUMF also designed an 800 MeV/c single-stage separated beam as a branch of the 1.1 GeV/c beam. Although it has only a single stage of separation, the beam is clean because, at the beginning of the beam line, there is an extra focus where the beam-defining slit can be placed. This beam is required by J-PARC's TREK experiment, which measures the polarization of the muon resulting from the Kμ3 decay. This experiment is the only one in the world that directly measures T-violation, unlike experiments that deduce T-violation from CP-violation, assuming CPT invariance.

Partners

International Partners: KEK, JAERI.

TRIUMF's Role

TRIUMF's expert advice has helped J-PARC develop credible plans for moving forward with the production of clean kaon beams.

Pellet-Beam Interactions at HESR

Introduction

TRIUMF provided pellet target and beam interaction Monte Carlo simulations to the 14.5 GeV high-energy storage ring (HESR) at the international Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt, Germany for the future PANDA experiment. A crucial question for the operation of HESR is the effect of target heating, which will, in combination with the stochastic/electron cooling, define the equilibrium beam conditions. This equilibrium is strongly dependent on the mechanisms of cooling.

For the envisaged luminosity at PANDA, the average target thickness will be a few times 10^{15} atoms/cm^2. The question of whether the density distribution of the target may also affect the heating is important here, because in contrast to, for example, a cluster-jet target, the target density is not homogeneous but concentrated in pellets of a few tens of micron diameter; the local thickness reaches values of a few times 10^{19} atoms/cm^2. Though this effect was investigated for the CELSIUS ring and found to be small, dedicated Monte Carlo simulations were made for the situations at the HESR.

TRIUMF was invited to join the PANDA collaboration as part of the Uppsala group in Sweden in October 2004 to do the Monte Carlo studies. Work ceased after the technical progress for PANDA was completed in 2005.

Results and Progress

For the first time, the simulations were done using a beam of $T_{[\overline{P}]} = 800$ MeV and $T_{[\overline{P}]} = 14.5$ GeV; the lowest and highest energies respectively at which the HESR could operate. For the target, two different scenarios were used: discrete pellet and continuous distribution, of the same effective thickness of 2.8Å—10^{15} atoms/cm^2. The results of the Monte Carlo runs show that the growth in emittance does not deviate significantly for the two cases. This result supports the earlier findings of studies in CELSIUS and COSY rings in which the effect of the strongly inhomogeneous distribution of a pellet target could not be distinguished from a homogeneous distribution of the same effective thickness.

Partners

International Partners: TSL (Uppsala), GSI.

TRIUMF's Role

TRIUMF contributed Monte Carlo simulations dedicated for the HESR. This has been included in the PANDA Technical Progress Report.

Microbunching for KOPIO

Introduction

TRIUMF performed beam-dynamics simulations of a new slow-extraction technique, called microbunching, for the CP-violation rare decay experiment KOPIO to be performed at the Brookhaven National Laboratory (BNL) AGS using 10^{14} protons per pulse.

From its inception in 1996 to cancellation in July 2005 for financial reasons, the KOPIO project spanned a decade. A series of microbunching demonstration experiments was performed at the AGS from 1997 to 2005. TRIUMF provided accelerator physics expertise on microbunched slow-extraction from 2000 to 2005.

Description

An experiment was designed to run at the BNL alternating gradient synchrotron (AGS) that would make use of a microbunched slow extracted proton beam for studies of the rare decay $K_L{}^0 \rightarrow \pi_0 \nu[(\bar{\nu})]$. This experiment, called KOPIO, would use time of flight to measure the momentum of K_L that decay in flight inside the detector. 25 MHz RF cavities in the AGS ring would be used to confine the resonantly extracted proton beam into microbunches with RMS widths of about 150 ps every 40 ns. Elimination of backgrounds from other K_L decays, generated outside of the microbunches, translated into the requirement that the intra-bunch extinguishment be less than 10^{-3} of the bunch intensity. The beam dynamics challenge was two-fold: to produce very short bunches without excessive cavity voltage, and to achieve extremely low leakage of the extraction scheme.

Results and Progress

Microbunching relies on the interplay of a chromatic 1/3-integer extraction process and the longitudinal cusps of proton intensity that occur near the fixed-points when RF buckets perform phase-space displacement acceleration. TRIUMF developed software to perform a detailed two-dimensional simulation of the extraction process, both as a tool to understanding experiments performed on the AGS and as a means to develop and optimize the technique to a level suitable for KOPIO.

TRIUMF proposed a combination of 25 MHz fundamental and anti-phased fourth harmonic RF acceleration to achieve the necessary bunch length with modest voltages and constructed a prototype of the 25 MHz RF cavity, scaled from a 27 MHz design for the RHIC. The BNL slow-extraction team performed a variety of beam experiments first with 93 MHz cavities verifying the calculated bunch lengths, and later used 4.5 MHz RF cavities to verify the intrabunch extinction of $\cong 10^{-5}$. Both were in good agreement with the TRIUMF simulations. The last series of results was reported in a NIM journal paper [N. Alberola *et al.*, Nucl. Instrum. Methods A560, 224-232 (2006)].

Partners

International Partners: United States (4), Institute for High Energy Physics, Protvino, Russia.

TRIUMF's Role

TRIUMF was responsible for developing the microbunching technique, originally conceived at BNL, to a level where it could meet the demanding specification of the KOPIO experiment. TRIUMF wrote simulation software, calibrated it against known slow-extraction properties of the AGS and, based on extensive exploration of design parameters, perfected the extraction scheme. Had the operation of the AGS for rare decay physics not been terminated in 2005, TRIUMF would have constructed the 25 MHz RF cavity.

Impedance and Collective-Effects at J-PARC

Introduction

J-PARC pursues frontier science in particle physics, nuclear physics, materials science, life sciences, and nuclear technology, using a new proton accelerator complex. J-PARC consists of a 180 MeV linac followed by 3 GeV and 50 GeV rapid cycling synchrotrons. TRIUMF was asked to consult on ring impedance estimates and advise on the potential for beam instability.

TRIUMF was invited to prepare estimates of collective effects in October 2002 and presented results and recommendations to the Accelerator Technical Advisory Committee (ATAC) in March 2003 and March 2004, at which time the work ceased.

Results and Progress

A wide variety of impedance sources were considered; in particular kicker magnets with reactive terminations, for which there were no previously existing formulae. Both bunched and coasting beam, longitudinal and transverse, instability thresholds, and growth rates were estimated. The study was complicated by the fact that there are vastly different parameter sets during injection, ramping, and the fast and slow extractions. For the bunched beams, a key issue was to understand the stability of high-order head-tail modes at very large chromatic tune shifts.

Recommendations made to the ATAC included: (1) methods of beam-load compensation for the RF cavities; (2) not to operate the ring with near zero chromaticity during slow extraction; (3) to be wary of introducing resonant transverse impedances into pumping-port enclosures and RF cavities by careless design; and (4) to add small resistive loads, or at least one matched termination to the TW-type kicker magnets to reduce troublesome reflections, etc. The head-tail modes were found to be stable throughout most of the main ring acceleration cycle, with the exception of a short period at injection.

Partners

International Partners: KEK, JAERI

TRIUMF's Role

TRIUMF provided beam-impedance and collective-effects calculation expertise to the 3 GeV booster and 50 GeV main ring at J-PARC.

TRIUMF's research in theoretical aspects of accelerator physics is dicussed next.

GEANT4

Introduction

Motivated by our local expertise in medium-energy hadronic reactions and in computing and simulation, TRIUMF was invited to join the GEANT4 collaboration during its formative stage. Since joining, TRIUMF has made major contributions to the design and implementation of GEANT4, has hosted two international GEANT4 workshops and continues to provide new functionality and user support for this ongoing software collaboration.

In recent years, we have seen significant efforts in the area of GEANT4 studies of beam lines, including detailed geometries of magnetic elements and other hardware. These have chiefly been in the areas of beam delivery systems for colliders (LHC and ILC), where experimental backgrounds need to be accurately predicted, and in muon cooling lines and experiments such as Muon Ionisation Cooling Experiment (MICE) at the Rutherford ISIS Spallation Neutron Source. In works related to spectrometers and nanobeams, it has been demonstrated that GEANT4 can accurately model magnetic elements and overlapping fringe fields, and that tracking is highly accurate, scalable, and can compete with dedicated ray-tracing codes.

GEANT4 is structured as a software toolkit and various beam-line tools based on GEANT4 have emerged, such as Fermi Beamtools, BDSIM, GMAD, and G4Beamline. The Muon Ionisation Cooling Experiment (MICE) appears to be the most advanced of these and is applicable to a number of TRIUMF systems, but it has essentially been designed around muon cooling systems. There are a number of additional needs and avenues of further development to be considered for the future of this or similar codes.

Results and Progress

There are now prototype models of several TRIUMF beam lines in GEANT4 or G4Beamline. In 2008, a G4Beamline application for extraction line BL2A will be developed with as high a level of optical accuracy as the knowledge of the hardware (particularly magnetic field data) will permit. The models give an opportunity to understand better the beam line behaviour and possibly to improve performance. G4beamline offers a number of features useful for this-application, but current indications are that further development of G4beamline would be needed to make it maximally useful for this and other TRIUMF beam lines. G4beamline is a product of the private company Muons Inc., but it is essentially written and supported by one person and is freely available with open source and GPL licensing. In principle, therefore, we can modify the source code to meet our needs, but doing so raises the question of whether these should be *ad hoc* modifications or whether there should be a more formal contribution to the evolution of the code or a product derivative of it.

TRIUMF's Role

TRIUMF's membership in GEANT4 brings obligations but also privileges, including direct access and involvement in the evolution of the code (instead of just public release packages), as well as an inside track on issues of support, feature requests, and the opportunity to learn and discuss with experts about all aspects of the GEANT4 toolkit. These privileges and opportunities, along with the laboratory's expertise in particle and nuclear physics, computing, and accelerators and beam lines, position TRIUMF to pursue advanced accelerator and beam-line tools and applications built from GEANT4.

Development and Support Activities for ACCSIM

Introduction

The Accelerator Design Group developed the tracking and simulation code ACCSIM and has benefited from its expertise in accelerators and beam lines as well as experience from previous well-known TRIUMF codes such as COMA and REVMOC. Like these codes, the emphasis for the ACCSIM team is on usability by those users who may not have advanced computing skills, and on direct interaction and consultation with users to determine the needed functionality and the path of further development.

Results and Progress

With its free availability and comprehensive documentation, ACCSIM has been used in a variety of applications, which has led to collaborations between TRIUMF and other accelerator labs such as CERN, LANL, KEK, BNL, ORNL, and J-PARC. Specifically, ACCSIM played a role in the design effort for the J-PARC 3 GeV rapid-cycling synchrotron and for the ORNL SNS 1 GeV accumulator ring, both recently constructed and either being commissioned or in operation. In addition, ACCSIM was the vehicle or catalyst for two tasks in the beam dynamics component of the Canadian contribution to the LHC, and has facilitated strong long-term relationships with a number of accelerator experts at CERN.

Other notable applications include several studies of the LANL PSR and its upgrades, simulation of the proposed LINAC IV H^- injection in the CERN PS Booster (part of the LHC upgrade program), the EURISOL Betabeam, and tracking in the KEK 12 GeV PS under high-current operation for KEK-to-Kamiokande neutrino production. The latter study included one of the few direct comparisons that have been made between a space-charge tracking code and actual measured beam profiles in a ring (with good agreement being observed).

Partners

International Partners: KEK, JAERI, (Japan); CERN; United States (3).

TRIUMF's Role

TRIUMF is the home base of ACCSIM where development, documentation and support is done, although the code has gained much by expert input and sharing of ideas from CERN and other laboratories. We have also engaged in direct collaborations with users towards new applications and enhancements to the code.

Space-Charge Simulation Codes

Introduction

The simulation of intense proton beams in synchrotrons and storage rings has been of widespread interest in recent years, in studies and designs of hadron facilities, spallation neutron sources, and proton drivers for future neutrino and muon facilities. The space-charge simulation code ACCSIM, developed at TRIUMF with input from a number of experts, is one of a generation of innovative codes, created at various institutes, which are devoted to modeling these intense proton machines.

Results and Progress

After a seminal ICFA workshop in Oxford, where much information on code development and progress was exchanged, the authors of several codes including ACCSIM, SIMPSONS, ORBIT, and others undertook a long-term collaboration to compare, test, and validate these codes using common baseline configurations, with the CERN PS being the first reference lattice to be considered. Although these codes tend to run at the practical limits of current computing hardware, data sets were obtained and comparisons and analyses were published for a number of simulation cases and levels of accuracy. This led both to insights about the behaviour and applicability of the codes, and to new questions about differences between the codes. The Group expects that there will be further phases of this collaboration that will lead to refinements of our methodologies and better understanding of numerical issues and physics models.

Partners

International Partners: CERN, GSI, KEK, Rutherford Appleton Laboratory.

In the United States: Oak Ridge National Laboratory, Brookhaven National Laboratory, Fermilab, Lawrence Berkeley National Laboratory.

TRIUMF's Role

The space-charge simulation codes field is a relatively small but active field of research in which the code authors have been able to establish long-term relationships and have collaborated with each other on various studies of actual and planned accelerators. In particular, with CERN and ORNL, TRIUMF's development and support of ACCSIM is valued, and our continued participation will be appreciated.

60 GeV/c RF Separated Kaon Beam

Introduction

High-energy RF separated kaon beams were built decades ago. They had very small intensities because of the large momentum-related higher order optics aberrations and the small electric gradients in the room temperature cavities. Nowadays, it is possible to make high gradient superconducting cavities that can be used in slow extracted beams.

Results and Progress

A solution to the aberrations problem was found at TRIUMF. The consequence of this solution and the higher gradients is that now RF separated beams can be built at high energies with phase space acceptances more than an order of magnitude higher than in the past. Therefore, RF separated beams can now be built that approach the intensities of unseparated beams, but without large contamination by pions and protons.

These techniques were applied at TRIUMF to design for a 22 GeV/c RF separated K^+ beam for the Cabbibo-Kobayashi-Maskawa (CKM) experiment at Fermilab. This experiment aimed to measure 100 events of the decay in flight of the kaon into a pion and two neutrinos. The E787 experiment at BNL had already measured three such events, but its continuation was cancelled. Unfortunately the development of the CKM experiment was also terminated.

Due to new detection techniques developed by the CERN NA48 collaboration that can handle very high particle rates, an attempt is now being made at CERN to measure the decay in a 75 GeV/c un-separated beam. In this way, they hope to measure 100 events. It was thought there that a separated beam would have too small a phase space acceptance. In order to demonstrate the feasibility of a separated beam at such high momenta, in 2006 an optics design was made at TRIUMF for a 60 GeV/c RF separated kaon beam with very high acceptance, using superconducting X-band cavities. If the presently intended experiment with an unseparated beam succeeds, the thinking is that a follow-up experiment using an RF separated beam, with the same rate as the unseparated beam, but now mainly kaons, will make it possible to measure 1,000 events.

Partners

International Partners: CERN, Brookhaven National Laboratory, Fermilab.

TRIUMF's Role

Initial ideas originated at TRIUMF, and we are still consulted on new designs.

FFAG Studies

Introduction

TRIUMF is engaged in designs for a new and novel type of charged-particle accelerator, the non-scaling fixed field alternating gradient (FFAG) accelerator, which promises more cost-effective accelerations of muons for HEP and of low-energy hadrons for cancer therapy. A demonstration model, EMMA

(Electron Model with Many Applications), is under construction at Daresbury, UK.

The TRIUMF involvement with FFAGs began in October 2003, with US-led designs for a future neutrino factory and muon collider. We quickly discovered that FFAGs were a cost-effective alternative to recirculating linear accelerators, such as CEBAF, because their enormous momentum acceptance meant that the costly multiple return arcs and much of the costly ionization cooling could be dispensed with. Later, the studies blossomed to include a demonstration model using low-energy electrons and proton and carbon accelerators for cancer therapy. The work is ongoing, at least through 2009.

Results and Progress

American and European scientists are developing FFAG research programs, and the TRUIMF Accelerator Physics Group has worked with them to achieve a breakthrough in understanding how FFAG designs may be simplified as well as the restrictions imposed by scaling avoided. In particular, we introduced "serpentine" acceleration (essential for muons), developed a theoretical model explaining the momentum dependence of orbit shape and period, and are now helping to guide the design of the 10–20 MeV electron model, EMMA. As with traditional isochronous cyclotrons, which are a type of non-scaling FFAG, this "first generation" machine has the demerit of resonance crossing due to the variation of the transverse betatron tune. Looking forward to the medical applications, and a much slower rate of acceleration than muons, we are actively working on designs involving wedge-shaped, combined-function magnets in which the contributions of increased path length and edge focusing are used to stabilize the transverse tunes. If the design proves feasible, the UK consortium intends construction of PAMELA, a medical prototype.

Partners

TRIUMF is a member both of the US-led Neutrino Factory and Muon Collider Collaboration, and of the UK-led CONFORM consortium of laboratories and universities building the EMMA model and studying alternatives for a proton or carbon medical accelerator design.

TRIUMF's Role

TRIUMF continues to play a key role in FFAG studies, particularly in these areas: providing intellectual and creative leadership to the development of non-scaling FFAGs to the understanding and optimization of the magnetic lattices, notably the extreme momentum compaction to the cyclotron-like method of bucketless RF acceleration to introducing the use of cyclotron orbit codes for FFAGs in place of synchrotron codes, which are awkward to use for spiral-orbit accelerators; to practical aspects of the EMMA design, such as selection of the L-band cavity design; and to a high-gradient small-aperture version of the PAMELA concept.

Intensity Limitations in Cyclotrons

Introduction

The 500 MeV TRIUMF cyclotron's limitation on peak intensity is due to repulsive space-charge forces overpowering the vertical focusing forces in the central region where beam energy is lowest. For upgrading to higher intensity, it is necessary to understand the limitation. Therefore, we plan to re-build the vertical section of the injection line. A study will determine optimum matching conditions into the cyclotron and therefore must be completed in 2008 so that the new injection line can be completed within the scope of the current Five-Year Plan.

Results and Progress

The dynamics in an isochronous accelerator is non-intuitive as the space-charge forces cannot relieve themselves by lengthening the bunches. In a sense, particles act as if they have infinite mass. One can model the dynamics using individual macro-particles, but the optimization is not transparent. A much more efficient formalism exists, one which is statistical in nature: the 21 six-dimensional second moments of the particle bunch distributions are followed rather than the motion of millions of individual particles. This formalism has never been used to study the effects of space charge in the first few turns of a cyclotron. Besides transport in six-dimensional phase space, acceleration must also be correctly handled. An error has been found in one standard code (TRACE-3D).

At sufficiently high intensity, the bunches become vortices, circular when observed from above the median plane. A new discovery is that this tendency alleviates the harmful influence of the "gap-crossing resonance" which causes a stretching of the beam in the median plane. This aspect is currently under study; it may result in higher charge per bunch than envisaged when the cyclotron was originally designed.

Partners

International Partners: Chinese Institute of Atomic Energy (CIAE).

TRIUMF's Role

This research is critical to cyclotron-upgrade plans, so TRIUMF plays the lead role.

Fringe Fields

Introduction

A highly accurate understanding of the focusing effects of dipoles and quadrupoles pays dividends in tuning time saved. If the elements are quite long compared with aperture, accuracy is easily obtained. On the other hand, when the fringe field is relatively long, its effect must be well understood. This understanding applies both to linear effects and aberrations.

New beam lines are now designed with the knowledge of the effect of fringe fields, so they are relatively more easily commissioned than in the past. Older beam lines, which have always been tuned empirically, are one-by-one becoming treated more scientifically.

Results and Progress

It is of course possible to use the element field map in a ray-tracing code, but this makes simple optics calculations very cumbersome. If only the linear and lowest order aberration are important, one can ask, "How much of the detail of the field map is needed?" The answer, it turns out is "very little." For example, the linear effect of the quadrupole can be summarized exactly using only three parameters: effective length, effective strength, and a fringe field parameter. And the lowest order (cubic force) aberration depends not at all on the fringe field shape.

These results are used to distil the field maps into a simple and efficient form. For example, of the hundreds of electrostatic quadrupoles used in both ISAC-I and ISIS (the cyclotron injection line), almost all are set to their theoretical values in spite of the fact that many are short compared with their aperture. Magnetic quadrupoles are also being treated in this way, which makes the beam optics calculations sufficiently efficient that beam envelopes can be calculated continuously in a graphical user interface as the operator tunes the elements.

Partners

Individual contact among collaborating research scientists around the world.

TRIUMF's Role

TRIUMF has contributed to the international body of knowledge with the publication of key research papers and presentations at confenreces.

Nonlinear Transfer Maps for Charged-Particle Beam Transport

Introduction

Charged-particle beam transport can be described with a Taylor map, which, in the linear case, coincides with the familiar beam-transfer matrix. Traditional accelerator design codes, such as TRANSPORT of K. Brown and MAD, developed by CERN, utilize the next (second) order map while methods to construct maps of higher order and use them for nonlinear analysis were developed in the 1980s by Dragt, Forest, Irwin, Berz and others. Such are the Lie-algebraic method, which fully accounts for the Hamiltonian (symplectic) nature of motion, or the differential algebra method, where the map is extracted directly from the equations of motion. In terms of mathematical apparatus, both these approaches, and especially the second one, require extensive numerical manipulations of polynomial functions. For this, the techniques of the truncated power series algebra (TPSA) are applied (also called automatic differentiation).

At present, increased power of analytic computational systems (such as Mathematica) provide the flexibility and speed needed to implement all the map-building methods described above. Nonlinear problems can then be studied with dedicated notebooks in a local environment. Work in this direction, pursued also by researches in many accelerator laboratories, has recently been initiated at TRIUMF. We have developed two packages - LieMath and DARK possessing many features and functions of two well-established codes: MARYLIE (of A. Dragt) and COSY (of M. Berz).

Results and Progress

Lie-algebra Applications

In 2004 and 2005, the TRIUMF Accelerator Group wrote LieMath, a code that builds a symplectic six-dimensional map in either Lie-factor, or Taylor form. The input to the code is a beam line of optical elements written in the most popular MAD-input format. The code provides nonlinear optimization and normal form analysis to octupole order. As of 2006, a TPSA module is installed to speed up operations on polynomials.

In 2004, an early version of LieMath was used to produce a seventh-order, off-momentum map for the basic cell of the FFAG. It is in full agreement with the corresponding map generated by COSY.

In 2006, Lie-algebraic theory was applied to test and refine the existing CERN program for multipole correction of the LHC interaction-region quadrupoles, or so-called triplet correction.

In 2007, Lie-algebraic treatment of weak-strong beam-beam interaction produced the effective Hamiltonian in the case of an arbitrary number of collisions or IPs. This result is related to the long-standing question of whether the beam-beam resonances may be cancelled by choosing some appropriate betatron phase advance between ATLAS and CMS, the two main IPs of the LHC. Such resonances, manifesting themselves as dips in dynamic aperture positioned dangerously close to the LHC tune working point, were clearly seen in the tracking data. As a result, we found that not all, but only some kinds of resonances would be cancelled, and that the conditions for cancellation are rather stringent. The idea to tune the machine to a specific phase between the IPs has been, at least for now, abandoned.

Differential Algebra Applications

DARK (Differential Algebra + Runge-Kutta) is a Mathematica package that applies the TPSA method to compute the transfer map for arbitrary equations of motion describing an optical system. It has the same interface as LieMath, so the Taylor maps produced by these two codes can be compared directly, but it can also tackle the case when the focusing strength of an optical element is not constant along its axis, *i.e.*, the case of fringe fields. The algorithm used is very similar to the one used in the code COSY.

In mathematical terms, DARK is a differential algebra integrator, a numerical solver of the complete variational equations describing an optical system.

The code has been tested against numerical integration of individual trajectories and, for magnetic quadrupoles with fringe fields, against high-order maps generated with COSY.

Possible applications include nonlinear optimization of beam lines, FFAG, a linear collider interaction region, existence of third-order achromats, etc. DARK was used recently to study fixed points and transition to chaos of the Duffing equation.

Partners

International Partners: CERN, University of Maryland.

TRIUMF's Role

In 2005, the LieMath package was added to the web-based dynamic accelerator physics software repository. Currently DARK is being used to study fixed points and transition to chaos of the Duffing equation. This is intended for Section 18.11 (Taylor Approximations) in the book "Lie Methods for Nonlinear Dynamics with Applications to Accelerator Physics" which is being prepared by Prof. A. Dragt.

4.2.5

Detector Development and Fabrication

All particle physics, nuclear physics, and condensed matter experiments require instruments to detect energetic subatomic particles. These detectors are required to measure various kinematic properties of each particle, such as its energy, momentum, the spatial location of its track, and its time of arrival at the detector. Scientific progress often emerges from advances in detector technology. Such advances include: enhanced precision in kinematic properties; the rate at which particles may be detected, leading to improved statistical precision; and in reduced costs, resulting in larger systems with greater sensitivity to rare processes.

Over the last several decades, TRIUMF's detector group has established an international reputation for developing, designing and constructing state-of-the-art detectors, as well as developing new detector technologies. New instruments have been successfully deployed in measurements at TRIUMF and in collaborative projects elsewhere in Canada and abroad.

Detectors exploit several technological approaches. One example is scintillating materials that emit a flash of light when stimulated by impact or passage of an energetic particle. The intensity of light is typically proportional to the energy of the particle deposited in the material, thereby leading to arrays of such scintillators being known as calorimeters. The light can be collected and detected by a variety of devices, which themselves are a topic of recent advances. The scintillator material can be organic or inorganic, a solid, liquid or gas, and is chosen from an array of established possibilities to optimize the precision in time or energy of the measurement while minimizing the cost. New materials with improved properties continue to be developed, for example, liquid xenon, which is a topic of future work by the detector group and is described below.

Another widely used detector technology exploits the trail of ions and free electrons produced in the track of a charged particle typically passing through gases, but also through certain liquids, to determine the spatial location of that track to a precision that may be as thin as the diameter of a human hair. The electrons are collected on a lattice or array of many electrodes in the medium. The tiny electrical signal on each electrode is amplified by an avalanche process in the high electric fields near the electrode and is detected by a sensitive electronic device. Such tracking detectors are often used in magnetic fields of large magnets in which the tracks of charged particles are curved to a degree proportional to their momenta. Measuring a track's curvature thus determines the particle's momentum. In addition, the density of the ionization along the track can be recorded and used to identify the type of charged particle.

All particle detectors ultimately produce information in the form of electrical signals that must be processed by electronic circuits, digitized to produce numerical data, which in turn may be further processed in real time and then recorded for further analysis. The initial signals may be so tiny that they need to be amplified by sensitive devices that have very little intrinsic noise. Continuing advances, in both this analog technology as well as in the digital processing devices and techniques, have played crucial roles in rapid enhancements in the capabilities of detector systems.

Description of Facilities

The facilities for detector construction occupy four substantial areas on the TRIUMF site. Two of these house three new machine tools: a Haas VF-5/40XT CNC vertical milling centre with a 5-axis spindle and 2-axis rotary table yielding a precision of ± 5 µm over a working volume of 1.5 m x 0.66 m x 0.64 m; a Haas TL-3 CNC lathe with a maximum cutting diameter of 0.5 m and a maximum cutting length of 1.5 m; and a Multicam CNC router with a precision of ± 50 µm over a working volume of 3 m x 3 m x 0.4 m.

All of these new machine tools are housed in temperature-controlled areas, with dust extraction systems suitable for machining the composite materials that play a major role in the fabrication of modern instruments. In addition, there are available three temperature-controlled class-1000 clean rooms, with volumes 7.8 m x 11.5 m x 5 m, 8 m x 10 m x 2.4 m, and 8 m x 9 m x 2.8 m, for assembling instruments of all sizes. One of these contains a 3 m x 2.4 m precise granite slab with a pneumatic press. Finally, there is a 10 m x 27 m detector test area equipped with several high-purity gas mixture manifolds. The replacement value of the entire infrastructure of the detector facility for construction is about $C1 million.

Particle Physics Experiments

KOPIO

The KOPIO experiment was an international project to be based at the Brookhaven National Laboratory in the United States. The collaboration had worked for about a decade to develop a detailed design and funding scenario, and had passed essentially all the stages of scientific and technical review. Unfortunately, the US National Science Foundation cancelled the project in 2005.

TRIUMF had responsibility for the challenging design and construction of the pre-radiator detector, which consisted of a sandwich of scintillator bars and wire chambers. The scintillator bars were to be produced at a local firm called CELCO. The production technique developed by TRIUMF in collaboration with CELCO led to a patent. This collaboration subsequently produced the fine-grained detector (FGD) bars for T2K (see below).

In addition, a collaboration with l'Université de Montréal developed an electronic digitizing system based on 50 MHz flash ADCs. This 48-channel VME board (VF48) is now used by a variety of experiments including liquid-xenon PET medical imaging, the ALPHA experiment at CERN, and the PIENU and TACTIC experiments at TRIUMF. A modified version running at 200 MHz is also used by the TIGRESS experiment at TRIUMF.

TWIST

The recently completed TWIST experiment at TRIUMF measured, with dramatically improved precision, the Michel parameters describing the weak decay of muons to electrons, thereby imposing much stronger limits on possible deficiencies or extensions to the standard model that embodies our present fundamental understanding of particle physics. Such discrepancies are sought because they would be clear indications of new physics that could be clues to a more profound and general model.

The core of the TWIST experiment, a tracking gas detector that challenged the limits on precision in construction, was built in the TRIUMF detector facility between 1999 and 2001. In 2004 a time expansion chamber, and associated gas purification and pressure control system, was installed to study the properties of the muon beam entering the main TWIST detector apparatus. Maintenance of the wire chambers and time expansion chamber was provided until the experiment was completed at the end of 2007.

T2K

The T2K (Tokai to Kamioka) experiment in Japan is an international effort that will pursue the widely recognized logical next step in unraveling the profound mystery of neutrino mass and flavour oscillation. Canada is contributing the central core of the Near Detector (ND280), which consists of two types of sub-detector: three identical tracking detectors called time projection chambers (TPCs), and two almost identical one-ton scintillator matrices or FGDs. The detectors are scheduled to be installed at the Japan Proton Accelerator Research Complex (J-PARC) laboratory in the middle of 2009.

The TPCs are gas-filled volumes of roughly 2 x 2 x 0.3 m^3, lined with precise electrodes to produce a strong electric field of high uniformity. Free electrons produced by particle tracks in this volume drift towards sensitive detection arrays on one side of each half-box, over a maximum drift length of 1 m.

The mechanical construction of the TPCs at the TRIUMF detector facility depends on new infrastructure acquired through the CFI-supported Laboratory for Advanced Detector Development (LADD). A prototype was also built in 2005 by the detector facility. LADD also provided electronics, power supplies, and a laser for the prototype tests, performed at the University of Victoria. The sophisticated system for purifying and re-circulating the special gas mixtures required for the TPCs at precisely controlled pressures was designed and is being constructed by the detector facility.

The FGD consists of 8,500 scintillator bars that were extruded at the local CELCO plant in 2007. The scintillation light produced in each bar is captured by a 1 mm diameter wavelength-shifting fibre in an axial extruded hole. One end of each fibre is optically coupled to a recently developed type of light detector called a multi-pixel photon counter (MPPC). The MPPC is a kind of Geiger-mode photon detector (GPD) produced by Hamamatsu Photonics. Characterization of these new devices was performed using LADD equipment and manpower and will lead to publication of several technical papers. The intricate FGD mechanical design depended on the skill and experience of the leader of the detector facility, and fabrication in the facility used new equipment purchased through LADD. The FGD signal-acquisition electronics was designed and fabricated under the leadership of the LADD group.

PIENU

The PIENU experiment is a project to improve, by about a factor of ten, the precision with which electron-muon universality has been tested experimentally in the decay of pions. If this symmetry were found to be broken, it would be a clear signal of departures from the standard model of particle physics. The measurement will exploit the excellent properties of the pion beam available from the M13 beam line at TRIUMF.

The design of the PIENU experiment started in 2006, and the start of actual measurements is expected in fall 2008. PIENU requires a combination of scintillator detectors, which are used to detect charged particles and stopped pions, wire chamber and silicon strip detectors measuring charged-particle positions, and a calorimeter measuring energies of the positron or photon from the pion decay. All scintillator detectors and wire chambers are being built by the detector facility. The signal-acquisition system for the calorimeters and silicon strips is based on the VF48 design developed initially for KOPIO.

G0

The goal of the G0 experiment at Jefferson Laboratory in the US is to learn more about how the various flavours of quarks in the proton or neutron contribute to its distributions of electric charge and magnetization.

A Canadian group led by the University of Manitoba made indispensable contributions to the design and construction of the experiment. In particular, the TRIUMF scintillator shop constructed large arrays of plastic scintillators and light guides. The first phase of the experiment was completed successfully, and the results published.

Nuclear Physics Experiments at TRIUMF

SCEPTAR

One of the main detection tools for nuclear physics at ISAC is the 8π spectrometer, the only existing large, high-resolution, high-efficiency γ-ray spectrometer for characterizing the decay of stationary radioactive nuclei. TRIUMF's Detector Group contributed both design and construction efforts towards the enhancement of this facility with ancillary detectors for beta particles or conversion electrons produced in time coincidence with the γ-rays. The leading example is SCEPTAR (SCintilator Electron-Positron Tagging Array), which is a segmented sphere of 20 thin plastic scintillators, one in front of each of the 20 high-purity germanium (HPGe) high-resolution γ detectors of the 8π.

SCEPTAR is intricate because its delicate elements must be supported precisely inside the HPGe array with a minimum of obscuring material, while connected to a tube of slim acrylic strips carrying the scintillation light out of the vacuum vessel to external sensors. This system's design and construction challenged the skill and experience of TRIUMF's Detector Group. The detector was installed successfully and has performed well.

TACTIC

TACTIC is a cylindrical time projection chamber (TPC) designed to study nuclear reactions that are important inside stars, at the relevant very low energies where the reactions occur with low probability. An ISAC beam of short-lived nuclei passes along the axis of the gas-filled cylinder, and the ionization tracks of the products of any interactions with the low-pressure gas are collected on the cylindrical walls. These walls are lined with gas electron multipliers (GEMs), which amplify the signals so that their intensities and arrival times can be recorded. This innovative TPC was designed by the Detector Group and built by the University of York in the United Kingdom. The signals are digitized and recorded by the VF48 boards of the type mentioned above.

MAYA

The MAYA detector is a unique device, on loan from GANIL in France, being applied at TRIUMF to study exotic halo nuclei. It was the very first experiment carried out in the new ISAC-II, in 2007. MAYA is essentially a small TPC in which the tracking gas serves also as the target material, a so-called active target. The Detector Group designed and assembled a system to provide the required high-purity gas mixtures.

TIGRESS

The Detector Group provided equipment, clean room, and testing facilities in support of the development of the new TIGRESS facility for the study of nuclear structure and basic symmetries at ISAC-II.

Medical Imaging

Complementing the TRIUMF Life Sciences program, the Detector Group is active in developing an innovative technology for medical imaging, an effort that began in 2004 with the now-subsumed LADD. Positron emission tomography (PET) is a widely applied medical method for three-dimensional imaging of internal organs. In this method, a short-lived radioactive isotope, chemically substituted in a biologically active molecule, is administered to the patient. The isotope is chosen to be one that decays by emitting a low-energy positron with a short range in tissue. The positron annihilates with an atomic electron, producing a collinear back-to-back pair of γ-rays, each with an energy of 511 keV. The patient is surrounded by an array of detectors that record the positions of the interaction of the γ-rays in the detectors, thereby defining a line through the point of annihilation. Sophisticated analysis of the two-dimensional information from a large number of such events yields a three-dimensional image of the concentration density of the isotope, which might reveal, for example, anomalous local deficiencies in metabolism of the carrier molecule.

The quality of the medical information available from PET images depends on both the number of events recorded (statistical precision) and the spatial resolution of the detectors. The recording rate is limited by the detector time and energy resolutions with which coincident γ-rays can be identified as coming from the same annihilation event. Today's conventional PET systems employ inorganic scintillators such as LSO.

While arrays of such scintillators have high detection efficiency, their resolution in time and space is limited by their granularity and lack of information about the depth into the scintillator of the interaction location where each γ-ray is absorbed, producing the scintillation light. An ideal detector would provide a fast timing signal as well as precise three-dimensional spatial information about each interaction. The detection medium of liquid xenon offers this possibility, as the interactions produced both prompt scintillation light to define the time with a precision of 1 ns and mobile ionization electrons to define the position via the TPC technique to within 1 mm.

These advantages have motivated work on applying liquid xenon detectors to particle physics. The focus of the TRIUMF Detector Group has been on demonstrating the feasibility of such a detector for PET. Simulations were performed to investigate how to identify Compton (quasi-elastic) scattering of γ-rays from electrons, which would otherwise limit the performance. The feasibility of simultaneously measuring light and ionization charge was demonstrated in a small test chamber.

Present efforts are focused on the design and construction of one prototype segment of an eventual 12-segment microPET ring detector suitable for small animals. The components have been fabricated, and the assembly will be completed in 2008. The cryostat and controls to maintain the required very high xenon purity have been built and tested. Avalanche photodiodes have been chosen as the most appropriate light detector and have been acquired and characterized. The electronics to sense and record the signals from the 32 photodiodes and 192 TPC electrodes has been developed and built. The prototype segment will be operated and studied through 2008. The group expects to demonstrate the feasibility of a PET detector based on liquid xenon by 2010. The success of this effort will be another example of the application of ideas emerging from basic research in particle and nuclear physics to enhance and even save the lives of the citizens funding this research.

Partners

In Canada: Guelph University, University of British Columbia, l'Université de Montréal, University of Regina, University of Victoria, University of Manitoba, and York University.

International Partners: France (2), Japan (1), Switzerland (1), the United Kingdom (3), and the United States (3).

TRIUMF's Role

The present TRIUMF detector group is the result of the 2007 amalgamation of the existing detector facility for design and construction with LADD, which was created with special funding from the Canadian Foundation for Innovation (CFI). Led by an experienced designer, R. Henderson, the detector construction facility has internationally recognized expertise and accomplishments in two main areas: gas detectors and scintillator detectors. CFI funding of LADD provided new infrastructure and enabled the hiring of two physicists, F. Retiere and L. Kurchaninov, with strong interests and experience in detector and electronics research and development. The focus of their research has been on detector and electronics development for particle physics and medical imaging.

4.3

Creating Future Leaders

4.3.1

Outreach and Public Engagement

Introduction

As a world-leading research laboratory, TRIUMF takes its commitment to the citizens of Canada seriously. A key component of that commitment is a formal outreach program with a mission of promoting science and research in the public arena. TRIUMF's outreach activities are also designed to tell Canadian students, teachers, and the public about the excitement of curiosity-driven research and about how a laboratory like TRIUMF adds value to Canada in new technologies, medical applications, and highly qualified people.

In 2003, funding from the Vancouver Foundation and the Life Members Organization of the Engineering Institute of Canada (now Canadian Society of Senior Engineers (CSSE)) allowed TRIUMF to broaden the laboratory's outreach activities. In just a few years, TRIUMF's Outreach Program developed a number of successful educational initiatives that have established the laboratory as a major contributor to Canada's science promotion community.

The TRIUMF Outreach Program uses the laboratory's facilities to provide stimulating and educational opportunities for students of all ages but most especially high-school teachers and their students. Programs have been created to stimulate the interest of students in the physical sciences, and to support science teachers with materials and experiences relevant to the classroom. These programs were developed both in-house and through partnerships with local and national science promotion agencies. Through these programs, TRIUMF is attracting a new generation of scientists into the wonder and excitement of fundamental research and its possibilities.

Programs for Teachers

Students respond to high quality video content as part of their learning experience. One of TRIUMF's most compelling outreach initiatives has been the production of animated physics education videos for schools. The Physics in Action series is intended as a supplementary teaching aid to show how the concepts and formulas taught in middle- and high-school physics are not purely abstract concepts; they are, in fact, in use every day and govern the performance of sophisticated equipment.

The Vancouver Foundation funded the first video, on the topic of special relativity. TRIUMF built on this first video's success with a second video on the applications of electromagnetism and circular motion in the cyclotron. This second video was made possible with funding from NSERC's PromoScience and was released with some fanfare at Catalyst 2008, a conference of the British Columbia teachers of science. Both videos are available, free, to every high school in Canada.

Teachers are often responsible for providing instruction on topics for which they have little or no practical experience. TRIUMF developed two programs to provide teachers with real-world research experience they could transfer to

Figure 1: High-school teachers visiting TRIUMF and learning about a beam line during the Fall Professional Development Day.

the classroom. Every other year, the British Columbia Association of Physics Teachers and the British Columbia Science Teachers Association organize a Fall Professional Development Day at TRIUMF. This event attracts approximately one hundred teachers from across the province (see Figure 1). TRIUMF provides the teachers with a full day of tours, talks, and hands-on physics demonstrations. For teachers who appreciate a more in-depth look into the world of TRIUMF physics, TRIUMF recently launched an internship program that offers high-school educators a three- to seven-day research experience working as part of an experimental research team on a running experiment (see Figure 2).

TRIUMF has also collaborated with the Universities of Alberta and Victoria and the US laboratory Fermilab to bring an authentic research experience into the classroom through the Alberta Large-area Time-Coincidence Array and QuarkNet programs. These programs bring into schools compact cosmic-ray detector equipment that can be operated and maintained by teachers and students. These systems integrate into a North American network of schools studying large-scale cosmic-ray showers. TRIUMF has helped develop the next-generation data acquisition systems for these systems, which are now ready to be deployed at schools across the province. To date, the cosmic-ray detector project and the internship program have been supported by funds from the Vancouver Foundation and the CSSE.

Programs for Students

TRIUMF is a favourite field-trip destination for high-school science classes and receives about 660 student visits per year. Field trips provide students with an overview of the laboratory, but some very interested students want more. In 2004, TRIUMF and the B.C. Innovation Council initiated a scholarship program that offers exceptional high-school science students a hands-on experience as a participating member of a research team. Graduating students going on to university science programs are eligible for the six-week research experience at TRIUMF, along with a $3,000 scholarship. The High-School Fellowship program attracts 100 applications per year, and the program has been a major success: of the six scholarship winners to date, three have chosen to return to TRIUMF as undergraduate co-op students (see Figure 3).

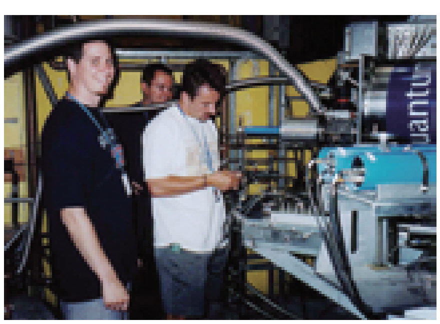


Figure 2: Pitt Meadows high-school teacher Michael Bruins assisting SFU Professor Jeff Sonier on an experiment.

Programs for the General Public

TRIUMF offers public tours twice daily from May through August and twice a week the rest of the year. Each year, TRIUMF attracts an average of 440 visitors who come specifically for the public tours program.

In response to an overwhelming demand, TRIUMF created the Saturday Morning Lecture Series, a monthly lecture featuring talks by scientists from TRIUMF, the University of British Columbia, Simon Fraser University, and the National Research Council's Fuel Cell Program as well as other notable visitors to TRIUMF. The lectures are aimed at high-school students but are well attended by adults interested in science. These lectures have proved to be very popular, with some lectures attracting capacity crowds of 100 or more (see Figure 4).

The scope and scale of science outreach is far too large to be tackled alone. To develop new outreach programs, TRIUMF has built strong relationships with other institutions involved in science outreach. These include: the BC Innovation Council (BCIC); the BC Association of Physics Teachers (BCAPT); the BC Science Teachers Association (BCScTA); outreach and science promotion programs at the University of Alberta, University of Victoria, and UBC; the Perimeter Institute for Theoretical Physics; QuarkNet at Fermilab in the US, Telus World of Science; the H.R. Macmillan Space Centre in Vancouver; Capilano College in Sechelt, B.C.; and NSERC-Pacific in Vancouver. Most of TRIUMF's outreach programs have been developed and/or delivered in conjunction with one of these partners.

TRIUMF has also supported the science promotion community through its support of the Scientists in Schools program at Telus World of Science in Vancouver, the Regional Science Fair (and the Canada-Wide Science Fair in 2005) run by the Youth Science Foundation Canada, the UBC Undergraduate Science Conference, the Canadian Undergraduate Physics Journal, BCScTA's journal Momentum, the Canadian Journal of High School Science; and others.

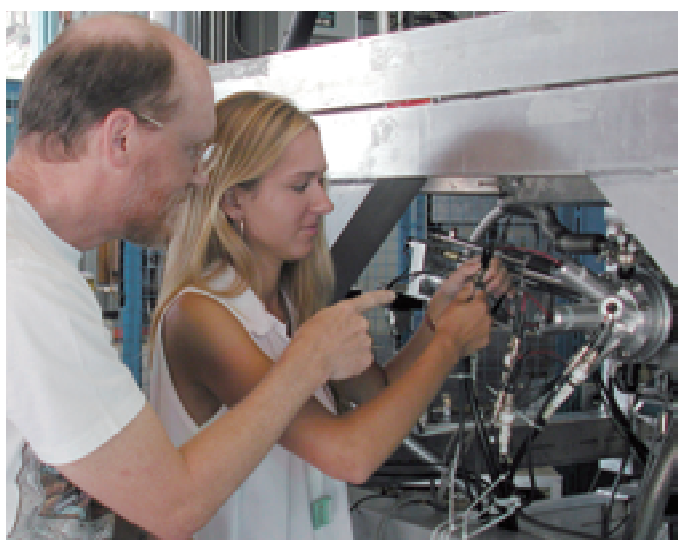


Figure 3: UBC Professor Jess Brewer working with Reka Moldovan of Kelowna, BC during her High-School Fellowship experience.

TRIUMF approaches outreach from many directions: as a creator of content linking the excitement of TRIUMF's curiosity driven research to the high-school classroom; as a facilitator, providing teachers unique tools to teach their students about fundamental science; and as a communicator, telling students, teachers and the public about the scientific, social, and economic impacts a fundamental research laboratory like TRIUMF has on Canada.

Partners

In Canada: British Columbia Association of Physics Teachers, British Columbia Innovation Council, British Columbia Science Teachers Association, Canadian Association of Physicists, NSERC Promo Science, Perimeter Institute, University of British Columbia, Vancouver Foundation, and others. Internationally, a number of key laboratories are involved, often through the mechanism of the InterActions Collaboration.

TRIUMF's Role

TRIUMF supports one roughly full-time position as Outreach Coordinator. The majority of the effort in this program comes from individual staff members at TRIUMF who work within the Outreach Program framework to make contributions. In recent years, the Outreach Coordinator has been working closely with the newly created communications office.

Figure 4: Packed auditorium listening to one of TRIUMF's Saturday Morning Lectures.

4.3.2

Training and Educating Students

Introduction

An important and integral part of TRIUMF's mission is educating and training Canadians. The educational experiences that TRIUMF makes available to young Canadians are not available anywhere else in Canada. As a national and international laboratory for subatomic physics, TRIUMF provides research facilities and educational opportunities that no single university could provide. They are available to the entire Canadian university community. In return, TRIUMF gains intellectual and technical strength from its ongoing relationships with the university community's highly qualified, talented, and innovative faculty and staff as well as access to their students, the scientific leaders of the future. This synergy between TRIUMF and the Canadian universities benefits all of us, but most particularly benefits Canadian students.

TRIUMF has an ongoing commitment to education at all levels. Student programs target high-school students, undergraduate, and graduate students, as well as post-doctoral and research assistant positions. TRIUMF provides scholarships, on-site educational opportunities, and student-focused conferences and initiatives. As well as academically focused educational opportunities, TRIUMF provides training for technical and trades careers through co-op programs.

Co-operative Education and Summer Students

TRIUMF works closely with Canadian universities to provide work experience to undergraduate students, mostly through the Co-operative Education Program. There are three work terms per year: January–April May–August, and September–December. Universities that do not have year-round co-op programs are invited to submit student applications for the summer work term, providing an equal opportunity for a TRIUMF work-term experience to all Canadian undergraduate students.

Academic co-op students receive a salary commensurate with their academic and work experience. TRIUMF also pays the cost of transportation between the student's university and Vancouver, ensuring that the best students from across Canada are able to apply for a TRIUMF co-op position without the financial penalty of paying for transportation costs to and from Vancouver. Figure 1 shows the geographical distribution of students.

Educational opportunities at TRIUMF are not limited to university students. Highly qualified technical people are critical to the success of Canadian industry as well as scientific research. For many years TRIUMF, has supported a small co-op program for technical students from local colleges and technical institutes. TRIUMF itself produces highly qualified technical people. In high demand, some of these technical people may leave TRIUMF for positions in industry.

Between 2003 and 2008, 319 undergraduate students worked at TRIUMF: 73 worked in the spring term, 174 in the summer term, and 72 in the fall term. The students worked on a wide range of activities at TRIUMF, including participation in the building of beam lines, programming computers, synthesizing radio-pharmaceuticals, guiding facility tours, constructing and testing particle

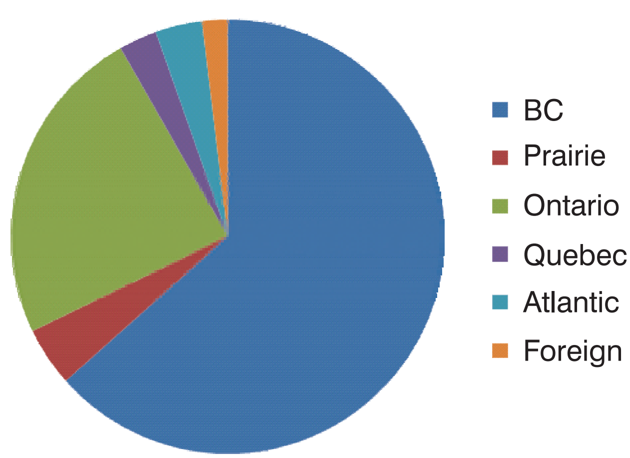


Figure 1: Distribution of TRIUMF co-op students by region of origin.

detectors, analyzing data, and working on electrical systems. The distribution of student activity by area of work is shown in Figure 2.

The summer students have the opportunity to learn about the wide spectrum of research that takes place at TRIUMF through special weekly lectures, specifically designed for undergrads by TRIUMF. This lecture series sets the TRIUMF co-op experience apart from others because it broadens the learning experience beyond the particular project on which each student is working.

During each summer co-op term, TRIUMF organizes a contest designed to teach students the presentation skills that will be necessary to their success in whatever career path they finally choose. The students are coached on the techniques and skills required for successful presentations and then compete with each other in presenting ten minute lectures on their TRIUMF project. The winner receives a scholarship to participate the Winter Nuclear and Particle Physics Conference at Banff, where he/she presents their paper. The opportunity for students from across Canada to get to know each other and develop networking and social relationships is also an important part of their work term at TRIUMF.

Employing co-op students benefits the employer as well as the students. Students bring new skills and points of view as well as enthusiasm and curiosity to their work. Patrick Bonnick (see Figure 3) is an example of this mutually beneficial relationship. Patrick was enrolled in the Chemical Physics program at the University of Guelph and had worked in a previous term at Bubble Technologies Inc., on gel detectors for nuclear radiation. Upon his arrival at TRIUMF, he was employed by the T2K neutrino group to help develop water-based scintillating liquid and gel detectors. The skills he learned at Bubble Technologies and the university lab were a key asset to the physicists directing the TRIUMF project. In turn, Patrick received encouragement, coaching, and instruction from TRIUMF's experts in this technology and hands-on experi-

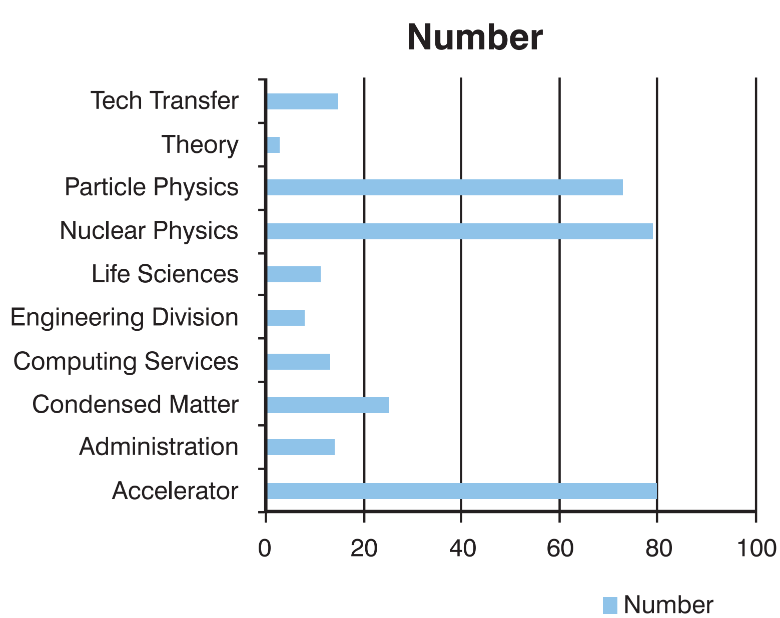


Figure 2: Distribution of TRIUMF co-op students by work topics.

ence in scientific state-of-the-art research. After completing two work terms at TRIUMF and successfully developing a scintillating gel, Patrick completed his B.Sc. in Chemical Physics and is now in the Department of Physics at Dalhousie University, doing graduate work on improving the efficiency of fuel cells.

In Patrick's words, "TRIUMF was easily the highlight of my undergraduate career. The opportunity to do cutting-edge research as an undergrad was unbeatable. By working alongside my supervisor, I developed all the skills you need to do research, but don't learn in school. I worked independently much of the time, and improved my own work ethic immensely…Our group also had weekly meetings, so I gained quite a bit of practice at presenting. Additionally, I participated in TRIUMF's summer presentation contest, which taught us proper presentation skills in a formal manner (*i.e.*, classroom setting). My experience [at TRIUMF] … ultimately led to my receiving an NSERC scholarship to perform my Masters at Dalhousie University."

Undergraduate Summer Research Awards

TRIUMF presents five prestigious Summer Research Awards annually to exceptional Canadian undergraduate students, one for each of the five regions of Canada. The scholarship program promotes subatomic physics research across Canada. In order to qualify, the applicants must have completed at least two years of an undergraduate program (or equivalent). One scholarship is awarded in each region: Atlantic, Quebec, Ontario, the Prairies, and British Columbia. The recipients work at TRIUMF for one term and receive the regu-

Figure 3: Patrick Bonnick during his work term at TRIUMF.

lar student salary, plus a $2,000 scholarship payable upon completion of a report on their term's research.

The scholarship program has been very successful in engaging students from universities who are not members of the TRIUMF joint venture. For example, prior to 2001, Saint Mary's University, Halifax, had a strong astrophysics program but only modest involvement with TRIUMF. With encouragement from the faculty at the university, summer, Sean McGee, a student from Saint Mary's applied for and won the TRIUMF Summer Research Award for the Atlantic Region in 2001. He chose to work on the DRAGON nuclear astrophysics program at TRIUMF. Upon returning to Saint Mary's, Sean wrote his B.Sc Honours Astrophysics thesis on his TRIUMF research and presented seminars on his work to fellow students and faculty. The following summer, two Saint Mary's professors, M. Butler and A. Sarty, visited TRIUMF and discussed starting a formal relationship between the institutions. Since then, Saint Mary's has joined the TRIUMF consortium as an associate member and has expanded its nuclear physics program by adding two new faculty members in nuclear physics, whose research programs are now centred at TRIUMF's facilities.

Graduate Students

Graduate students are a crucial component of TRIUMF's commitment to education. Students working on their Masters and Ph.D. degrees gain hands-on research experience at TRIUMF and learn to work in teams as part of a research group, a learning experience not often available at their university. Research performed at the graduate student level trains the scientists of the future.

In the period 2003–2008, the number of graduate students who completed theses based completely or partially on research performed at TRIUMF is summarized in the chart below.

Area	Ph.D	Masters
Subatomic Physics	65	126
Molecular & Materials Sciences	32	69
Accelerator Technology	1	3
Life Sciences	6	25

Table 1: Graduate students at TRIUMF from 2003-2008 by area of study.

The graduate students at TRIUMF come from Canadian universities and international universities and laboratories that use the research facilities of TRIUMF. Figure 4 shows the geographical distribution of these students. It is worth noting the strong representation from Canadian universities, though the majority of graduate students using TRIUMF facilities are from foreign countries. This is the hallmark of a laboratory with world-class facilities and an international reputation for excellence in both science and educational opportunities.

GRAEME LUKE

Professor, McMaster University

Graeme Luke received his B.Sc. in Engineering Physics from Queen's University in 1984 and his Ph.D. from UBC in 1988. While completing his Ph.D., "Quantum Diffusion of Positive Muons in Copper," at TRIUMF under the supervision of J. Brewer working at TRIUMF, he joined the first muon spin rotation experiments on the high-T_c cuprates.

After graduation, Dr. Luke moved to New York to start an NSERC post-doctoral fellowship at Columbia University. Over the next ten years, he continued his studies in high-T_c and other highly correlated superconductors. In 1998, he joined the Department of Physics and Astronomy at McMaster University. He also joined the Canadian Institute for Advanced Research Superconductivity Program, which has now evolved into a program in Quantum Materials.

Graeme currently studies superconducting states that are characterized by broken time reversal symmetry or, in other words, are intrinsically magnetic, which is usually forbidden for superconductors. Using the exquisite sensitivity of muon spin relaxation, he has illuminated the magnetic properties of these exotic superconductors. He has also begun studying the use of hydrostatic pressure to tune the electronic/magnetic ground state of various systems.

Dr. Luke's work on these extremely demanding experiments have, he feels, greatly benefited from the technical expertise of the TRIUMF-CMMS support staff.

Post-doctoral Fellows and Research Associates

Upon completion of their Ph.D.s, scientists at the beginning of their careers will often join a research group for a term of two to three years as a post-doctoral fellow (PDF) or a research associate (RA). This career phase is an important step to experience new and different scientific opportunities and acquire additional skills and experience. Researchers are then better prepared as they move toward career positions in academia, research, or industry. Between 2003 and 2008, TRIUMF was host to 88 PDFs and RAs. Many of these work full time at TRIUMF, while others spend most of their time at their home institutes and come to TRIUMF only for limited periods of time, usually when their research group has been allocated experimental beam time or they are building or preparing experimental equipment.

University Teaching

In addition to providing educational opportunities for students at TRIUMF, some of the scientific staff teach courses for some of the member universities. The proximal universities obviously have an advantage in this regard, but the video conferencing technologies now available have allowed some courses to be taught across Canada. TRIUMF scientist B. Jennings has taught courses on nuclear structure that were simultaneously available to the University of British Columbia and Simon Fraser University students as well as broadcast by video link to universities in Eastern and Central Canada. The video link allowed students from McMaster University, the University of Guelph, and Dalhousie University/Saint Mary's University to watch the lectures and ask questions in real time. This technology allows the teaching of courses in multiple institutions, permitting universities to provide educational opportunities that might not be possible for them because of small enrollment or lack of faculty to teach the course. This is an example of how a national laboratory like TRIUMF can use resources to benefit all of its member universities.

In addition, some TRIUMF research scientists have adjunct professor positions at member universities. These individuals are: J. Behr, J. Dilling, J. Ng, and S. Yen at the University of British Columbia; B. Davids, G. Ball, B. Jennings, and R. Woloshyn at Simon Fraser University; and H. Fearing and A. Olin at the University of Victoria. These adjunct positions allow the TRIUMF researchers to share their expertise by teaching courses and supervising graduate students.

University students have also benefited from field trips to TRIUMF for "hands-on" learning. In the fall of 2006 and again in 2007, the "Particle Detectors" class at the University of Victoria came to TRIUMF for a two-day learning experience using particles from the M11 beam channel, under the supervision of S. Yen. The students attended a lecture about the TRIUMF cyclotron and beam channels and then conducted experiments on particle identification, using time-of-flight and energy loss measurements. The students also studied relativistic mechanics by examining the velocity and momentum parameters of relativistic pions and muons, determining the pion mass, and measuring the lifetime of the pion.

Some courses taught by TRIUMF research scientists are listed in Table 2.

TRIUMF Summer Institute

Recognizing the important role that a national laboratory with extensive intellectual and physical resources can play in education, for the past 20 years TRIUMF has organized a summer course for graduate students called the TRIUMF Summer Institute (TSI). This two-week summer school is designed to provide graduate students and young researchers with an in-depth course covering one of the areas of research pursued at TRIUMF and elsewhere around the world. Local and international experts give the lectures and spend the two weeks with the students, answering their questions and fostering their interest in the research topic. Typically, the schedule provides three hours of

Date	University	Course	Title	TRIUMF staff
2002	UBC	Physics 505	Graduate Introduction to Nuclear Physics	S. Yen
2003	UBC	Physics 514	Electrodynamics	J. Ng
2004	UBC, Saint Mary's	Physics 505	Graduate Introduction to Nuclear Physics	S. Yen, J. Dilling
2004	UBC	Physics 526	Quantum Electrodynamics	J. Ng
2005	UBC, Dalhousie	Remote	Graduate Nuclear Structure	B. Jennings
2005	UBC	Physics 508	Quantum Field Theory	J. Ng
2006	SFU	Physics 390	Introduction to Astrophysics	B. Davids
2006	UBC/SFU (at TRIUMF)	Phys 522/842	Modern Techniques for Nuclear Science	J. Behr, L. Buchmann, J. Caggiano, J. Dilling, J. Ressler
2006	UBC	Physics 528	Elementary Particles	J. Ng
2006	UBC	Physics 505	Graduate Introduction to Nuclear Physics	J. Behr, S. Yen
2007	UBC	Physics 508	Quantum Field Theory	J. Ng
2007	UBC/SFU/Guelph/McMaster	Remote	Graduate Nuclear Structure	B. Jennings
2007			Fundamentals of Scientific Instrument Making	J. Lassen
2008	SFU	Nuclear Science 344	Nucleosynthesis and Distribution of the Elements	B. Davids
2008	UBC	Physics 508	Quantum Field Theory	J. Ng

Table 2. University courses taught by TRIUMF scientists.

lectures in the morning, and informal tutorials, problem-solving sessions, and discussions in the afternoons. Students have the option of participating in TSI for university credit, in which case homework is assigned and marked. A poster session is scheduled during the TSI to give students the opportunity to present their research and learn about the research their peers are doing.

The Summer Institute typically attracts about 40 students, mostly from Canada and the United States, with the occasional student from overseas. The topics of past Summer Institutes were:

- 2003: CKM and MNS: Quark and Lepton Mixings
- 2004: Nuclear Astrophysics: Experiment, Theory and Observations
- 2005: Atom and Ion Traps: Theory and Applications
- 2006: Collider and Energy Frontier Physics
- 2007: Radiation Detectors: Applications in Nuclear and Particle Physics and Medical Imaging

TRIUMF strongly encourages students to interact and learn from each other in informal settings with each other and the lecturers, so field trips and group activities are an important part of the TRIUMF Summer Institute. These events typically include ocean kayaking, volleyball games, a bike tour, or a barbeque. The TSI provides an excellent opportunity for graduate students to learn from the best experts in the world, as well as become acquainted with each others' research and build lasting friendships.

Winter Nuclear and Particle Physics Conference

The Winter Nuclear and Particle Physics Conference (WNPPC) is an annual conference aimed specifically at providing a forum for young researchers (students and PDFs). Formerly known as the Western Regional Nuclear Physics Conference, it has evolved into a national meeting for the Canadian subatomic

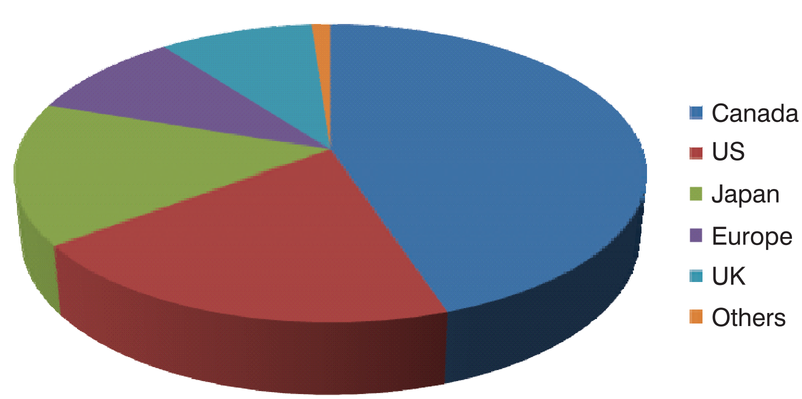


Figure 4: Distribution TRIUMF graduate students by region of origin.

physics community. WNPPC features both student presentations and invited talks by experts in the field. Awards are given to the top three student presentations. TRIUMF has been and continues to be involved in overseeing the organization and logistical support for this conference.

Students at TRIUMF Conferences

There is a strong focus on including students in TRIUMF-hosted national and international conferences. It is important for students to have the opportunity to interact with researchers and students from Canada and abroad, learn the information being presented at the conferences and learn to present their own research in a formal setting.

For example, during the Linear Accelerator Conference in the fall of 2008, a special poster session has been scheduled for students. The poster session will be held in conjunction with the welcome reception to ensure the greatest possible exposure for the students among the delegates. Prizes will be awarded for the best presentations, and the winner will be invited to give an oral presentation during the conference.

Most of the national and international conferences hosted by TRIUMF provide a subsidy or grant for student registration fees. Many laboratories and universities are reluctant to send students to conferences because they are not guaranteed a return on their investment to the same extent as they do with scientists. By providing student registration subsidies and grants, a large part of the expense for the universities and laboratories is reduced or eliminated, thus allowing more students to attend. In addition to a student registration budget, TRIUMF now encourages sponsorship of students by industrial vendors displaying their products at the conferences.

Many of these same initiatives will be in place for the Particle Accelerator Conference in the spring of 2009. In addition, for the first time, this large international conference will have a full student program including lectures and a dedicated student poster session.

It is evident that TRIUMF's many and diverse education initiatives are contributing to the creation of highly qualified people who will become the scientists, teachers and leaders that will have a major impact in the future of government, industry and academic institutions in Canada and abroad. TRIUMF pushes the frontiers of fundamental science with the use of innovative technologies and partnerships. TRIUMF's innovative approach to education and the creation of highly qualified people also pushes the frontiers of education in partnership with the Canadian universities and academic communities.

4.4

Generating Economic and Social Benefits

Introduction

Discoveries in fundamental physics research often result in major advances in technology that benefit society, from Lord Thompson's 1898 discovery of the electron to Sir Tim Berners-Lee's 1990 invention of key protocols for client and server to communicate via the Internet. The first discovery led to the commercial cathode ray tube used in older televisions; the second to the World Wide Web.

If fundamental research is to result in commercial applications, the commercial possibilities of the research must be recognized and extensive development efforts over many years are usually required before the project is ready for the marketplace. TRIUMF has developed a successful, internationally recognized program for the development and transfer of the knowledge resulting from its research that translates into social and economic activity benefiting all Canadians. TRIUMF's "technology transfer" now encompasses a broad and diverse spectrum, ranging from the commercialization of viable technology opportunities to the outreach activities that transfer the knowledge behind the technology and foster understanding of the research performed at TRIUMF.

Since the establishment of the TRIUMF Business Development Plan in 1996, one of TRIUMF's mandates, as set out in the National Research Council (NRC) Contribution Agreement is "to maximize the economic benefits of the Federal Government's investments in TRIUMF to Canadian companies through pro-active technology transfer activities, contracts, and procurement policies." Over the past twelve years, TRIUMF has established itself as the most successful facility in Canada for the commercialization of technology arising from fundamental research.

TRIUMF has also contributed its scientific knowledge to high-value Canadian products now sold around the world. For example, twenty-four hours of every day, from Asia to Europe to North America, TRIUMF-designed and Canadian-built commercial cyclotrons are producing short-lived isotopes for medical imaging, diagnosis, and treatment of disease. At the TRIUMF laboratory, scientists, engineers, and technical personnel have made discoveries and advances that benefit Canada's medical, pharmaceutical, and agricultural industries. The world's satellite communications and terrestrial flights are safer and more reliable because of TRIUMF's ability to test radiation effects on electronic equipment.

TRIUMF's Technology Transfer Division (TTD) is responsible for the laboratory's commercial activities. It is the responsibility of the Technology Transfer Office (TTO) staff to ensure TRIUMF is accountable for, and complies with, the Federal Government's mandate to pursue "all financially and technically viable opportunities for commercializing technologies derived from the research at TRIUMF." In addition, the TTD is responsible for the Applied Technology Group (ATG), the highly qualified technical personnel who maintain and operate the on-site commercial cyclotrons for one of TRIUMF's major licensees, MDS Nordion.

Recent Results

The term "technology transfer" is the conventional term used to describe the movement of ideas, equipment, and people among institutions of higher learning, the commercial sector, and the public. The conventional approach to technology transfer is now evolving into the broader concept of "knowledge transfer," which describes the movement of knowledge, ideas, concepts, and techniques from a formative location, generally an institution of advanced education or a laboratory such as TRIUMF, to all areas of the social and economic environment. Over the years, TRIUMF has increased the number of its partnerships with businesses and organzations in Canada and around the world by applying the concepts of technology and knowledge transfer and now works with many different organizations on a commercial basis.

MDS Nordion

Among TRIUMF's many successes, the TRIUMF-MDS Nordion relationship is internationally recognized as a leading example of technology transfer from a research laboratory. In 1978, TRIUMF and the Commercial Products Division of Atomic Energy Canada Limited (AECL) signed an agreement to produce medical isotopes for AECL. The AECL Commercial Products Division became Nordion Ltd., which in turn was purchased by MDS, creating the company MDS Nordion, TRIUMF's current licensee in the production of medical isotopes. A first TR30 cyclotron was commissioned around 1992. In 2003, increasing demand for medical isotopes led MDS Nordion to invest $20 million in a new TR30 cyclotron and related infrastructure, including buildings, on the TRIUMF site. MDS Nordion currently has three operating cyclotrons at the Vancouver site, supplying over 50,000 doses of medical isotopes a week for the diagnosis and treatment of disease (see Section 3.3). MDS Nordion employs 62 full-time staff and contracts with TRIUMF for an additional 35 highly qualified technical and professional staff to maintain and operate their cyclotrons. The demand for medical isotopes is projected to rise as diagnostic techniques improve and screening capabilities increase, and TRIUMF and MDS Nordion are prepared to meet the demand.

British Columbia Cancer Agency (BCCA)

TRIUMF and the BCCA have a long-standing partnership. In 1996, BCCA and the Woodward's Foundation made TRIUMF their facility of choice to construct the only Proton Therapy Facility in Canada. This facility is designed to treat ocular melanomas, a potentially life threatening cancer. As of May 30, 2008, 134 patients from Canada and the US have been successfully treated at TRIUMF's Proton Therapy Facility.

In addition to the Proton Therapy Facility, TRIUMF is provides BCCA with florine-18 to use in its new positron emission tomography/computed tomography (PET/CT) scanner. The scanner is used for clinical medical imaging for the diagnosis and treatment of cancer. A PET/CT machine contains both PET and CT cameras, producing images that show both chemical (functional) and anatomical (structural) information. The scanner has the ability not only to identify cells with a high metabolism that may be cancerous, but also to show the size and location of these cell groupings. In 2005, the PET/CT scanner was installed in the BCCA's Centre of Excellence for Functional Cancer Imaging but needed a regular and assured supply of the isotope ^{18}F to perform the clinical trial work. The ultimate goal of the BCCA is to acquire and operate its own PET cyclotron and radio-pharmacy but setting up a dedicated PET pharmacy is a long and complex task. In May 2005, the BCCA and TRIUMF entered into a supply agreement for the isotope ^{18}F. The initial one shipment per day has increased to two shipments, and the BCCA goal is to perform 3,000 scans per year on an ongoing basis. From inception until March 31, 2008, it has performed 6,202 scans.

Canadian Space Agency

In the late 1990s, the Canadian Space Agency approached TRIUMF to develop a proton irradiation facility (PIF) to conduct tests on the radiation hardness of space equipment. The PIF facility has been extremely successful and now includes a neutron irradiation facility (NIF) for terrestrial equipment testing, both of which are described below. TRIUMF's success with the Canadian Space Agency has attracted major and diverse industrial customers from Europe and North America including, among others, CISCO Systems, Sandia National Laboratories, Boeing, NASA, CEA, MD Robotics, Argus Tech, QinetiQ, Lockheed Aerospace, Goodrich and IROC. Testing of materials and products is done on a fee-for-service basis unless the researcher has received approval from one of TRIUMF's Experiments Evaluation Committees.

Proton Irradiation Facility (PIF)

TRIUMF's PIF facility is a truly unique facility for radiation testing of electronic devices and components with protons. The energy range of the TRIUMF 20 MeV to 500 MeV H^- cyclotron matches the proton energies that are of most concern for electronics used in space, and this range of energies is not available at any other single accelerator laboratory in the world.

All equipment sent into space is subject to much higher fluxes of protons and cosmic rays than at ground level, and all electronic equipment, including computers, lasers, and motor controllers, must be checked for sensitivity to radiation. Radiation damage can occur from single event upsets, a problem caused by a single energetic particle interacting in the silicon device, or by an accumulation of radiation, called total dose damage. In addition, there are a number of different types of radiation (gamma rays, electrons, protons, neutrons, heavy ions) and electronic equipment will respond differently to each type of radiation. The PIF facility at TRIUMF makes use of two beam lines, which enter the same test area, one covering the energy range from 65 M3V to 116 MeV and the other from 180 MeV to 500 MeV. Lower energies can be obtained by using variable thickness plastic degraders. The TRIUMF PIF facility can deliver the typical ten-year radiation dose for the International Space Station in ten minutes, or more slowly if desired. The testing results in significant cost savings to the users.

Neutron Irradiation Facility (NIF)

Atmospheric radiation, caused by cosmic rays from space interacting with Earth's atmosphere, consists of neutrons and other particles that can also interfere with the functioning of electronic devices. TRIUMF's Neutron Irradiation Facility (NIF) offers a neutron beam that simulates exposure to atmospheric radiation and can be used for testing avionics and ground-based electronic systems. The NIF has an energy spectrum matched to the atmospheric neutron spectrum, and can simulate the radiation effects of ten years of atmospheric exposure in a matter of minutes. The facility's neutron flux, or the number of neutrons per square centimeter per second passing through a material, is comparable to that at the Los Alamos Neutron Science Center (LANSCE) in New Mexico. The neutrons produced at TRIUMF have energies up to 400 MeV, with the additional feature that thermal neutrons from the water moderator are also present. TRIUMF and Los Alamos are the only two facilities in North America that offer such a wide range of neutron energies.

Innovative Diamond-Like Carbon (DLC) Foils

Carbon foils are used at particle accelerators as extractor or stripper foils and, as such, are important to many of the experiments and production activities that take place at TRIUMF. Triggered by an interruption in foreign suppliers, two TRIUMF scientists invented a process to make them in-house, using a well-known process called "carbon arc deposition," that offered a dramatic (and now patented) improvement on the devices. The process involves the sublimation of a material, in this case amorphous carbon, onto glass slides, so that a film can be deposited and removed easily and afterwards used to extract beams. In their attempt to find an adequate film for MDS Nordion's cyclotrons, these two scientists, along with a colleague from Texas, discovered the benefits of layering foils in a sandwich-like manner with diamond-like carbon in the centre of two amorphous carbon layers.

With this new technique, the laboratory can construct various types of film. Not only can the scientist using the film change the number and order of the layers, he/she can also change the relative thickness of the layers according to the desired performance of the composite film. Typically, thin foils can be made to measure 5 $\mu g/cm^2$ to 100 $\mu g/cm^2$; however, the new foils made at TRIUMF are at an astounding weight of 200 $\mu g/cm^2$ to 300 $\mu g/cm^2$. Other benefits of using diamond-like carbon foils include extreme hardness, optical transparency, chemical inertness, and high-wear resistance, all of which enable longer foil lifetimes. Because the film is more durable, the replacement time diminishes, allowing decreased radiation exposure to maintenance personnel and lower foil replacement costs. Having these higher-quality foils also allows researchers to use higher beam densities in their experiments while causing less graphitization of the carbon in the foil.

Official patent applications have been filed for this technology, and there is now strong commercial interest from isotope producers and accelerator manufacturers. Given the performance characteristics of DLC films and the current market conditions, they are expected to capture the majority of the market share within several years. Commercialization of DLC extractor films will establish Canada as the undisputed leader in the micro-niche market for extractor foils, and other uses for the manufacturing technique are being investigated and may lead to much larger markets. Possible future applications include nuclear medicine, PET centres, the radiopharmaceutical industry, and laser ablation techniques.

D-Pace

In 1995 Dr. M. Dehnel was a graduate student at TRIUMF writing a Ph.D. thesis on charged particle physics. The thesis led Dr. Dehnel to the idea of designing and manufacturing a variety of diagnostic devices for commercial and laboratory beam line injection systems. Dehnel – Particle Accelerator Components and Engineering, Inc. (D-Pace) is a rapidly growing Canadian supplier of the latest cyclotron components and peripherals, and a good example of an innovative Canadian company based on the licensing and transfer of technology from TRIUMF.

D-Pace has doubled its sales every year for the past several years. With customers from Chicago to Seoul, D-Pace, along with TRIUMF, is recognized worldwide as a supplier of technologically advanced, physics-related products. Customers of its semiconductor industry products include: Bristol-Myers Squibb (USA), CERN (Europe); Daiichi Radioisotope Laboratories Ltd. (Japan); the Institute of Nuclear Energy Research (INER, Taiwan), Thales Corporation (France), and Tyco-Mallinckrodt (USA). D-Pace recently formalized a preferred supplier status with Thales for several TRIUMF licensed products.

Other Partnerships

In addition to the partnerships mentioned above, TRIUMF routinely works with or assists other organizations in many capacities. These collaborations can often lead in directions not originally foreseen by either TRIUMF or the company we are working with. One of many examples is a Vancouver company, UMA Engineering, who has worked with TRIUMF on several projects, including the construction of the ISAC-I and ISAC-II experimental buildings. UMA gained a knowledge and expertise working with TRIUMF which they were able to use to successfully bid on Project Management contracts for laboratories in many parts of the world, including the Canadian Light Source (CLS), and laboratories in North Carolina, Hawaii, and Australia.

In other examples, TRIUMF is playing a leadership role in the international collaboration of the experimental physics and industrial control system (EPICS) and hosting the 2009 meeting. Research at TRIUMF also contributed to the development of the EXTREMA general-purpose graphics and analysis package. EXTREMA is a powerful visualization and data analysis tool that enables researchers to distill quickly large, complex data sets into meaningful information; it is in widespread use around the world.

TRIUMF is also a facility with a broad reach and a strong social conscience and many groups approach TRIUMF for assistance with physics related problems. Solving these problems does not necessarily translate into economic benefit for TRIUMF, but does provide social benefits to Canada. For example, recently the Royal Canadian Mounted Police detachment in North Vancouver developed a problem with their vacuum metal deposition chamber, an advanced fingerprint coater that uses vacuum technology. It is the only one in Western Canada and several court cases were dependent on results from this equipment. The RCMP contacted TRIUMF for assistance. The laboratory provided and installed a spare pump to keep the chamber operational; TRIUMF staff volunteered to quickly repair the pump and vacuum chamber and continued to liaise with the detachment to maintain the pump and vacuum chamber until they were fully operational.

Evaluating Performance

TRIUMF has adopted an approach to performance metrics based on output rather than input. TRIUMF focuses on achievements instead of effort expended and measures its knowledge transfer activity with quantifiable economic metrics. In addition to those commonly used by other publicly funded research organizations, TRIUMF strives to use innovative measures of effectiveness. Although these metrics do not have an obvious impact on revenues, they indicate the effective transfer of knowledge resulting from TRIUMF activities.

In addition, TRIUMF has developed an increasingly sophisticated set of metrics to monitor its contribution to commercialization and economic development. Table 1 shows 17 such statistics that are being collected. In evaluating the targets, it is important to remember that TRIUMF is primarily a facility for fundamental research in sub-atomic physics. Unlike commercial enterprises, TRIUMF does not produce “research products” at a constant rate, or with a constant rate of growth. If a target is either under- or over-achieved in one year, it should not be assumed that this has any implication regarding the possibility of under- or over-achieving in the following year.

Item	Description		2001/2002	2002/2003	2003/2004	2004/2005	2005/2006	2006/2007	4 Year Total
1	Dollar Value of Sponsored Research for the Year	TARGET	$10,000,000	*$10,000,000	*$11,000,000	*$11,000,000	$6,000,000	$6,000,000	
		ACTUAL	$4,783,305	$6,078,010	$5,605,575	$6,578,992	$5,601,572	$5,766,630	$23,552,769
2	Number of Disclosures During the Year	TARGET	15	*15	*16	*16	10	10	
		ACTUAL	14	11	12	7	4	6	29
3	Number of Disclosures Reviewed During the Year	TARGET	4	*4	*5	*5	9	9	
		ACTUAL	2	3	9	6	3	6	24
4	Number of Disclosures Funded During the Year	TARGET	2	*2	*3	*3	5	5	
		ACTUAL	2	2	0	3	3	3	9
5	Value of Funding for Disclosures During the Year	TARGET	$25,000	*$25,000	*$30,000	*$30,000	$60,000	$65,000	
		ACTUAL	$13,000	$28,000	$0	$60,000	$60,000	$17,000	$137,000
6	Number of Patents Applied for During the Year	TARGET	5	*5	*6	*6	8	9	
		ACTUAL	5	12	8	13	15	35	71
7	Number of Patents Granted During the Year	TARGET	2	*2	*3	*3	5	6	
		ACTUAL	2	8	12	3	2	11	28
8	Value of Purchase Orders Placed by TRIUMF in Canada During the Year	TARGET	$18,000,000	*$18,000,000	*$20,000,000	*$20,000,000	$12,000,000	$12,000,000	
		ACTUAL	$25,013,874	$28,304,164	$14,327,977	$13,727,400	$11,450,338	$14,040,118	$53,545,833
9	Value of Purchase Orders Placed by TRIUMF in Foreign Markets During the Year	ACTUAL	-	-	$7,315,642	$8,201,214	-	$6,410,518	
10	Number of Start-up Companies During the Year	TARGET	1	2	2	3	2	2	
		ACTUAL	1	0	0	0	0	0	0
11	Number of Spin-out Companies During the Year	TARGET	1	*1	2	*2	2	1	
		ACTUAL	1	0	0	0	0	0	0
12	Number of Licenses Granted During the Year	TARGET	3	4	5	6	3	2	
		ACTUAL	3	1	0	0	1	1	2
13	Cumulative Number of *Active Licenses	TARGET	*9	*10	*11	*12	14	16	
		ACTUAL	5	11	9	9	9	10	37
14	Royalty Income for the Year	TARGET	$500,000	*$500,000	*$600,000	*$600,000	$1,200,000	$1,250,000	
		ACTUAL	$427,819	$694,414	$1,070,000	$1,402,995	$1,307,900	$833,459	$4,614,354
15	Contract Income for the Year	TARGET	$100,000	*150,000	*$150,000	*$200,000	$150,000	$250,000	
		ACTUAL	$208,000	$144,106	$98,000	$80,000	$776,832	$880,707	$1,835,539
16	Value of TRIUMF Sponsored Canadian Conferences during the Year	TARGET	*$1,000,000	*$1,500,000	*$1,500,000	*$1,500,000	$800,000	$800,000	
		ACTUAL	$227,100	$774,900	$488,800	$1,117,600	$1,689,600	$1,169,600	$4,465,600
17	Number of Industrial Alliances During the Year	ACTUAL	-	-	-	-	-	48	48

Table 1. Performance versus targets for the years 2002 to 2007.

Purchase Order Analysis 2006/2007

TRIUMF's purchasing has a direct impact on the Canadian economy. Figure 1 summarizes TRIUMF's total purchases, excluding expenditures on power and construction funded by the provincial government. TRIUMF's procurement policy gives preference to Canadian vendors, but only if price and quality are comparable. Given the highly specialized nature of certain purchases, foreign supply is sometimes the only viable option.

Commercial Revenues

During the period 2005 through 2010, it is projected that annual commercial revenue to TRIUMF, in Canadian dollars, will increase from \$1.1 million to \$2.5 million. Based on its success to date, by 2010 TRIUMF is projected to have received total cumulative commercial revenue approaching \$25 million. The yearly breakdown for 2003-2008 is given in Figure 2.

The growth in annual commercial revenue to TRIUMF from 2005 through 2010 suggests that, by fiscal year 2009/2010, TRIUMF is projected to generate over \$2.5 million of total commercial revenue. This represents a 25% return on the approximately \$10 million annual research budget and a 5.7% return on the \$44 million annual investment from the federal government. This level of return places TRIUMF performance in the top grouping for universities and fundamental research institutions in Canada and around the world.

Accumulation and Protection of TRIUMF's Intellectual Property

Beginning with two patents 15 years ago, TRIUMF now has over 50 patent families and more than 150 patents in process worldwide (see Figure 3). This significant increase in patents has led to a systemized approach in evaluating scientific or technical disclosures with commercial potential. After approval by a review panel, the innovation is processed for protection of the Intellectual Property (IP).

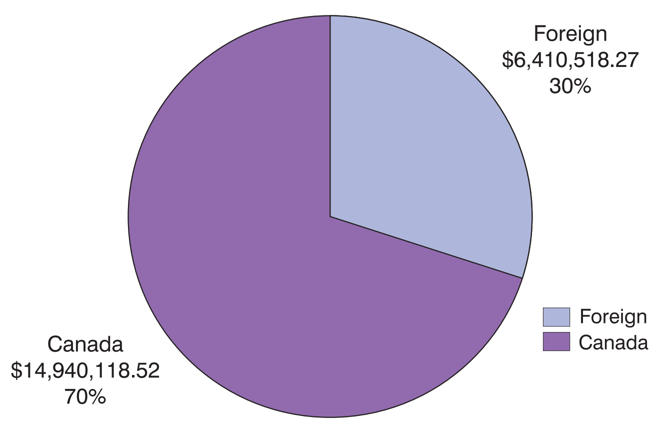


Figure 1: Purchasing Order Analysis – 2006/2007, by geographical location of selected vendor.

Awards and Recognition

Between 2003 and 2008, TRIUMF received several awards for its performance in transferring knowledge to industry and commercializing its technologies. In 2004, TRIUMF and MDS Nordion were awarded the prestigious Natural Sciences and Engineering Research Council of Canada (NSERC) Synergy Award for Innovation. The Synergy Award recognizes outstanding achievements in university-industry collaborations, and is judged on three criteria: partnership, effective use of resources, and tangible benefits. In 2007, TRIUMF again won the NSERC Synergy Award, this time with D-Pace, the Canadian supplier of accelerator components and peripherals.

In February 2008, TRIUMF's application to the Networks of Centres of Excellence for Commercialization and Research Program was successful, and Advanced Applied Physics Solutions, Inc. (AAPS), was awarded a C$14.95 million grant. The AAPS mission is to "improve the quality of life of people around the globe by developing technologies emerging from worldwide subatomic physics research." AAPS will collaborate with academic, government, and industry stakeholders to research and develop promising technologies to a commercially viable stage, including a new underground imaging system to improve productivity in the natural resource sector, and other technologies with a range of applications, including medical-isotope production and pollution mitigation.

Conclusion

Knowledge transfer extends beyond evaluating the quantifiable economic outputs of TRIUMF. It must include the numerous social and economic benefits that result from the laboratory's research. Measuring and recording the impact of research activities is becoming prevalent around the world, although in

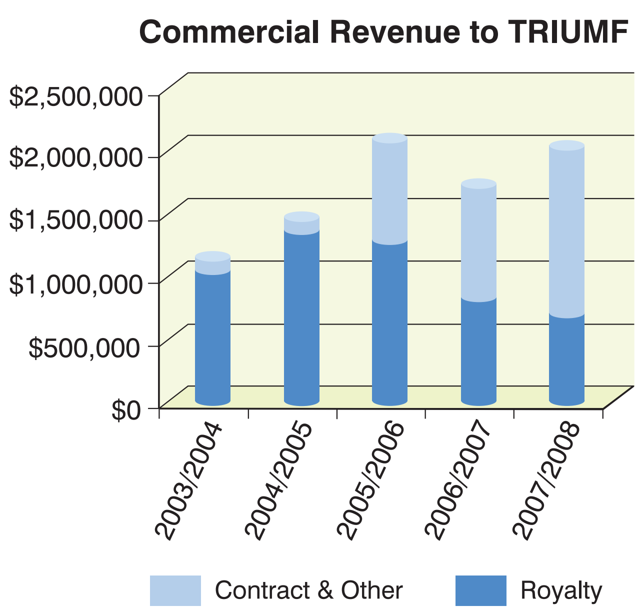


Figure 2: History of commercial revenues accumulated by TRIUMF.

many respects, the methods of measurement are still evolving. The TRIUMF approach described here is also evolving and will evolve still further in the years ahead.

Since the inception of the first Business Development Plan in 1996, TRIUMF has demonstrated the significant social and economic impact it has on Canada. The 2010–2015 Five-Year Plan builds on past successes to further expand the scope of TRIUMF's social and economic impact.

TRIUMF has an enviable record within Canada and internationally for its scientific achievements, its commercialization of technology, and the impact of the laboratory on Canadian society and the Canadian economy. The next five years will build on the achievements of the past to prepare for the future.

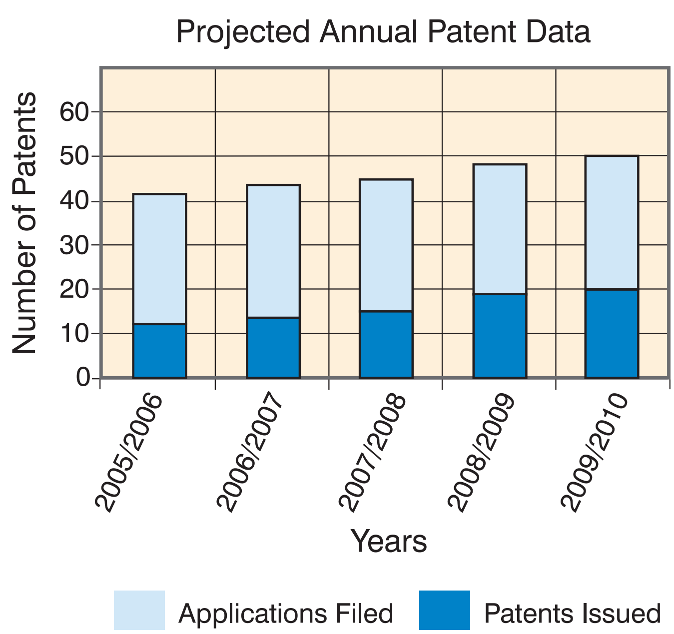


Figure 3: Annual number of patent applications filed and issued.

Chapter 5

Assets: Physical and Intellectual Capital

Chapter 5

Assets: Physical and Intellectual Capital

5.1

Introduction

TRIUMF's many important achievements (see Chapter 4) over the last five-year period were enabled by public funding from the provincial and federal governments and through the judicious use of all available resources: financial, intellectual, and physical. Similarly, TRIUMF's plans for the next five-year period (see Chapter 6) will be enabled by future funding and by continuing to build on the foundation of the current resources described in this section. These resources are a culmination of more than $C1 billion of public investments over the past 40 years coupled with the wisdom and experience of a highly trained staff with, at present, over 300 members. Taken together, these resources represent a formidable asset that can be deployed on key areas of the nation's research agenda.

TRIUMF's resources are very diverse but can be classified as follows:

Intangible resources:

- University partnerships
- International partnerships
- Commercial partnerships

Tangible resources unique to TRIUMF:

- Technically qualified people (technologists): cyclotron operators, specialized technicians, scientific computer programmers, other technologists.
- Hardware and infrastructure design for specific physics experiments: the accelerator, beam lines, detectors, detector development facilities, and other hardware.

Tangible resources not unique to TRIUMF, but key to its operation:

- Ph.D. scientific staff
- Senior management and administration
- Administrative and other supporting staff

TRIUMF's most valuable resource is its connection to the universities (see Section 3.1). TRIUMF has been successful and will continue to be successful only to the extent that it engages the university community. One clear example of this success is the awarding of the Canadian Association of Physicists 2008 Brockhouse Medal to the University of British Columbia's J. Brewer for pioneering μSR at TRIUMF.

TRIUMF also benefits enormously from its international collaborations.

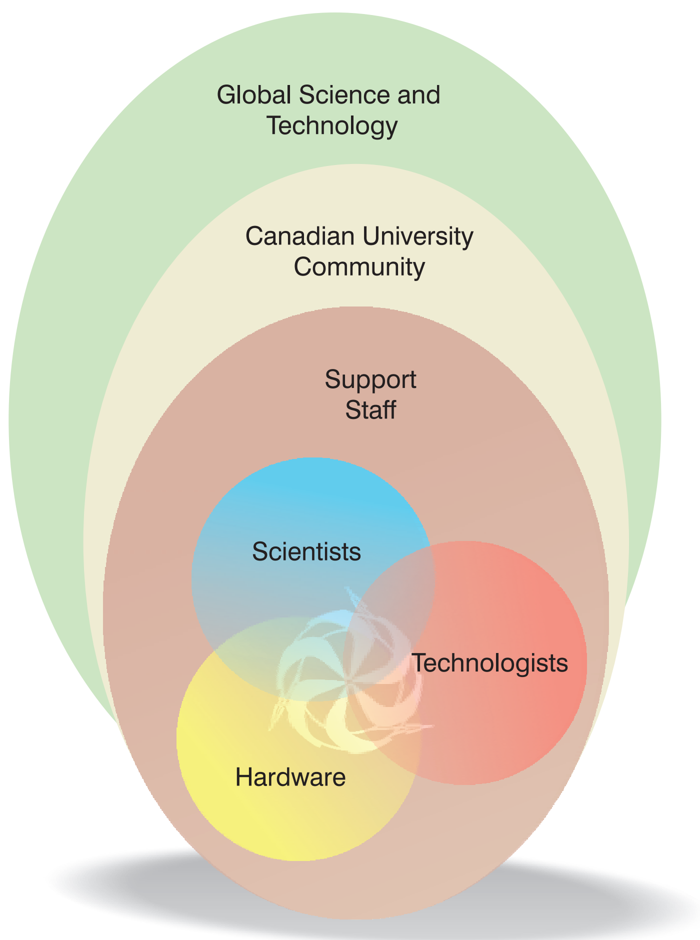


Figure 1: The yellow and red areas represent the TRIUMF unique resources (hardware and technologists), while the brown and blue areas represent the non-unique resources (scientists and support staff). The cream and green areas represent utilization of TRIUMF resources at the university and global levels.

TRIUMF's expertise, in areas like accelerator and detector development, is sought out by international collaborators who, in return, contribute their expertise to TRIUMF.

The collaboration with commercial enterprises also plays an important part in TRIUMF's success, providing TRIUMF with advanced technology. At the same time these collaborations allow Canadian companies to benefit from TRIUMF's accumulated expertise.

Section 5.2 discusses the highly skilled TRIUMF staff, which represents a key asset for Canada in the pursuit of national objectives in science, technology, and innovation. People provide the expertise to build, maintain, and operate TRIUMF facilities. TRIUMF's technologists have skills that simply are not available elsewhere in Canada and in some cases are very uncommon worldwide (see Figure 1). In addition to supporting the TRIUMF program, they are a unique resource for all Canada.

TRIUMF's scientific staff is not unique in the sense that universities also have scientists; however, the job description of a TRIUMF scientist is different from that of a university professor. The TRIUMF scientist can devote more of his or her time to research and has more knowledge of the other TRIUMF resources than outside users. They help set TRIUMF's priorities and provide a bridge between unique TRIUMF resources and the university community.

A comprehensive description of TRIUMF physical resources is given in Section.5.3, which details the accelerators, beam lines, detectors, and other facilities that are a part of TRIUMF. The facilities for the Centre for Molecular and Materials Science and for the Life Sciences program are given in the previous chapter in conjunction with their science results. TRIUMF has, on site, five cyclotrons (three operated for MDS Nordion), three linear accelerators, and a multitude of beam lines. Proton beams from the 500 MeV cyclotron are used to produce rare isotopes for ISAC and muons for the μSR program. The lower energy cyclotrons are used to produce rare isotopes for biological use. To use the particle beams, TRIUMF has many detector facilities; in ISAC-I alone there are six major detector facilities each with a dedicated beam line. There are another eight facilities for the μSR program. An overview of the TRIUMF site highlighting the different key areas of the program is shown in Figure 2.

Fundamental to the organizational success of TRIUMF's everyday operations are members of the senior administration and support staff. TRIUMF's structure for management and accountability is discussed in Section 5.4.

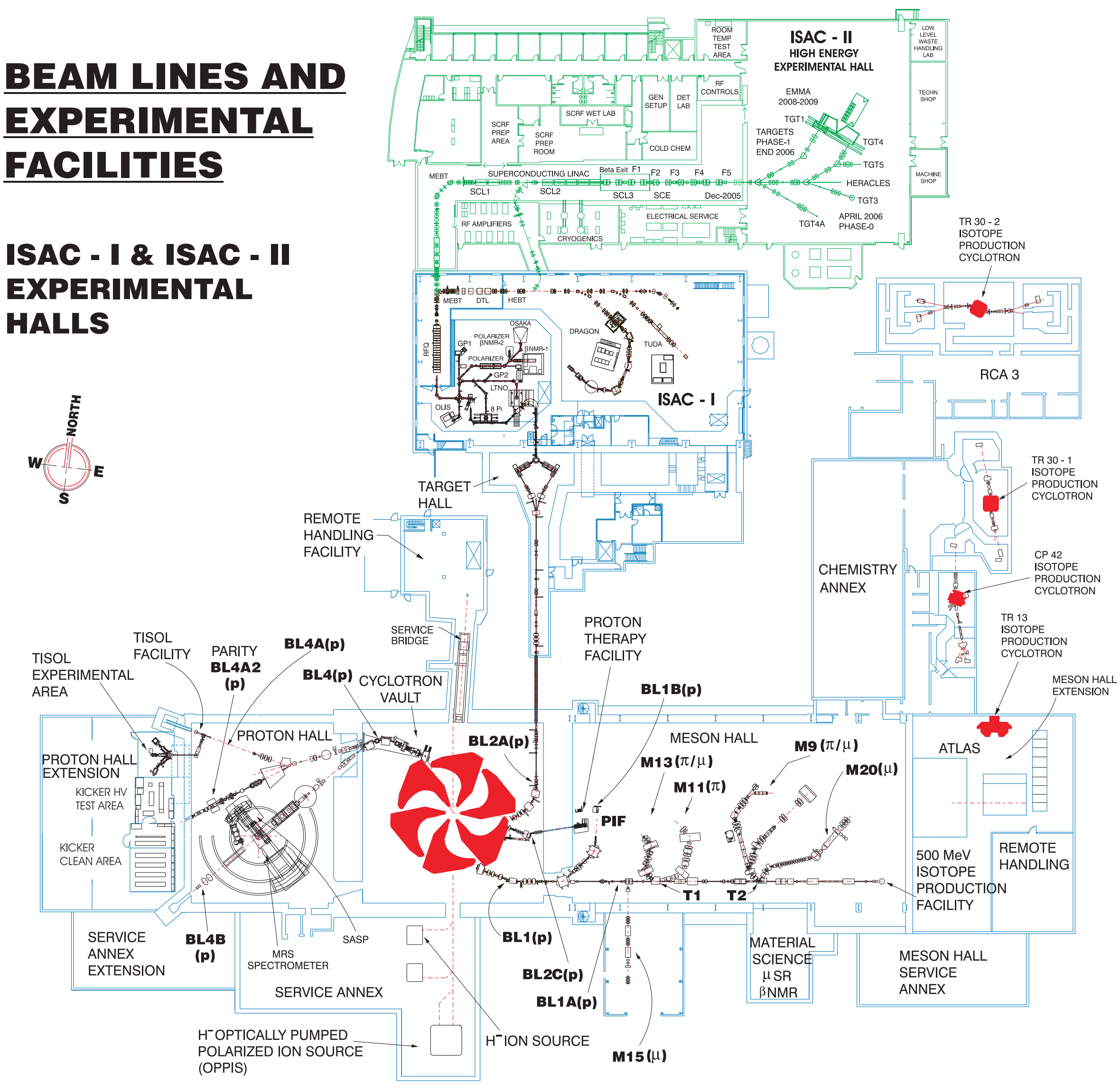


Figure 2. Schematic of the TRIUMF site showing the key experimental halls and resources. The cyclotron is the main engine of the laboratory. The ATLAS Canadian Tier-1 Data Centre is presently located in one of the power supply rooms of the ISAC-II building. The ISAC-II is outlined in green and was completed in the 2005-2010 five-year plan.

5.2

Expert Personnel

Over the 40 years of its existence, TRIUMF has assembled a core staff of approximately 350 people with a remarkably strong and diverse skill set. As Figure 1 illustrates, this skill set can be divided into four categories: scientific, engineering, technical, and support. The scientific staff, in collaboration with their university faculty colleagues, defines the scientific goals and manages the scientific challenges undertaken by the laboratory. The scientific, engineering, and technical staff provides the essential skills needed to undertake the extremely technical and complex tasks that allow TRIUMF to successfully achieve its goals and meet its challenges. The support staff provides a smoothly operating environment in which these goals will be met.

Scientific Staff

TRIUMF scientific personnel are primarily qualified at the Ph.D. level and represent about 17% of the laboratory's core staff. About one-fifth of the scientific staff are resident at Canadian universities, strengthening both TRIUMF's and the universities' intellectual and scientific abilities. Scientists from Canadian universities and laboratories, as well as institutions from abroad, visit TRIUMF for periods ranging from a few days or weeks to a year. These visitors also add to TRIUMF's intellectual and scientific strength and diversity. The list below illustrates the skills of the scientific staff. These skills naturally match the core research areas of the laboratory as well as provide a key resource for technology transfer to Canadian industry.

- Accelerator Physicists
- Chemists
- Experimental Physicists

- Medical Scientists
- Molecular and Materials Scientists
- Theoretical Physicists

Engineering Staff

TRIUMF's engineering personnel are primarily qualified at the B.Sc. level, but they do have a diverse skill set ranging from high power radio-frequency engineers to specialists with unique skills in, for example, magnet design, and construction. About one-third of the engineering staff are resident at Canadian universities. This situation strengthens both TRIUMF's and the universities' intellectual and scientific abilities, especially in the area of detector modeling and design.

- Accelerator Engineers
- Electrical Engineers
- Mechanical Engineers

Technical Staff

Technical personnel represent 65% of TRIUMF's core staff. TRIUMF's technicians, many of whom hold M.Sc. degrees or other technical degrees, are highly trained personnel with unique skills (see list below). This extensive and

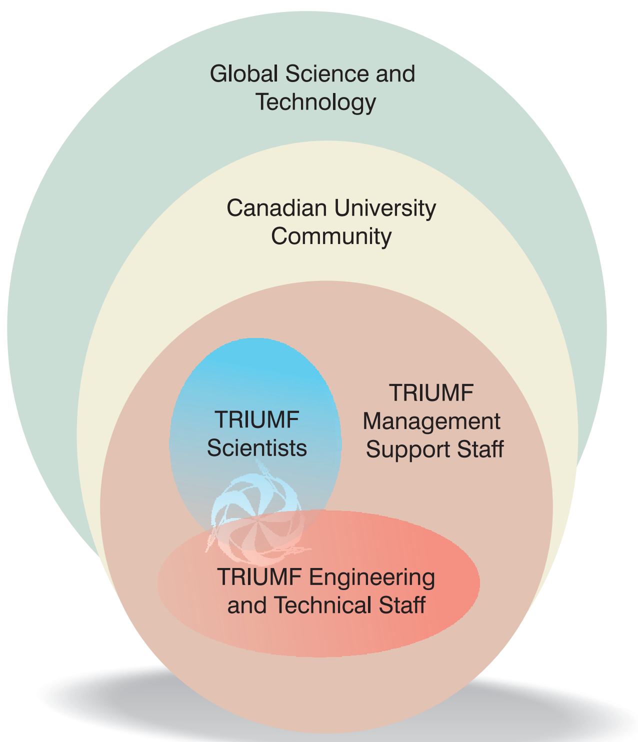


Figure 1: Simplified view of TRIUMF staff and the larger context.

diverse skill set allows technicians to operate effectively with TRIUMF's scientific staff and the university community.

TRIUMF technicians perform the extremely complex technical tasks required to successfully achieve the scientific goals of the laboratory, whether at the TRIUMF site, at other laboratories or institutions in Canada, or at laboratories abroad. Our technicians maintain, operate, and upgrade TRIUMF's infrastructure, which has a replacement value of approximately $C1 billion.

In addition to their responsibilities to the TRIUMF infrastructure and scientific program, TRIUMF's technicians are also responsible for the smooth and safe operation of the cyclotrons that produce medical isotopes for MDS Nordion Inc. TRIUMF technicians are integral to providing the BC Cancer Agency with isotopes used for clinical diagnostics and treatment as well as producing isotopes for the TRIUMF/UBC PET Centre for the study and treatment of Parkinson's disease and other neurological diseases.

The TRIUMF technical staff has also contributed their unique skills and talents to international collaborations. For example, at CERN in Geneva they have contributed to the construction of magnets, kickers, and control systems for the Large Hadron Collider accelerator system. Similarly, high power targets have been provided by TRIUMF to J-PARC in Japan. These contributions from the TRIUMF staff are highly valued by the international community and facilitate the participation of Canadian scientists in international experiments.

- Accelerator Operations
- Beam Lines
- Chemistry
- Controls Electronics and Software
- High Current Power Supplies
- High Power RF
- Ion Source Technology
- Lasers
- Magnets
- Nuclear Engineering and Accelerator Technology
- Positron Emission Tomography (PET)
- Radiation Detectors
- Remote Nuclear Handling
- Radiation, Nuclear, and Industrial Safety and Hazards Reduction
- Scientific Computing
- Specialized Electronics
- Specialized Mechanical Design
- Superconducting RF
- Technology Transfer

Support Staff

The TRIUMF's small but effective support staff, which makes up 19% of the total staff, provides and maintains the administrative infrastructure necessary for the efficient operation of the laboratory in several areas.

- Accounting
- Administration
- Human Resources
- Machine Shop
- Physical Plant
- Plant Engineers
- Purchasing
- Shipping and Receiving
- Senior Management
- Stores
- TRIUMF House Operations and Management

5.3

Accelerators and Experimental Facilities

5.3.1

Beam Lines and Beam Production

5.3.1.1

Main Cyclotron and Proton Beam Lines

Introduction

At the heart of TRIUMF is the 500 MeV cyclotron that produces the primary proton beams. A large fraction of the TRIUMF program relies on these beams. These include the ISAC, the Centre for Molecular and Materials Science programs in μSR and βNMR, and the Proton Treatment Facility. The operation of the main cyclotron has enabled TRIUMF to acquire the expertise to operate the three cyclotrons for MDS Nordion and the TR-13 cyclotron used to produce medical isotopes, and assist companies to exploit commercial opportunities for the sale of cyclotron and other accelerator technologies.

The 500 MeV Cyclotron

TRIUMF produces negatively charged hydrogen ions (H^-: 1 proton, 2 electrons) from an ion source. The ions are transported through an evacuated electrostatic beam line containing elements to focus and steer the beam over its 60 m to the cyclotron. The 500 MeV (million electron volts) variable energy cyclotron accelerates these ions with a high frequency alternating electric field and uses a massive six-sector magnet to confine the beam in an outward spiral trajectory. Inserting a very thin graphite extraction foil strips, or removes, the electrons from the H^- ion while allowing the proton to pass through. The proton, because it is a positively charged particle, is deflected in the outward direction due to the magnetic field and is directed to a proton beam line (see Figure 1). The accelerating process takes approximately 0.3 ms before the proton achieves three-quarters the speed of light.

The success of TRIUMF's programs depends on the ability to deliver protons from the cyclotron reliably. Typically, the cyclotron, although over 30 years old, averages an uptime of greater than 90% (2000–2007), with the 15-year average just under 90% (see Figure 2).

Typically the beam is delivered for about 5,000 hours per year with one major (three month) and one minor (one month) maintenance periods. The cyclotron beam properties and capabilities have improved over the years as a result of systems upgrades. The fundamental infrastructure providing the magnetic and electrical fields and the RF resonators as well as the vacuum vessel remain sound and will serve TRIUMF for many more years. In order to maintain and improve the accelerator facilities, TRIUMF has an ongoing refurbishment program that replaces old and obsolete equipment. This strategy has allowed TRIUMF to maintain the availability of the extracted beam steady at more than 90%.

The Four Primary Proton Beam Lines

TRIUMF has four independent extraction probes with various sizes of foils to provide protons simultaneously to up to four beam lines. Because of the high

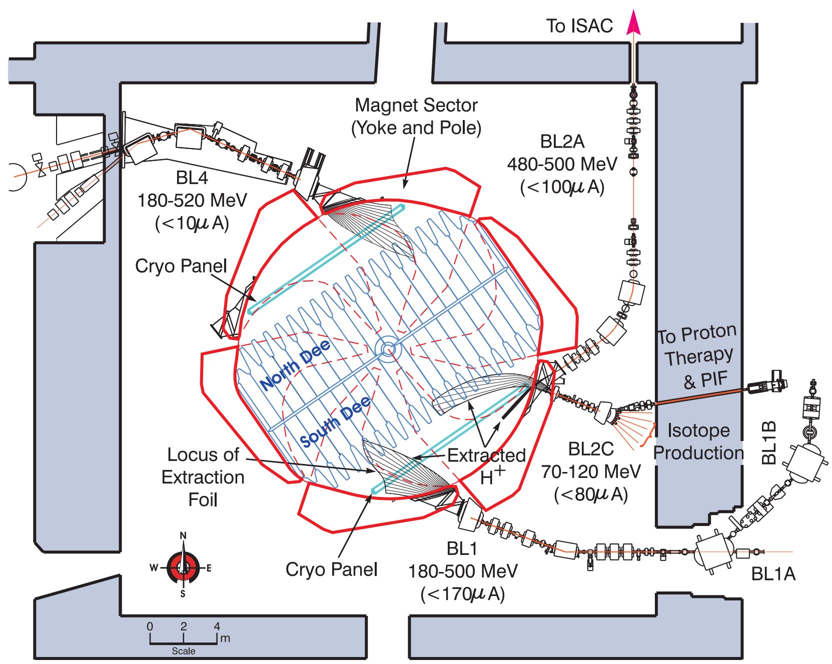


Figure 1: 500 MeV cyclotron and four primary proton beam lines: BL1, BL2A, BL2C, and BL4.

energy of the proton beam, these beam lines use magnetic rather than electrostatic focusing and steering elements.

Beam line 1A (BL1A) (see Figure 3) can deliver 180 to 500 MeV protons to two target systems. The beam power ranges from 50 to 75 kW. The first target, T1, services three experimental channels, one of which is used for detector tests for the T2K (Tokai to Kamioka) project. The second target, T2, services two μSR experimental channels. Downstream of T2 is a 500 MeV facility used to produce strontium isotopes for medical-imaging generators as well as the Thermal Neutron Facility (TNF).

Beam line 1B separates off BL1 at the edge of the cyclotron vault and provides international users with the Proton Irradiation Facility (PIF) that is used for radiation testing of electronic circuits, for example, mimicking space radiation for testing computer chips.

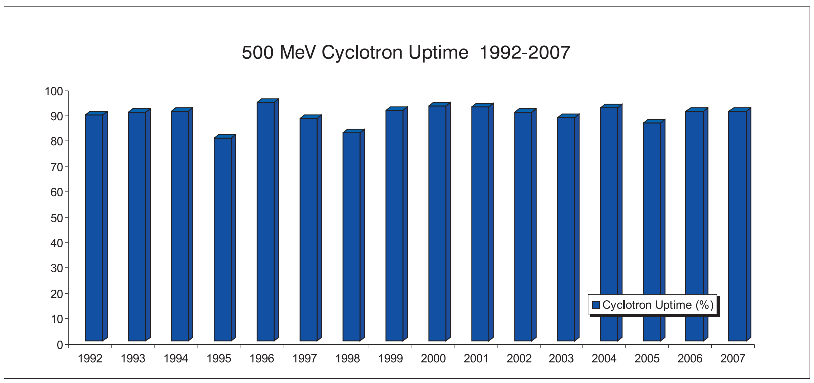


Figure 2: Cyclotron uptime as a percentage of scheduled operational hours per year.

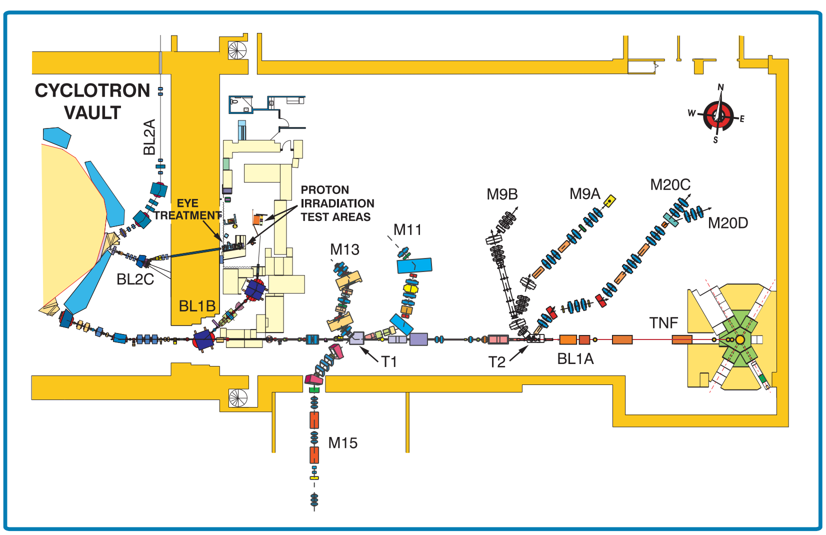


Figure 3: Schematic of BL1A, BL1B, and BL2C. BL4 is on the west side of the vault.

Beam Line 2A (BL2A) is capable of providing 475 to 500 MeV proton beams at up to 50 kW to the ISAC target facility that produces rare-isotope ion beams for a host of Canadian and international experiments.

Beam Line 2C (BL2C) is used for the Proton Therapy Program (PT) to treat choroidal melanomas (eye tumours) and proton irradiation to produce strontium isotopes, which are chemically processed and then used for medical imaging generators. This beam line also has the flexibility to provide protons of lower energy for PIF users. The energy range for this line is 70 to 120 MeV.

Figure 4 shows the percentage of beam delivered as a fraction of the amount of charge scheduled for BL1A. The 15-year average is 95%, although the cyclotron uptime during this period averages about 90%. Similar beam delivery efficiency is available for the ISAC facilities from BL2A.

Beam line 4 (BL4) in its present configuration can deliver protons of energy from 180 to 500 MeV, albeit at only 5 kW and was last used as a production facility in 2000 for the parity violation experiment. Other significant experiments on this beam line include charge symmetry breaking and TISOL, the TRIUMF Isotope Separator On-Line, the predecessor to the ISAC facility. An extension of this line, Beam Line 4 North (BL4N), will be used for the proposed ISAC expansion.

Summary

The 500 MeV cyclotron delivers four simultaneous proton beams for both production and test purposes. The total mAh charge has increased annually since ISAC came on-line in 1999. During this period, there has been no corresponding increase in downtime, which demonstrates the cyclotron's capacity to deliver increased beam currents (see Figure 5). The total charge delivered in 2007 was reduced by approximately 80 to 100 mAh due to the upgrade and recommissioning activities at the BL2C solid target facility. The total charge to BL2A (green) for ISAC has more than doubled in the past four years.

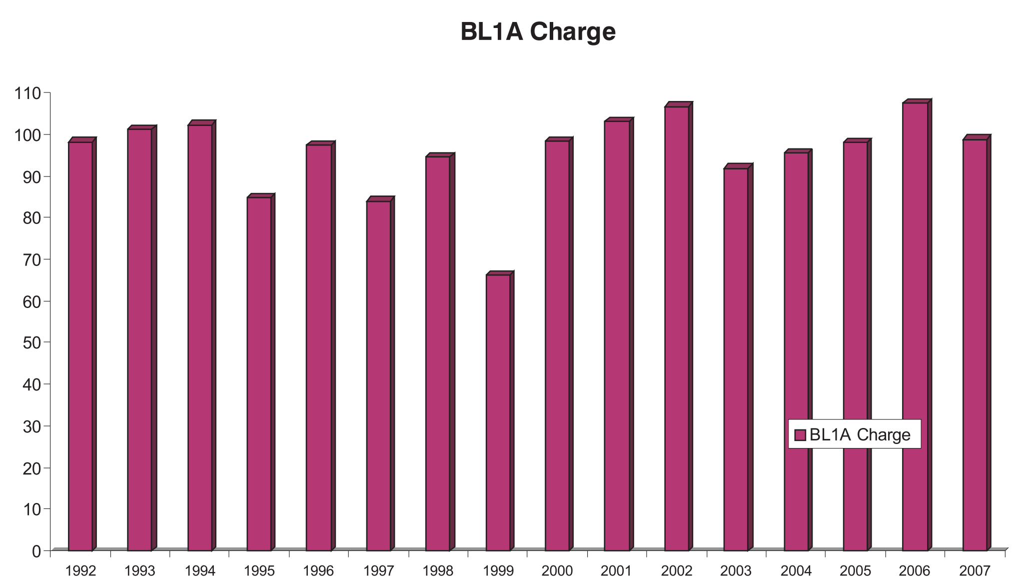


Figure 4: Beam delivered to BL1A as a percentage of charge scheduled per year.

Accelerator operation is proposed to expand in the 2010-2015 period to support new initiatives. The cyclotron intensity upgrade will allow increasing the extracted beam current to 300 µA. The new intensity would support beams for four beam lines: BL1A (for meson production), BL2A (for ISAC), BL2C (for strontium production), and the proposed Beam Line 4 North (BL4N) for ISAC expansion. Developments in support of high intensity operation were initiated in 1988; more recent development initiatives have demonstrated that accelerating to 300 µA over five years is a realistic and attainable goal.

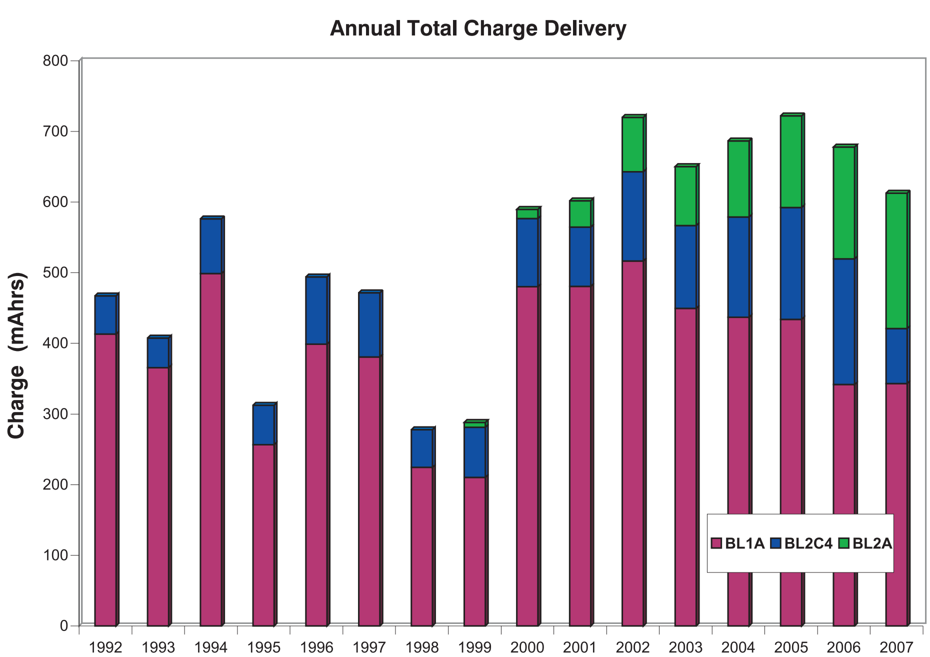


Figure 5: Total annual proton charge (mAh) delivered to three beam lines.

5.3.1.2

ISAC Target and Ion Sources Development

Introduction

The TRIUMF Isotope Separator and Accelerator (ISAC) facility uses the isotope separation on-line (ISOL) technique to produce rare-isotope beams (RIB). The ISOL system consists of a primary production beam, a target/ion source, a mass separator, and beam transport system. The rare isotopes produced during the interaction of the proton beam with the target nucleus are stopped in the bulk of the target material. They diffuse inside the target material matrix to the surface of the grain and then effuse to the ion source where they are ionized to form an ion beam that can be separated by mass and then guided to the experimental facilities.

When ISAC was launched in its first phase (ISAC-I), existing on-line target designs could only accommodate up to 2 μA incident proton beam intensities. From 2003–2008, TRIUMF developed techniques that allow operation of the ISOL target up to 100 μA at 500 MeV. Among the techniques developed, were a high-power target that is equipped with radial fins that can dissipate up to 20 kW and composite targets that allow a larger variety of target material, which in turn allowed the production of a larger variety of intense beams of rare isotopes.

The overall release efficiency (diffusion and effusion) depends strongly on the operating temperature of the target material. For this reason, ISAC uses mainly refractory, or high-temperature, metals such as Ta, Nb, and carbide foils for the target material. The development of composite carbide target is a breakthrough that permits the ISAC facility to produce rare isotopes with a larger target material inventory thus allowing us to produce intense rare isotope beams. The composite carbide target presently operates routinely at an intensity of 70 μA.

Because ISAC operates uniquely at very high proton intensity (beam currents), the development of the ion source in such an environment is a challenge. The hot surface ion source was the first ion source implemented at ISAC, followed by an electron cyclotron resonance (ECR) ion source, resonant laser ion source (TRILIS), and a forced electron beam ion arc discharge (FEBIAD) ion source. Because of the gas load from the target, the first ECRIS had very low ionization efficiency; a new type of ECRIS with improved electron confinement is under prototyping. The ISAC-II accelerator requires the injection of ion beam with higher charge-to-mass ratio to extend the mass range from $A \leq 30$ to 150. To do this, TRIUMF have developed a charge-state

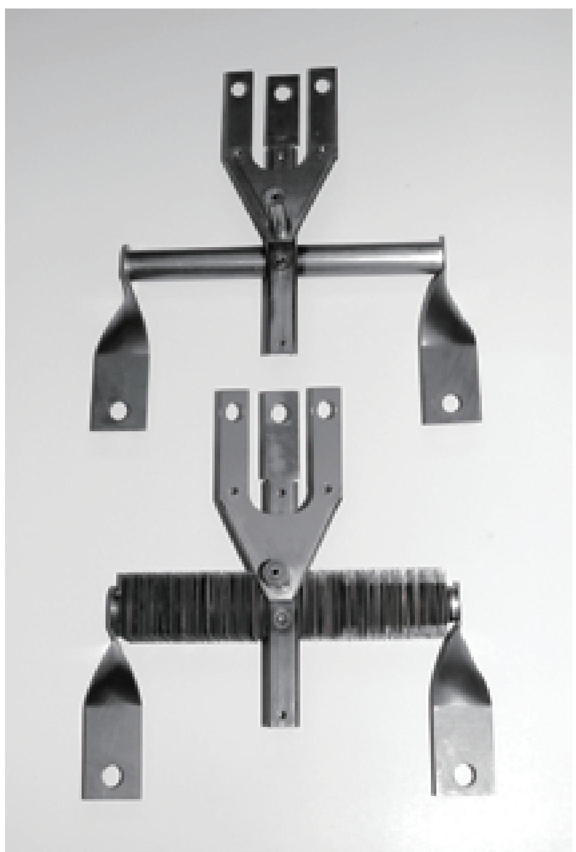


Figure 1. The ISAC target containers. The top photograph shows the normal target container that can dissipate up to 5 kW of proton beam power. The bottom photograph shows the high power version that can dissipate up to 20 kW of proton beam power.

booster (CSB) based on an ECR ion source. The device has been tested off-line, and TRIUMF is in the installation phase for on-line production during the summer 2008.

Off-line ion sources play an important role at ISAC because they are used to provide pilot beams for the accelerator tuning and for experiments. From 2003–2008, TRIUMF installed three types of ion source, which allow us to cover most of the periodic table. A new ECR ion source (SUPERNANOGAN from Pantechnik S.A.) is being installed, and it will improve the stable beam delivery by increasing the intensity and reliability of available stable beams.

Finally, polarized beams are being developed using a special facility. These polarized beams will be used for molecular and materials science experiments and nuclear physics research.

ISAC Production Targets

The major focus of target development at ISAC from 2003–2008 has centred on increasing operational p^+ intensity on targets by investigating high power target designs capable of using the full 50 kW of p^+ beam power available and developing composite foil target materials of high thermal conductivity to allow for higher p^+ currents on compound target materials such as SiC, TiC, ZrC and Nb_5Si_3 (see Figure 1).

ISAC High Power Targets

The high power target (HPT) design was developed by diffusion bonding radial Ta fins onto the standard ISAC target container. This surface modification increases the effective emissivity of the target surface from about 0.34 to 0.92 (a black body = 1.00) resulting in an increased radiative-power dissipation capacity. The HPT design was tested off-line between 2001 and 2003, and the first HPT was commissioned on-line in 2004. Since that time, HPTs of Ta metal foils and composite foil compound targets have been routinely operated with p^+ currents of up to 70 μA, double the intensity of standard ISAC target containers. During 2006, a HPT using Ta foil was operated at 100 μA intensity, the design limit of ISAC.

Composite Target Materials

Many rare-isotope beams are best produced from reactions on elements that do not withstand high temperatures. In such cases, refractory compounds of the elements in question (such as carbides, oxides, nitrides or borides) may exist that can be used as target materials. Initially, ISAC targets made of materials such as CaO and SiC were fabricated by pressing powders into pellets of ≤ 60% density. Due to the reduced thermal conductivity across the porous pellet and the poor thermal transfer between pellet rim and inner target container wall, the operational limit on p^+ intensity for SiC targets was ≤ 15 μA and ≤ 3 μA for CaO. To increase both internal heat transfer and to provide better thermal transfer to the target container, composite foil target forms of carbide ceramics were developed that mimicked the refractory (high-temperature) metal-foil target materials.

The composite foil fabrication starts with the desired carbide powders that are intimately mixed in a plenary ball mill with ~11% organic binders, plasticizers, and surfactants in either aqueous or non-aqueous solvents. The resultant slurry is slip cast onto sheets of flexible exfoliated graphite foil (0.13

mm thick). After solvent evaporation, the result is a flexible thin (~ 0.25 mm) layer of ceramic bonded to graphite foil. In the "green" form, the composite form can be cut to shape and inserted into the target container in a manner analogous to metal foils. The composite foils are cut slightly oversize to ensure good thermal contact with the target container wall, and the organic components are subsequently burned off during off-line sintering and conditioning of the target prior to irradiation. Ceramic layer densities of 50 to 60%, which are equivalent to what was previously achieved with pellet target forms, are routine. The thermal conductivity of the composite foils is a function of both the thermal conductivities of ceramic and graphite layers, and the high thermal conductivity of the graphite component allows increased beam power transfer.

With composite foils, the maximum p^+ current on SiC targets was increased to 35 µA. By using composite carbide/graphite forms of SiC, TiC, and ZrC in ISAC HPT containers, the operational limits of these materials have been increased to 70 µA. Table 1 shows an example of the combined development of the target material, target container, and ion source to deliver the required intensity for key experiments. In 2006, the technique was extended to a silicide ceramic when a composite target of Nb5Si3 bonded to 0.076 mm Nb metal foil was commissioned to 15 µA. The ongoing development of oxide/metal composites has seen the achievement of successful bonding of Al_2O_3 to Nb.

Isotope	Composite Graphite Target Material	Maximum Operating Current	Delivered Rate
^{26}gAl	SiC pellets	15 µA p^+	7.7 x 108/s
^{26}gAl	SiC/C_{gr} composite foils	35 µA p^+	3.8 x 109/s
^{26}gAl	SiC/C_{gr} composite foils in high power target	70 µA p^+	1.1 x 1010/s
^{26}gAl	SiC/C_{gr} composite foils in high power target with laser ionization	70 µA p^+	5.1 x 1010/s
^{62}Ga	ZrC/C_{gr} composite foils	35 µA p^+	2.9 x 102/s
^{62}Ga	ZrC/C_{gr} composite foils with laser ionization	35 µA p^+	9.6 x 103/s

Table 1: Beams developed using a combination of target and ion source development.

On-Line Ion Source

The on-line ion source is the set of systems used to extract and provide the rare isotopes produced in the target.

Hot-Surface Ion Source (SIS)

The hot-surface ion source was the first on-line ion source used at ISAC. Because of its simplicity, it has been the easiest ion source to use in the new high-radiation environment. The principle is quite simple, a high work function material such as Re is inserted into the transfer tube from the target container, which is operating at a high temperature of 2200ºC. The atoms with low ionization potential, such as alkali, are ionized with high ionization efficiency. It increases with the *Z* of the atom to reach nearly 100% for Cs and Fr.

Resonant Laser Ion Source

The second ion source that was installed on-line was the laser ion source (LIS). The principle of the LIS is the following: laser beams, usually three, enter into the transfer tube through a laser port in the pre-separator magnet. The laser beam pulses are synchronized to arrive at the same time in the ionization

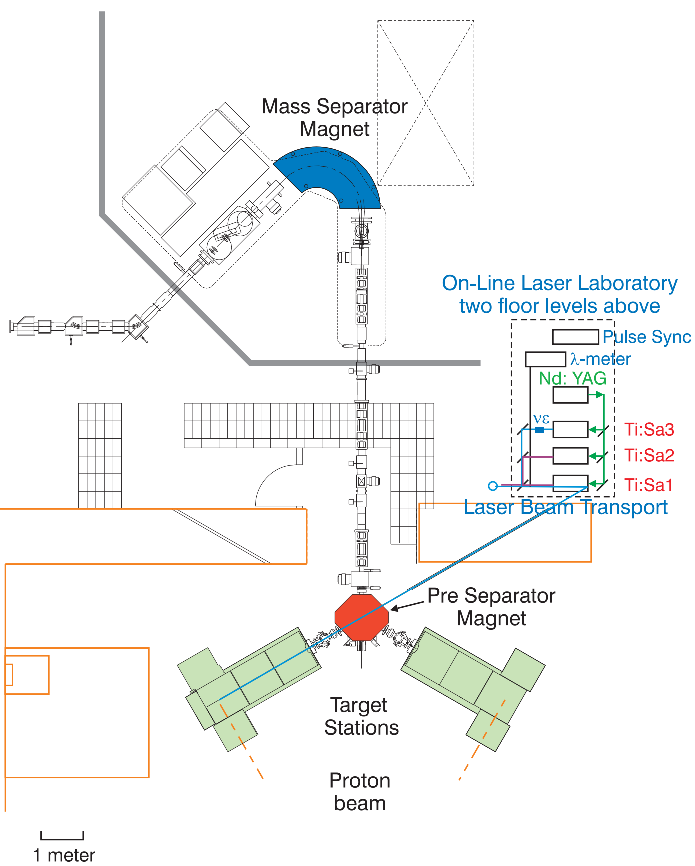


Figure 2: Layout of the mass separator showing the laser beams transport to the target transfer tube.

region. The repetition rate is such that each atom drifting inside the transfer tube sees at least one pulse of each laser beam. Such a resonant laser ion source operates by exciting an electron of a particular atom in multiple steps through a series of energy levels above the ionization potential. It is highly selective, in that resonant laser ionization only operates on a particular chemical element, which results in rare-isotope beams with minimal contamination.

The laser ion source utilizes the same hardware as the surface ion source. The laser beams are produced far from the high radiation environment of the target. Thus, the critical components of the ion source can be far removed from the high radiation area of the isotope production, allowing for ready access and serviceability while avoiding radiation damage to critical source components and minimizing the amount of material irradiated. The laser ion source is, therefore, ideal for on-line radioactive isotope production (see Figure 2).

In 2002, TRIUMF began developing a selective and efficient laser ion source for ISAC to expand the ISAC ion beams capabilities. The lab decided to employ state-of-the-art, all solid-state laser systems for a compact, low maintenance, high uptime laser ion source.

For a majority of elements, TiSa laser-based excitation schemes have been developed conceptually and are under investigation experimentally. By 2009, an independent LIS test stand for the development of laser ionization schemes will be operational. This test stand will allow direct transfer of developed ionization schemes to on-line production and facilitate rapid laser spectroscopy and development.

Overall, TiSa laser-based ionization scheme development is a collaborative effort within the TiSa network among several TRIUMF partners, including Mainz University in Germany, Oak Ridge National Laboratory in the United States, and the JYFL Laboratory in Finland. The success of the TRIUMF Laser Ion Source (TRILIS) as the only on-line, all-solid-state laser-based laser ion source is the basis for similar projects at GANIL in France as well as ORNL and JYFL. In our collaboration with Mainz University, TiSa lasers and laser applications for on-line facilities are continually being developed.

Plasma Ion Sources

For the elements that have a high ionization potential, such as He, B, C, N, O, F, Ne, etc., a surface or a laser ion source cannot be used. For those elements, we need to use a so-called plasma ion source. In this source, the plasma is generated using fast electrons that can be either produced by a forced electron beam induced arc discharge (FEBIAD), *i.e.*, a hot cathode or by an electron cyclotron resonant (ECR), a radio-frequency induced discharge ion source. Between 2003 and 2008, TRIUMF has been developing a FEBIAD ion source for the production of intense ^{18}F beams and a new generation of ECR ion source for on-line application.

FEBIAD Ion Source

TRIUMF has developed a FEBIAD to produce the F and Ne isotopes necessary for the nuclear astrophysics study of the proton capture reactions $^{18}F(p, \gamma)$ and $^{18}Ne(p, \gamma)$. The design is a combination of the Kirchner and Sundell FEBIAD types that were developed at GSI and CERN [R. Kirchner and E. Roeckl, Nucl. Instrum. and Methods 133, 187-204 (1976); and S. Sundell *et al.*, Nucl. Instrum. and Methods B70, 160-164 (1992)]. It is a very compact version that can be housed into the same volume as the usual ISAC target/ion source heat shield. The biggest challenge in designing any ion source for the ISAC facility is the extremely high radiation field produced at high proton intensity. It is very difficult to predict the behaviour of insulator material in such a harsh environment. For this reason, the prototypes were tested off-line.

In November 2006, the first prototype was installed on-line using a composite $TiC/C_{graphite}$ target. The main goal was to test the behaviour of the ion source under real conditions. Therefore, we operated the TiC target up to its maximum proton beam intensity, 70 μA. We produced several isotopes from ^{6}He to ^{45}Ar and demonstrated that the cathode, which is the weakest part of the ion source, could operate reliably for at least three weeks. During the test, we noticed a quick degradation of one of the insulators made from boron nitrite.

A modification of the insulators was made, and a second prototype was tested on-line in June 2007. This time, the ion source was combined with a high power composite $SiC/C_{graphite}$ target that was operated up to 70 μA proton intensity. During this development run, we produced $^{18}F^{+}$ for a $^{18}F(p,\gamma)$ measurement. In addition, the out gassing of the insulator was reduced, but the ionization efficiency decreased with time. Insufficient cooling of the magnets, which caused the axial magnetic field to degrade with time, caused this problem. The present prototype incorporates several up-grades: a radiation resistant electromagnet, a solid Ta grid to replace the W wires, and a water-cooled heat shield to protect the insulators. The electromagnet is made of a 6 mm x 6 mm copper conductor, insulated using the same fibrous material we used for the MISTIC ion source (see below). Calculation shows that, with 100 A and 16 turns coil, we can produce a 400 Gauss magnetic field in the centre of the plasma chamber. We have modified our design of the grid. This new grid is made from 1 mm thick Ta foil, and the slots are machined using a computer-controlled machine (see Figure 3). The grid transparency is 75%. A thick steel plate directly attached to a water-cooled copper plate is placed between the high power target and the FEBIAD ion source.

On-line tests during November 2007 were conducted using another high power $SiC/C_{graphite}$ target. The FEBIAD ion source produced 5.9×10^{7} $^{18}F^{+}$ per second, and the beam was used by the TUDA group for the $^{18}F(p,\gamma)$ radiative proton capture experiment. During that development run, we also produced ^{8}He for the high accuracy mass measurement with the new TITAN facility.

ECR Ion Source (MISTIC)

The demand for isotopes for the nuclear astrophysics program means that TRIUMF must be able to ionize, with high efficiency, the gaseous elements, C, N, O, F, Ne. These elements are ionized efficiently with an electron cyclotron resonance ion source (ECRIS).

An early version of an ECRIS operating at 2.45 GHz was first tested with stable beams in ISAC in the summer of 2002. In 2003 and 2004, we discovered that, during subsequent tests with various modifications to improve the performance, the pressure required to operate the ion source was not compatible with on-line operation. As a result, we started a different ECRIS approach that should be able to operate on-line under the nominal pressure from the heated target. After the initial test in 2007, with stable beams and on an ion source test stand, we decided to improve four aspects: the electron confinement, increasing the frequency from 4 to 8 GHz, lowering the gas pressure, and using a movable extraction electrode.

Collaboration between TRIUMF and GANIL allowed an engineer from GANIL to spend 18 months at TRIUMF working on the design and fabrication of a new ECRIS taking into account these specifications.

To improve the electron confinement, we used a design similar to the ECRIS MONOBOB developed at GANIL, where four permanent magnet rings produce the required magnetic field distribution. The design was modified because we could not use permanent magnets due to the high radiation level at the target. Instead, we used two symmetric pairs of coils surrounded by a ferromagnetic structure to produce the same magnetic field as MONOBOB's for axial and radial magnetic field confinements. The coils are made from hollow copper conductors for water cooling. They are wrapped with radiation-resistant glass insulation. When operating the coils at 600 A for one pair and -600 A for the other pair, the magnetic field has an axial symmetry, and the last closed equipotential field surface is at 0.4 T.

The new ECR ion source test stand is equipped with four 1,000 A-15 V independent power supplies supply and an analogue broadband signal generator in conjunction with a 500 W RF amplifier. The RF signal is transported into the ion source via a coaxial cable coupled to a coaxial antenna.

From the first tests, it appears that the ECRIS is very stable over a large range of frequency, pressure, and magnetic field. The plasma is very easy to ignite, even at pressures as low as 2.6 x 10^{-6} mbar. A quartz chamber has been

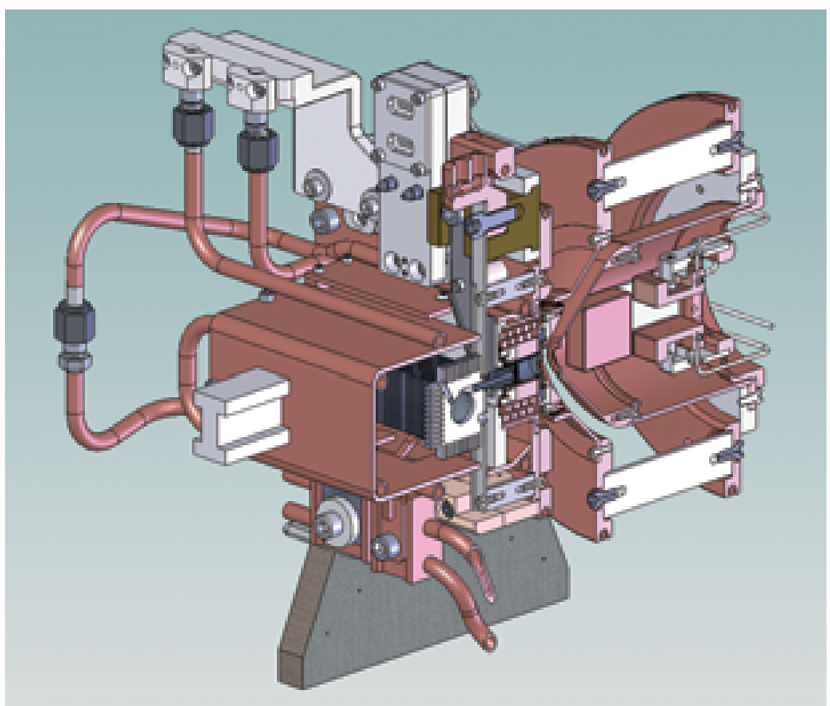


Figure 3: A section view of the FEBIAD ion source. The target is located on the left. The transfer tube is connected directly to the target and also acts as the hollow cathode.

manufactured that will allow us to bias the plasma at high voltage while the magnet coils and the steel yoke are at ground potential.

The extraction system is an adjustable, three-electrode system equipped with an Einzel lens. The objectives for 2008 are to determine the best operating conditions for this source, which will allow us to specify the next ECRIS target module. The design and fabrication of this target module will then be undertaken.

Off-Line Ion Source and Upgrade: OLIS

Until 2002, the off-line ion source (OLIS) terminal employed a microwave-driven ion source and provided charge +1 beams from gaseous elements up to 58 kV. In 2002, the microwave ion source was upgraded (OLIS upgrade I) with the incorporation of two ovens (0–1200 °C) and a sputtering system. This upgrade enabled the OLIS to provide ISAC with beams from liquid and solid elements.

OLIS upgrade II has started with the addition of a "Y" box, which enables us to add two more ion sources to the system. A surface ion source is installed onto the left port of the "Y" box while the microwave ion source is mounted to the right side of the "Y" box. The surface ion source is equipped with an ionizing chamber and three ovens. The three ovens give the flexibility to run three different temperature regions simultaneously: 25–600 °C, 600–1200 °C, 1200–2000 °C, to provide low-energy spread beams from alkali and semi-alkali elements.

In 2005, a hybrid, surface-arc, discharge ion source was developed to meet specific ISAC needs. This ion source produces 10^3 times less impurities for specific beams. These sources provide a variety of beams to ISAC experiments, for commissioning the accelerators, for setting up the radioactive experiments, and for tuning the beam lines.

In 2007, the OLIS high-voltage cage was modified to add a multi-charge ion source to increase ISAC's stable beam production above mass 30. The multi-charge ion source SUPERNANOGAN, purchased from Pantechnik, arrived in March 2007 and mapping of the magnetic field of the source was finished by the end of April 2007. It will be installed in the OLIS HV cage as a third independent ion source, which will go up to 30 kV extraction. The present two ion sources will keep performing up to 65 kV for charge +1 and +2 requirements. The concept of the design was completed, and detailed design work started in mid-December 2007. After installation of this multicharge ion source, OLIS will be able to provide beams of all stable elements to ISAC as pilot beams for highly charged ions from the CSB or directly for experiments.

Charge-State Booster: CSB

The ISAC ion sources are producing mainly singly charged ions. The front-end radio-frequency quadrupole (RFQ) can only accept mass-to-charge ratio less than 30. At ISAC, the beam delivery of masses greater than 30 requires the use of highly charged ions. The conversion of singly charged ions, which are normally emitted from the on-line ion sources into highly charged ones, has been investigated at TRIUMF over the past four years.

An ECR ion source (ECRIS), the 14.5 GHz Phoenix, was purchased from Pantechnik in France, in 2003. To determine the optimum operation parameters suitable for ISAC, it has been installed as an extension of the ion source test stand (ISTS) so that singly charged ions could be injected. The source and the analyzing beam line were commissioned with gaseous ions directly emitted from the source. A combination of a magnetic and two electrostatic sector fields was used to analyze the beam coming from the ECRIS. This combination proved to be very useful because it cleaned up the beam from scattered or charge exchanged ions and allowed the detection of weak beams.

Singly charged ions have been injected from ion sources similar to those used on-line at ISAC. Additionally, a small test surface ion source for Cs ions has been used. Source parameters for the breeding of highly charged ions have been optimized. Both the ion optics for the injection and the extraction have been changed from the original design from Pantechnik to adapt to the special needs at ISAC, mainly the possibility to operate at different extraction voltages. Efficiency, charge-state distributions, and breeding times have been determined as function of source parameters for different elements (see Table 2).

Element	Mass	Charge state with maximum efficiency (A/Q)	Efficiency (%)	Rise time (90%) for charge state with maximum efficiency (ms)	Charge 1+ ion source
Ar	40	8+ (5)	5.5	102	ECRIS
Kr	84	12+ (7)	6.3	401	ECRIS
Xe	129	17+ (7.6)	4.8	432	ECRIS
K	39	9+ (4.3)	2.1		surface
Rb	85/87	13+ (6.5)	3	230	surface
Cs	133	20+ (6.7)	3.5	300	surface + test source

Table 2: Efficiency, maximum charge state, and breeding time for different ion charges bred with the Phoenix source at the ion source test stand.

Figure 4 shows a plan view of the charge-state booster in the mass separator room. The singly charged ions will be reflected out of the existing beam line with a movable electrostatic bender into the charge booster beam line. The highly charged ions produced will be separated with a combination of a magnetic and two electrostatic sector fields. Eventually, they will be brought back into the existing beam line by an additional movable electrostatic bender. The installation in the ISAC mass separator room will be carried out in the winter shut down period of 2008, and first results on charge bred radioactive ions are expected by 2009.

The efficiency for transporting the highly charged ions from the source to the accelerator is limited by the charge exchange with residual gas molecules in the beam lines. The cross sections for this process will determine the requirements on the vacuum for a given length. Very little data on these cross sections in the energy range of the ion the source are available in literature. Therefore measurements have been performed with highly charged Rb and Cs ions at 10 and 15 q keV in O_2 and N_2. In contrast to extrapolations from low charged ions, no significant dependence on the ionization energy of the gas could be found for charge states above 10+. Within an estimated accuracy of about 30%, the dependence on the charge state q can be described by a simple linear function as

$$\sigma = (6.58\times10^{-19} + 1.01\times10^{-19}\times q)\ \mathrm{m}^2.$$

At ISAC, the distance to transport the ions from the CSB to the RFQ is about 25 m. This transport would result in a 20% beam loss for the transport of ions with charge state 20 at an average pressure of 1×10^{-7} Torr.

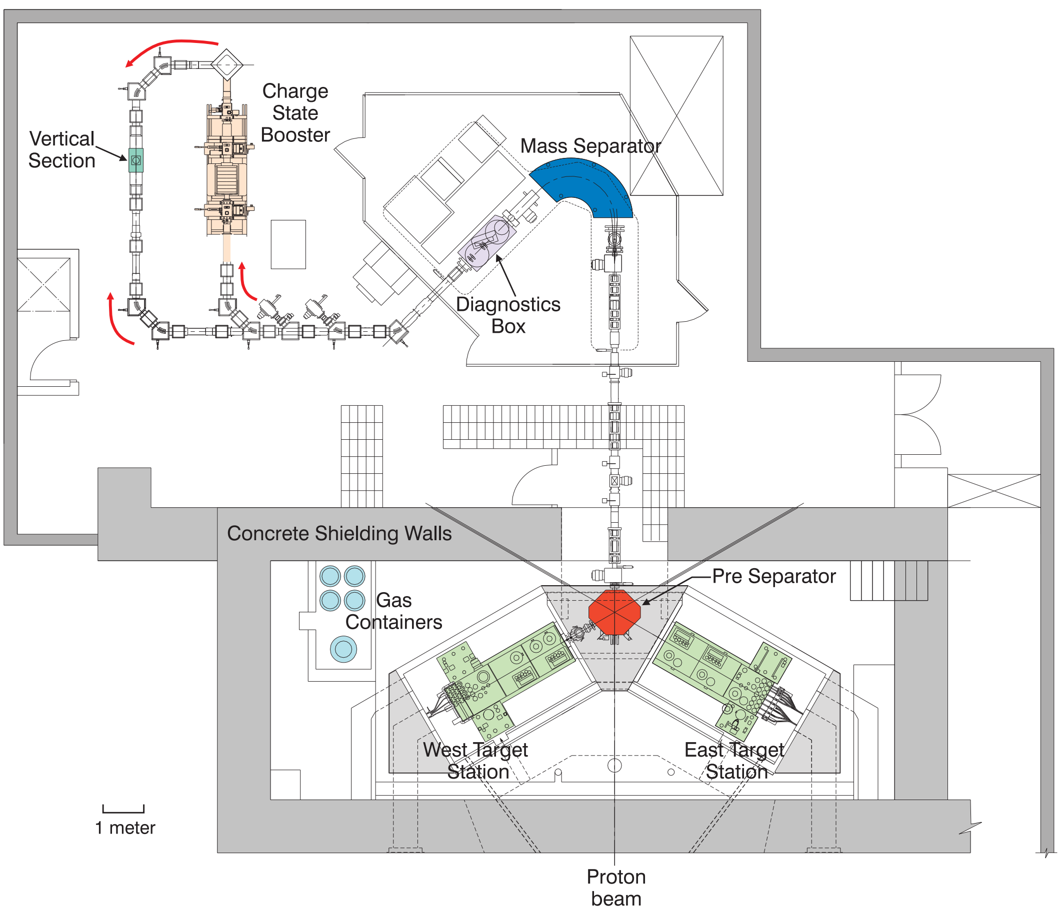


Figure 4: Plan view of the target station hall and mass separator. The Charge State Booster is installed in the mass separator pit just after the mass separator. A switchyard will bring the beam to the booster, if needed. Otherwise, it will go straight to the vertical section to be delivered to the experiment.

Polarizer

The ISAC polarizer is a facility in which the alkali isotopes $^{8,9,11}Li$ and $^{20,21,26,28,29}Na$ have been nuclear-spin polarized in flight by optical pumping with collinear laser light. The polarized ions are implanted into a target and the ensuing β-decay spatial asymmetry detected as a function of time or other experimental variable. This powerful experimental tool has been used at ISAC to study thin films in condensed matter, fundamental symmetries, and nuclear structure.

Alkali-metal beams are relatively easy to polarize, using neutralization and re-ionization steps to access the neutral atom and its loosely held valence electron. The polarizer has been further developed to polarize elements that have paramagnetic ions, where the nuclear polarization is easily destroyed in transit to the experiment by precession of the total angular momentum in the Earth's magnetic field. The simple solution was to add a guide field between the polarizer and the experiment that extends the east-west direction of the guide field in the polarizer. Polarized ^{11}Be will be provided to the condensed matter β-NMR program. It is a spin half isotope, which has no electric quadrupole moment, unlike the spin 2 ^{8}Li in use by the condensed matter group up to now. Polarized Be production has also required frequency doubling of the laser light into the ultraviolet. We have demonstrated the feasibility of polarizing fluorine beams, motivated by the interest shown by a group led by Osaka University in Japan.

Partners

The work on the CSB has been performed in a collaboration with the Laboratoire de Physique Subatomique et de Cosmologie, in France. Work on MISTIC was performed in collaboration with GANIL in France.

TRIUMF's Role

The beam development and targetry group is a core resource at the laboratory; all researchers using exotic beams rely on this expertise and equipment.

5.3.1.3

ISAC-I Accelerators and Beam Lines

Introduction

In the ISAC-I facility, 500 MeV protons at up to 100 µA can be steered onto one of two production targets (see Figure 1) to produce radioactive isotopes. The isotopes pass through a heated tube to a source where they are ionized, accelerated off the source's high-voltage platform at up to 60 kV and sent through a mass separator to select the ion beam of choice. The beam is transported in the low-energy beam transport (LEBT) electrostatic beam line and sent via a switchyard to either the low-energy experimental area or to a series of room-temperature accelerating structures to the ISAC-I medium-energy experimental area.

Description of Facility

The mass separator consists of a pre-separator magnet and mass-separator magnet in series. The pre-separator magnet, at a resolution of ~100, gives a rough species selection and localizes the ions. A series of optics match the beam to an object slit before passing through the mass separator for mass selection. The mass separator is a single dipole with a bending radius of one metre, a bending angle of 135 degrees, and a radial gradient index of 0.5. The magnet and optics layout is capable of a resolution of >8,000 but is usually run with a resolution of ~2,000. It is installed on a high voltage platform (V ≤ 60 kV) to improve further the mass resolution for low-mass beams.

A LEBT system composed of electrostatic optics elements transports the beam to the experimental hall. An electrostatic switchyard is used to select whether the beam will be sent to the linear accelerators for accelerated beam delivery or to the low-energy experimental area. Beams to the low-energy experimental area can be at any energy available from the source (E ≤ 60 kV) and any mass. Beam acceleration requires a fixed velocity for matching into the radio-frequency quadrupole (RFQ) given by a normalized energy of 2.04 keV/u and only a specific range of mass-to-charge ratio of $4 \leq A/q \leq 30$ is possible. Because the ISAC-I sources produce 1^+ charge states, a charge-state booster is required when accelerating ions with $A > 30$.

An electron cyclotron resonance (ECR) charge-state booster is installed just downstream of the mass separator on the ion source level (see Figure 1). The ECR is a PHOENIX type from Pantechnik with a 14.5-GHz RF source operating in continuous mode. The device produces modest efficiencies in the 3 to 5% range with mass-to-charge ratios ranging from 5 for $A \sim 50$, 7 for $A \sim 1$ 50, and up to $A = 9$ for heavier masses. A modest separator ($m/\Delta m = 200$) consisting of a separate magnetic and electrostatic dipole is used to select the correct ion after charge breeding.

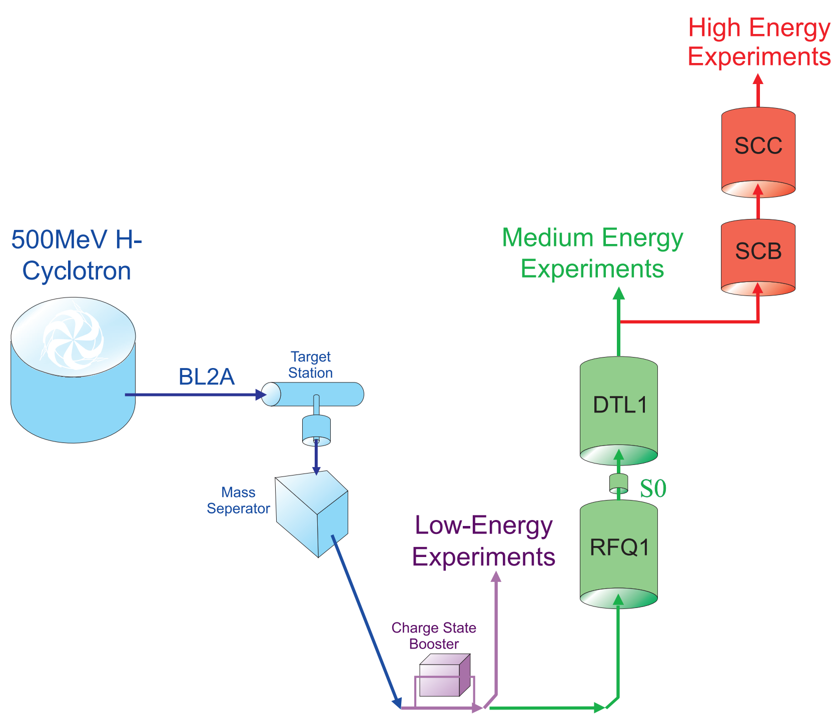


Figure 1: A schematic view of the ISAC-I downstairs facility including target station, mass-separator area, charge-state booster, and the ISAC-I and ISAC-II accelerator chain.

The ISAC-I accelerator chain consists of an RFQ to accelerate the beam from 2.04 keV/u to 153 keV/u and a post-stripper, variable energy, drift tube linac (DTL) to further accelerate the ions to a maximum of 1.8 MeV/u for delivery to the medium-energy experimental area. For high-energy delivery, the DTL beam is deflected north along an S-bend transfer line to the ISAC-II superconducting linac for acceleration above the Coulomb barrier (4-12 MeV/u). A plan view of the ISAC-I and ISAC-II accelerators, beam lines, and experimental areas is shown in Figure 2.

The RFQ was designed and fabricated at TRIUMF and is capable of accelerating ions with $4 \le A/q \le 30$, while the post-stripper section, including medium-energy beam transport (MEBT) and DTL accept ions with $2 \le A/q \le 6$ (see Figure 3). The RFQ is an 8 m long split ring structure operating in continuous mode at 35.4 MHz and producing up to 4.5 MV of accelerating potential. The RFQ is unique in that there is no bunching section; it accelerates at a continuous synchronous phase of 25 degrees. Capture efficiency is improved by the addition of a multi-harmonic buncher (pre-buncher) located 5 m upstream from the RFQ. The combination of pre-buncher and no capture section produces a reduced acceptance but results in beams with a reduced longitudinal emittance of 0.5π keV/u-ns and therefore better quality beams. Typical capture transmissions through the RFQ are ~75%. The pre-buncher's fundamental frequency is 11.8 MHz, the third sub-harmonic of the RFQ. Users thus have about 85 ns between bunches.

A medium-energy beam transport section delivers the beam from the RFQ to the DTL and is composed of three basic sections. A first section focuses the beam both transversally and longitudinally onto the stripping foil to reduce the emittance growth due to multiple scattering and energy straggling. The beam is focused in time using a 106 MHz buncher. A dual frequency chopper is available to clean up the trace of beam in the 35 MHz satellite buckets or to eliminate every second bunch to produce 170 ns between bunches. The second

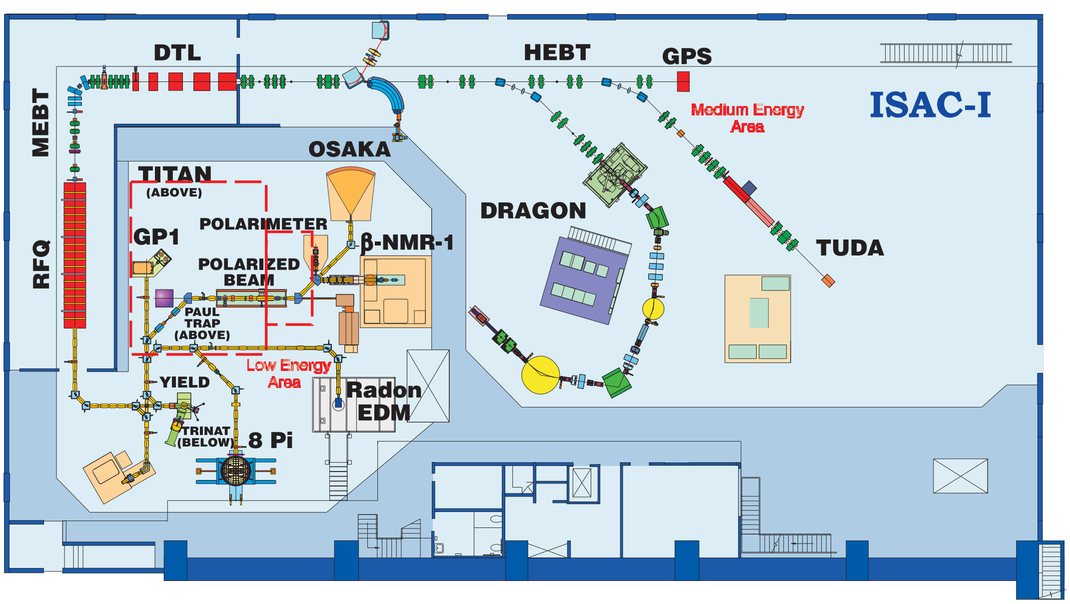


Figure 2: Plan view of the ISAC-I accelerator chain and experimental areas.

section is an achromatic bend section that selects the charge state of choice after stripping. The final section matches the beam both transversally and longitudinally in the DTL. A 35 MHz spiral buncher provides the longitudinal matching.

The DTL, which was designed and fabricated at TRIUMF, is a unique separated function device that provides up to 8.1 MV of accelerating potential and operates in continuous mode at 106 MHz (see Figure 4). The linac provides a full continuum of energy variability from 0.15 to 1.5 MeV/u for ions with $2 \leq A/q \leq 6$, with maximum energies up to 1.8 MeV/u for ions with lower A/q values. The linac is composed of three basic elements: five accelerating tanks with an interdigital H-mode structure to provide the acceleration, quadrupole triplets between tanks to provide periodic transverse focusing, and three triple-gap split ring bunchers before the second, third, and fourth tanks to provide periodic longitudinal focusing.

The linac design is flexible, so it is possible to accelerate the beam for ions up to $A/q = 7$ but at a lower final energy. At present, we are limited by the MEBT dipole power supplies which limit the beam to maximum mass-to-charge values of $A/q = 6$. The MEBT section could be upgraded to $A/q = 7$ with a modest capital expenditure.

The high-energy beam transport (HEBT) delivers the beam from the DTL to one of two experimental areas. The two areas are the DRAGON recoil mass spectrometer and the TUDA scattering chamber and detector array. The HEBT is equipped with a diagnostic station for accelerator tuning, bunchers for optimizing the longitudinal phase space, achromatic bend sections, and matching sections to tune the beam to the targets. The diagnostic station consists of a magnetic spectrometer to measure both the energy and the energy spread in the beam. The bunching section consists of a low-β buncher of 11.8 MHz designed

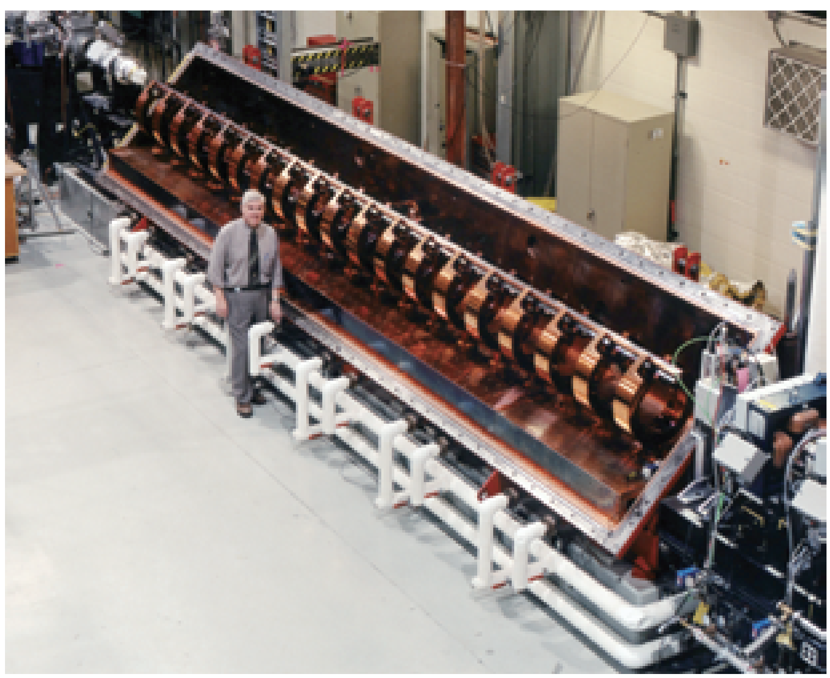


Figure 3: The ISAC-I 35 MHz split ring RFQ.

for beams with $E < 400$ keV/u and a 35 MHz spiral high-β buncher for higher energy beams. The bunchers have been tuned both in bunching mode for a time focus at the target or in debunching mode to minimize the energy spread. The accelerators and transport lines have been operational since 2001, producing high-quality beams with high reliability. Typical beam spots are 2 mm with a focused time spread of ~1 ns and accompanying energy spread of 4 keV/u.

The room-temperature ISAC-I accelerator complex has been optimized for nuclear astrophysics experiments. Beams with mass up to $A = 30$ can be accelerated with full energy variability from 150 keV/u to 1.5 MeV/u and with an efficiency given by the stripping efficiency and the accelerator transmission. The global efficiency ranges from 20 to 40% depending on the mass. The high beam quality, low-emittance beams, and high reliability are strong features of the medium-energy experimental program.

Partners

In Canada: Atomic Energy of Canada, Limited.

International Partners: Germany (2); Russia (1); Switzerland (1), and the United States (1).

TRIUMF's Role

The ISAC-I accelerators and beam lines were developed in-house. TRIUMF was responsible for the beam dynamics design, specification, and engineering design. In most cases, parts were detailed at TRIUMF and fabricated in British Columbia. TRIUMF provided the specifications for the DTL bunchers, which were designed and fabricated at INR-Troitsk.

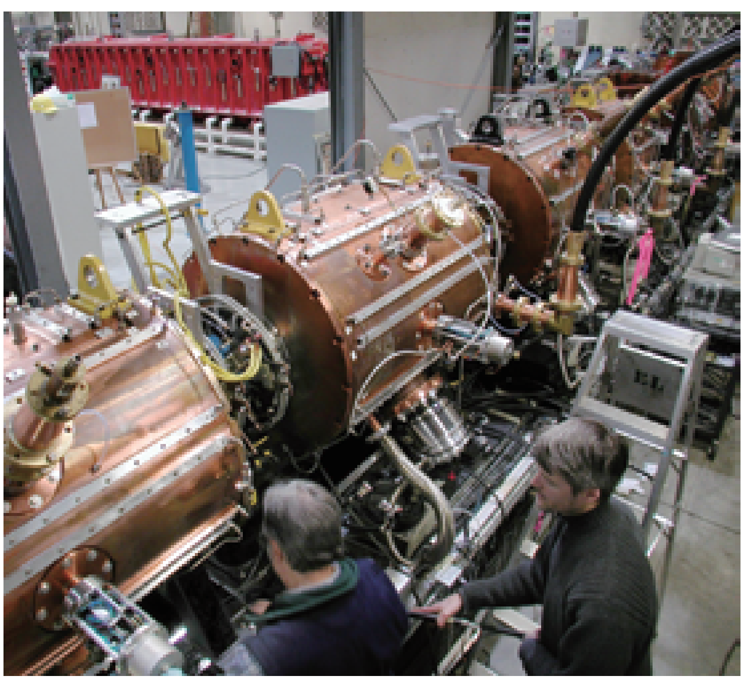


Figure 4: The ISAC-I separated function DTL

5.3.1.4

ISAC-II Accelerators and Beam Lines

Introduction

The rare-isotope beams produced in the ISAC-II facility are transported in the low-energy beam transport (LEBT) electrostatic beam line and sent via a switchyard to either the low-energy experimental area or to a series of room-temperature accelerating structures in the ISAC-I medium-energy experimental area. For high-energy delivery, the drift tube linac (DTL) beam is deflected north along an S-bend transfer line to the ISAC-II superconducting linear accelerator (SC-linac) for acceleration above the Coulomb barrier (5-11 MeV/u) (see Figure 1). TRIUMF began developing superconducting accelerator technology in 2001 and is now a leader in the field with a demonstrated accelerating gradient significantly above other operating facilities.

Description of Facility

The ISAC-I accelerator chain consists of a radio-frequency quadrupole (RFQ) to accelerate the beam from 2.04 keV/u to 153 keV/u and a post-stripper variable energy DTL to further accelerate the ions to a maximum of 1.8 MeV/u for delivery to the medium-energy experimental area. A first phase of the SC-linac has been installed in the ISAC-II vault and was commissioned in March 2006 (see Figure 2). The first rare-isotope ion beam was accelerated in January 2007.

The SC-linac is divided into three sections defined by the beta or velocity acceptance of the section's RF cavities where beta ($\beta = v/c$) is the fraction of the velocity of light. The designations are the low-β (SCA), the medium-β (SCB), and the high-β (SCC) sections. Only the medium-β section has been completed so far. The high-β section is scheduled to be installed during 2009. The low-β section is part of the Five-Year Plan for 2010–2015.

The present medium-β installation consists of five cryomodules with four 106 MHz cavities in each cryomodule for acceleration and one superconducting solenoid for transverse focusing. The cavities, fabricated in Italy, are two-gap, quarter wave structures made from bulk highly purified niobium. The cavities and solenoid are cooled to 4K using liquid helium delivered from a cryoplant in an adjacent room. A cryomodule top assembly showing the cold mass is illustrated in Figure 3. One cavity delivers about 1 MV of accelerating potential but with only ~5W of RF power due to the extremely low surface resistance of the niobium. The short, independently phased cavities have a broad velocity acceptance and provide a flexible beam delivery because ions do not have to follow a fixed velocity profile as in the ISAC-I RFQ. Ions with a lower mass-to-charge (A/q) ratio can be accelerated to a higher velocity than those with a larger A/q, and full energy variability can be achieved by turning cavities off. The 20 cavities of the medium-β section add 20 MV of accelerating potential to the 1.5 MeV/u beam from ISAC-I, yielding beams with final energies ranging from 5 MeV/u to 11 MeV/u.

A second phase, consisting of twenty 141 MHz resonators grouped into three cryomodules, is scheduled for installation by the end of 2009 (see Figure 4). The technical infrastructure for this section essentially copies the very successful technology developed in the first phase. The main technical goal for

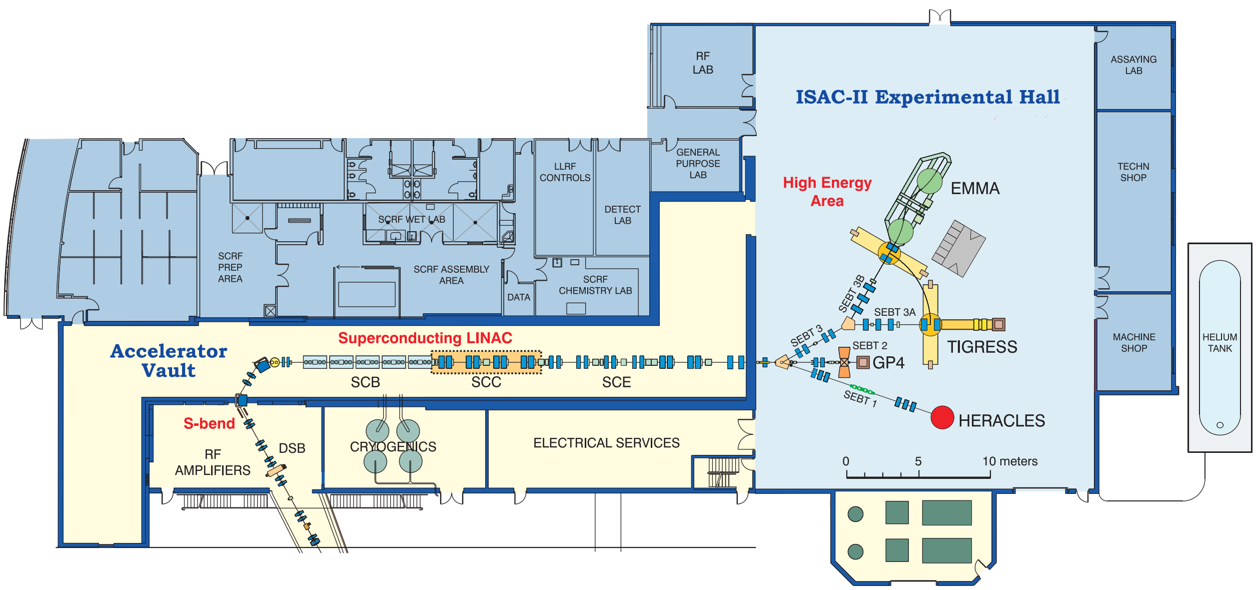


Figure 1: Plan view of the ISAC-II accelerator chain and experimental area.

this section is to develop a local supplier for the superconducting RF cavities, a technical capability currently absent from Canadian industry.

TRIUMF has worked with PAVAC Industries of Richmond, BC, since 2005 with the goal of producing two prototypes of the 141 MHz high-β cavity. This collaboration performed a first successful cold test using technical knowledge transferred to PAVAC from TRIUMF. Based on the test results and its strong technical capability, PAVAC has been awarded the contract for supplying the 20 production cavities for the second phase. Once on-line, the cavities will add a further 20 MV of accelerating potential to the ISAC-II beam, giving the full energy capability of the original ISAC-II proposal, with beams of $2 \leq A/q \leq 6$ ranging from final energies of 8–18 MeV/u.

The beam from the ISAC-II SC-linac is injected directly into the SEBT beam line (see Figure 1) and is transported into the ISAC-II experimental hall (see Figure 5). Various diagnostics in the SEBT line help to tune and monitor the beam delivery. Cavity tuning is done via a phase monitor directly downstream of the linac while a time-of-flight monitor near the end of the vault measures the beam energy. A non-intercepting intensity monitor is installed in the vault to monitor beam intensity during delivery. At present, two stations are available: SEBT2, which serves as a general-purpose station, and SEBT3A, which serves the TIGRESS γ-ray spectrometer. A third beam line, SEBT1, will be installed in 2008 to serve the TUDA-II and HÉRACLES experimental stations. The SEBT3B beam line to the recoil mass separator EMMA is scheduled for completion in 2009.

The full program of nuclear physics experiments in ISAC-II is dependent on the operation of the charge-state booster scheduled to begin operation in August 2008. Beams with mass up to $A = 30$ can be accelerated with an efficiency given by the stripping efficiency at 150 keV/u (~30 to 40%) and the

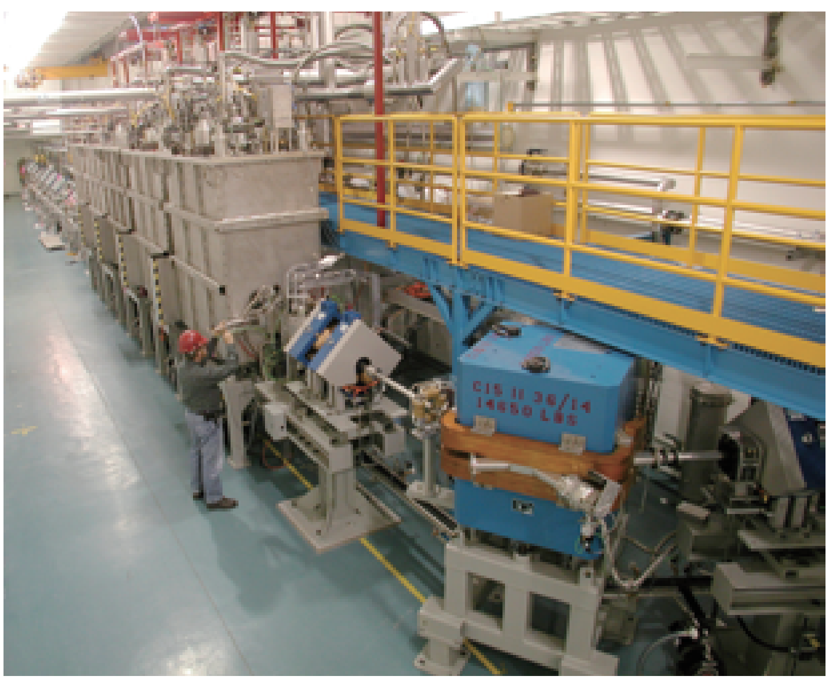


Figure 2: The ISAC-II SC-linac phase I.

accelerator transmission (~70%). Masses with $A > 30$ require a boost to higher charge states to overcome the voltage limitation at the RFQ. Masses up to ~120 are charge boosted with most probable charge states yielding mass-to-charge values given by $A/q = 6$ and compatible with ISAC acceleration with overall efficiency of ~5%. Masses heavier than $A = 120$ cannot be accelerated efficiently. Plans for the 2010-2015 era propose to lift this limitation.

Partners

International Partners: INFN (International Laboratory at Legnaro), Italy, and in the United States: the Argonne National Laboratory.

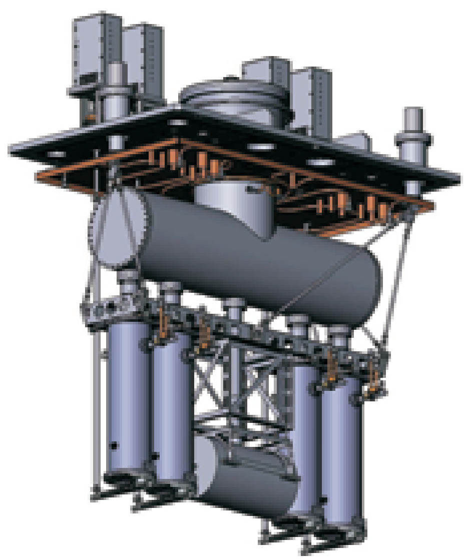


Figure 3: The medium-β cryomodule top assembly.

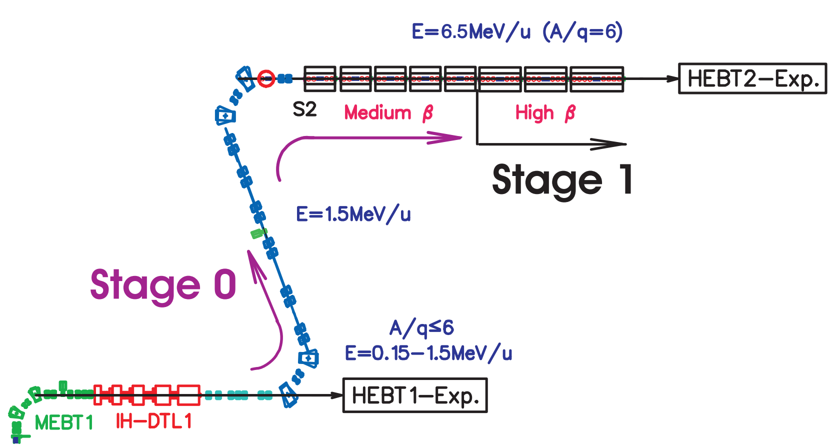


Figure 4: A schematic of the S-bend transfer line and expected status of the ISAC-II SC-linac by the end of 2009.

TRIUMF's Role

The cavities of the ISAC-II SC-linac were developed by a collaboration between TRIUMF and INFN-LNL and based on an existing design used on the low-β section of Legnaro's ALPI accelerator. The cavities were produced in Italy.

TRIUMF was responsible for the beam dynamics design and specification and the engineering design of the cryomodules and cryogenic infrastructure. In most cases, parts were detailed at TRIUMF and fabricated in British Columbia. The high-β section of the linac is based on cavities modeled at TRIUMF and fabricated at PAVAC Industries, Inc., the first Canadian company ever to produce bulk niobium superconducting cavities.

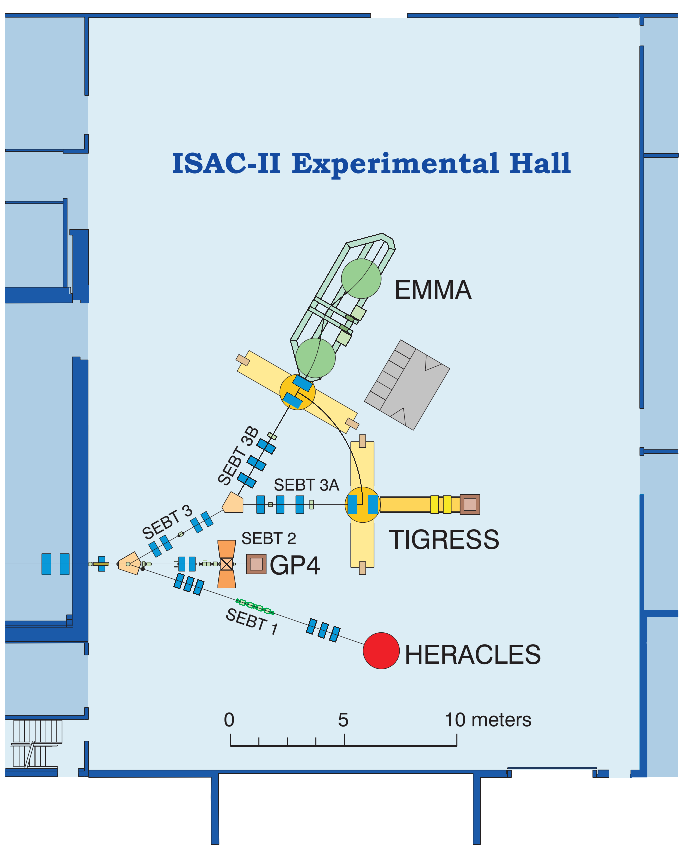


Figure 5: The ISAC-II experimental hall.

5.3.2

Facilities

5.3.2.1

ATLAS Canadian Tier-1 Data Centre

Introduction

The standard model predicts that a particle called the Higgs boson determines the mass of all subatomic particles. This prediction has never been proven, but proof of the existence of the Higgs boson and exciting new discoveries in particle physics may be found when the ATLAS experiment begins in 2008.

The ATLAS experiment at the Large Hadron Collider (LHC) at CERN will use proton-proton collisions at the highest energy ever achieved in the laboratory to look for the Higgs boson, the particle central to the current model of how subatomic particles attain mass. ATLAS will also search for phenomena "beyond the standard model" of particle physics such as supersymmetry, extra dimensions, and quark compositeness. The ATLAS detector will observe the particles emerging from the roughly 900 million proton-proton collisions per second and, although fast electronics will filter the events so that only those most likely to be of interest will be recorded, ATLAS will produce 3.5-5.0 petabytes of data per year (one petabyte is one million gigabytes). In addition, secondary data sets will be produced that could double the amount of data produced.

In order to analyze this enormous amount of information, CERN is coordinating an international network of large high-performance computing centres that are linked by "grid" tools so that they act as one huge system. This network is called the Worldwide LHC Computing Grid (WLCG). Canada has

PEOPLE

MICHEL VETTERLI

Professor of Physics, SFU-TRIUMF Research Scientist

Michel Vetterli graduated with a First-Class Honours degree in physics from McGill University in 1980 and a Ph.D. from McMaster University in 1985. After graduation, he moved to SFU-TRIUMF where he was a post-doctoral fellow until joining the laboratory's staff in 1989.

Dr. Vetterli's early work was in intermediate energy nuclear physics, in particular the study of nucleon charge-exchange reactions with implications for stellar evolution. During the 1990s, he studied the substructure of the proton and the neutron at the HERMES experiment at DESY in Hamburg, where he was the Canadian project leader from 1989 to 2001. He was also the deputy spokesman of HERMES during the construction, installation, and commissioning phases of the experiment.

In 2001, Mike moved to SFU where his work has focused on ATLAS. He is currently the computing coordinator for ATLAS-Canada and the project leader of the ATLAS Tier-1 Data Analysis Centre at TRIUMF. He has also worked on the liquid argon calorimeters, which detect the energy of the particles emerging from the high-energy proton-proton collisions at the LHC.

Dr. Vetterli is a founding principal investigator of WestGrid, a network of high-performance computing facilities in Western Canada that serve the needs of academic computing in the sciences and engineering.

provided one of the world's eleven Tier-1 centres (10 for ATLAS, one for CMS). The Canadian Tier-1 Data Centre, located at TRIUMF, will work with nine of the other ATLAS Tier-1 centres in the world to reprocess the raw data produced by the experiment. In addition, Tier-2 centres will be built in universities, both in Canada and abroad, to further process the results of the Tier-1 analysis and extract groundbreaking physics results from the data. The Tier-2 centres will also be the primary sites for computer simulations of ATLAS, which is an integral part of the data analysis.

The requirements at a Tier-1 centre are such that a dedicated facility is mandatory. One can think of the Tier-1 centres as extensions of the experiment. In Canada, it was decided to build such a facility at TRIUMF because of the laboratory's experience with providing 24/7 data and networking services in large volume. The data centre was funded in late 2006 by an Exceptional Opportunities Grant from the Canada Foundation for Innovation (CFI) to a consortium of Canadian universities. This was supplemented by a grant from the British Columbia Knowledge Development Fund (BCKDF). The grants totaling just over C$15 million are summarized in Table 1, where contributions from vendors and TRIUMF are also included, bringing the total value of the project to about C$23.5 million.

	Capital	Operating	Total
CFI	8,179	2,450	10,629
Vendors	8,268		8,268
BCKDF	4,060		4,060
TRIUMF		525	525
Total	20,507	2,975	23,482

Table 1: Grants for the Canadian Tier-1 Data Centre in thousands of dollars. Vendor contributions come from discounts available beyond educational pricing.

The expanded Canadian Tier-1 Centre began full operations in August 2007 and is participating in ATLAS data and service challenges, as well as cosmic-ray tests and a full-dress rehearsal of the data-taking.

Description of Dedicated Apparatus

Analysis of particle physics experiments is done in several stages. First, digitized electronic signals from the various detectors are calibrated and the information is combined to reconstruct particle trajectories and energy deposits in the detectors for the particles emerging from the proton-proton collisions. This results in Event Summary Data (ESD) files. This information is processed further to produce a list of the particles coming from each collision, as well as their properties (energy, scattering angle, etc.). These lists, stored as Analysis Object Data (AOD), form the basis of physics analyses on a multitude of phenomena. Groups concentrating on specific physics topics then further filter the data and refine the analysis to produce Derived Physics Data (DPD) from which final results will be extracted.

This staged analysis, with data sets of decreasing size at each stage, lends itself well to a layered network of computing facilities. The ATLAS computing model is illustrated in Figure 1, as a tiered structure of centres ranging from the Tier-0 at CERN to relatively modest-sized clusters in the universities, the Tier-3 centres. The Tier-0 stores all of the raw data from the experiment on tape, distributes one copy across all of the Tier-1 centres and performs a first-pass analysis using the best knowledge we have of the detector at the time of data-taking. As calibrations and analysis algorithms improve, the raw data are reprocessed in the Tier-1 centres in a coordinated way, producing new ESDs and AODs. The Tier-1 centres are also responsible for storing the simulated data generated in the Tier-2 centres. The new AODs are distributed to the Tier-2s in the universities where further analysis is done. The Tier-1 centres require large compute farms and large storage systems to fulfill their role. Fast network interconnection to CERN and the other centres on the grid is crucial.

The access patterns to the AODs are such that peaks and valleys occur in the CPU requirements. It was therefore felt more appropriate to build the Tier-2 centres in the context of shared facilities in the universities, where ATLAS-Canada would have access to very significant resources for short periods of time, above and beyond its steady-state requirements. Tier-2 centres have been

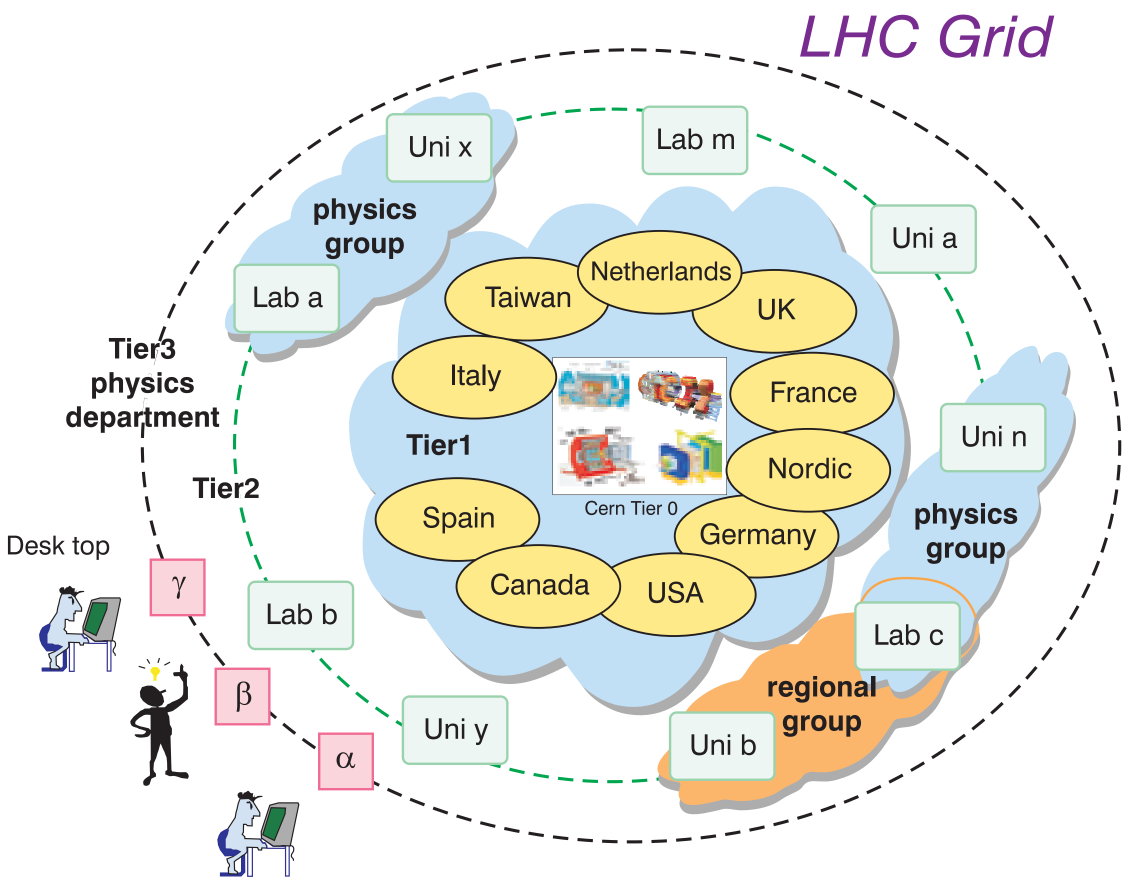


Figure 1: The Worldwide LHC Computing Grid showing a layered structure of high-performance computing centres distributed around the globe.

funded through the CFI National Platforms Fund (NPF) and will be built at McGill University, Simon Fraser University, the University of Alberta, the University of Toronto, and the University of Victoria.

The Tier-1 centre will be built in stages as requirements for equipment increase during data-taking. The anticipated resources are summarized in Table 2. Note that resources for 2008 have already been purchased and commissioned. Note also that the size of the data centre was increased beyond WLCG requirements by 20% to provide Canadians with dedicated resources to allow them to fulfill their responsibilities with respect to detector calibration, as well as to give them a competitive advantage in the analysis of the data.

The data centre is housed in the power supply hall of the ISAC-II building. A portion of this room was renovated in order to handle the high-density heat load generated by the new equipment. The renovations were designed with a capacity that should be sufficient until 2011. Beyond this, a new site will be required to allow for expansion driven by the ever-increasing data from ATLAS.

Year	2007	2008	2009	2010	2011
CPU (kSI2k)	228	1304	2179	3801	5423
Disk (TB)	156	716	1544	3063	4344
Tape (TB)	111	554	1171	2226	3471

Table 2: Planned resources for the Canadian Tier-1 Data Centre at TRIUMF. The numbers are cumulative. Computers are quoted in kSI2k, which is a benchmarking unit; a typical desktop computer corresponds to 2.5-3 kSI2k. Storage is quoted in terabytes and is the useable space available.

Results and Progress

As mentioned above, the Canadian Tier-1 Data Centre underwent a significant expansion in August of 2007. The Tier-1 is now at full capacity for 2008 and will be expanded each year as data are collected by ATLAS. Prior to August 2007, resources were purchased using funds from SFU, TRIUMF, and UBC to provide a modest scale data centre that nevertheless had all of the grid services required of a Tier-1. This allowed Canadians to participate in large-scale ATLAS simulation exerciseswhich help in the design of the experiment, to develop the analysis software by providing pseudo-data that could be treated in the same way as real data, and finally to develop and test the computing model and the WLCG. These tests were referred to as Data and Service Challenges.

Canada is responsible for providing 5% of the common computing for ATLAS, based on our fractional membership in the collaboration. Figure 2 is a chart of contributions in 2007 by the Tier-1 centres to ATLAS simulation, which shows that the goal to provide 5% of the total was met. Canada's fraction increased to almost 9% in October–November 2007 after the expansion to a full-scale Tier-1 centre.

Another performance yardstick for Tier-1 centres is uptime. WLCG requirements for reliability are very high, ranging from 91% in June of 2007 to 98% by the time data-taking starts in 2008. Note that TRIUMF ranks among the best for this metric, averaging 95% in the latter half of 2007, despite having the smallest staff of all the Tier-1 centres.

Networking is important for the WLCG because of the large amount of data continuously transferred from CERN to the Tier-1s, as well as the large amount of traffic between Tier-1s and Tier-2s. A dedicated point-to-point connection (a "lightpath") has been established between TRIUMF and CERN by CANARIE, Canada's optical research network, and HEPNet-Canada, which is responsible for networking for Canadian subatomic physics. This link is currently 5 gigabits per seconds (gbps), but can be increased to 10 gbps if the need arises. Dedicated lightpaths: between TRIUMF and Brookhaven National Laboratory (the US-ATLAS Tier-1) and between TRIUMF and the Canadian Tier-2 centres have also been set up. This communication network was tested under realistic conditions in 2007 during cosmic-ray data-taking tests. Data from cosmic rays passing through the ATLAS detector were sent to the Tier-0 at CERN. Reconstruction was performed, and the data (raw, ESD, and AOD) were distributed to the Tier-1s in the same way it will be with data from collisions when the LHC starts up. An example of transfer rates between CERN and the Tier-1 centres is shown in Figure 3. TRIUMF exceeded the requirement of 50 MB/s continuous transfer rate.

The ATLAS experiment will launch a full-scale test of the computing system in 2008, including the analysis chain all the way from raw data in the experimental area to physics results at the Tier-3 centres. This Full Dress Rehearsal will test all aspects of the hardware and software a few months before the LHC starts up. The Tier-1 Centre is fully ready for this exercise.

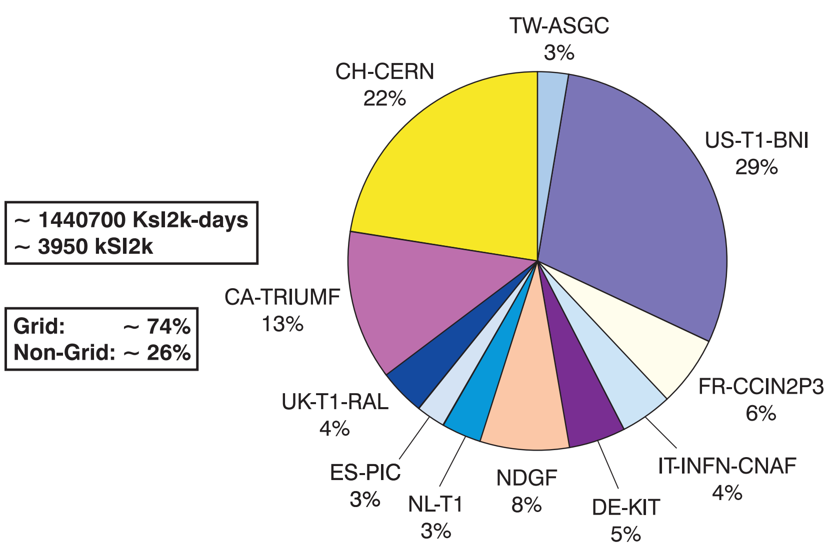


Figure 2: TRIUMF's contribution to the Tier-1 share of the simulation of the ATLAS experiment (Jan. –Sept. 2007).

Partners

The Canadian Tier-1 Data Centre consortium members are: Carleton University, McGill University, Simon Fraser University, University of Alberta, University of British Columbia, l'Université de Montréal, University of Toronto, University of Victoria, and York University.

TRIUMF's Role

TRIUMF has been the ideal site in Canada for the Tier-1 Data Centre. The laboratory has extensive experience in large international collaborations and can provide 24/7 support for the equipment. TRIUMF also has long-standing expertise in long-distance file transfers and international networking. Although all but one Tier-1 employee is paid through the CFI and BCKDF grants, TRIUMF is committed to pursuing ongoing support and funding for the data centre beyond 2011.

The experience gained through running the Tier-1 facility has made TRIUMF a centre of excellence in large-scale distributed grid computing. The LHC experiments are the first large-scale deployment of grid technology. It is difficult to imagine that this technology will not be further deployed in science and industry. It has the potential to do for large-scale serial computing what the World Wide Web (also developed at CERN) has done for the global sharing of information. Through this involvement in early deployment, TRIUMF is well placed to ease Canadian entry into any further developments in grid computing technology.

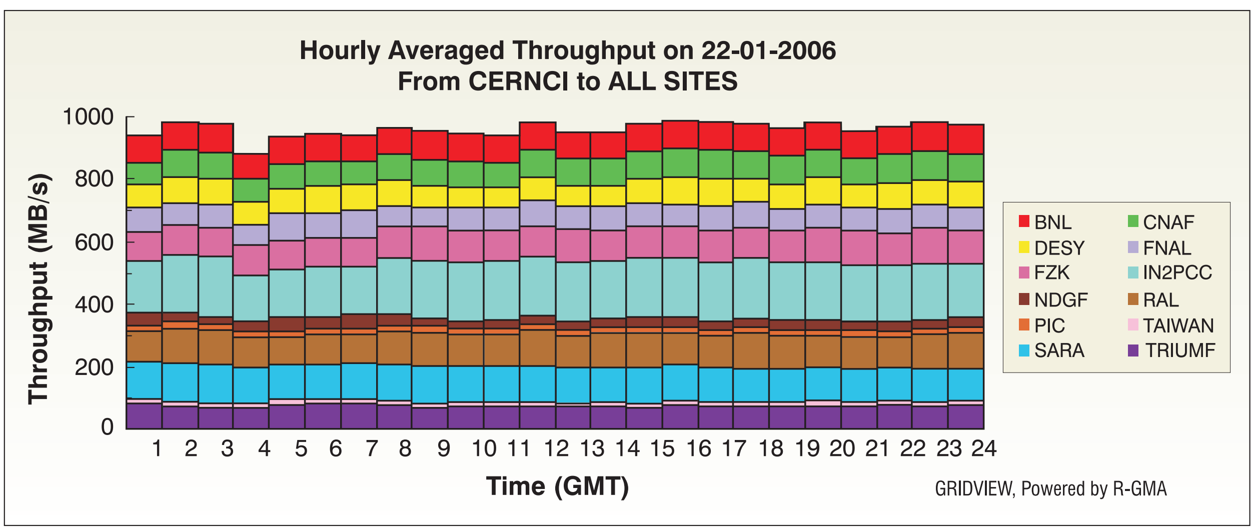


Figure 3: Data transfer rates from CERN to the Tier-1 centres during a coordinated test in 2006. The target for TRIUMF of 50 MB/sec was comfortably achieved.

5.3.2.2

ISAC Facilities

5.3.2.2.1

ISAC-I Facilities

5.3.2.2.1.1

Detector of Recoils and Gamma Rays for Nuclear Astrophysics: DRAGON

Introduction

Our universe is filled with ordinary stars but also less well understood objects such as supernovae and X-ray bursts, where nuclear reactions occur in cataclysmic explosions, creating radioactive nuclei whose signatures can be observed by orbiting space telescopes. DRAGON is a high-performance recoil separator, designed and built to measure nuclear reactions (see Figure 1) of importance in astrophysics, the nucleosynthesis reactions which occur in the explosive environments of novae, supernovae and X-ray bursts.

The first reaction measured by DRAGON was $^{21}Na(p,\gamma)^{22}Mg$, an especially important reaction to understand in order to calculate the processes occurring in classical novae, a white dwarf star which accretes material from a companion star in a binary system. In classical novae, the reaction happens when a proton impinges on a sodium nucleus and is absorbed, forming an excited state of magnesium, which acquires extra energy when it absorbs the proton. The excited magnesium then de-excites or goes back to its lowest energy state by emitting the energy in the form of a γ-ray.

DRAGON studies this reaction using a technique called "inverse kinematics," putting a heavy beam of heavy elements onto a target made of light elements. In this technique, the short-lived ^{21}Na nucleus, produced by ISAC-I, impinges on a proton in a hydrogen target. It is then absorbed forming ^{22}Mg which de-excites, giving off a γ-ray. The DRAGON spectrometer separates the recoiling magnesium nucleus from the beam that has passed through the hydrogen target and measures its properties. The de-excitation γ-ray energy is

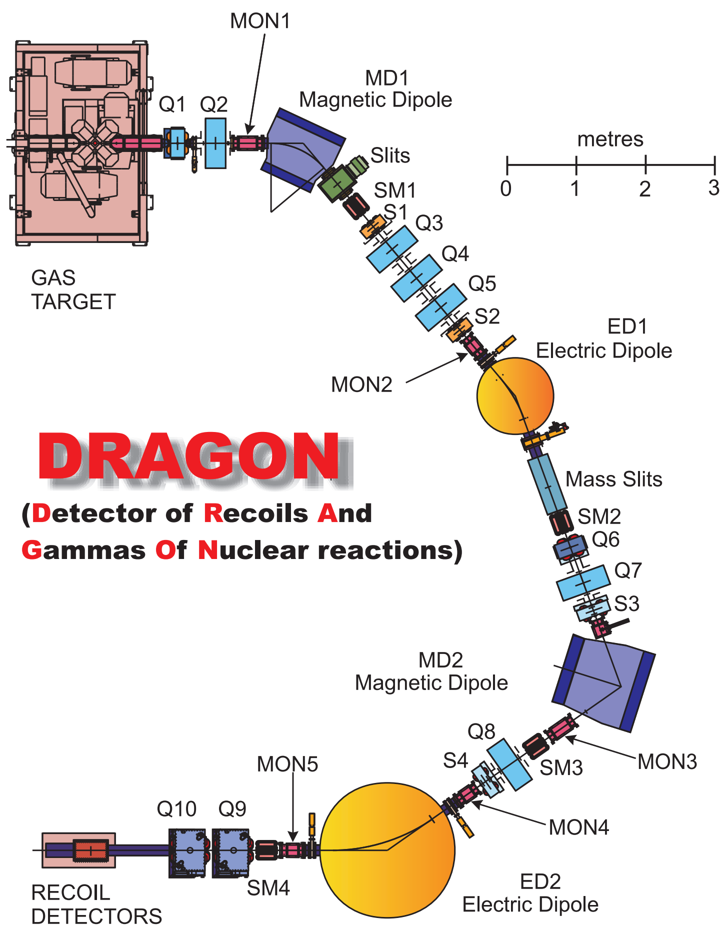


Figure 1: Plan view of the DRAGON recoil separator, showing the gas target where the nuclear reactions occur, the electromagnetic devices that separate the recoil nuclei from the unreacted beam, and the detectors that measure properties of the recoil nuclei.

measured in a bismuth-germanate (BGO) crystal array that surrounds the thin-walled hydrogen gas target volume.

Using this technique, DRAGON has, over the last seven years, waged successful campaigns to study some of the most important proton- and alpha-capture reactions to astrophysics, including the ^{21}Na(p,γ)^{22}Mg, ^{12}C(α,γ)^{16}O, ^{26g}Al(p,γ)^{27}Si and ^{40}Ca(α,γ)^{44}Ti reactions (see Section 5.1.2.3).

Description of Dedicated Apparatus

DRAGON is a high-performance recoil separator for the measurement of astrophysical fusion reactions in inverse kinematics. Using radioactive and stable beams in the range 150–1800 keV/A provided by the ISAC-I accelerator, DRAGON studies the radiative capture on hydrogen and helium relevant to nucleosynthesis on the neutron-deficient side of stability, for scenarios such as supernovae, classical novae, and X-ray bursts. The hydrogen or helium is circulated within a windowless gas target capable of holding up to 4 x 10^{18} atoms/cm^2. Fusion reactions that occur within the gas target produce excited recoiling nuclei in a forward-focused cone that quickly de-excite with the emission of one or more γ-rays. An array of 30 BGO crystals almost entirely surrounds the thin-walled gas target, enabling the detection of the de-excitation γ-rays with high efficiency.

The recoiling nuclei, mixed among unreacted beam particles of similar momentum, travel through a dipolar magnetic field and set of slits to select the most populated charge state originating from in-gas atomic interactions. Particles of the selected mass-to-charge ratio are then analyzed by an electric dipole field, which separates the similar momentum particles according to mass, filtering out the unreacted beam with high efficiency. After continual refocusing and a second stage of separation, the recoiling reaction products are detected at the end of the 21-m long separator using a variety of techniques, including position-sensitive silicon detectors, a microchannel plate, and an ionization chamber for chemical-element identification.

The DRAGON separator is designed to accept recoils within a 1° half-angle at the tuned energy, and with a momentum spread of less than ±2% [S. Engel *et al.*, Nucl. Instrum. Methods A553, 491 (2005)]. The momentum and angle spread are induced by the range of momentum given to the recoil as the γ-rays are emitted and are thus dependent on the decay branching ratios and angular distributions. The separator is capable of accepting all recoils from most proton-capture reactions of astrophysical interest using rare-isotope beams.

For some lower-mass beams and some alpha-capture reactions, including ^{12}C(α,γ)^{16}O, the cone angle of recoils is larger than the geometric acceptance of the separator. In this case, the transmission of recoils is deduced by modeling the entire separator using a full-transport ion-optical Monte Carlo simulation based on GEANT and RAYTRACE. In the cases, where decay branching ratios and angular distributions are unknown, the full envelope of possibilities is explored and the resulting acceptance spread incorporated into the systematic measurement uncertainties of the experiment.

The efficiency of the BGO array has been extensively studied by comparing GEANT calculations to laboratory measurements, and shows impressive consistency [D.G. Gigliotti *et al.*, Nucl. Instrum. Methods B204, 217 (2003)]. This efficiency ranges from around 40% to 80%, depending on the number and energy of γ-rays available.

Recent Developments

The beam suppression capability of the electromagnetic separator has been demonstrated in several experiments. For proton-capture, this ranges from around 1–2 x 10^8 at low energies to 10^{13} at around 1200A keV. For favourable alpha-capture reactions such as $^{12}C(\alpha,\gamma)^{16}O$, the suppression is around 10^{12}–10^{13} for the energy range 750A–1250A keV.

The total background suppression capability of DRAGON, when combining γ-ray detection, recoil separation and particle identification is at minimum 10^{13}, making DRAGON sensitive to extremely small resonance strengths, such as the 34 μeV resonance recently measured in the $^{26g}Al(p,\gamma)^{27}Si$ reaction.

In 2008, DRAGON upgraded its detection system to include a local-time-of-flight capability with time resolution $\Delta t \sim 400$ ps, providing an extra layer of background rejection and enabling the pursuit of even more difficult measurements.

The combination of ISAC-I's accelerated ISOL beams and DRAGON is unique, and it is the only facility capable of measuring the majority of the important radiative-capture reactions with rare-isotope beams. The results reported in Section 5.1.2.3 highlight the important contributions of DRAGON to the field of nuclear astrophysics.

The DRAGON program was recently fully funded again by NSERC with the comments that it has provided "outstanding contributions" to the field and is a "key, cutting-edge program at a world-class facility."

Over the course of the next Five-Year Plan years (2010–2015), DRAGON will continue to pursue the measurement of difficult and important astrophysical reactions with the development of novel radioactive beams.

Partners

In Canada: McMaster University, Simon Fraser University, University of Alberta, University of Guelph, University of Northern British Columbia, University of Prince Edward Island, University of Toronto, and the University of Victoria.

International Partners: Austria (1), Belgium (1), China (1), England (2), France (1), Germany (3), India (1), Ireland (1), Israel (1), Italy (1), Japan (1), Scotland (1), Spain (2), and the United States (5).

TRIUMF's Role

TRIUMF's dedicated research scientists, post-doctoral research assistants, and technicians make up the DRAGON Group, which is joined by a large number of Canadian and international academic collaborators in both experimental physics and astrophysics theory.

5.3.2.2.1.2

TRIUMF Neutral Atom Trap: TRINAT

Introduction

A revolution has recently occurred in subatomic physics. Physicists can now cool neutral atoms, those atoms with an equal number of electrons and protons, to very low energies and trap them in a vacuum, using new laser technologies. TRIUMF is harnessing these new laser technologies, which function like a thick liquid to slow the atoms' movements and confine them to a small region, to do precision, low-energy experiments that allow scientists to study the individual atoms in great detail with glimpses of their inner structure.

TRIUMF's neutral atom trap uses the pressure of laser light to confine atoms of radioactive isotopes and measure their decay properties. The atoms are held very weakly in space, so that the momentum of the low-energy daughter nuclei is unperturbed after the decay and can be measured accurately. This lets us measure the neutrino momentum from the momentum of the other products in three-body β-decay. The angular distribution of the neutrino with respect to the beta and the nuclear spin is predicted in the standard model. The techniques are being extended to let us search for exotic massive particles in missing-mass spectra in two-body γ-decay of nuclear isomers, metastable excited nuclear states. The best isotopes for such experiments are often short-lived, so we have optimized the trap to collect the isotopes from the ion beam produced by ISAC-I.

Description of Dedicated Apparatus

The complete trap system fits on a large table top (see Figure 1). Laser beams from all six directions cool and gather the atoms in the "collection" trap. To avoid radiation backgrounds from untrapped atoms, the atoms of interest are then transferred with laser beams to the "detection" trap where the decay detectors are housed. The transfer time is about 40 ms, with more than 75% efficiency; the atoms that are not trapped end up on surfaces baffled from the recoil detector. The result is millions of atoms trapped at a time in a 1-mm-sized cloud at temperatures of less than 1 mK, *i.e.*, typical velocities of about 1 m/s. These velocities are negligibly small compared to the recoil velocities produced in the decays.

The recoiling daughter nucleus from each decay is collected in a carefully characterized electric field and detected with a microchannel plate (see Figure 2). The momentum is reconstructed from its time of flight and position on the detector. The time-of-flight start trigger is either the beta or a low-energy atomic electron produced in β- decay.

The nuclei can also be spin-polarized by optical pumping, which adds angular momentum to the trapped atoms by absorption of circularly polarized light. Spin-polarization of 99.6% in stable species and over 97% in unstable species has been achieved. Together with the beta-recoil coincidence method, this enables the measurement of new observables like the asymmetry in neutrino direction with respect to the nuclear spin.

A small percentage of the trapped atoms is photoionized and accelerated onto the same MCP, which provides a textbook measurement of the average electric field by placing a test charge in it and measuring its acceleration. It also precisely probes the cloud size (important for the beta-neutrino correlations) and the excited state atomic population (important to deduce the degree of spin-polarization). For future atomic parity violation work in francium atoms, similar collection schemes will be used, but for the measurement trap, geometries optimized for atomic physics will be used.

The main trap laser is a tunable Ti:S ring laser driven by an argon ion laser.

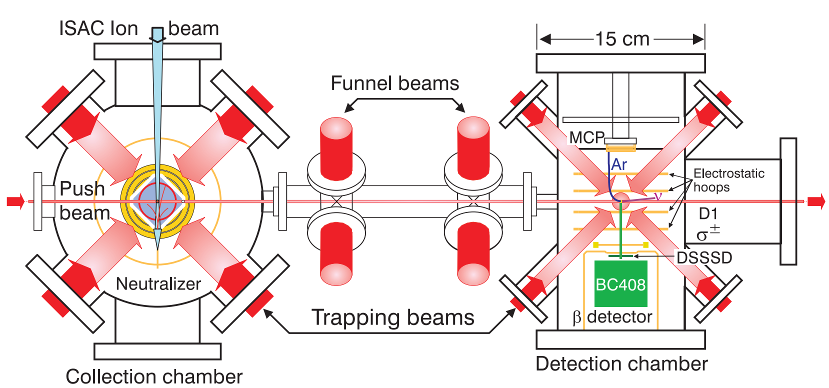


Figure 1: Top view of TRIUMF's neutral atom trap.

Another Ti:S is better optimized for very narrow-frequency work. Several smaller diode lasers are used for optical pumping. The dollar replacement value for the experiment is $C750,000 ($C500,000 in lasers and $C250,000 in the vacuum systems, detectors, and other equipment).

Recent Developments

Recent physics results include the best measurement of a beta-neutrino angular correlation in the pure Fermi decay of ^{38m}K. This observable is deliberately insensitive to the absolute handedness, *i.e.*, helicity, of the outgoing particles, which makes it sensitive to all types of new scalar interactions independent of this "chirality" property.

More recently, a highly efficient technique measuring the recoiling daughter nuclei in coincidence with low-energy atomic electrons collected in an additional MCP by the same electric field has been developed. This should help with the beta-neutrino correlation, along with missing-mass searches for exotic massive particles in two-body decay of nuclear isomers. Using the spin-polarization techniques together with the recoil-coincidence technique, a neutrino spin asymmetry measurement has been published [Melconian *et al.*, Phys. Lett. B649 370 (2007)].

Partners

In Canada: University of British Columbia, University of Manitoba , and Simon Fraser University.

International Partners: Israel (1) and the United States (1).

TRIUMF's Role

TRIUMF supplies the short-lived isotopes via rare-isotope beams from ISAC-I, along with 1.4 FTE research scientists. TRIUMF also provides technical support via the electronics, machine, and design shops

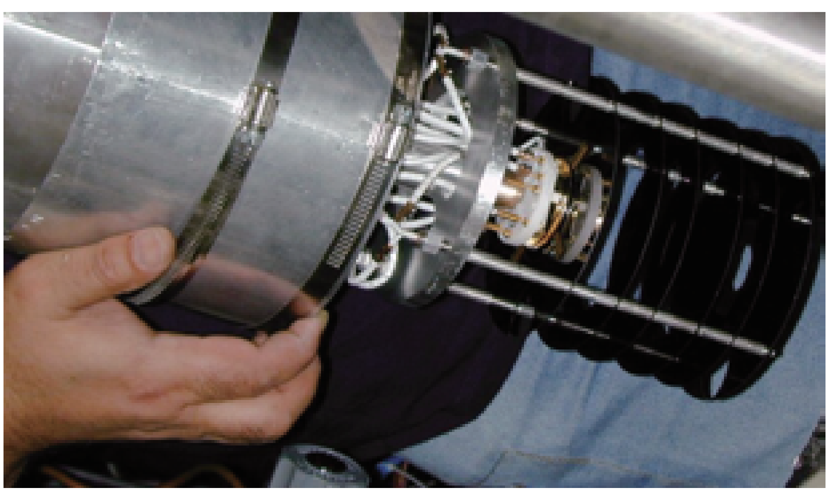


Figure 2: The electrodes and microchannel plate used to detect ions from atoms decaying in the neutral atom trap.

5.3.2.2.1.3

8π Facility

Introduction

The 8π detector, in its current configuration, is the only large high-resolution, high-efficiency γ-ray spectrometer in the world dedicated to measuring the decay of stationary rare-isotopes. Between 2003 and 2008, collaborators have integrated a full complement of ancillary detectors for measuring beta particles, conversion electrons, and fast lifetimes. This facility has made high-precision measurements of weak branches, discovered new rare decay branches, made precision measurements of nuclear lifetimes by electronic and Doppler-shift techniques, and investigated exotic nuclei produced at rates as low as 1 ion per second.

Scientists using the 8π spectrometer at ISAC-I recently discovered a small, never-before-seen γ-decay of the 0^+ excited state in the rare-isotope ^{38}K. By nuclear decay standards, it is a weak branch — the state is 30,000 times more likely to decay by beta decay than by γ emission. The discovery of this branch means that previously reported measurements were in error. This branch is a non-analogue decay and is 16 times larger than the upper limits for such decays established in previous measurements. Ultimately, this and similar 8π experiments show whether or not we really understand the subatomic world, from the standard model of fundamental particle interactions to the standard shell model of nuclear structure.

Description of Dedicated Apparatus

In the early 1980s, scientists from l'Université de Montréal, McMaster University, and the Atomic Energy of Canada Limited (AECL) forged a collaboration to build the 8π. The $C5 million (in 1982) construction cost was shared equally between NSERC, through the universities, and AECL. For over a decade, the 8π operated at the Chalk River Tandem Accelerator and Superconducting Cyclotron laboratory for nuclear physics research with heavy-ion beams. In 1997, it was moved to the 88” Cyclotron at Lawrence Berkeley National Laboratory. In 2000, the 8π was moved back to Canada, and reconfigured for use in β-decay experiments. In its current configuration, the 8π includes 20 high-purity germanium (HPGe) high-resolution γ spectrometers, with bismuth-germanate (BGO) escape suppressors.

Recent Developments

The main permanent addition to the device is a fast in-vacuum continuous-loop tape-moving system (see Figure 1) that was funded by the United States Department of Energy (DOE) and built by Louisiana State University (LSU). In a typical experiment, a rare-isotope ion sample is deposited on the tape, in view of the HPGe detectors. The tape system then removes the sample in a programmable cycle out of view of the detectors to remove background that arises from long-lived progeny or beam contaminants.

The vacuum chamber can also accommodate SCEPTAR (SCintilator Electron-Positron Tagging ARray). SCEPTAR, funded primarily by NSERC, counts beta particles with 20 fast plastic scintillators covering 80% of a full 4π solid angle (Figure 2). SCEPTAR can be used simultaneously in a “singles” mode for normalizing of high-precision branching ratio measurements and for β-γ coincidence spectroscopy to eliminate the ~2000/s γ background events from one to two decays of weakly produced, exotic beams. The geometry is such that each HPGe views the sample with one, and only one, unique SCEPTAR element. Applying a veto to events with collinear SCEPTAR and HPGe detection reduces continuum bremsstrahlung in the γ-ray spectra.

While SCEPTAR is well suited for simply counting beta particles with high efficiency, PACES (Pentagonal Array for Conversion Electron Spectroscopy) measures electron energies with high resolution [P.E. Garrett *et al.*, Acta Phys-

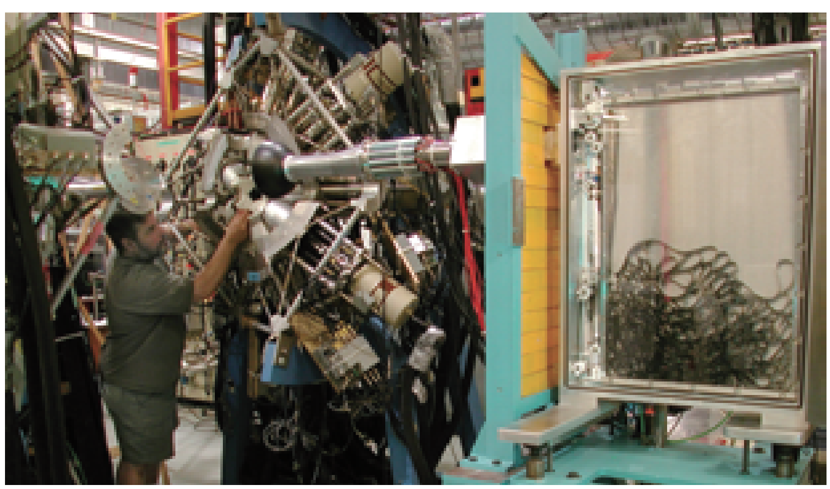


Figure 1: The east half of the 8π spectrometer, the tape system, and the downstream half of SCEPTAR during experiment set up.

ica Polonica B38, 1169 (2007); P.E. Garrett *et al.*, Nucl. Instrum. Methods B261, 1084 (2007)]. PACES replaces half of SCEPTAR with five Si(Li) detectors cooled to near liquid nitrogen temperature (Figure 3). PACES was supported by the DOE and NSERC. The cooling system was designed by LSU, and a variant has been adopted for the Doppler-shift lifetimes program. Conversion electron spectroscopy probes nuclear structure phenomena such as shape coexistence, which can arise from shell gap crossings and impact the nuclear structure corrections to superallowed beta-decay determinations of V_{ud}. PACES' efficiency for conversion electrons is approximately 10%.

The most recent addition to the 8π is DANTE (Dipentagonal Array for Nuclear Timing Experiments). Ten barium fluoride (BaF_2) counters provide relative timing information for detected γ-rays with a resolution two orders of magnitude superior to HPGe. These measurements with stopped beams access lifetimes down to 10 ps, covering the upper end of lifetime ranges for which in-beam techniques (Doppler-shift attenuation method or Coulomb-exchange) are appropriate. Building on experience gained by equipment on loan from the University of Surrey, the remainder of the array was funded by TRIUMF.

These new detectors were accompanied by upgrades and expansion of the readout system. There are now four parallel FERA readouts for each of the HPGe, fast plastic, Si(Li), and BaF_2 systems. These data acquisition upgrades were funded by TRIUMF, NSERC, and the US Lawrence Livermore National Laboratory.

With the extensive ancillary detector development and electronics upgrades done between 2003 and 2005, the 8π spectrometer at ISAC-I now represents a world-unique facility for decay spectroscopy with rare-isotope ion beams. A further dramatic increase in the sensitivity of this unique facility could be realized by replacing the 8π HPGe detectors (now more than 20 years old) with state-of-the-art large-volume clover-type HPGe detectors. This upgrade would increase the efficiency of the spectrometer by a factor of 20 (a factor of 400 for

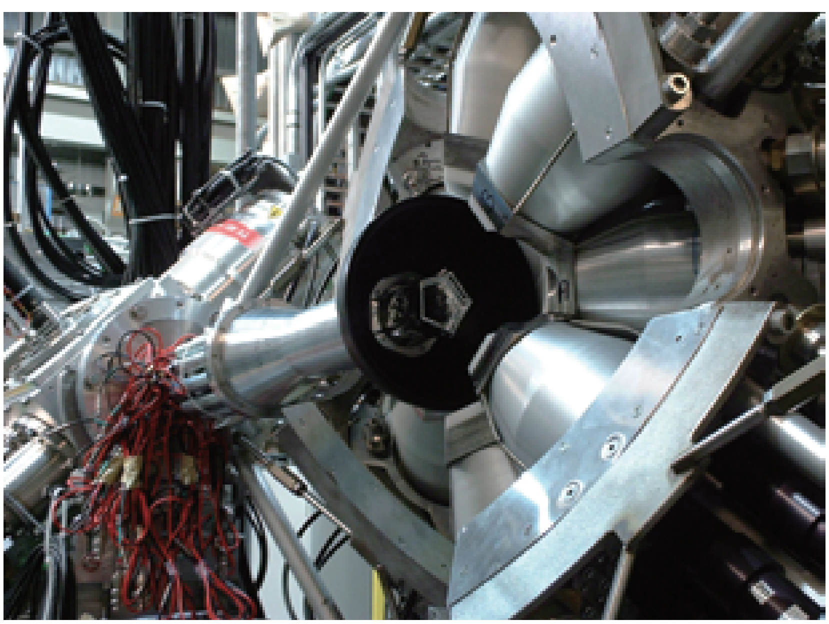


Figure 2: Upstream half of SCEPTAR with the east half of 8π.

γ-γ coincidence detection) and would allow detailed spectroscopic studies of the most exotic nuclei produced by the ISAC-I facility with intensities well below 1 ion/second. This proposed new facility, Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN), is currently being considered as a Canada Foundation for Innovation application led by collaborators at the University of Guelph.

Partners

In Canada: McMaster University, Queen's University, Saint Mary's University, Simon Fraser University, the University of Guelph, and the University of Toronto.

International Partners: France (1), the United Kingdom (3), and the United States (7).

TRIUMF's Role

TRIUMF provides a dedicated technician for 8π, TIGRESS, and GPS. One staff scientist manages the 8π and GPS programs; a second staff scientist provides support. TRIUMF designed, fabricated, and installed several components of 8π including the beam line, modified detector mounts, and Hevimet collimators for the HPGe, rails, and the stand for the tape system, target chambers for SCEPTAR and PACES, detector mounts for DANTE, cable trays, electrical service, and an enclosed, cooled hut for the electronics. TRIUMF also provides front-end readout computers, back-end workstations, data acquisition software, networks, and mass data storage.

Figure 3: PACES. As installed, it replaces the upstream half of SCEPTAR shown in Figure 2.

5.3.2.2.1.4

TRIUMF's Ion Trap for Atomic and Nuclear Science: TITAN

Introduction

To understand the nature of the atomic nucleus and to generate a coherent picture of how all the elements in the universe were made in a process called nuclear synthesis, it is necessary to determine both the basic properties of these "exotic nuclei," and to study their interactions. TITAN (TRIUMF's Ion Trap for Atomic and Nuclear Science) is ideally suited to perform these measurements. It is a multi-purpose, multi-component apparatus, designed and built to carry out precision experiments on the most exotic isotopes available at ISAC-I; it is a unique facility in the world.

Experimenters using the TITAN facility will determine such fundamental properties as the mass of the atom, and the shape and internal interactions of the nuclear core by using X-ray and laser-spectroscopy techniques. They will investigate the decay of exotic nuclei to help solve the Majorana neutrino puzzle of whether the anti-neutrino and the neutrino are actually the same particle.

Their contribution is via precision branching ratio measurements of double β-decay, which tests the underlying nuclear theory. Matrix elements are needed to determine the mass of the Majorana neutrino, when found.

The key to making successful measurements is achieving precision through excellent control of the nuclei and the experimental apparatus. This level of control is reached by carrying out the measurement on only a single ion at a time. The measurements are performed using ion-trapping techniques, employing Penning and Paul traps, devices for which their inventers, H. Dehmelt and W. Paul, received the Nobel Prize in Physics in 1989.

The TITAN facility started construction in April 2003 with an NSERC Research Tools and Instruments grant. A year later, a significant Canada Foundation for Innovation component of $C250,000 was awarded to G. Gwinner of the University of Manitoba. In December 2006, ISAC successfully delivered the first test beam, and TITAN achieved proof of principle. In August 2007, the TITAN Group carried out its first successful on-line mass measurement on singly charged ions. Next steps will include the integration of the electron beam ion trap (EBIT) for experiments on highly charged ions in summer 2008. The collaboration partner from the University of Giessen, Germany, will bring an isobar separator multi-time-of-flight reflectometer for tests in the winter of 2008–2009. The double-β decay experiments are scheduled for detector testing in the winter of 2008–2009, and the first branching ratio measurements in the summer of 2009.

Description of Dedicated Apparatus

The TITAN facility consists of three independent ion trap systems: the radio-frequency quadrupole (RFQ) cooler and buncher; the electron-beam ion trap (EBIT), charge breeder, and the Penning trap for the mass measurements (see Figure 1). Later, a Cooler Penning trap will be installed from University of

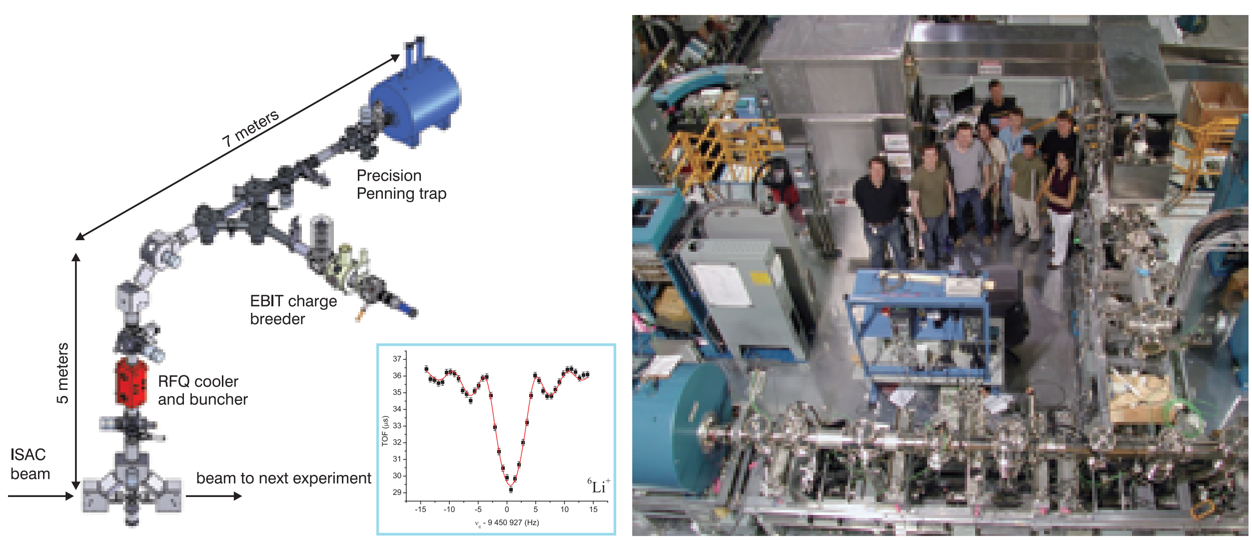


Figure 1: Schematic diagram, photograph of the TITAN Group, and spectrum from TITAN. The diagram of TITAN shows the RFQ cooler and buncher, the EBIT, and the precision Penning trap. Centre: the characteristic time-of-flight resonance curve for $^6Li^+$ from the Penning trap.

Manitoba to allow for cooling of highly charged ions, and for isobar-cleaning. The system is set up following the principle of separation of functions, which makes the individual units maximally efficient and allows optimal flexibility.

The RFQ is coupled to the ISAC-I beam (from the left in Figure 1). The 60 keV DC ion beam is decelerated in the RFQ to a few tens of eV. It is then trapped and cooled with inert buffer gas. Once the ions are cool, the trap potential is opened, and the ions are released as a bunch. This can be done uniquely at TITAN, either in the forward or backward direction. The backward option brings the beam back to the ISAC-I beam line, and makes a cooled and bunched ion beam available for the next experiments (to the right in Figure 1), such as collinear laser spectroscopy, or β-NMR. In the forward extraction mode, the beam is delivered to the next TITAN component, which is the EBIT or the Penning trap.

The EBIT's main function is to change the charge state of the ions from singly charged to highly charged ions, which is done by trapping the ion in the EBIT and stripping electrons away with an energetic electron beam. EBITs are typically employed for stable isotopes, and this is the first and only EBIT coupled to a rare-isotope beam facility. The requirements of short-lived isotopes demand very fast and efficient charge breeding, hence the TITAN device is adapted to that by having a factor of ten higher electron currents than typical EBITs, and it is fitted with seven radial ports for on-line diagnostics and for experimental purposes. Once the ions have reached a high charge state, they are delivered to the Penning trap.

In a Penning, charged particles are trapped by the combination of a strong homogeneous magnetic field and a weak quadrupolar electric field. The motion of the particles is well understood, and we can determine the mass via the cyclotron frequency. For a particle with mass m and charge q in a magnetic field B, the cyclotron frequency is given by $\nu_c = q/m \times B/2\pi$. A typical time-of-flight resonance curve for stable Li is shown in the inset of Figure 1. The

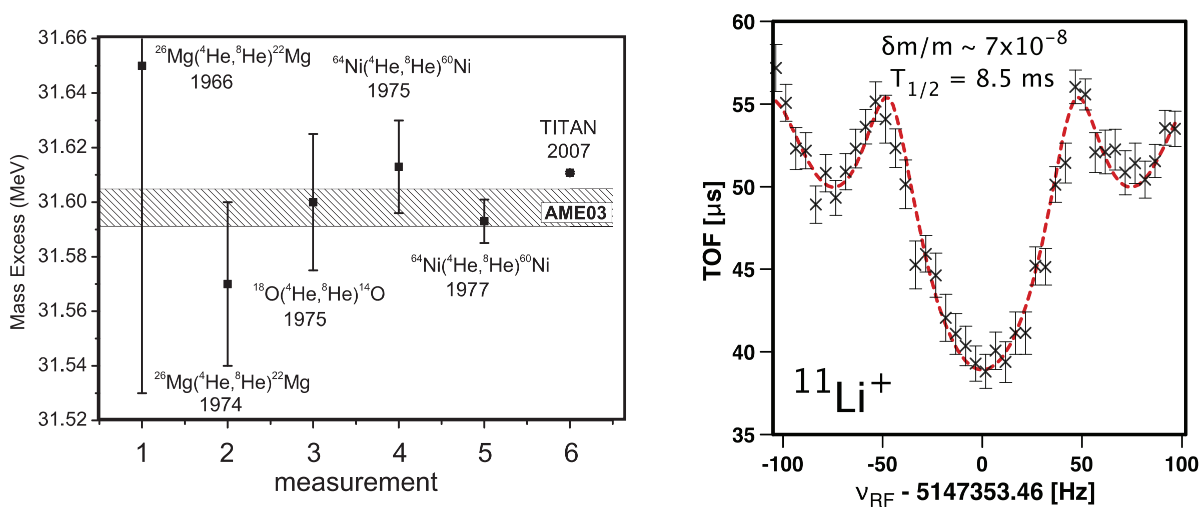


Figure 2: Examples of TITAN's experimental capabilities. Left: Older measurements of the mass of the 4-neutron halo ^{8}He are compared with the new TITAN result. Right: The characteristic time-of-flight resonance curve, of the neutron halo ^{11}Li, of the Penning trap.

JENS DILLING

TRIUMF Research Scientist
Adjunct Professor of Physics, UBC

Jens Dilling is an expert in precision experiments for nuclear physics using atomic physics techniques, expertise he acquired during his graduate studies at the University of Heidelberg. In 1997, he carried out his M.Sc. work at TRIUMF with the TRIUMF Neutral Atom Trap facility (TRINAT) and investigations of the standard model of weak interactions, measuring beta-neutrino correlations.

Dr. Dilling completed his Ph.D. thesis in 2001 at CERN's ISOLDE facility and at SHIP, the super-heavy ion in-flight facility at GSI in Darmstadt. His thesis focused on the ion trap technique of 1989 Nobel prizewinners Dehmelt and Paul and was the first to include measurements carried out both with Penning traps at ISOL-type and in-flight facilities.

Dr. Dilling returned to TRIUMF in 2001 as a research scientist and leader of the TITAN (TRIUMF Ion Trap for Atomic and Nuclear science) project. This highly successful program now delivers the most precise mass data on the halo-nuclei, such as ^{11}Li.

Jens is actively involved in the Canadian and international physics community. He served on the TRIUMF Users' Group from 2005–2007 and on the NSERC Long-Range Planning Committee. He is currently the Canadian representative on the IUPAP (International Union for Pure and Applied Physics) C2 commission for masses and fundamental constants, and Chair of the 2010 International Nuclear Physics Conference (INPC) to be held in Vancouver.

precision of the mass measurement scales with the charge state q, and hence the use of the EBIT for charge breeding.

Recent Developments

At present, TITAN is the most advanced mass spectrometer in the world coupled to a rare-isotope beam facility. It has the unique capabilities to carry out experiments on highly charged ions that will lead to an increase in precision in the mass determination of almost two orders of magnitude, for example, for francium isotopes.

TITAN holds the record for measurements on short-lived isotopes on both the lightest nuclei ever trapped and the shortest-lived isotopes (see Figure 2). For the half-life, an improvement of almost an order of magnitude was reached. These two unique features enabled the precision measurements on the halo nuclei, for example ^{11}Li ($t_{1/2} = 8.5$ ms).

TITAN's future scientific program will include the full exploitation of ISAC-I's capabilities to produce very exotic nuclei for mass measurements, laser spectroscopy, X-ray spectroscopy on highly charged rare isotopes, and to determine electron-capture branching ratios. Electron-capture branching ratios represent an ideal way to probe the framework, which is used to determine the nuclear transition matrix element for double beta decay. These, in turn, are needed for neutrinoless β-decay and the search for Majorana neutrinos, for example at the Sudbury Neutrino Laboratory.

Partners

In Canada: McGill University, the University of British Columbia, University of Calgary, University of Manitoba, University of Windsor, and York University.

International Partners: France (4), Germany (4), Japan (1), the United Kingdom (1), and the United States (2).

TRIUMF's Role

J. Dilling, TITAN's principal investigator, is a TRIUMF scientist. TRIUMF's staff and university scientists together drive the science program. TRIUMF provides the vast majority of technical support including engineering and design, mechanical and electrical machine shops, and control support for the system. TRIUMF plays a decisive role by providing continued maintenance by a full-time technician.

5.3.2.2.1.5

Laser Spectroscopy Facilities

Introduction

By its very nature in an atom, the nucleus is surrounded by and interacts with a cloud of atomic electrons. The use of high-precision laser spectroscopy as a probe of electronic structure yields detailed information about the interaction between the nucleus and its orbiting electrons. Detailed spectroscopic studies of the electronic structure along a chain of radioactive isotopes of the same chemical element can yield information not only on electronic structure, but also on nucleus-electron interactions. When undertaken at very high precision, these studies provide a method to determine some nuclear properties: the changes in the mean squared charge radii and the ratio of ground and long-lived isomeric state nuclear moments. To achieve the high precision necessary for these measurements at a radioactive beam facility, where beams of exotic species are available as slow (~metres per second) ionic beams, it was necessary to remove the inherent velocity spread of the ions that occur during production and ionization. TRIUMF has achieved this by using two different methods.

The first method provided the measurement that gave the first direct evidence for the ^{11}Li nucleus having a single neutron halo. In collaboration with

GSI, which developed the technique, TRIUMF, determined the measurement of the charge radius of ^{11}Li by first stopping the beam within a carbon foil prior to being re-evaporated, giving a thermal vapour upon which laser spectroscopy could be performed. This ensured the ^{11}Li atoms lost any memory of their production mechanism.

The second, and more universal, method increases the energy of an ionic beam to reduce the velocity spread of the beam. With this method, it is possible to reduce the Doppler width to levels where it is possible to extract the nuclear information of interest. If an ionic (or atomic) beam is arranged to propagate collinearly with a narrow line-width, tunable laser beam, the resulting fluorescence spectrum exhibits a line-width greatly reduced from one that would be achieved within the ion source. A schematic of the set-up is shown in Figure 1. This method has been used to make measurements of the ground state moments of ^{131}La, giving the first evidence for the existence of tri-axially deformed or pear-shaped ground state nuclei in this region.

Description of Dedicated Apparatus

The collinear fast beam, laser spectroscopy facility utilizes the polarizer beam line as well as the radio-frequency quadrupole (RFQ) cooler buncher within the TITAN facility. Beams from the ISAC target are either taken directly into the beam line where they either pass through as an ionic beam or are neutralized to provide an atomic beam. This fast beam is then overlapped with a laser beam and the laser frequency scanned. When the laser frequency exactly matches that of an atomic transition, light is absorbed and then re-emitted. As the re-emission is isotropic in space, a detector mounted at 90° to the direction of propagation of the laser and atomic/ionic beams sees predominantly photons from the re-emission providing a direct measure of the adsorption of the laser light. A plot of laser frequency (in the centre-of-mass frame) against emitted fluorescence gives a direct measure of the energy of the atomic transition (see Figure 2). A fast beam is used to compress the velocity spread inherent from the ion source. The incorporation of the TITAN RFQ into the beam line prior to the light interaction region has further increased the sensitivity of the system. The energy and therefore velocity spread is greatly reduced by cooling and bunching the beam. Also, by bunching the beam and only

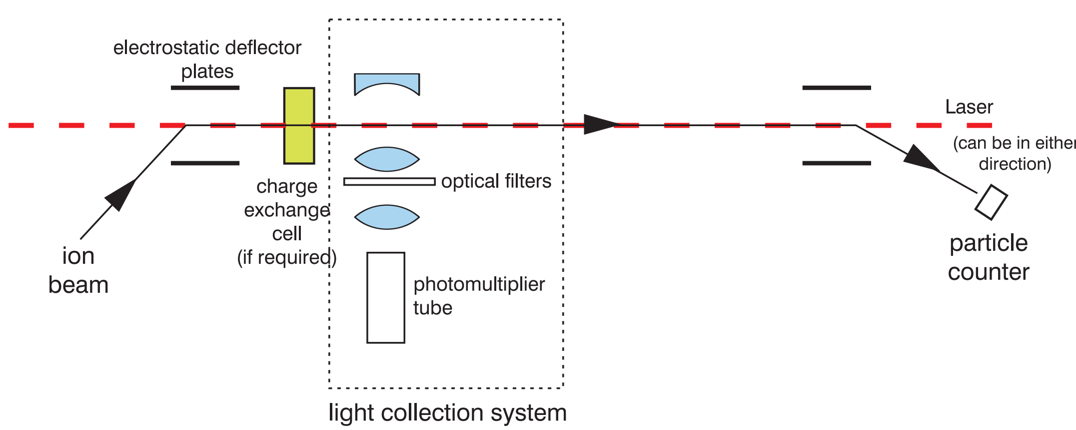


Figure 1: The collinear spectroscopy facility.

accepting photons from the light collection region while the ion beam is passing through it, the background is reduced by the duty cycle of the bunched beam (currently a 2 μs bunch produced at a frequency of 10 Hz therefore an increase in sensitivity of 50,000) with negligible loss of real fluorescence photons.

Recent Developments

Since the commissioning as a collinear beam line, several upgrades have been performed. The post-acceleration region and light collection optics have been constantly upgraded. In 2007, the TITAN RFQ came on-line, which allowed cooled, bunched beams to be utilized. The data acquisition system has been adapted to incorporate this facility.

Partners

In Canada: McGill University, University of Calgary, and the University of Western Ontario.

International Partners: Japan (1); Sweden (1), the United Kingdom (1), and the United States (1).

TRIUMF's Role

Besides being the world's premier rare-isotope beam facility for the production of the most intense radioactive beams, TRIUMF has contributed in many other ways to the success of laser spectroscopy. The beam quality within the ISAC facility is second to none, and results in high spatial overlap of the laser and ion beams. The construction and continuing support of the TITAN RFQ has permitted spectroscopy on cooled, bunched beams to enhance the sensitivity of the system by many orders of magnitude.

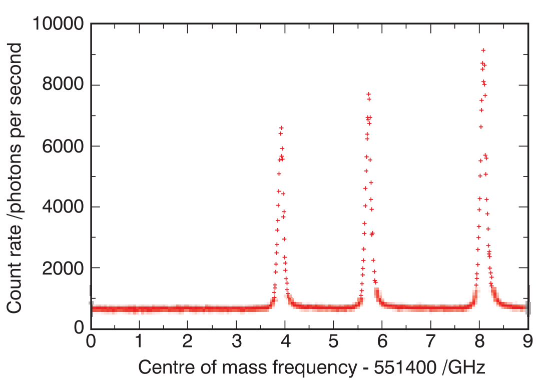


Figure 2: The intensity of the fluorescence light as a function of the laser light frequency on the ^{139}La atom. The electronic transition is from the metastable $6s^2\ ^1S_0$ to the $5d6p\ ^3D_1$ state. The three transitions arise from the hyperfine splitting of the $J = 1$ upper state (the lower state is $J = 0$, therefore there is no splitting).

5.3.2.2.2

ISAC-II Facilities

5.3.2.2.2.1

TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer: TIGRESS

Introduction

The TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) is a major new international user facility. It is a state-of-the-art γ-ray spectrometer developed specifically for use at TRIUMF's higher mass and higher energy Isotope Separator and Accelerator (ISAC) rare-isotope ion beam facility. TIGRESS has been designed and built to answer many important questions on nuclear structure using several different reaction mechanisms. Each of these reaction mechanisms accesses different energies, spins, and components of the wave functions, and each shines a different light on the nucleus. The two features they share are that they require beams accelerated to the energies provided by ISAC-II, and the γ-rays are measured with TIGRESS.

We think we know that nuclei contain protons and neutrons. But what does a nucleus look like? Do the protons and neutrons (or together, called nucleons) stick together to form a bumpy, round ball? The answer to this question is very definitely no: the nucleus is small enough that the nucleons are better described as waves than as particles. Beyond that, the questions become more challenging. Do the waves act independently of one another, like the orbits of planets around the sun? Or do they pile up on one another? If they pile up on one another, does the nucleus end up looking like a drop of wiggling goo, or a solid, spinning pear-shaped lump?

The answer to all of the above is "yes and no", or, "depends on the numbers of protons and neutrons." The question can be better asked, "What is the structure of the nucleus?" From an experimental perspective, the answer means measuring the energy, spin (a quantum mechanical property analogous to rotation), and parity (does it look the same in a mirror) of states of the nucleus. Theoretically, the question is whether the structure is dominated by the wave functions of a small number of valence nucleons outside a closed shell, the single-particle picture, or do the wave functions become coherent and resemble a semi-classical vibrating or rotating object, *i.e.*, the collective picture. Understanding nuclear structure means searching for the closed shell numbers and understanding how the wave functions change from single-particle to collective by adding or removing protons or neutrons.

One aspect of nuclear structure is the mass of a nucleus, which is measured with TRIUMF's TITAN (see Section 5.3.2.2.1.4). Another aspect is energy of the excited states. Quantum systems can absorb or release energy in well-defined steps corresponding to the energy differences between states. One way of releasing energy is by emitting photons, which, when they come from a nucleus, are called γ-rays. The energy of the γ-rays directly measures the difference in energies between states, while the direction of emission depends on the spins of the states.

Energy can be put into an individual nucleus by turning it into a projectile. By accelerating the nucleus to high enough speeds, it can overcome the electric repulsion between the beam nucleus and a stationary nucleus in a fixed target. If the nuclei touch, *i.e.*, the wave functions of the projectile and target overlap, the two nuclei can stick together. These "fusion-evaporation" reactions impart the most energy to the final, residual nucleus, and several γ-rays (and possibly particles) are released in the process. If the wave functions just barely overlap, a "transfer reaction" may occur in which several, or possibly only one or two neutrons or protons move from one nucleus to the other. In these experiments, γ-rays are valuable for identifying whether the projectile, target, or both are excited, and if so, by how much. Finally, in a near-collision, where the nuclei do not touch, the violence of the repulsion of the target and projectile is enough to shake one or both into an excited state. Because this process occurs solely due to electric repulsion, it is called Coulomb excitation.

Description of Dedicated Apparatus

TIGRESS will comprise of twelve 32-fold segmented clover-type high-purity germanium (HPGe) detectors purchased from Canberra Canada. Each of these detectors consists of four individual HPGe crystals packed in a four-leaf-clover geometry (see Figure 1). Each crystal is read out by 8 ground connections: one on each of the volumes (labeled 1 to 8). The high voltage is applied to the central bore of each crystal, on an electrical contact on a hole drilled from the back of the crystal through about two-thirds of the crystal (not visible in the orientation of this figure). A signal is also taken from this core contact to measure the full energy for each crystal. This segmentation provides coarse-grained information about the locations of the γ-ray interactions within the crystals. Fine-grained position information is then obtained by pulse-shape analysis of the 9 charge-collecting signals. By the combination of these techniques, sub-mm position resolution for single γ-ray interaction has been demonstrated for the TIGRESS detectors.

Reconstruction of the initial γ-ray interaction positions within ± 2.5 mm is expected in typical in-beam experimental conditions. This position sensitivity allows the angle of emission of the γ-rays relative to the recoiling nuclear sources (which determines the Doppler broadening of the resulting γ-ray energy resolution) to be well determined even for detectors positioned in close proximity (11 cm) to the target location. The resulting large solid-angle coverage by a modest number of detectors (12) leads to large gains in γ-ray detection efficiency, compared to previous generation spectrometers, without sacrificing γ-ray energy resolution in in-beam experiments. The full TIGRESS array will, for example, have an absolute detection efficiency of 10% for 1 MeV γ-rays. This high-detection efficiency enables in-beam experiments with accelerated rare-isotope beams with typical intensities that are orders of magnitude below stable beam standards.

In addition to the highly segmented HPGe clover detectors, TIGRESS also employs 20-fold segmented bismuth-germanate (BGO) and CsI(Tl) Compton

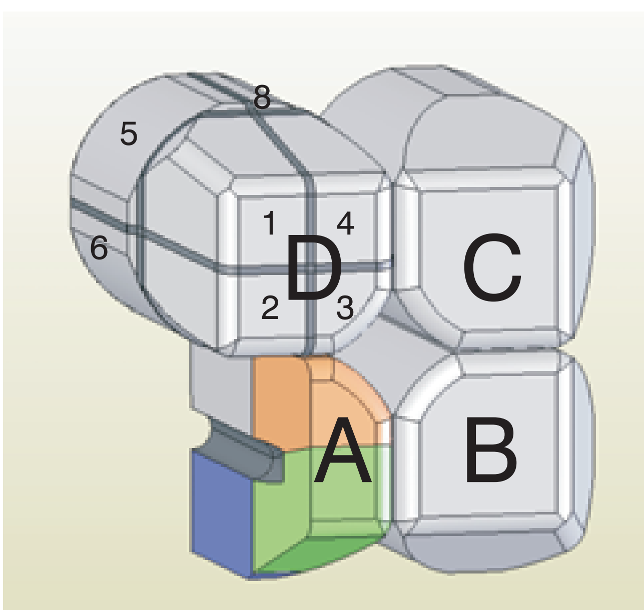


Figure 1: The TIGRESS clover detector consisting of four HPGe crystals labeled A, B, C and D.

suppression shields to provide segment-specific vetoing of events in which γ-rays escape the HPGe volume without depositing their full energy. These are mounted in a versatile mechanical structure that enables rapid redeployment of the array between a maximum-efficiency and an optimal suppression configuration. Both the HPGe and BGO detectors are read out by fast (100 MHz, 14-bit) 10-channel waveform digitizer (TIG-10). Collector (TIG-C) modules make trigger decisions and provide dataflow between the TIG-10 modules and the data acquisition computers. Both types of of modules have been custom designed for TIGRESS and produced at l'Université de Montréal.

Recent Developments

TIGRESS was funded in 2003 by an C$8 million, six-year NSERC Major Installation Grant. Six of the twelve HPGe plus Compton suppressor systems have now been received, fully tested, and installed in the TIGRESS mechanical support structure at ISAC-II (see Figures 2 and 3).

The final version of the TIG-10 digitizer cards is in production, and 45 of these modules, together with 6 TIG-C collector modules that demonstrate the full multi-level TIG-C hierarchy, have been tested and are now operational at ISAC-II. This six-detector early implementation of TIGRESS was used in the first experiment with accelerated radioactive beam (^{29}Na) from the newly commissioned ISAC-II superconducting linac in July and August 2007. All subsystems of the spectrometer were interfaced flawlessly, representing the achievement of a major milestone for the project.

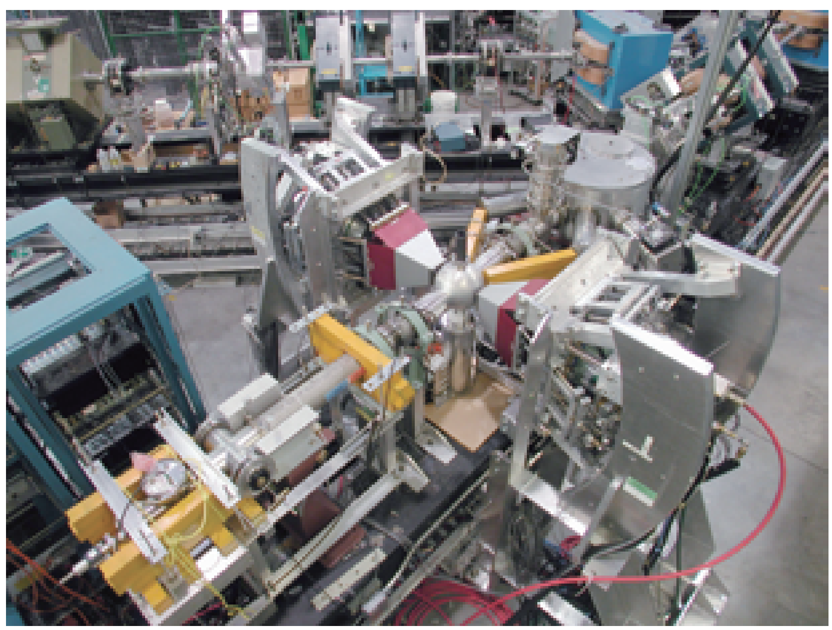


Figure 2: Two TIGRESS detector systems at the ISAC-I zero-degree beam line used for the first TIGRESS Coulomb excitation experiments with accelerated radioactive beams ^{20,21}Na in July 2006. The detectors have their Compton suppression detectors in place, as will be the case when the full array is in its maximum signal-to-noise configuration.

TIGRESS is now operational as an experimental user facility for the Canadian and international γ-ray spectroscopy communities. Additional experiments with light accelerated beams (^{11}Be and ^{21}Na) are being carried out in the spring and summer of 2008, as well as the first heavier ($A > 29$) accelerated beams from the new ISAC charge-state booster scheduled for spring 2009. These latter experiments are expected to be performed with 9 TIGRESS detector systems, with the full complement of 12 detector units installed and operational in summer 2009.

In parallel with the installation of TIGRESS itself, rapid development has been taking place in the implementation of the suite of associated detectors necessary to provide detection of scattered heavy ions, light charged particles, and neutrons in coincidence with the γ-rays detected by TIGRESS. The first of these, employed in the ^{20,21}Na and ^{29}Na Coulomb excitation experiments at ISAC-I and ISAC-II, respectively, is the Bambino Si CD detector, (so named because it is shaped like a compact disc), which was assembled at Lawrence Livermore National Laboratory and mounted in a TIGRESS target chamber designed and built at the University of Rochester (see Figure 4). The new Silicon Highly Segmented Array for Reactions and Coulex (SHARC), comprised of 576 channels of double-sided silicon strip detectors for use with TIGRESS, has been funded by the United Kingdom and is under construction at the University of York in the UK and Louisiana State University and Colorado School of Mines in the US. The York TIGRESS collaborators are also building an

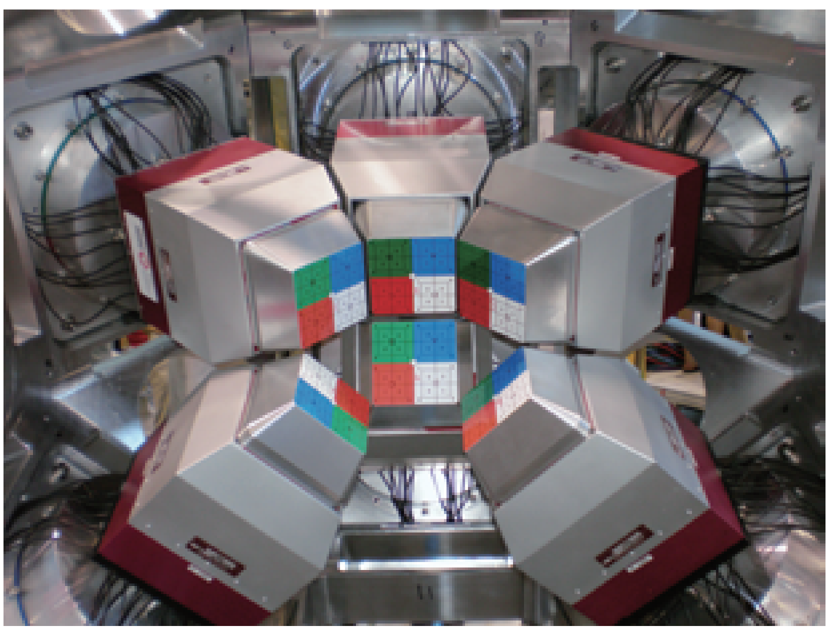


Figure 3: Six TIGRESS detector systems used in the first Coulomb excitation experiment with accelerated radioactive beam (^{29}Na) from the new ISAC-II superconducting linac in July 2007. The detectors are in a close packed configuration, and do not have their Compton suppression detectors in place, as will be the case when the full array is in its maximum efficiency configuration.

array of five Bragg curve detectors that will couple to TIGRESS for heavy-ion detection and *Z* identification.

The C$1.79M Deuterated Scintillator Array for Neutron Tagging (DESCANT) was funded by the Canada Foundation for Innovation (CFI) in 2007 and is under development at the University of Guelph and TRIUMF. A CsI(Tl) charged-particle detector for TIGRESS was funded by NSERC for C$71,833 in 2006 and is under development at Saint Mary's University, together with a pool of TIG-10 and TIG-48 waveform digitizers for TIGRESS auxiliary detectors funded by a C$324,089 award from the CFI. For many experiments at ISAC-II, TIGRESS will also operate together with the ElectroMagnetic Mass Analyser (EMMA) funded jointly by a C$2.085 million NSERC award and a C$1.0 million TRIUMF contribution in 2006. Each of these associated devices will provide unique capabilities that will enhance the sensitivity of TIGRESS and permit whole classes of experiments at ISAC-II that would otherwise be impossible.

Partners

In Canada: Laval University, l'Université de Montréal, the University of Guelph, McMaster University, Saint Mary's University, Simon Fraser University, and the University of Toronto.

International Partners: France (1), the United Kingdom (3), and the United States (4).

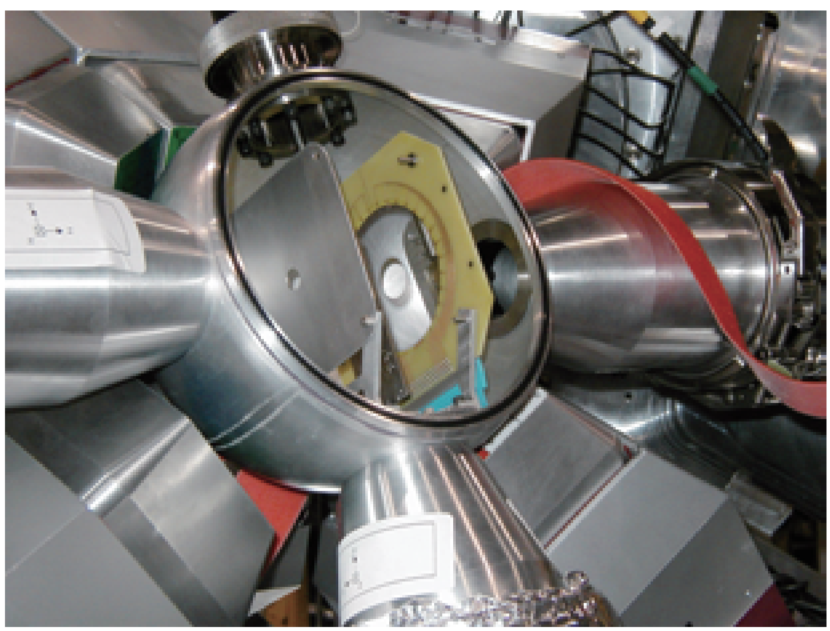


Figure 4: The BAMBINO Si CD detector mounted inside the TIGRESS target chamber. The beam enters from the left, impinges on a thin foil target (behind the Al collimator plate) and passes through the hole in the centre of the Si CD detector.

TRIUMF's Role

TRIUMF has made major contributions to the design and installation of TIGRESS. F. Cifarelli of the TRIUMF Design Office designed all of the TIGRESS mechanical support structure and detector mounting machines, and TRIUMF engineers verified them through finite element analysis. The machining of components was carried out in parallel by the TRIUMF and the University of Guelph machine shops, as well as by external contractors.

TRIUMF has also provided a dedicated detector laboratory in the ISAC-II building for the testing, characterization, and maintenance of TIGRESS detectors. The precision scanning table in this laboratory was supported through the Laboratory for Advanced Detector Development at TRIUMF.

In addition to the ISAC-II superconducting linear accelerator, the TRIUMF Accelerator Division designed and constructed the dedicated high-energy beam transport line (SEBT-3A) to the TIGRESS location in the ISAC-II hall.

A dedicated TRIUMF technician, R. Churchman, provides ongoing technical support for TIGRESS, while a second technician, R. Maharaj, coordinated design, procurement, parts, and machining during the mechanical construction phase. Staff Scientist G. Hackman manages all on-site activities related to TIGRESS and is supported by G. Ball, a second TRIUMF scientist.

Two members of the TRIUMF Data Acquisitions Group, P. Amaudruz and C. Pearson, provide ongoing support for TIGRESS. They have been, and continue to be, instrumental in the development and implementation of the custom TIGRESS waveform digitizer modules. Isolated electrical power distribution, an air-conditioned electronics enclosure, an instrumented beam dump, front-end readout, back-end workstations, and networks for TIGRESS data acquisition have all been provided by TRIUMF.

5.3.2.2.2.2

ElectroMagnetic Mass Analyser: EMMA

Introduction

Nuclear astrophysics is concerned with the creation of the elements that make up our world. To do this, physicists have had to develop a wide range of tools to probe, study, and understand the nuclei and the many reactions nuclei undergo. Different tools are required for different applications. The ElectroMagnetic Mass Analyser (EMMA) is one of the tools that will be used at TRIUMF's Isotope Separator and Accelerator (ISAC) rare-isotope ion beam facility.

EMMA is an advanced recoil mass spectrometer for use with heavy rare-isotope ion beams. ISAC-II will provide intense, high-quality beams of radioactive ions with masses up to 150 atomic mass units and maximum energies of at least 6.5 MeV/nucleon. These beams will be used to study the single-particle structure of exotic nuclei, the evolution of nuclear structure and shapes far from stability and at high spin, fundamental symmetries, and nuclear astrophysics.

EMMA will be an integral part of the experimental program at ISAC-II, both as a stand-alone device and in conjunction with other particle detection systems. One important avenue of research will involve the coupling of EMMA with the TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer

(TIGRESS). By positioning TIGRESS around the target position of EMMA, prompt gamma rays emitted by a recoiling nucleus formed in a fusion-evaporation or transfer reaction can be correlated with the arrival of the recoil at the focal plane of EMMA. Focal plane detectors will allow the determination of the mass, and in many cases the atomic number of the recoil using position, energy loss, and time-of-flight measurements. The recoil information allows very weak reaction channels to be studied in the presence of very high yield background channels, enabling the exploration of high-spin states in exotic nuclei as well as their low-lying, single-particle structures.

In 2006, EMMA was funded by a $C2 million NSERC Subatomic Physics Research Tools and Instruments award, and a $C1 million contribution from TRIUMF. This will allow EMMA to be commissioned in 2010. When it begins operation, EMMA will be an important new international user facility for nuclear structure and astrophysics with accelerated rare-isotope beams, demonstrated in part by overwhelming interest in the two recent EMMA workshops.

Description of Dedicated Apparatus

EMMA is an electromagnetic recoil mass spectrometer designed to separate the recoils of nuclear reactions from the primary beam and to disperse them in a focal plane according to their mass-to-charge ratio (*m/q*) (see Figure 1). Measurements of position, energy loss, energy, and time of flight will serve to uniquely identify the transmitted recoils. In addition to having a large solid angle of 16 msr, the spectrometer will accept recoils within a large range of m/q (±4%) and energies (±20%) about the central values. These large acceptances result in high detection efficiencies approaching 50% for the recoils of many fusion-evaporation reactions. The trajectories of mono-energetic ions of a single mass within the spectrometer are isochronous within 0.1%, allowing high-resolution time-of-flight measurements and large real-to-random ratios in coincidence experiments. These properties make EMMA a recoil mass spectrometer of unprecedented quality that is ideally adapted to the very strin-

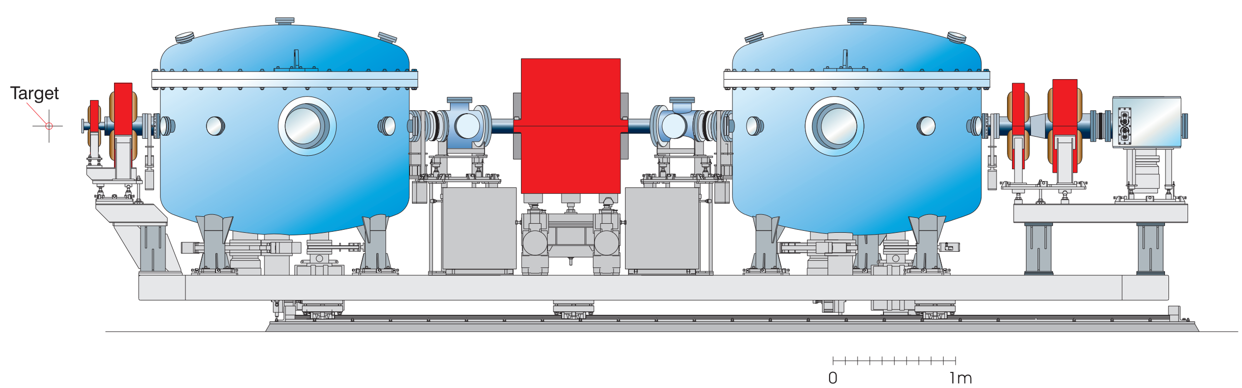


Figure 1: Schematic view of EMMA showing the two large electric dipoles on either side of the central magnetic dipole. Magnetic quadrupole doublets at the front and back serve to spatially focus the recoiling nuclei and allow for variable mass dispersion.

gent requirements for precision ISAC-II experiments at the edge of nuclear existence.

Figure 2 shows the calculated focal plane position spectra for EMMA and the FMA, a similar recoil mass spectrometer at Argonne National Laboratory. The same recoil mass, energy, and angular distributions were used as input in the simulations, which show the results for 11 masses centred about $A = 100$ with charge state $q = 20$ having uniform ±10% spreads about the central energy of 1.8 A MeV and uniform angular distributions filling 30 msr (± 5°). As the figure shows, EMMA has twice the angular acceptance of the FMA and a larger m/q acceptance without compromising m/q resolution.

Separation of reaction products from the primary beam at 0° allows the detection of recoils from fusion-evaporation reactions as well as transfer reactions induced by rare-isotope heavy ions, which emerge from the target in narrow cones centred about the beam direction. The capacity to disperse ions according to *m/q* combined with multi-wire gas detectors in the focal plane will allow high-resolution determinations of the atomic masses and atomic numbers of recoils. These capabilities of large acceptance, beam rejection at 0°, and high mass resolution make EMMA an unparalleled instrument for nuclear physics research. When commissioned in 2010 and coupled with the unique radioactive ion beams from ISAC-II and the advanced γ-ray spectrometer TIGRESS, EMMA will position TRIUMF as the world leader in rare-isotope beam physics at the Coulomb barrier.

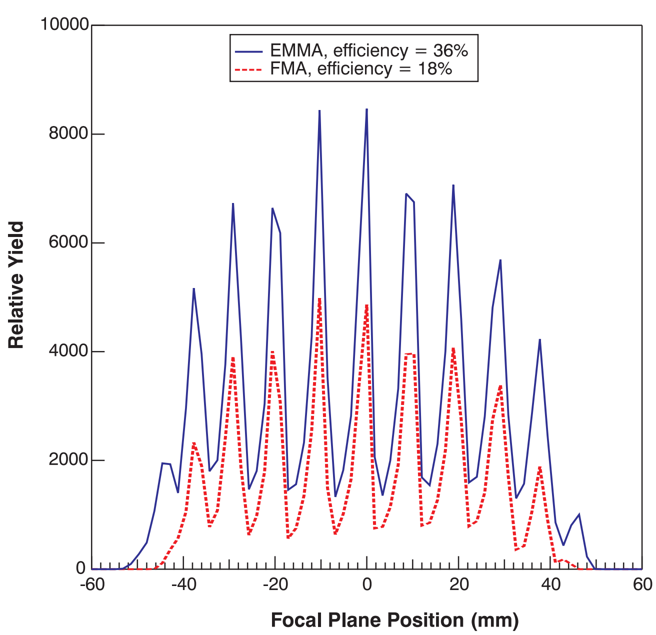


Figure 2: Calculated mass spectra for EMMA and the FMA of Argonne National Laboratory with identical recoil mass, energy, and angular distributions. EMMA exhibits efficiency twice as large as that of the FMA while preserving superior mass resolution.

Recent Developments

After funding was obtained in 2006, a dedicated effort was required to precisely specify the electromagnetic and mechanical properties of the spectrometer that are so crucial in determining its quality. The firms that bid on the large electromagnetic elements of EMMA were evaluated on their ability to meet these rigorous technical specifications as well as cost. The contract was awarded to Bruker BioSpin in 2007, and fabrication has begun.

In addition to the work on EMMA, substantial progress has been made on other ISAC-II detector systems. EMMA will operate together with many experiments at ISAC-II, and its associated detector systems such as the Silicon Highly Segmented Array for Reactions and Coulex (SHARC) and the Deuterated Scintillator Array for Neutron Tagging (DESCANT). Each of these detector arrays will provide unique capabilities to enhance the utility of EMMA and enable experiments at ISAC-II that would otherwise be impossible.

Partners

In Canada: University of Alberta, University of Guelph, McMaster University, Saint Mary's University, and Simon Fraser University.

International Partners: Germany (1), Japan (1), United Kingdom (3), and the United States (5).

TRIUMF's Role

TRIUMF has made major contributions to the design of EMMA and will make major contributions to its installation. All of the design effort for the EMMA mechanical support structure, the target chamber, and the focal plane box is being carried out by the TRIUMF Design Office, led by Mechanical Designer F. Cifarelli and Project Engineer N. Khan. TRIUMF also will provide the high voltage power supplies for the electric dipoles of EMMA. The TRIUMF Detector Group will construct and test the position-sensitive multi-wire gas detectors and the ionization chambers for the focal plane.

5.3.2.2.2.3

DEuterated SCintillator Array for Neutron Tagging: DESCANT

Introduction

Much of the structure of neutron-rich nuclei is unknown, and extrapolations using current theories and knowledge possess a high degree of uncertainty due to the modifications of shell structure as the neutron drip line is approached. Studies of neutron-rich nuclei using reactions, such as fusion-evaporation reactions, which have formed the backbone of techniques to study nuclear structure, will be hampered because of the tendency of the compound system to emit multiple neutrons during the cooling phase. Thus, methods for nucleus identification that rely on charged-particle detection will not be as useful, and neutron or recoil detection will be an absolute necessity. However, for many reaction networks, the recoil will not be sufficiently energetic or constrained within the narrow acceptance cone of EMMA (ElectroMagnetic Mass

Analyser). Furthermore, there will be a definite need to characterize the number of neutrons, or neutron multiplicity, emitted in the reaction. Thus, there is a definite need for a neutron detector array that can be coupled with TIGRESS.

ISAC-II represents major advancements in the technology that produces and delivers rare-isotope beams for experiments. Along with the need to continually develop production and accelerator technology to boost the beam intensity, is the need to develop advanced detector capabilities. TRIUMF and its partners have developed state-of-the-art γ-ray detectors such as TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS); with a team at TRIUMF, a principal investigator at the University of Guelph is now developing the Deuterated Scintillator Array for Neutron Tagging (DESCANT), a major new capability in neutron detection that will serve as an auxiliary detector for the TIGRESS spectrometer. The proposed array of neutron detectors, using a liquid scintillator based on a deuterated hydrocarbon, will be the first detector array based on this technology ever developed.

In addition to the need for neutron detection in fusion-evaporation studies, a neutron detector array will also be used in reaction studies, notably those involving halo nuclei such as ^{11}Li. Small-angle correlations between neutrons emitted in reactions of ^{11}Li off of various targets contain structural information about the halo neutrons in the parent nucleus. However, in typical neutron detector arrays, these small opening-angle events must be rejected due to the large amount of detector-to-detector scatterings that are always present. A method that could successfully distinguish between multiple scattering events and true high-multiplicity events would offer a tremendous advantage.

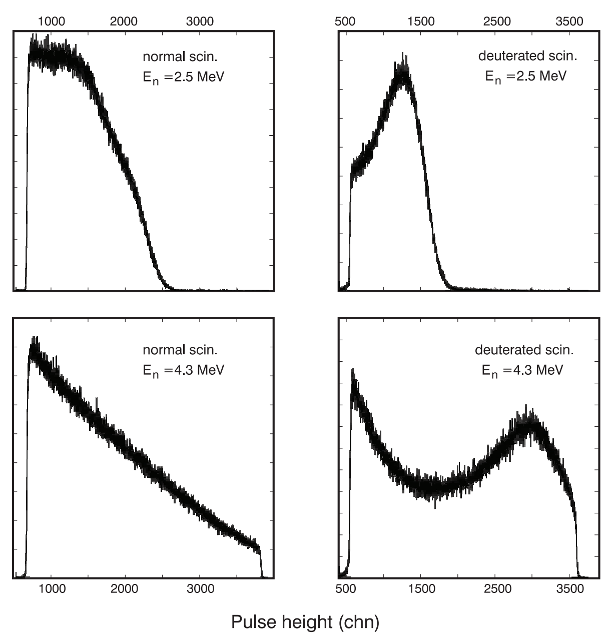


Figure 1: Pulse-height spectra for neutron energies of 2.5 MeV (top) and 4.3 MeV. (bottom) incident on a normal liquid scintillator (left) and a deuterated scintillator (right). The position of the peak in the deuterated scintillator varies as ~$(E_n)^{3/2}$.

Description of Dedicated Apparatus

DESCANT is an innovative design that will use a deuterated-benzene liquid scintillator. Due to the asymmetric nature of *n-d* scattering in the centre of mass (unlike *n-p* scattering that is isotropic), the pulse-height information from the deuterated scintillator contains information on the initial neutron energy. While deuterated detectors have been used in active-target experiments, and as γ-ray detectors in the presence of large thermal neutron fluxes, they have not been used in an array of detectors for fast neutrons.

Recent Developments

To evaluate the performance of deuterated scintillators for fast-neutron detection, a small container with active-volume dimensions of 4.5 in. diameter and 1 in. thickness filled with BC537 from St. Gobain was acquired and tested at the University of Kentucky accelerator facility. Nearly mono-energetic neutrons were produced by either the $t(p,n)^3$He or $d(d,n)^4$He reactions, and pulse-height and time-of-flight (TOF) data were recorded from both the BC537-filled cell and a cell filled with a normal scintillator like BC501 (see Figure 1). The superiority of the pulse-height spectrum over the deuterated scintillator is obvious, and it displays a definite peak-like structure. Combined with the TOF, the pulse height will allow for a much more efficient rejection of multiple scattering than has been achieved previously, yielding much higher quality data, particularly from adjacent detectors.

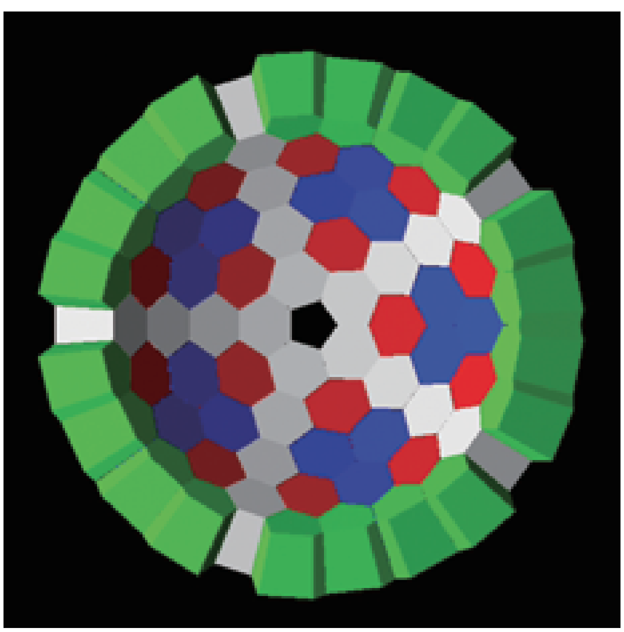


Figure 2: Arrangement of detector cells for DESCANT, seen from the upstream position looking downstream. Four different shapes, distinguished by their colour, are used to cover the available 65.5°. The detectors subtend a total solid angle of 1.08π sr.

A proposal for \$C1.8 million was submitted to the Canada Foundation for Innovation in February 2006 to construct an array of 70 approximately hexagonal-shaped truncated cones using up to 190 litres of deuterated scintillator. The proposal was accepted in November 2006, and matching funds from the Ontario Ministry of Research and Innovation (OTR) were approved in April 2007. The final budget was submitted in October 2007, and the funds released in April 2008. Included in the proposal was the development of new TIG-4G modules that will contain 4 channels of 12-bit 1-GHz waveform digitizers to be used to analyze the pulses from the anodes of the photomultiplier tubes. These cards will be engineered to be completely compatible with the TIGRESS data acquisition system.

The design of the scintillator cans, which defines the geometry of the array, has been finalized at the University of Guelph. They will be approximately 15 cm thick with the front faces at a distance of 50 cm from the target. Four different shapes are used to fill the open 65.5° in the downstream direction of the TIGRESS array (see Figure 2).

Partners

In Canada: Laval University, l'Université de Montréal, McMaster University, Saint Mary's University, Simon Fraser University, the University of Guelph and the University of Toronto.

In the United States: the Colorado School of Mines, the Georgia Institute of Technology.

TRIUMF's Role

TRIUMF's Design Office will design and manufacture the frame to accommodate the DESCANT detectors, as well as the VME64 crates required for data acquisition with the TIG-4G cards. Construction should be completed in late fall 2008 or early winter 2009. TRIUMF's personnel activities for DESCANT are coordinated by Staff Scientist G. Hackman.

5.3.2.2.2.4

Silicon Highly-Segmented Array for Reaction and Coulex: SHARC

Introduction

The Silicon Highly-segmented Array for Reactions and Coulex[1] (SHARC) is a very compact detector array designed to fit within the inner volume of the TIGRESS γ-ray spectrometer. SHARC's main purpose is to enable the study of closely spaced excited states in unstable nuclei by considering coincidences of charged particle and γ-rays. The combination of SHARC and TIGRESS will create a powerful tool to study the spectroscopy of nuclei far from stability and to understand better the structure of short-lived nuclei some of which are involved in astrophysical processes responsible for the nucleosynthesis in stars.

Description of Dedicated Apparatus

The array consists of one CD detector at backward angles and two box sections, one at backward angles, and one at forward angles with ΔE-E capability

1 Coulex is a term used to refer to the Coulomb-exchange process.

(see Figure 1). Each box's front face is made of a double-sided silicon strip detector with 48 transverse strips and 24 longitudinal strips to satisfy the required angular resolution ($\Delta\theta < 2°$ and $\Delta\phi < 5°$) (see Figure 2).

Through simulations with GEANT4, the optimal thickness of the ΔE detector was established to be 140 μm, while the E detector was made as thick as possible (1.5 mm). One of the major design challenges will be to accommodate the large number of electronics channels (732) required to instrument it within the constraint of the relatively small inner volume of the TIGRESS array (11 cm radius sphere). To get all the electronic signals out without interfering with any part of the full TIGRESS array, it will be necessary to remove the forward lampshade of the TIGRESS support structure to provide a path for the signals to exit the chamber.

Partners

In the United Kingdom: the University of York and the University of Surrey.

In the United States: The Colorado School of Mines and Louisiana State University.

TRIUMF's Role

TRIUMF will provide the designs that will integrate SHARC with TIGRESS and its beam line. TRIUMF's partners will design and construct the SHARC array.

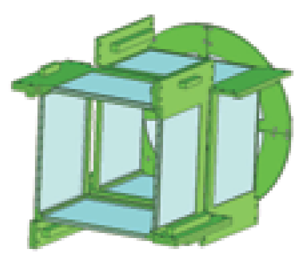


Figure 1: The SHARC array.

Figure 2: Left: Current chamber design. Right: SHARC inside TIGRESS.

5.3.2.2.2.5

HEavy-ion Reaction Array for the Characterization of Light, Excited Systems: HÉRACLES

Introduction

Why do nuclear scientists study exotic nuclei far from the valley of stability? The answer is that these nuclei were created in the thermonuclear fusion reactions that power the stars and produce the chemical elements with which the earth and all of us were made. Many of the atomic nuclei born in these reactions are rare and they decay very quickly, making them difficult to study in the laboratory. Nevertheless, because they play an important role in stellar energy generation and the synthesis of the chemical elements, nuclear scientists must understand the properties of these nuclei.

To study these rare and very short-lived nuclei, specialized tools such as the TIGRESS, EMMA and HÉRACLES detectors are required. The HEavy-ion Reaction Array for the Characterization of Light, Excited Systems (HÉRACLES) multi-detector is dedicated to the study of heavy-ion reaction dynamics. It was operated extensively at the Chalk River Tandem Accelerator and the Superconducting Cyclotron at the Chalk River Laboratories. It moved to the Cyclotron Institute at Texas A&M University in 1997. In 2003, it was moved to TRIUMF where it has been adapted to ISAC-II energies and subsequently mounted in the ISAC-II experimental hall.

The detector will be used to understand the effect of changing the ratio of protons to neutrons on the nuclear energy, referred to as the asymmetry term in nuclear mass formulae. This term is poorly determined in stable nuclei because of the limited range of proton-to-neutron ratios available. Information on its value can be obtained by studying nuclear reaction dynamics for a string of isotopes with the same number of protons but different numbers of neutrons.

Heavy ion reaction dynamics studies at ISAC-II offer the opportunity to measure nuclear interactions in which both the static and dynamical nuclear properties are important. To disentangle the various effects taking place in nuclear reactions, the HÉRACLES multi-detector will study the difference between reaction dynamics for a variety of isotopes of the same element. In this way, the effect on reaction dynamics of nuclear asymmetry can be studied on an individual element. By studying a variety of elements in this manner, nuclear scientists will gain a better understanding of the effect of asymmetry on reaction dynamics.

Description of Dedicated Apparatus

HÉRACLES is designed to detect and measure the properties of all the particles and fragments produced in a nuclear collision. Each reaction can be

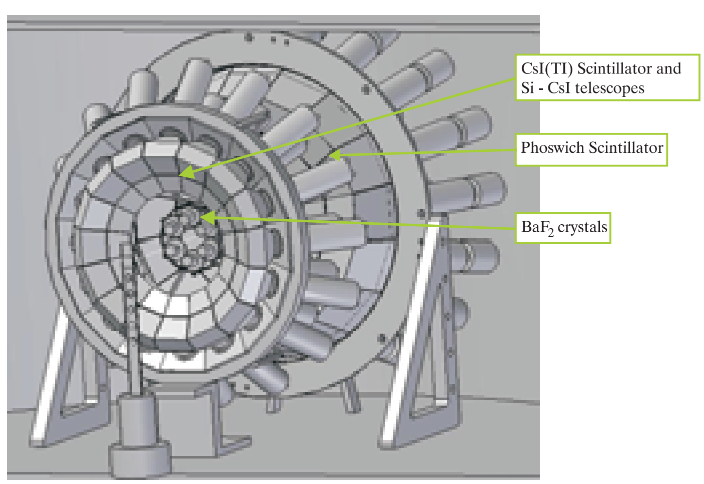


Figure 1: Sketch of the HÉRACLES multi-detector in which the three rings of segmented combined ΔE and E can be seen.

reconstructed from the measurements made on its particles and fragments. The detector is segmented in order to give directional information (see Figure 1). To measure the energy and species of the particles and fragments, most of the detectors in the array are composed of a thin detector to provide timing information and measure $\Delta E/dx$ in front of a crystal that measures the total energy. Table 1 lists the detector systems used in each ring. The first innermost ring (2–5°) is a single ring of five BaF_2 phosphorus mounted detectors. The second ring (6–10°) is a single ring of five Si – CsI telescopes. The third ring is composed of two rings each of 16 Phoswich scintillator detectors, and the outermost ring (24–46°) is made of two rings comprising a mixture of CsI(Tl) scintillator and Si – CsI telescope detectors.

Detector System	Angular Coverage (degrees)	ΔE thickness (μm)	E Threshold (MeV/nucleon)
BaF_2 Phosphorus Mounted	2 – 5	100	^{32}S : ~ 6.6
Si – CsI telescopes	6 – 10	50	^{12}C : ~ 3.5
Phoswich Scintillator	10.5 – 24	100	^{12}C : ~ 4.6
CsI(Tl) Scintillator	24 – 46	None	p,α : < 2 MeV
Si – CsI telescopes	24 – 46	50	^{24}Mg : ~ 4.6

Table 1: HÉRACLES multi-detector components: angular coverage and detector type of the various rings.

Partners

In Canada: Laval University.

In France: INDRA Collaboration at Ganil (France).

TRIUMF's Role

TRIUMF will provide the beam line, data acquisition system, the vacuum system, and the technical support for installation. HÉRACLES is mounted in its own vacuum chamber for which a new stand has been designed and ordered by the TRIUMF Design Office. Once available, the newly adapted detection units will be installed inside the scattering chamber. The silicon detectors have been ordered, and test runs will be held when the beam line for the facility is installed.

5.3.2.2.3

ISAC-I/II Facilities

5.3.2.2.3.1

TRIUMF UK Detector Array: TUDA

Introduction

The TRIUMF ISAC-I nuclear astrophysics program is carried out at a set of complementary facilities in the ISAC-I post accelerator area: the two key detectors are a large-acceptance recoil spectrometer system called DRAGON, and a large-acceptance scattering facility called TUDA. The scientific objective of the TUDA facility is to study the nuclear reactions important to our understanding of explosive astrophysical scenarios, such as novae, supernovae, and X-ray bursters, *i.e.*, events that create the heavy elements of our universe. In particular, TUDA is designed for the direct and indirect study of those reactions with charged-particle exit channels. The results of these measurements play a significant role in the understanding of explosive astrophysical phenomena.

The TUDA experimental technique, solid and gas cell targets surrounded by upstream and downstream solid-state detectors, is extremely versatile and adaptable to other nuclear physics measurements. TUDA's collaborators are involved in nuclear structure programs, including proposals involving ^{11}Li beams to study the properties of this exotic halo nucleus. The availability of

TUDA for these nuclear structure investigations attracts proposals from the Canadian and international nuclear physics community.

Description of Dedicated Apparatus

Radioactive ion beams from ISAC-I are focused onto targets inside the chamber, and products from nuclear reactions between the ion beam and the target material are detected both downstream and upstream in arrays of silicon strip detectors. The chamber itself (see Figure 1) is divided into three rectangular sections separated by two cylindrical sections. The cylindrical sections provide drift space for the beam and nuclear reaction products. The rectangular sections house the internal apparatus. The beam entrance section houses a collimator wheel, the middle section holds the target, and the end section houses the downstream flange to which the detectors are mounted.

In Figure 2, the downstream flange has been pulled back from the chamber to expose a LEDA detector pancake and its mounting. As shown, the LEDA detector (the flat plate with the cross) is mounted on long forks attached to the downstream flange. The structure behind the LEDA houses the electronics. The detector shown is composed of 8 pie-shaped segments (only 4 are installed in the picture),each having 16 individual concentric silicon strip detectors, 0.3 mm thick. Thus, each detector pancake has 128 individual independent channels. When one of the individual strip detectors detects a particle, not only is the energy measured, but the position is also determined. The hole in the centre of the array allows the unscattered beam to pass through. It is possible to stack several detector pancakes together and assemble TUDA experiments in a variety of configurations depending on the reaction being studied. LEDA detectors of 0.3 and 1.0 mm thicknesses have been used as well as a variety of other

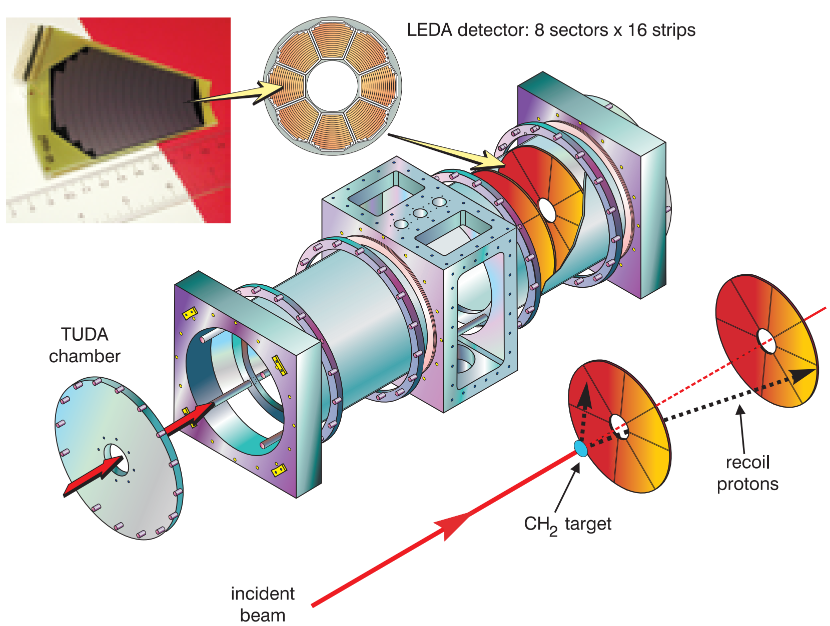


Figure 1: Artist's rendition of the TUDA facility.

detectors such as CDs and S2s. In fact, any detector can be used as long as it is properly mounted.

TUDA was designed to be mobile. It can be removed to install another facility at its beam line location. In 2007, it was removed to install TACTIC (TRIUMF Annular Chamber for Tracking and Identification of Charged Particles) for a stable beam test run and was subsequently reinstalled after the test. In 2008, TUDA will be moved to the SEBT1 beam line on ISAC-II. The higher ISAC-II energies will allow indirect studies of reactions of astrophysical significance, using (*d,p*) and (^{6}Li, *d*) reactions, plus time-reversed studies of (α,p). The facility will also be used for studies of nuclear structure such as ^{11}Li. Future TUDA experiments will be run at the ISAC-I and ISAC-II locations.

Recent Developments

As an example of how TUDA complements experiments at other TRIUMF nuclear astrophysics facilities, a TUDA proton elastic scattering experiment, which used a radioactive ^{21}Na beam on a polyethylene hydrogen target $(\text{-CH}_2)_n$ was run for energies of 0.45–1.4 MeV. This study complemented the radiative-capture reaction ^{21}Na(p,γ)^{22}Mg experiment at DRAGON. The TUDA experiment observed protons elastically knocked out of the target. With thick targets, a complete scan of the excitation function was obtained using a few energy settings by correlating the recorded proton energy to the beam energy as it slowed while transversing the target. Thin targets were used to investigate selected energy regions in more detail. Particle ID was assisted by a time-of-flight correlation with the ISAC-I accelerator RF signal. Background β-decay was completely uncorrelated to the RF signal.

Figure 3 shows the composite excitation function derived from several thick target measurements using eight detector elements at 4.8° (lab). The prominent monotonically decreasing cross section in the upper plot is from Coulomb

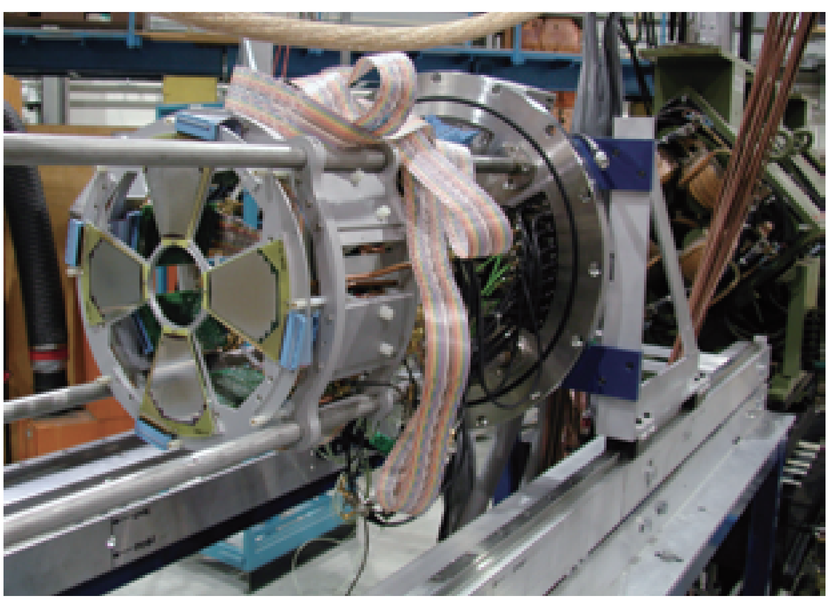


Figure 2: Picture of the TUDA detector system.

scattering. The resonances, or nuclear excitations of ^{22}Mg, interfere with this amplitude. The interference of the resonance amplitude with that of Coulomb scattering can determine the spin-parity of the resonance. Four states of ^{22}Mg have been identified in this plot. These states will dominate high-temperature burning as well as influence the low-temperature stellar rate of this reaction. The 1^- state at 1083 keV, mainly produced with ^{21}Na promoted to the 332 keV-excited state (lower plot), had not been seen before. DRAGON later measured the $^{21}Na(p,\gamma)^{22}Mg$ reaction rate through this resonance using the TUDA-measured resonance parameters to tune the facility.

Partners

In Canada: McMaster University, Saint Mary's University, Simon Fraser University, and the University of British Columbia.

International Partners: Belgium (1), Spain (1), the United Kingdom (2), and the United States (1).

TRIUMF's Role

TRIUMF provided the electronic housing environment for the TUDA electronics. TRIUMF also provides annual maintenance support for the facility. This provides access to the design office and the electronics and machine shops. TRIUMF is also financing the move to ISAC-II. Two TRIUMF Scientists, P. Walden and L. Buchmann, contribute significantly to the experimental collaboration.

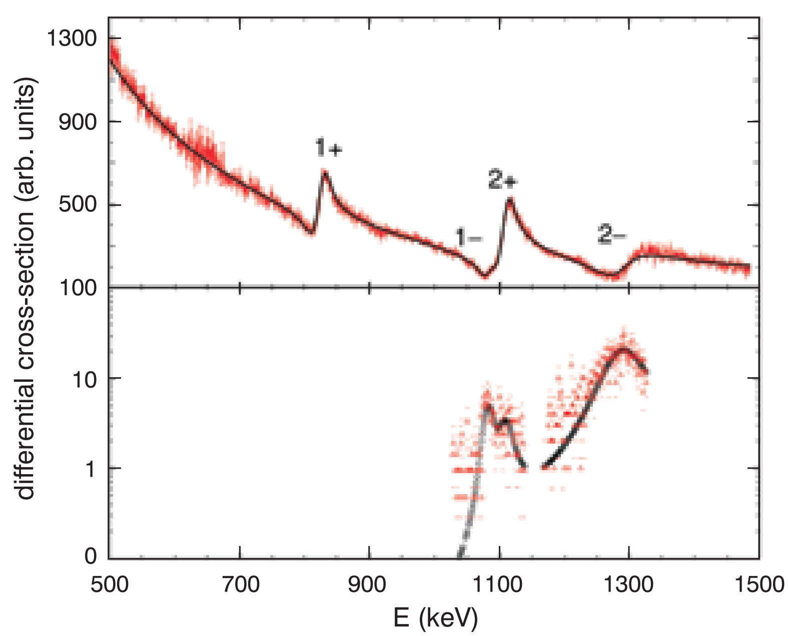


Figure 3: Excitation function for $^{21}Na(p,p')^{21}Na$.

5.3.2.2.3.2

TRIUMF Annular Chamber for Tracking and Identification of Charged Particles: TACTIC

Introduction

TACTIC (TRIUMF Annular Chamber for Tracking and Identification of Charged Particles) is a pioneering instrument that will improve our understanding of some of the most spectacular explosions in space and provide clues that could help us understand the origins of the elements in the universe. TACTIC will measure the strength of significant astrophysical nuclear reactions that occur in stars, such as the seed reaction that feeds the nucleosynthesis of the heavy elements inside supernovae.

Together with TUDA, DRAGON, and EMMA, TACTIC will study astrophysical reactions that have charged particles in their exit channels. However, because the ion chamber gas serves as the target, the reaction studies can proceed down to very low ion energies required in astrophysical nuclear reaction studies. In addition, the chamber has an extremely large solid angle (almost 4π) that allows the detector to track the exiting ions. Unlike active target ion chambers, TACTIC can take high beam fluxes because of a reduced-sensitivity target region. TACTIC is a unique detector, and future developments will very likely see it incorporated in many areas of nuclear physics research at TRIUMF.

Description of Dedicated Apparatus

The TACTIC detector is a cylindrical time projection chamber with an electric field in the radial direction. The central or target region (see Figure 1) is marked off by two sets of longitudinal wires strung at slightly different radii. The outer set provides the negative high voltage of the drift region. The inner set, at a slightly more positive bias, sweeps up electrons generated by beam particles ionizing the detector gas. Hence, the TACTIC detector is not sensitive to beam particles like active target ionization chambers, and subsequently can take higher beam fluxes. The detector gas, however, is the target gas. The target length is defined by vacuum inserts projected into the gas enclosure.

Ions, emanating from a nuclear reaction in the target region, pass through the wire grid into the drift or detection region where they range out by ionizing detector gas particles along their track. Electrons produced along the track move towards the anode pads on the outer radius of the region (see Figure 1). The (ϕ,z) coordinates of the activated pads give the projection of the ion track on the cylindrical surface. The r coordinates are provided by the electron drift times to the pads. Thus, the complete three-dimensional track can be reconstructed (see Figure 2).

The charge collected at each individual pad is proportional to the energy-loss rate of the ion at that point along the path. A summation of the charge of each pad along the path gives a value proportional to the total kinetic energy of the ion. With track position, energy loss, and energy, all the information necessary to identify the reaction is present.

Before the electrons reach the pads, they pass through a gas electron multi-

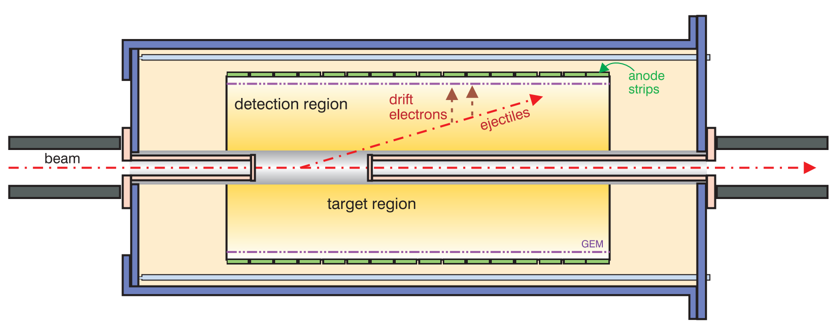


Figure 1: Schematic view of the TACTIC chamber.

plier (GEM) foil. The GEM works as preamplifier. It is a 50 μm-thick isolating foil with a conducting copper layer on both sides, perforated by a grid of 50 μm-large pinholes with a 150 μm pitch. There is a high voltage (450 V) applied between the layers, which produces a high field gradient through the holes. The high field inside the holes causes an avalanche effect that produces an electron multiplication of about 100. The signal that arrives at the pad is strong enough for direct electronic amplification.

The design of the TACTIC chamber will allow the use of suitable γ-ray detectors such as the bismuth-germanate (BGO) array from DRAGON in close proximity to the drift region. Coincidences between TACTIC and γ signals from the BGO array will be crucial to disentangle some astrophysical processes. For example, detecting the γ emitted by an ^{11}B excited state is essential to resolve the ^{8}Li(α,n)^{11}B process, which is an experiment approved for TACTIC.

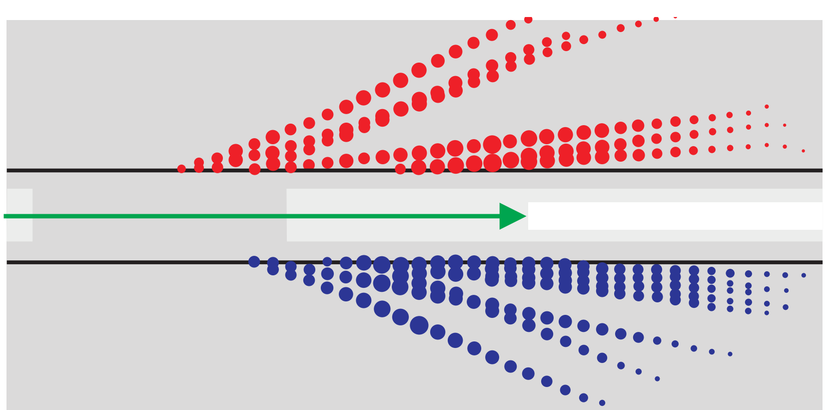
TACTIC is instrumented by pre-amps attached to the chamber (see Figure 3) along with VME-based flash ADCs (VF-48s) and a VMIC processor. VF-48s will also be used to process the BGO signals. There are a total of 512 channels.

Different detector gases can be used depending on the reaction to be studied. Nuclear astrophysics studies require ^{1}H and ^{4}He targets. The ^{4}He target for the ^{4}He(^{8}Li,n)^{11}B experiment is provided by a 90% Helium–10% CO_2 mixture. This mixture was tested in the initial stable ^{11}B beam commissioning run in 2007. For a ^{1}H target, isobutene has been proposed. This can be used for the approved ^{1}H(^{7}Be,p)^{7}Be experiment. With a modified TACTIC chamber, two gases can be used: one gas for the detector region and one gas for the target region.

Additional TACTIC chambers can be built for a modest cost and, with slightly different configurations, could be used as target chambers for the TIGRESS and EMMA facilities. The current TACTIC chamber will be used at the TUDA locations in both ISAC-I and ISAC-II. Its small size makes it very transportable.

Partners

In Canada: McMaster University, Simon Fraser University, and the University of British Columbia.



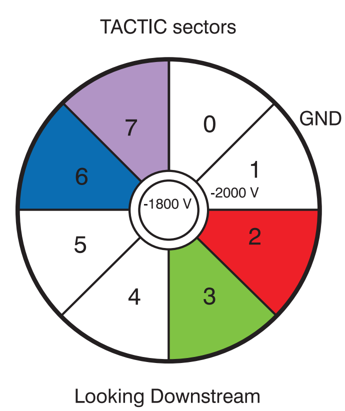


Figure 2: Track reconstruction during the initial run. Colours indicate different φ sectors activated.

International Partners: The University of Edinburgh, and the University of York.

TRIUMF's Role

TACTIC will use the infrastructure provided by TRIUMF for the TUDA facility, both at ISAC-I and ISAC-II. This infrastructure includes access to the design office and the electronics and machine shops for labour costs. TRIUMF provided invaluable services in the design and initial operation of TACTIC in terms of loaned equipment and expertise. Two TRIUMF scientists contribute to the experimental collaboration.

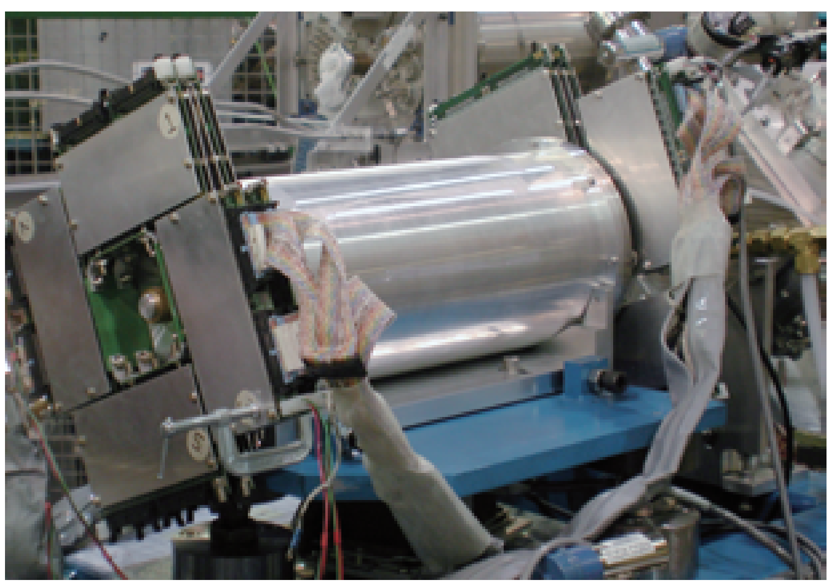


Figure 3: TACTIC on stand with preamp cards.

5.3.2.2.3.3

Doppler-Shift Lifetimes Facility: DSL

Introduction

Nuclear astrophysicists want to understand how stars and other astrophysical phenomena produce energy and the chemical elements that make up our world. To do this, nuclear physicists measure the rates of nuclear reactions. Ideally, these measurements are done in the laboratory by directly measuring the probability that a particular nuclear reaction will occur at the energies present during the big bang or in stars. Unfortunately, in most cases, these measurements are impossible because the probabilities of a reaction occurring are so low that experimental backgrounds or time constraints prevent direct measurements. Another difficulty is that many of the atomic nuclei involved are radioactive and don't survive long enough for an experiment to be performed.

Even when a direct measurement is impossible, there are indirect ways to determine a nuclear reaction rate. One such measurement uses the Doppler effect, which is the change in the energy of the photons measured by an observer moving relative to the source, to study what is known as "resonant capture." This process, in which a nucleus interacts with a proton or another nucleus creating an excited state of the compound nucleus, dominates most reaction rates of astrophysical importance. Resonant capture occurs when the wave function describing the two reacting nuclei of interest is very similar to the wave function of the excited state in the compound nucleus. When resonant capture is the dominant process in a reaction, the reaction rate can be deduced by studying the energies of the emitted γ-rays, inferring the lifetimes of the excited states of the compound nucleus that is the end product of the reaction.

TRIUMF's Doppler-Shift Lifetimes (DSL) facility is an experimental apparatus for the measurement of the lifetimes of excited states of nuclei. A measurement of an excited nuclear state's lifetime requires several steps. First, one must populate the excited state. At the DSL facility, this is accomplished by transfer reactions, in which two reacting nuclei exchange one or more protons or neutrons, leaving the recoiling nucleus in an excited state. Experimenters induce these reactions by colliding a beam of nuclei with a thin metal target into which a layer of a lighter nuclei has been implanted.

Recent Developments

DSL's first experiment used a gold target implanted with ^{3}He ions. The reaction occurred in the thin implanted layer, and the products of the reaction passed through that layer, continuing through the metal foil. The two products of the reaction had drastically different properties. The lighter of the two passed right through the metal foil, losing a small amount of energy, and was detected in a Si charged-particle detector telescope. Measuring the remaining energy of the light product determined which state in the heavy recoiling nucleus was excited. The heavy recoil nucleus on the other hand lost all of its energy in the metal foil, slowed down, and eventually stopped. The time it took to stop depended on the energy and charge of the recoiling nucleus and some properties of the foil's atomic nuclei, such as their charge and mass. Many measurements of the stopping powers of different materials along with theo-

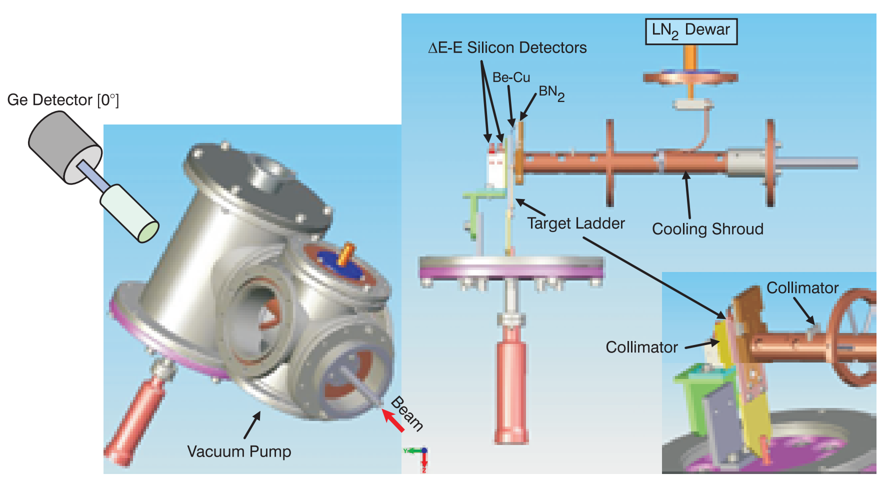


Figure 1: TRIUMF's DSL facility, showing the liquid nitrogen-cooled shroud along the beam axis, the target ladder, the Si detector telescope, and the high-purity germanium detector used to measure Doppler-shifted γ-rays.

retical calculations allow reasonably precise determinations of the stopping times for nuclei with speeds around a few percent of the speed of light.

How can one measure the lifetime of the excited state formed in the reaction? These lifetimes typically range from femtoseconds to picoseconds. When the excited states we're interested in decay, they usually do so by emitting a γ-ray. The lifetime is determined by measuring the energies of the γ -rays that are emitted when the state decays. Depending on the lifetime of the excited state, the recoiling nucleus will emit its γ-ray while still moving or after it has stopped in the foil. The energy of the γ-ray depends on the speed of the nucleus at the time it was emitted. One of the γ -ray detectors is located just beyond the target along the beam path. The energies of γ-ray emitted by recoil nuclei that are still moving forward are measured by this detector to have larger energies than γ-rays emitted by already stopped recoils because of the Doppler effect.

By measuring the spectrum of the γ-ray from the excited state of interest, we obtain a distribution of γ-ray energies that is characteristic of the lifetime of the state. The reason is that the decay of the excited state is a random process like the decay of radioactive nuclei. One can't predict exactly when a given nucleus will decay, but the distribution of decay times can be understood on the basis of simple statistics and characterized by a single number: the mean lifetime. Finally, by knowing the stopping characteristics of the recoil nucleus in the metal foil, we can deduce the mean lifetime of an excited state from the energy distribution of the γ-rays it emits. The DSL facility is schematically depicted in Figure 1.

Recently, the DSL facility made the most precise measurements of the lifetimes of excited states in ^{19}Ne relevant to the rate of the ^{15}O(α,γ)^{19}Ne reaction on accreting neutron stars. Figure 2 shows experimental data and the best fitting calculations of two γ-ray transitions from the most important state.

The DSL facility will soon move to ISAC-II, where it will be used in conjunction with TIGRESS γ-ray detectors to measure the lifetime of the 6.79 MeV state in ^{15}O. The lifetime of this state is one of the dominant uncertainties

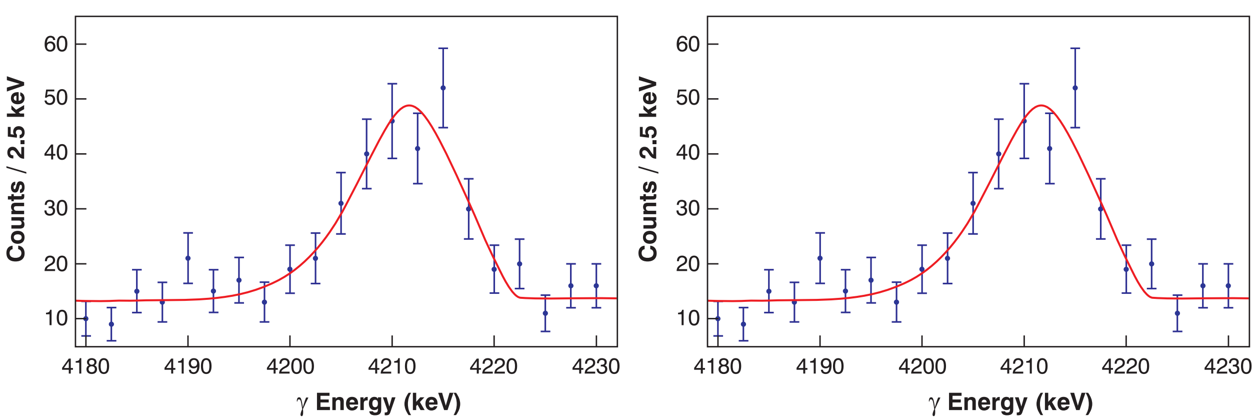


Figure 2: Doppler-shifted line shapes due to two transitions of the 4035 keV level in ^{19}Ne. The experimental data are shown along with the calculated line shape and background that best fit them. (a) Decay to the ground state with a lifetime of 7.1 ± 1.9 (stat.) ± 0.6 (sys.) fs; and (b) Decay to the 1536 keV level with a lifetime of (stat.) ± 0.7 (sys.) fs.

in determining the rate of the $^{14}N(p,\gamma)^{15}O$ reaction, which strongly affects the estimated age of the oldest stars in the Milky Way Galaxy.

Partners

In Canada: Saint Mary's University, l'Université de Montréal, Simon Fraser University, Queen's University, University of Guelph.

TRIUMF's Role

TRIUMF was solely responsible for the design and fabrication of the DSL facility. It was conceived by scientists G. Ball and B. Davids and implemented by R. Churchman and M. Subramanian in 2005 with some assistance from R. Kanungo.

5.4

Ensuring Accountability and Performance

Scientific Administration

Introduction

TRIUMF is Canada's national laboratory for particle and nuclear physics, and the need for scientific discovery is the reason for TRIUMF's existence. Individual scientists proposing projects that lead to scientific discovery drive scientific discovery from the bottom up. In contrast, TRIUMF's advisory bodies deliver general advice on scientific policy, a process that must be driven from the top down. Good management of the laboratory requires that TRIUMF manage and merge, to good effect, these important bottom-up and top-down processes.

Management of Scientific Projects

All science is curiosity driven: curious individuals try to understand how our world and the universe around us work. In addition, these enquiring and curious individuals challenge established ideas, playing an essential role in scientific progress. In Canada, such individuals drive subatomic research by creatively exploiting TRIUMF's facilities and infrastructure. With demand for access to TRIUMF far beyond what the laboratory can supply, TRIUMF has developed a process to evaluate and prioritize proposed research (see Table 1).

All experimental proposals for internal research programs are submitted to an Experiments Evaluation Committee (EEC) (see below). Experiments approved by the EECs must have independent peer-reviewed funding in place before TRIUMF management will schedule the experiment. This funding may come from the Natural Sciences and Engineering Research Council of Canada (NSERC) for Canadian experimentalists, or external foreign funding for experimentalists from abroad. In addition, if the experiment requires material infrastructure support, TRIUMF management must determine if, or when, this infrastructure support can be provided. Experiments are not scheduled for beam shifts until TRIUMF is able to supply the beam and beam intensity required, and the researcher is able to provide documentation showing they are technically ready to do the experiment, and that all safety requirements have been met.

The external science program supported by TRIUMF may be initiated by TRIUMF scientists or by other members of the Canadian scientific community. The capital costs and operating funds for the Canadian involvement are not provided by TRIUMF, but rather through peer-reviewed NSERC grants. Before funding is secured for a program that requires substantial TRIUMF infrastructure support, TRIUMF, NSERC, and the principal investigators of the proposal determine whether sufficient TRIUMF infrastructure can be identified and provided to support the program. For those projects TRIUMF is able to support, engineering, technical and infrastructure support for detector development and construction will be provided. TRIUMF may also provide accelerator expertise. Scientific peer-reviews for external experiments are undertaken at the laboratory where the experiment will be conducted. Figure 1 shows the oversight bodies that provide advice and accountability on TRIUMF's programs.

External Scientific Advisory Committees

The National Research Council (NRC) appoints three separate committees to review TRIUMF's activities and performance. These three committees are composed of international scientists and representatives from Canadian industry who are internationally known for their expertise and experience in the areas of science and technology transfer. The three external committees appointed by NRC are:

The Agency Committee on TRIUMF (ACT) consists of the President of NRC, the President of NSERC, and a senior representative from Industry Canada. This committee meets twice a year to review TRIUMF's progress in meeting the scientific and technology transfer milestones set by NRC in the Five-Year Plan Contribution Agreement.

The International Peer Review Committee consists of senior, internationally known scientists who meet once every five years to review the scientific progress TRIUMF has made during the five years under review, and evaluate the strengths and weaknesses of the proposed new Five-Year Plan.

The Advisory Committee on TRIUMF (ACOT) is a committee of internationally known scientists and business people. ACOT meets twice a year and has the expertise to comment, evaluate, and offer suggestions to NRC and TRIUMF on TRIUMF's progress in meeting scientific and technology transfer goals.

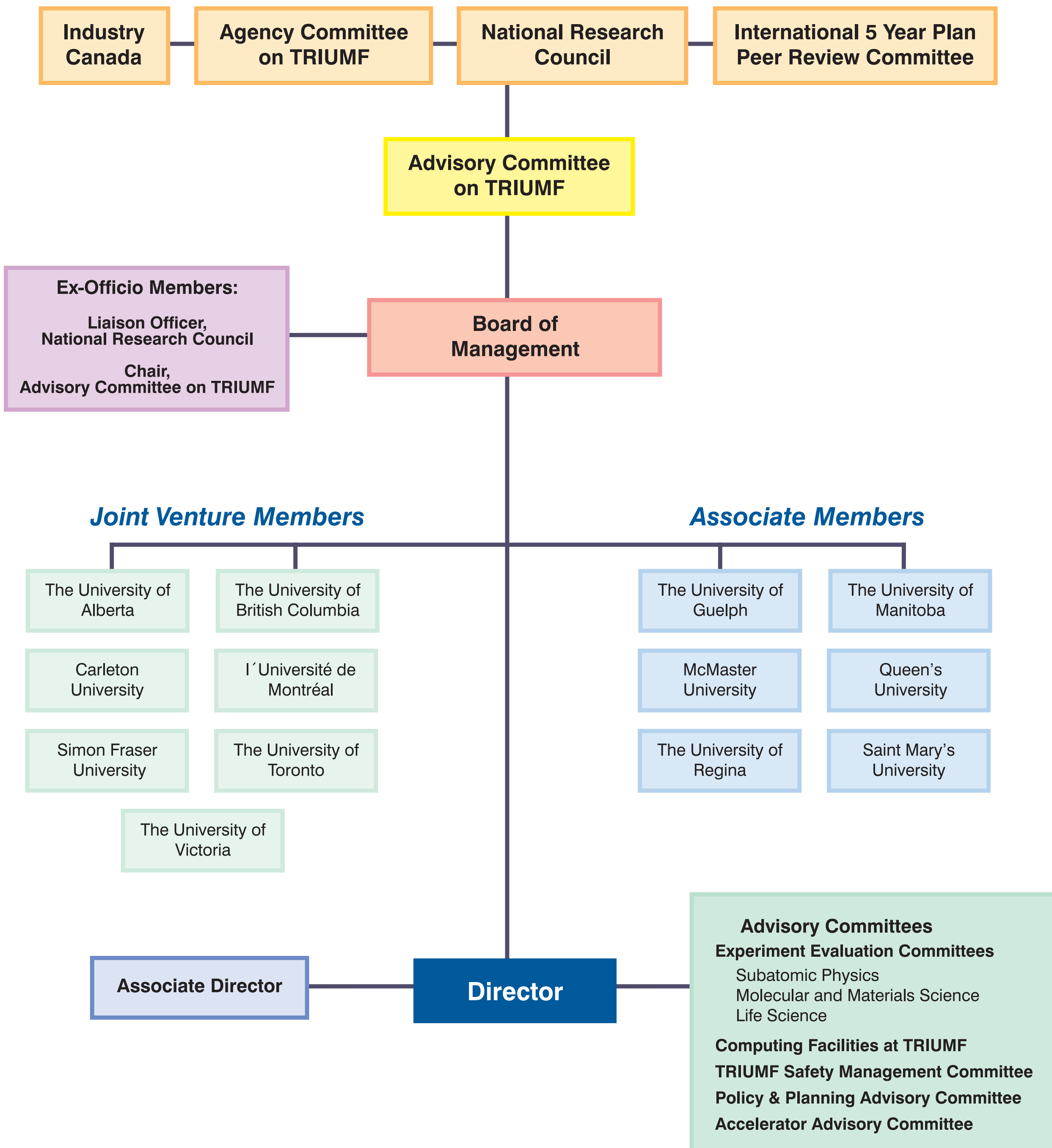


Figure 1: Accountability structures at TRIUMF. This diagram shows schematically the structure and relationship of the internal and external committees that oversee TRIUMF's programs.

The TRIUMF joint venture universities also appoint a committee to oversee TRIUMF's activities.

The Board of Management (BOM) consists of two voting representatives from each of the seven joint venture universities and a non-voting representative from each of the six associate member universities. The BOM also includes two members from the private sector appointed by the universities. In addition, NRC and ACOT each appoint a non-voting member to represent them. The BOM meets quarterly to review TRIUMF's financial, human resources, technology transfer and security activities, as well as the progress TRIUMF has made on the scientific program and priorities assigned in the NRC Five-Year Plan Contribution Agreement.

Internal Advisory Committees

The TRIUMF Director, in consultation with the TRIUMF Division Heads, senior administrative staff and several advisory committees appointed by TRIUMF, is responsible for the day-to-day management of TRIUMF and the long-term planning of the laboratory's scientific program and activities. The senior committees appointed by TRIUMF are:

The TRIUMF Operating Committee (OPCOM) membership consists of the Director, Associate Director, two members nominated by the TRIUMF Users' Executive Committee (TUEC), a TRIUMF staff representative, and a member from each of the joint venture universities. OPCOM was designed as a mechanism to inform university members and users of TRIUMF's activities and progress. OPCOM meets bi-monthly to discuss the operational requirements of TRIUMF, including reviewing budgets and human resource issues, as well as facility operations and concerns. In early 2007, TRIUMF management determined that OPCOM, as structured and mandated, was no longer the optimal means of providing university input to TRIUMF. In November 2007, OPCOM was disbanded in favour of a new committee called PPAC.

The TRIUMF Policy and Planning Advisory Committee (PPAC), which reports to the Director and Board of Management, advises on scientific policy and facilitates two-way communication with the research communities at the member universities. To ensure the entire community is well represented, the Director appoints the members of the Committee, which include one member from each of the joint venture universities, one of whom the Director may appoint as Chair, and one or more members from the larger TRIUMF community. Non-voting, *ex-officio* members of the Committee include the Head of Strategic Planning and Communications, the Associate Director and a Scientific Secretary appointed by the Director to assist the Chair. The Director does not sit on this Committee.

The Experiments Evaluation Committees (EECs) consist of three separate committees, Subatomic Physics (SAPEEC), Materials Science (MMSEEC) and Life Sciences (LSPEC). SAPEEC and MMSEEC meet twice a year and LSPEC once a year. Each committee evaluates and prioritizes experimental proposals submitted by scientists wishing to use the TRIUMF facility. Membership on these three committees consists of Canadian and international scientists who are well qualified to judge the scientific merits of an experimental proposal. Without EEC and LSPEC approval, no experiment can be carried out at TRIUMF.

Activity	Internal Experiments	External Experiments	Initiator
Scientific Ideas	Proposal	Proposal	Scientific Community
International Scientific Reviews	TRIUMF EEC	External Laboratory PAC	Laboratory
Funding Reviews	NSERC (RTI)	NSERC (RTI)	NSERC
Resource Review	TRIUMF (MOU)	TRIUMF (MOU)	TRIUMF
Safety Review	TRIUMF	External Laboratory	Management

Table 1: TRIUMF's experimental research approval process. MOU: Memorandum of Understanding; RTI: Research Tools and Instrumentation.

Laboratory Administration

Laboratory Organization

In July 2005, with funding in place for 2005–2010, Dr. Shotter believed it was the appropriate time to review the organizational structure of TRIUMF and determine how best this structure could be arranged to support the operations of the laboratory, meet the needs of the TRIUMF user community, and accomplish those tasks requested by the federal government in the NRC Contribution Agreement. It was understood that any reorganization recommendations and decisions had to take into account existing budget resources, and that any increases in resource allocation had to come from a redistribution of existing resources.

Dr. Shotter set up eight task groups to review various aspects of TRIUMF's operations:

- Science Support and Administration
- Computing
- Beam Delivery from Accelerators
- Support Groups for Accelerators, MRO
- Accelerator and Beams R&D
- Engineering and Technical Support
- QA and Safety
- Communications

After all reports were received from the task groups and reviewed by senior management, it was agreed that the process would move forward in three stages; immediate, intermediate, and long term. The new organization came into effect February 1, 2007 and encompassed most of the short-term recommendations of the various task groups.

Intermediate and long-term changes are under review by the current Director, Nigel Lockyer, who assumed the Directorship of TRIUMF May 1, 2007, and most recommendations are being implemented.

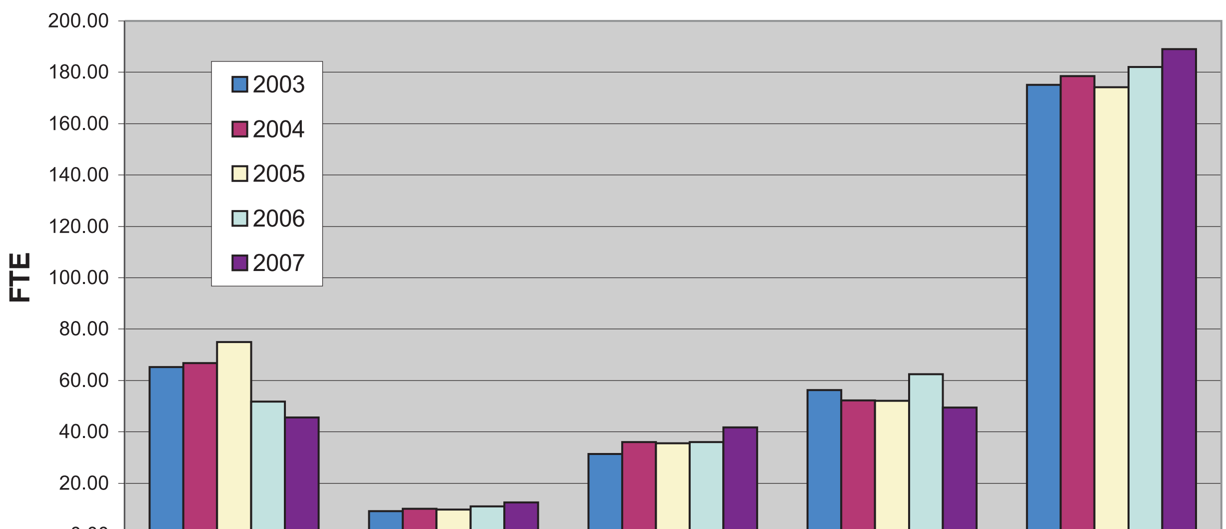
Staff Deployment

TRIUMF staff work on a variety of projects and activities. Table 2 shows the deployment of TRIUMF staff supported by the NRC contribution through the period April 1, 2003 to March 31, 2008. The areas shown in Table 2 are ISAC development and operations, academic activities, science internal and external to the TRIUMF site and infrastructure.

The ISAC component shows a ramp-up through 2005 for ISAC-II construction, as components of the facility were completed and construction personnel began operating and maintaining facilities full time. This staff deployment pattern should continue until early 2010 when all components will be complete.

Direct TRIUMF contributions to the Large Hadron Collider (LHC) at CERN ended with the completion of the construction project, but TRIUMF continues its involvement in the ATLAS experiment at CERN on behalf of the Canadian physics community. In addition, TRIUMF is involved in building accelerator components for T2K at J-PARC. TRIUMF's involvement in T2K has resulted in a small but steady increase in manpower committed to external science projects.

TRIUMF staffing efforts for internal science projects have decreased



	ISAC General	Academic	Science (Ext.)	Science (Int.)	Infrastructure (incl. ADMIN)
2003	65.29	9.19	31.43	56.24	175.07
2004	66.78	9.97	36.01	52.28	178.50
2005	74.91	9.73	35.49	52.15	174.19
2006	51.80	10.93	35.95	62.40	182.10
2007	45.66	12.53	41.70	49.39	189.04

as of January 8, 2008

Table 2: Deployment of TRIUMF's NRC contribution supported staff from April 1, 2003 to March 31, 2008.

between 2003 and 2008 as construction of several major experimental installations were completed and technical and engineering staff were able to return to their operation and infrastructure activities. When new installations are ready for construction, their services will once again be split between capital construction and operations.

Finally, from 2003 to 2008, TRIUMF scientists continued their efforts to become more involved and connected to the academic activities of their university colleagues through teaching, writing, external committee work, and supervising students.

Financial Resources

The NRC contribution to TRIUMF for the 2005–2010 Five-Year Plan was $C222.3 million. This funding will maintain the laboratory's operations and complete most of the ISAC-II major facilities. Table 3 shows the annual operating and capital expenditures or budgets for the current Five-Year Plan. Completing the ISAC-II facility and beginning the science program as quickly as possible has been a major focus for the laboratory. The NRC Contribution Agreement specified the facilities and experimental stations that must be completed within the five years and TRIUMF has met all ISAC-II facility and experimental milestones set by NRC.

During 2005–2007 the Director and university academic staff involved with TRIUMF, pursued additional funding from CFI for capital projects. TRIUMF cannot apply directly for CFI awards; grants must come through one or more Canadian universities. The effort spent on obtaining CFI funding met with considerable success. The capital projects funded for 2005–2010 were:

ATLAS Tier-1 Centre: In 2006–2007, a consortium of Canadian universities, led by Simon Fraser University, was awarded $C23 million for the ATLAS Tier-1 Data Centre, which was operational by August 2007.

Centre for Molecular and Materials Science: TRIUMF undertook to provide funding for partial refurbishing of the M9 beam line at a cost of $C1.8 million. A consortium of Canadian universities, led by Simon Fraser University, obtained $C6 million in funding for the refurbishment of the M20 beam line. TRIUMF will provide 20% in matching funds through an in-kind contribution of labour and cash. It is expected the M20 project will begin in late 2008 or early 2009.

It should be noted that CFI does not fund 100% of a project. CFI contributes 40% of the required funds with the expectation the host province will contribute an equal 40%. The host institution must contribute the final 20%, either through in-kind contributions, special supplier discounts, or cash. Where TRIUMF has been expected to provide the final 20% of matching funds, we have reduced our operations in order to provide a combination of cash and in-kind labour contributions from our technical and engineering staff.

Licensing, Safety, and Security

TRIUMF Accelerators Inc. (TAI) was established September 1, 2006 to address the CNSC regulatory requirements as legislated by the Nuclear Safety and Control Act. TAI was awarded an operating license effective April 1, 2007 and is responsible for those aspects of TRIUMF's operations identified in the operating license as well as control over the assets of the TRIUMF facility. As a result of incorporating TAI, the joint venture members of TRIUMF agreed to redraft the Joint Venture Agreement to incorporate a Management Agreement between TAI and TRIUMF. The revised Joint Venture Agreement, completed March 31, 2008, fully defines the rights and responsibilities of each party.

The agreement put in place ensures the owners of TRIUMF, the full members of the joint venture, control TAI. TAI's officers, who carry out the day-to-day activities, are appointed by the TRIUMF Board of Management and consist of the President and Chief Executive Officer, Vice-President of Finance, Vice-President of Safety and Vice-President of Security, who hold these positions by virtue of their equivalent TRIUMF appointments.

The TRIUMF Accelerators Inc. Operating License was renewed April 1, 2007, but CNSC set conditions that had to be met by March 31, 2008, for the license to be issued for the full term of five years. These conditions were:

1. Funding of an approved preliminary decommissioning plan for the future decommissioning of the TRIUMF facility.

2. A revised Joint Venture Agreement signed by the member universities recognizing the role of TAI and the funding of the decommissioning plan. In addition to this requirement, it was necessary for TRIUMF to arrange a Management Agreement between the Joint Venture and TAI, and negotiate a lease between TAI and the University of British Columbia, on whose lands the TRIUMF facilities are located.

3. Submission of an Environmental Protection Program in compliance with CNSC regulatory standard S-296.

4. Upgrade to the Fire Protection Program to ensure that the TRIUMF facility is operated, maintained, tested and inspected annually in compliance with the NFPA-801(2003) Standard for Fire Protection for Facilities Handling Radioactive Materials.

By the March 31, 2008 deadline, TRIUMF had met all the CNSC requirements of the license conditions on which the Operating License was issued. In addition, between 2003 and 2008 TRIUMF has put additional effort into continuing the development and expansion of TRIUMF's regulatory programs. A summary of the programs where significant changes have occurred is included below.

Decommissioning Plan

A preliminary decommissioning plan (PDP) to address eventual decommissioning of the TRIUMF facility is a CNSC requirement for all Class I facilities.

The TRIUMF PDP, written in 2003, was updated in 2007 to include the new TR30-2 and ISAC-II facilities. Additional changes included definition of a 'safe state of closure' to ensure that all highly radioactive material is removed and secured immediately after shutdown; definition of a conceptual schedule for the licensing and review activities prior to decommissioning; and costing using outside contractor rates for the project management and all radiological as well as conventional demolition tasks. The total cost of decommissioning TRIUMF facilities to a green-field site, including a 30% contingency, was estimated at $C44 million (2007).

TRIUMF FUNDING ALLOCATIONS FIVE YEARS ENDING MARCH 31, 2010						
	ACTUAL 2005/06	ACTUAL 2006/07	BUDGET 2007/08	BUDGET 2008/09	BUDGET 2009/10	TOTAL
SALARIES & BENEFITS	27,265	28,648	28,900	31,125	32,185	148,123
OPERATIONAL COSTS						
ADMINISTRATIVE SUPPORT	774	1,035	1,121	1,000	1,000	4,930
SITE INFRASTRUCTURE/ OPERATIONS	3,094	3,998	3,878	3,075	3,075	17,120
EXPERIMENTAL SUPPORT	3,014	3,670	3,332	2,700	2,700	15,416
NET POWER COSTS	1,914	2,192	2,200	2,200	2,200	10,706
TOTAL OPERATIONAL SPENDING	8,796	10,895	10,531	8,975	8,975	48,172
CAPITAL PROJECTS						
ISAC FACILITY	4,402	2,967	3,642	2,400	1,130	14,541
ISAC TARGET DEVELOPMENT	1,052	1,795	653	850	1,010	5,360
CYCLOTRON UPGRADE	594	650	563	300	200	2,307
LIFE SCIENCES	0	0	0	0	0	0
CENTRE FOR MATERIALS SCIENCE	0	0	825	750	250	1,825
TRIUMF/ATLAS DATA ANALYSIS CEN-TRE	351	234	0	0	0	585
INTERNATIONAL ACCELERATORS	540	311	186	200	250	1,487
INTERNATIONAL DETECTORS	0	0	0	0	0	0
ATLAS COMMONG FUND	0	0	0	0	0	0
CERN MAGNET REPAYMENT	1,500	0	0	0	0	1,500
TOTAL CAPITAL SPENDING	8,439	5,957	5,869	4,500	2,840	27,605
TOTAL EXPENDITURES	44,500	45,500	45,300	44,600	44,000	223,900
CONTRIBUTION FROM OTHER FUNDS	(500)	0	0	(1,100)	0	(1,600)
NRC CONTRIBUTION	44,000	45,500	45,300	43,500	44,000	222,300

Table 3: TRIUMF funding allocations between operations and capital for the five years ending March 31, 2010.

The preliminary decommissioning plan for TRIUMF includes three phases. The first phase is the cleaning out of all structures that do not have radioactivity concentration above the "clearance" levels and either reusing or demolishing them at the time of decommissioning. The remaining radioactive components would be consolidated and secured in two areas. The first area is the low-energy cyclotron vault and target caves whose concrete enclosure and components would need an additional 20 years to decay below clearance levels. The second phase of decommissioning would involve the removal of all materials having decayed to below clearance levels and the consolidation of the remaining radioactive materials such as the low-energy cyclotron magnets and some components of the high current beam lines into the second area, the 500 MeV cyclotron vault.

Those remaining components and the vault enclosure would be allowed to decay for an additional 25 years for a total of 45 years after shutdown. At that point, the third phase of decommissioning would be completed resulting in the release of all the material below clearance levels and disposal as radioactive waste of the components still above clearance levels, such as parts of the main cyclotron magnet.

Funding the Decommissioning Plan

The Canadian Nuclear Safety and Control Act requires that all nuclear facility PDPs be fully funded, either with cash or a combination of cash and financial guarantees from reputable and financially stable organizations. A proposal for funding TRIUMF's eventual decommissioning costs was developed between TAI and the TRIUMF Joint Venture member universities. The funding plan, which was approved by CNSC in late December 2007, consists of a cash deposit of $C9.6 million, which is sufficient to pay the Phase 1 costs of decommissioning, and financial guarantees from the member universities for the balance of the costs.

The funding and maintenance of the financial guarantee is the responsibility of TAI, the TRIUMF Joint Venture and each full member university of the Joint Venture.

Fire Protection

A review of TRIUMF facilities was performed to ensure that operation of the TRIUMF facilities, maintenance and testing of the fire protection systems is carried out in compliance with the regulatory code NFPA-801. TRIUMF enlisted the assistance of outside fire protection expertise to perform the review.

One area that was identified as needing remediation in the context of the new regulatory requirements is the area at the end of the Meson Hall, used for storage of low-level radioactive waste. TRIUMF has reduced the fire load through the elimination of the wooden containers and reduced the volume of flammable material stored in this area. This has resolved this identified area of weakness and reduced or eliminated the potential for spread of contamination in the event of fire.

In addition, the annual inspection of the fire protection program will in future include an ongoing assessment for compliance with NFPA-801.

Quality Assurance Program

TRIUMF began developing a Quality Assurance Program (QA) in 2002 to meet CNSC requirements. TRIUMF submitted a QA Manual and a set of TRIUMF Standard Operating Procedures (TSOPs) to CNSC in 2003, and these were accepted in 2004 on the condition of acceptable implementation.

The CNSC conducted an audit of the TRIUMF QA in September 2006. The audit report highlighted seven directives, seven action notices, and one recommendation. The audit team assigned an inspection grade of "C – Does Not Meet Requirements". Most of these concerns were with the implementation of the program.

To address the issues identified in the CNSC audit, the TRIUMF Director created the QA Implementation Panel, composed of a cross section of group leaders. The panel reviewed the audit report and the QA program and concluded that the best course of action was to rewrite the TSOPs in a manner that would address the audit concerns and facilitate implementation. The panel drafted these documents and they were sent to the CNSC in November 2007.

The new TSOPs are more generic so the specifics of implementation will be addressed in group manuals outlining the procedures each group has in place that demonstrate their compliance with the TRIUMF QA Program. It is expected that these manuals will be completed by July 2008.

Emergency Preparedness

The CNSC requires all Class I facilities to have an Emergency Preparedness Plan, based in part on the CNSC Regulatory Guide G-225, Emergency Planning at Class-I Nuclear Facilities and Uranium Mines and Mills.

The TRIUMF Emergency Preparedness Plan (TRI-EHS-05-05) addresses the planning for, response to, and recovery from emergencies or disasters that may occur at TRIUMF. This plan applies to all facilities, employees and visitors at TRIUMF. The scope of this plan and the extent of emergency planning and preparedness are based on the hazards and potential consequences associated with the location and operation of TRIUMF.

This plan identifies the roles and responsibilities of emergency responders, and provides broad guidance for preparing for emergencies as well as responding to them effectively. The plan describes the emergency facilities on site, defines optimum and minimum staffing levels for the various components of emergency response and defines the type and frequency of training, drills and exercises for the emergency response organization and TRIUMF staff. To facilitate access to this information in times of emergency, response procedures for various types and severity of emergencies are contained in a separate document, TRIUMF Emergency Response Plan (TRI-EHS-05-06). The plan received final approval by the CNSC in July 2007.

Accelerator Safety Systems

The radiation safety systems for several facilities were either expanded or upgraded between 2003 and 2008. TRIUMF installed an ISAC Safety System that includes an ISAC-II vault lock-up and interfaces to ISAC rare-isotope beams, off-line ion sources, and radio-frequency devices. Considerable development of the ISAC Radiation Monitoring System also took place and gamma/neutron monitor pairs were added in ISAC-II to complement the original gamma monitors in ISAC-I.

The hardwired CP42 Access Control Interlock System and the CP42/TR30-1 Radiation Monitoring System were upgraded in 2005 allowing the control rooms for all three ATG accelerators to be consolidated into the new control room built for the TR30-2.

Some very old 500 MeV facility equipment also received attention, most noticeably the accelerator "trip" and "beam inhibit" systems, and the M20, M15 and BL1B Area Safety Units, all of which were redesigned for reliability and maintainability.

All safety systems work, including design, calibration, commissioning and routine testing, met evolving Standard Operating Procedures in Quality Assurance policies.

Site Security

As a result of general increased security awareness, TRIUMF augmented its own security by increasing the number of daily patrols made by the University of British Columbia Security Services and increasing the coverage of its external contracted security service.

In 2003, TRIUMF installed a security system using photo access cards. This system enabled site access to be monitored and ensured that only those authorized could access the site. Site access is now managed through a TRIUMF Standard Operating procedure (TSOP) and improvements to the process are ongoing.

A confidential site security plan, summarizing all the components of TRIUMF's security program was prepared and submitted to CNSC. The plan defines the roles and responsibilities for monitoring and maintaining security, the site access control procedures, contingency plans and response during a security breach. In addition, the plan addresses the role of off-site security services and co-ordination with TRIUMF's head of security. The TRIUMF Security Plan was approved by CNSC in March 2007.

Chapter 6

The Plan: Pursuing the Vision

Chapter 6

The Plan: Pursuing the Vision

6.1

Introduction to the Plan

TRIUMF is a national laboratory devoted to pursuing the answers to some of the most important scientific questions of our time. It also provides an excellent vehicle for the transfer of knowledge, the training of highly qualified personnel, and the commercialization of research for the benefit of all Canadians. The laboratory has an impressive track record in all these areas and it will be significantly expanded by full support and implementation of the 2010–2015 Five-Year Plan. This plan is motivated by a number of observations about the present TRIUMF landscape:

- **A Critical Shortage of New Rare-Isotope Beams.** Canada is on the cusp of international leadership in nuclear physics. The state-of-the-art detector systems at ISAC have been deployed to address the most critical questions in nuclear physics, and the TRIUMF facilities and expertise for the development and deployment of rare-isotope beams have created an overwhelming international demand for ISAC beam time. High-impact, cutting-edge investigations of neutron-rich nuclei important for understanding elemental abundances in the universe, supernova-explosions, neutron-density models, neutron star crusts, 3-nucleon interactions, the limits of nuclear existence and fundamental symmetries are within technical reach. In the area of molecular and materials science, β-NMR is used to study the physics of nanometre-scale and superconducting structures. All the ISAC programs critically need more rare-isotope beams: demand has outstripped supply. TRIUMF's future scientific productivity is tied to providing additional beams that will fully exploit the existing accelerators and detector systems. The 2010–2015 Five-Year Plan outlines a strategy that will more than double the scientific output through increased beam availability.

- **A Nuclear Medicine Revolution.** Nuclear medicine is on the verge of a revolution. The ability to image the metabolism of disease and the construction of tumours using medical isotopes will soon be possible for many different medical conditions. This in turn will drive a major shift towards increased demand for isotopes, PET cameras, and accelerators to produce these isotopes. Through its expertise in radiochemistry, targets, cyclotron design, construction and operations, and partnerships with clinicians working in neurology and oncology, TRIUMF and Canada are in a position to lead in this area. Canada's dominance of the global medical-isotope market is at risk as other countries seek to develop their own domestic capabilities. Therefore, the development of targeted, highly specific biomarkers with radioisotope labels as envisioned in the TRIUMF Five-Year Plan can play a significant role in Canada by developing competitive positions in all aspects of this emerging new field.
- **Advanced Accelerator Partnerships.** International collaborators in Europe, Japan, India, China, the US, and elsewhere seek partnerships with TRIUMF in areas as diverse as cryogenics engineering technology, advanced accelerator development, and high-power target development. Likewise, recent successes with the transfer of TRIUMF superconducting radio-frequency (SRF) expertise to industry places Canada at the leading edge of international accelerator technology. The accelerator developments in the plan will enable Canada to expand this position in the international technology arena.
- **Information Technology.** The world's largest scientific project, the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland, is scheduled to begin operations in 2008. Canada's involvement in this amazing project is through the ATLAS Canada collaboration. The LHC will address the most compelling questions in particle physics. The impact of Canadian groups on the ATLAS physics program depends critically on the success of the high-performance GRID computing analysis centre at TRIUMF whose continued operation is included in the TRIUMF Five-Year Plan.

Overview of the Plan

In the context of the laboratory's mission, TRIUMF's five-year planning process has identified targeted opportunities that are ripe for exploitation: they build on TRIUMF's successes, play to Canadian strengths, and promise high-impact results. The goals of the plan outlined in this chapter are as follows:

- **Substantially expand TRIUMF's rare-isotope beam program.** This goal will be achieved by building an electron linear accelerator (e-linac) photo-fission driver and a specialized proton beam line, coupled with a target station suitable for handling actinide targets. By increasing the number of beams available to experiments and by constructing a new driver, Canada will take a dominant position in this field. The growing Canadian demand for TRIUMF's unique capabilities in β-NMR will also be met with additional beam time. Not only will TRIUMF have the highest intensities of a large fraction of rare-isotope beams in the world, it will also have the ability to provide them simultaneously to several experiments.

- **Expand Canadian access to international science.** The plan will take full advantage of past Canadian financial and intellectual investments in Terascale physics experiments around the world. ATLAS science will be established, and the ATLAS Tier-1 Data Centre will expand as planned to accommodate the wealth of data collected over the 2010–2015 time period. TRIUMF will seek to keep Canada positioned for taking a leading role in upgrades to the Large Hadron Collider (LHC) and its detectors as well as the next potential project known as the International Linear Collider (ILC). Tapping its significant expertise in detector science and technology, TRIUMF will participate in and contribute to the SNOLAB laboratory and its experiments in Ontario.
- **Pursue advanced accelerator technologies.** TRIUMF will actively engage industry in the development and commercialization of superconducting radiofrequency (SRF) and other sophisticated technology. The development of this technology will also position Canada to play a significant role in proposed global high-energy physics facility developments. Collaboration with the Canadian Light Source (CLS) in Saskatoon will begin on compact X-ray sources, suitable for pharmaceutical applications, as well as prototyping for a next generation light source that would build upon the CLS facility. These activities will emphasize building up Canada's high-technology sector and positioning Canadian industry in this competitive, emerging field.
- **Lead the coming revolution in nuclear medicine.** The plan proposes a substantial strengthening of the life sciences program with new initiatives in nuclear medicine. TRIUMF will continue and expand its world-renowned partnership with the Pacific Parkinson's Research Centre (PPRC). Together with UBC, TRIUMF will lead a national network for the development of radiotracers. The TRIUMF nuclear medicine initiative also includes a new partnership with the BC Cancer Agency (BCCA). TRIUMF's role in cancer imaging and therapy closely aligns with the recent expansion by BCCA into nuclear medicine through the purchase of their own cyclotron and PET imaging. TRIUMF will also continue to work with MDS Nordion in the development and production of radioactive tracers and will initiate a major R&D initiative on radiotracer development. With a strong team, modern laboratory space, and a national network of partners, TRIUMF will play a lead role in advancing the understanding and treatment of disease with medical isotopes using safe, stable and robust facilities.
- **Exploit targeted opportunities for commercialization with partners such as Advanced Applies Physics Solutions, Inc.** TRIUMF formed Advanced Applied Physics Solutions, Inc., (AAPS) in early 2008 with support from the prestigious National Centres of Excellence for Commercialization and Research program. TRIUMF will strengthen its commercialization and knowledge-transfer success by working with Canadian private-sector to develop accelerator, nuclear-medicine, and detector technologies.

These advances are expected not only to increase the competitiveness of Canadian companies but also open whole new markets to them.

- **Train the next generation of leaders in Canadian science, technology, and innovation.** The expansion of TRIUMF's science program will naturally lead to a significant increase in the opportunities for training graduate students and technologists. TRIUMF is a magnet for international students wanting to specialize in the study and applications of unstable nuclei. Dedicated programs will be developed to further engage students and the general public in the scientific culture.

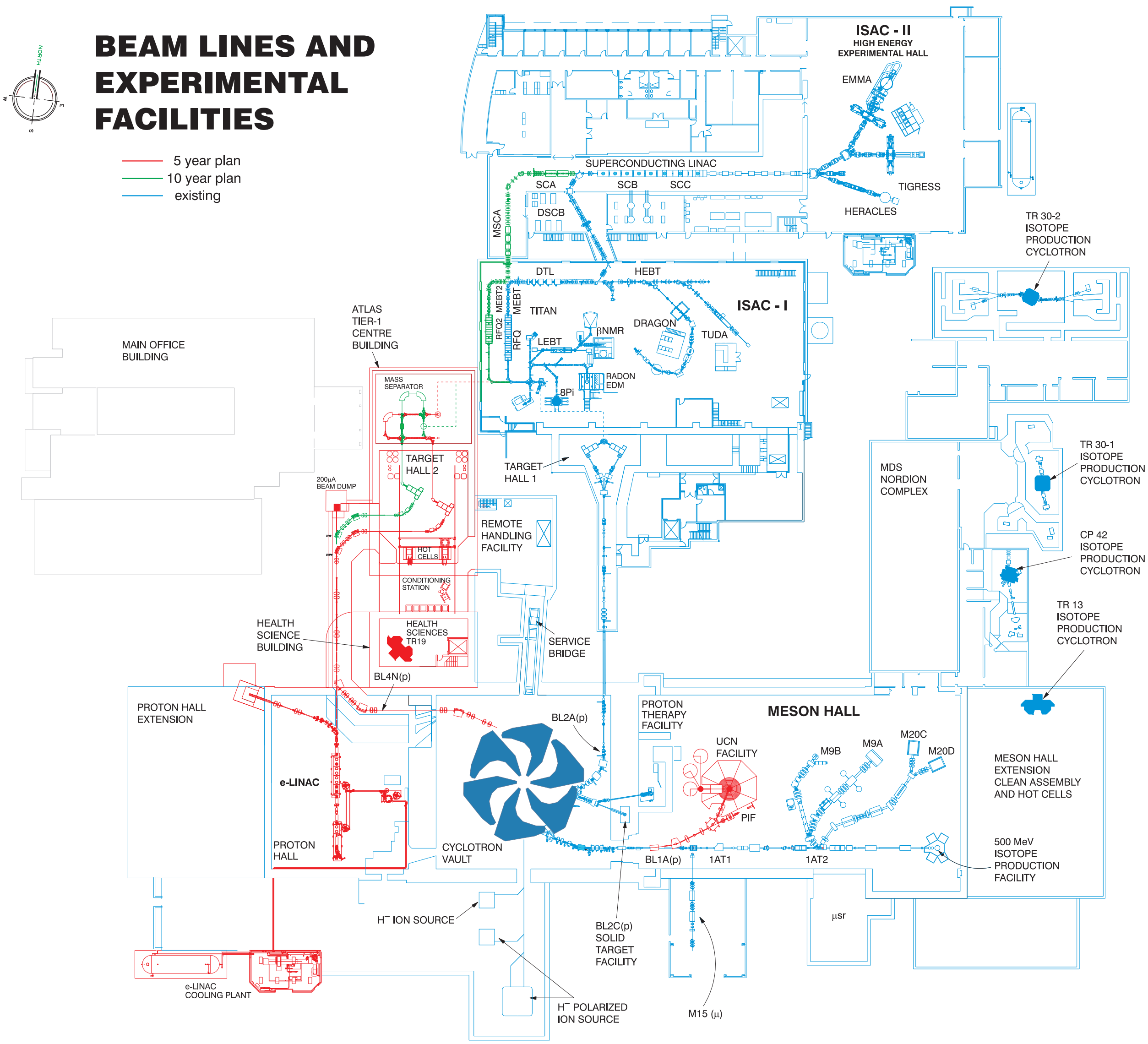


Figure 1 depicts the evolution of the TRIUMF site plan to support these initiatives.

Alignment with Canada's Strategic Goals

The program is well aligned with Canada's science and technology strategy and was specifically constructed to maximize the balanced impact on the three highlighted competitive advantages for the benefit of Canada: the knowledge advantage, the people advantage, and the entrepreneurial advantage.

- **Knowledge Advantage.** TRIUMF's focus has always been on advancing knowledge. TRIUMF's contribution to Canada's knowledge advantage is directly affected by total accelerator running time for experiments, including TRIUMF's on-site, internationally renowned, molecular and materials sciences program and nuclear physics program. Canadian accelerator expertise at TRIUMF is also critical to the country's future participation in global particle physics projects. To continue to be competitive and maintain a knowledge advantage, TRIUMF must:
  - Excel globally in research areas of national priority;
  - Provide leadership and intellectual contributions for the development of innovative techniques and technologies;
  - Engage in the continued development of GRID computing technology;
  - Increase scientific publications, citations, and involvement in international conferences; and
  - Increase investment in key areas ripe for discovery.
- **People Advantage.** One of the strong side benefits of scientific research is the creation of highly qualified personnel. Cutting-edge technological development in accelerator design, detectors used in subatomic physics, medical imaging, molecular and materials sciences, advanced computing, data mining and analysis techniques, all generate trained people, who are then sought after in Canadian and international science and industry. Canada's national base of skilled workers in these fields depends on the viability of the TRIUMF program and its ability to:
  - Attract international scientists and students to work at TRIUMF;
  - Enhance Asia-Pacific scientific personnel exchange;
  - Create undergraduate and graduate student research opportunities;
  - Establish initiatives to attract and retain talent from traditionally underrepresented communities;
  - Increase the engagement of Canadian universities in the TRIUMF program; and
  - Participate in international student research exchange.
- **Entrepreneurial Advantage.** TRIUMF consistently works with Canadian industry to expand national capabilities in emerging technological fields. This success has been recognized in the past through two NSERC Synergy awards, one in 2004 with MDS Nordion, and one in 2007 with

D-Pace, and is evident in the 2010–2015 Five-Year Plan. TRIUMF will increase its entrepreneurial advantage with more beam time for medical-isotope production at the MDS Nordion Solid-Target Facility and increased availability of TRIUMF personnel to provide guidance to companies like D-Pace, MDS Nordion, Thales, and Advanced Applied Physics Solutions, Inc. (AAPS). In addition, the development and deployment of GRID computing and data-mining by the ATLAS Tier-1 Data Centre personnel will position Canada as a leader in a critical and emerging field of information technology. Similarly, benefits to companies like PAVAC Industries, Inc. from the e-linac project will position Canada to be among the leaders in this emerging high-technology area. TRIUMF is also expanding its connections with national and international research partners such as PPRC, BCCA, Japan's RIKEN, the US's ORNL, ANL, and MSU, Germany's GSI, France's GANIL, CERN'S ISOLDE, and Canadian universities. All of these connections will further expand the markets for Canadian industry. To ensure this expansion, TRIUMF must:

- Triple the economic impact from technology transfer and commercialization via Advanced Applied Physics Solutions, Inc.;
- Forge new industrial partnerships related to TRIUMF's world-recognized leadership in medical-cyclotron design;
- Establish a major new partnership with India in accelerator science;
- Connect radiotracer know-how with drug-development activities at the major pharmaceutical companies; and
- Establish a new partnership with MDS Nordion in radiotracer development.

Conclusion

TRIUMF's five-year vision is transformational. It fully exploits TRIUMF's core competencies in (a) accelerator technology, (b) detector technology, (c) scientific computing and large-scale data management, and (d) isotope production, thus expanding and strengthening both scientific and entrepreneurial advantages. The 2010–2015 Plan calls for the financial means to realize TRIUMF's full scientific and technological potential and optimize its role in support of the scientific communities it serves. In doing so, the plan maximizes the educational and societal benefits, and provides an excellent return on investment for Canadians.

The layout of this section is as follows: The scientific program proposed for the 2010–2015 period is discussed in Section 6.2 and the role of accelerator-technology development and stewardship in the plan is discussed in Section 6.3. Several of the CFI proposals depending on TRIUMF that partner universities are putting forward are described in Section 6.4. Section 6.5 discusses the broader benefits of the plan to Canadian society. Recognizing that tradeoffs are inherent in policy making, several implementation strategies are presented along with analysis of the relative impacts in Section 6.6.

6.2

The Research Program

6.2.1

Rare-Isotope Beams

6.2.1.1

Science

6.2.1.1.1

Overview of Physics with Rare Isotopes

Nuclear physics, the study of nucleons (the substructure of protons and neutrons), nuclei (finite nuclear systems), and nuclear matter ("infinite" nuclear systems, *e.g.*, neutron stars), is entering a very exciting time because of the recent convergence of a number of separate paths of research.

On the experimental side, two major milestones have advanced the research: large arrays of detectors with extraordinary data-collecting power, and accelerator facilities which provide experimental access to intense mass-selected (isotope-selected) beams with lifetimes down to the microsecond scale. The combination of these two capabilities marks a unique, major advance in nuclear physics that has not been seen in a number of decades.

On the theoretical side, major developments are energizing the field. As discussed in Section 4.2.1.1 on the TRIUMF Theory Group activities, the development of many-body techniques like the coupled-cluster model coupled with a better understanding of the nucleon-nucleon interaction is opening up the *ab initio* calculation of the properties of finite nuclei for the first time. Major progress is also being made in understanding the types of models needed to describe collective motions in nuclei (shapes, phases, and their dynamics and coexistence).

Observational astronomy is also entering a golden age. The ability of current satellite instruments to observe different stellar phenomena over the range of photon energies corresponding to γ-rays, X-rays, ultraviolet, visible, infrared and microwaves is truly astounding. With these instruments, discoveries of new phenomena and new perspectives on known phenomena are occurring at an impressive rate. The interpretation of these observations is placing new demands on our knowledge in key physics areas. One of the most important areas is nuclear physics, since the source of energy that drives many stellar phenomena derives from nuclear reactions. Also, nuclear reactions are directly responsible for the chemical evolution of material from basic primordial hydrogen and helium to elements all the way to uranium.

As main sequence stars evolve, energy is produced primarily through nuclear reactions involving stable nuclei. In contrast, for cataclysmic events such as nova, supernova and X-ray bursters where prodigious outbursts of energy can occur on the time scale of seconds, the relevant nuclear reactions can involve very exotic unstable nuclei. Nuclear astrophysics concerns the study of the relevant nuclear reactions that drive these stellar engines.

The TRIUMF-ISAC facility has invested heavily in experimental capabilities of all of the frontiers involved and has been a major contributor to proving that we are entering a period of unprecedented research potential. Specifically, it is at TRIUMF-ISAC that the most intense mass-separated beams ever have been used for experimental studies. Some of these studies have used the 8π and TIGRESS arrays of detectors that are among the most advanced, in their respective deployment, ever applied to nuclear structure studies. In addition, at TRIUMF-ISAC highly competitive experimental capabilities for trapping and characterizing rare isotopic species, such as TRINAT and TITAN and for investigating reactions produced by secondary beams of these species, such as DRAGON, TUDA, and TACTIC have been built.

In this Five-Year Plan, the new directions before TRIUMF are outlined that will build on existing experimental capabilities: a proposed new accelerator, a proposed actinide target, and a second proton beam line.

When defining the subject of nuclear physics, it is important to emphasize that it does not stand alone as a sub-area of physics. Nuclei are parts of atoms, and as discussed above, the origin of the atoms that constitute all the different chemical elements in the universe is a nuclear physics issue. We live in a world controlled by conservation laws and symmetries, and the proof of and refinement of these laws has often fallen to the nuclear physicist, working with the nucleus as a “laboratory” for the study of fundamental processes. In particular, the intense beams of high-Z isotopes that will be produced at ISAC using an actinide target will allow for an order of magnitude improvement on the current limits of the CP-violating atomic Electric Dipole Moment (EDM) and further constrain both atomic and nuclear parity non-conservation effects.

Finally, one should also be mindful that nuclear science is part of everyone’s daily lives whether they know it or not, from smoke alarms to medical diagnostics and therapies to nuclear power. Quite apart from the above specifics, nucleons, nuclei, and nuclear matter are fundamental levels of organization of matter and have natural places as cornerstones of exploration in the world that we find around us.

6.2.1.1.2

What is the Structure of Nuclei and Nuclear Matter?

Introduction

"What is the structure of nuclear matter?" is a central question that touches upon many different areas. The central goal of nuclear physics is to explain the properties of nucleons, nuclei, and nuclear matter. Ultimately, it is desirable to attain this goal, starting from an understanding of the nucleon-nucleon interaction based on the fundamental theory of quantum chromodynamics. Indeed, considerable progress is being made in this direction with the development of *ab initio* methods, a more sophisticated understanding of the nucleon-nucleon interaction, and the application of advanced many-body techniques to nuclear physics. But connecting the fundamental theory to the nucleon-nucleon interaction poses a severe challenge, and the complexity of the strongly interacting many-body system requires that the study of detailed properties of nuclei rely on both *ab initio* calculations and more phenomenological models for the foreseeable future.

These models, both *ab initio* and phenomenological, have largely been tested on the properties of nuclei located at or near the line of stability because that is where the most data are available. Extrapolations into areas where no data exist are highly uncertain and are very often proven wrong by experiments. We cannot at this point give a satisfactory answer to the question posed above. To make progress, we need to break the question down into smaller, more manageable questions. While there are many questions that can be asked in relation to "What is the structure of nuclear matter?" TRIUMF and its user community have concentrated on the following:

1. What are the limits of nuclear existence?
2. How do the properties of nuclei evolve as a function of the neutron-to-proton asymmetry?
3. How do the properties of nuclei evolve as a function of proton and neutron number?
4. What are the mechanisms responsible for the organization of individual nucleons into the collective motions that are observed?

What is the role of nuclei in shaping the evolution of the universe?" is a question intimately related to the structure of nuclei and nuclear matter. The synthesis of hydrogen, helium, and Li in the Big Bang is probably understood. Elements as heavy as iron are predominately produced as a result of stellar burning, while elements above iron are probably produced in supernovae explosions and other astrophysical phenomena. It is a goal of nuclear astrophysics to understand fully the origin of the elements in the universe and how nuclei impact directly the nature of the astrophysical objects and their dynamics. We cannot yet give a satisfactory answer to the question posed above. As before, we break this one central question down into manageable pieces that TRIUMF and its user community is concentrating on:

1. How does stellar evolution proceed?
2. How and where are nuclei heavier than iron created?

Nuclear structure and nuclear astrophysics, as broad fields of investigation, attempt to answer these questions. Nuclear structure and nuclear astrophysics are so intertwined that any separation between them is quite arbitrary and artificial. To explain stellar evolution, we need to understand key phenomena including the mechanism of supernovae explosions and the nature of neutron stars, as well as precisely measure basic nuclear properties such as half-lives, masses, reaction rates and nuclear equations of state. Given the complexity of many of the reaction networks that are thought to be present in stellar burning and explosive nucleosynthesis, and the locations of the various process paths, which often occur very far from stability, it cannot be expected that all necessary data will be measured. Therefore, nuclear models must, at least partly, be relied upon. The development of accurate and predictive nuclear models, however, has proven to be a challenge for decades. The very nature of the strongly interacting many-body system does not lend itself to easy computation. Nuclear structure investigates the properties of nuclei in an attempt to understand their natures and to guide the development of nuclear models so that they are able to accurately predict properties beyond the reach of experiment.

This section of the plan addresses the fundamental questions relevant to nuclear structure while the nuclear astrophysics questions are addressed in Sections 6.2.1.1.3.1 and 6.2.1.1.3.2.

What are the Limits of Nuclear Existence?

Nuclei are finite many-body quantum systems which exhibit a rich variety of single-particle, few-body, and many-body phenomena. Precise control over the particle (nucleon) number permits very detailed systematic studies to be made. Such studies reveal behaviour that would be impossible to see in isolated species and can only be discerned by systematic study as a function of changing particle number. Such studies also reveal "emergent" phenomena that would be unimagined if only a microscopic approach were available [P.W. Anderson, Science 177, 393 (1972)]. For example, current ab initio calculations starting with the nucleon-nucleon interaction systematically depend on data for light nuclei to establish three-and many-body forces in nuclei, without which the calculations would be useless.

One of the critical questions in nuclear physics concerns the limits of existence, *i.e.*, at what point do nuclei become unbound? Not only is this question of profound importance in our understanding of the nature of the nucleonic system, but it also has a deep impact on nuclear astrophysics, especially in connection with the nucleosynthesis of heavy nuclei through the r- or rapid-neutron-capture process. On the proton-rich side of the valley of stability, the position of the proton drip line has been delineated for many of the elements because this region can be accessed by stable beam/target experiments. On the neutron-rich side, however, the location of the neutron drip line is largely unknown except for the lightest elements, up to oxygen. Figure 1 is a chart of the nuclides indicating the known stable and unstable nuclei, as well as the

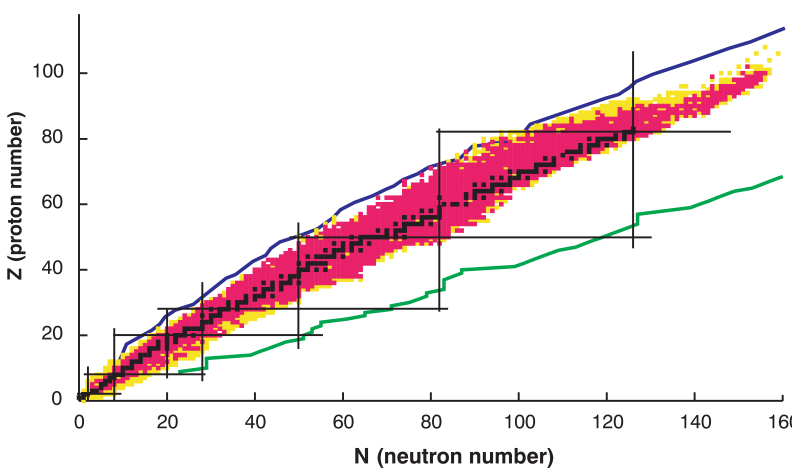


Figure 1: The chart of the nuclides with proton and neutron drip lines as predicted by the FDRM model (AME2003). Stable nuclei are marked by black squares, nuclei for which excited states are known are pink (ENSDF), and nuclei with measured masses (AME2003) are yellow. Thousands of nuclei have yet to be explored.

region predicted where bound nuclei exist but as yet have not been observed. The uncertainty in predicting the limits of nuclear existence is due to an incomplete knowledge of nuclear properties progressing away from the line of stability. Already, between mass 25 and 35, two major breakdowns in "well-established" descriptions of nuclear structure occur. Surprises also appear to be looming near N ~ 28 [B. Bastin *et al.*, Phys. Rev. Lett. 99, 022503 (2007); T. Baumann *et al.*, Nature 449, 1022 (2007)].

All nuclear models use detailed properties of known nuclei to determine the proper form of the effective interactions and their parameters. However, it is mostly at or near stability where these have been determined. As an example, Figure 2 displays the uncertainty in predicting the location of the neutron drip line, *i.e.*, where $B_n = 0$, for the tin isotopes. While all mass models reproduce the known experimental data reasonably well, extrapolating to the drip lines results in an uncertainty of nearly ten mass units. One of the main reasons for this uncertainty is the interplay between the bulk, smoothly varying properties of nuclei and the structure of nuclear shells. The exact location of the proton and neutron shells, and whether these shells are open or closed, can result in substantial change in the binding energy. Accurate and precise mass measurements on nuclei farther from stability are needed to fix model interactions and parameters.

How Do the Properties of Nuclei Evolve as a Function of the Neutron-to-Proton Asymmetry?

The advent of rare-isotope beams has made it possible to explore how the properties of nuclei evolve along a chain of isotopes extending to both proton-

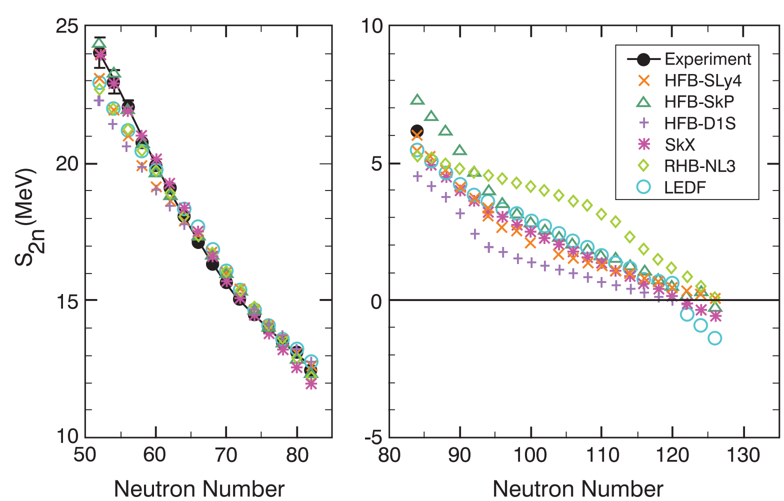


Figure 2: Values of the two-neutron separation energy, S_{2n}, versus neutron number for the Sn isotopes. Where experimental data exist, up to $N = 84$, the mass models reproduce the data reasonably well. However, uncertainties in the interactions and their parameters result in an uncertainty of nearly 10 mass units in the limit of existence.

and neutron-rich nuclei. This capability has led to the discovery of new and unexpected phenomena close to the edge of stability where nuclei with extremely small separation energy of one or two nucleons can form so-called "halo" systems. In these nuclei, the weakly bound valence nucleons have a significantly large probability of being located far outside the rest of the nucleus called the "core." One of the first examples of this exotic structure was ^{11}Li, where two neutrons bound to a ^{9}Li core by only 380 keV give rise to a giant nucleus comparable in size to a heavy nucleus like ^{208}Pb [I. Tanihata *et al.*, Phys. Rev. Lett. 55, 2676 (1965)]. In addition to weak binding, the orbitals occupied by the halo neutrons in ^{11}Li also contribute to its large size. In particular, the low angular momentum $2s_{1/2}$ orbital intrudes into the *p*-shell. Such a reordering of orbitals also leads to a breakdown of the $N = 8$ shell gap for ^{11}Li.

The removal of one neutron from ^{11}Li results in the unbound nucleus ^{10}Li, indicating that it is the extra pairing energy of the valence neutrons that is responsible for the additional binding energy, which leads to the existence of ^{11}Li. It has been proposed that the extra pairing strength is mediated by the exchange of low-frequency surface vibrational quanta, and confirmation of this mechanism would lead to the understanding of the ^{11}Li halo as an isolated neutron Cooper pair [F. Barranco *et al.*, Phys. Rev. Lett. 83, 2147 (1999)]. Another outstanding question is whether and how the excess neutrons in halo nuclei influence the proton distribution. For the halo nucleus ^{11}Li, this question has already been addressed at ISAC by determining the isotope shifts through precision laser spectroscopy in order to extract the charge radii for $^{6-11}$Li [R. Sanchez *et al.*, Phys. Rev. Lett. 96, 033002 (2006)].

Heavier very neutron-rich nuclei, rather than forming halos may instead form neutron skins. The extension of the neutron skin is less dramatic than the halo but its presence can be expected to have important influences on fusion cross sections because of the localization of neutron matter at the surface of the nucleus. A complete characterization of the neutron skin will require the knowledge of the single-particle neutron states occupied in these nuclei in addition to their decay properties and reaction rates. Further, the establishment of the thickness of the skin determined by examining the difference between the nuclear matter radius and the charge radius, is a crucial quantity for testing models of nuclear matter.

The decoupling of the protons and neutrons in halo/neutron skin nuclei can lead to an oscillation of the halo/skin neutrons with respect to the core [K. Ikeda, Nucl. Phys. A538, 355c (1992)]. Such an excitation process would result in dipole resonances that are located much lower in excitation energy than the standard giant dipole resonance. In halo/neutron skin nuclei, these modes of excitation are called soft dipole and pygmy resonances, respectively. The existence of such dipole modes just above the neutron threshold might also have an important effect on fusion cross sections and thereby affect *r*-process nucleosynthesis. So far, the presence of low-lying dipole strength in ^{11}Li has been observed, but the existence of a full-fledged resonance state is yet to be clearly confirmed.

Finally, the halo/skin neutrons could also experience different nucleon-nucleon correlations and pairing effects since on average they reside well separated from the protons. The proximity of the halo neutrons to the continuum could also affect these correlations. The two-neutron transfer reaction is a highly sensitive way of probing the correlations of halo neutrons because the shape and magnitude of the angular distribution reveals information on the neutron orbitals and the spatial and momentum correlations. To this end, a pioneering measurement has already taken place at ISAC-II, where the two-neutron transfer reaction H(^{11}Li,^{9}Li)*p* was investigated.

Future Program for Investigating Halo Nuclei and Neutron Skins at ISAC-I

As discussed in Section 4-2-1-1-2-1, research at the ISAC-I facility at TRIUMF has made a significant contribution to the understanding of halo nuclei through several pioneering studies on ^{11}Li. To discuss the future scope of the program at ISAC-I and other complementary facilities, international experts on the field gathered at the “Halo 08 Workshop” at TRIUMF on March 27–28, 2008. Some future directions and physics goals for the coming years at ISAC-I emerged from the Workshop and are discussed below. These studies will use a variety of experimental techniques including: inelastic scattering, one- and two-nucleon transfer reactions, Coulomb excitation, mass measurements and spectroscopy using ion and atom traps, β-decay studies, and the use of polarized beams for laser spectroscopy studies.

A program of one- and two-nucleon transfer reactions has already been initiated at TRIUMF to determine nuclear orbital occupancies and neutron-neutron correlations in light halo nuclei. In addition to the ^{11}Li(*p,t*) experiment mentioned above, TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer) studies the ^{11}Be(*d,pγ*)^{12}Be reaction to provide information on the distribution of intruder *s*-wave strength in the levels in ^{12}Be. In the coming years, when beams of neutron-rich carbon and oxygen isotopes are available, this program will be extended to include experiments such as ^{18}C(*d,pγ*)^{19}C. For Borromean nuclei, the resonances in the unbound subsystem will be probed through transfer reactions such as ^{12}Be(*d,p*)^{13}Be. The characterization of neutrons forming the nuclear skin can be accomplished using single nucleon transfer reactions such as (*p,d*), (*d,t*), or (*d,p*) using the proposed IRIS facility (see Section 6.4.4) on neutron-rich nuclei such as ^{30}Na, ^{54}Ca, $^{70-78}$Ni, and ^{134}Sn. Proton-skin can be studied using (*d,*^{3}He) reactions on proton-rich Cl isotopes, which could be produced by protons on actinide targets. Two-neutron transfer reactions such as (*p,t*) will be used to probe the neutron-neutron correlation in neutron-skin nuclei such as ^{30}Na and ^{134}Sn. Finally, soft dipole modes in ^{11}Li will be studied through inelastic proton scattering. The access to heavier neutron-rich nuclei will open future possibilities to search for pygmy resonances in ^{54}Ca and ^{132,134}Sn by using inelastic scattering with light targets such as hydrogen and deuterium.

The 8π spectrometer, and later GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei), will be used to study the β-decay of light halo nuclei such as ^{14}Be, ^{19}C, and ^{23}O. DESCANT (DEuterated SCintillator Array for Neutron Tagging) will further enhance the study of β-delayed neutron emitters. In the region of neutron skins, there exists a tremendous opportunity as much is still unknown. High-precision mass measurements using TITAN (TRIUMF Ion Trap for Atomic and Nuclear Science) will continue to be used to determine the binding energies of halo and neutron skin nuclei such as ^{14}Be , ^{19}C , ^{17}Ne, and ^{26,27}F. These measurements are of critical importance as input to three-body models and are also essential to limit the uncertainties in charge-radius measurements. Polarized rare-isotope beams, together with the β-NMR and β-NQR facilities can be used to measure the ground state magnetic dipole and electric quadrupole moments of halo and skin nuclei. A proposal to measure the moments of ^{11}Li has already been approved. Future measurements will focus on neutron-rich halo nuclei from Be to F. Nuclear skin studies will be facilitated by measurements on neutron-rich Na, Mg, and Ca isotopes.

Finally, precise laser spectroscopy measurements will be extended to measure the charge radii of ^{11,12,14}Be. For heavier nuclei such as Ni and Sn, where long chains of isotopes are available for study, systematics of the change in the mean-squared charge radii as well as the radial distribution of valence neutrons can be deduced. Knowledge of the nuclear matter radius, deduced from the analysis of nuclear reactions, will provide a consistency check and give confidence in the extracted value of the neutron-skin thickness. The proton distribution in very heavy nuclei beyond the regime of stable nuclei, such as francium, will be explored from ^{206}Fr extending as far out in the neutron-deficient direction as possible. High-precision laser spectroscopy on the light Fr isotopes will also allow for an investigation of the wave function of the valence neutron via the Bohr-Weisskopf effect.

How Do the Properties of Nuclei Evolve as a Function of Proton and Neutron Number?

This question underlies all other questions in nuclear structure and has a major impact on nuclear astrophysics. To a very large extent, the question of the evolution of nuclear properties with proton and neutron number can be recast as the question "How does the nuclear shell structure evolve with proton and neutron number?" The limits of bound nuclei are intimately connected with the properties of nuclear shells: their locations and nature as a function of proton and neutron number. The location of shells also determines how the organization of nucleons into collective behaviour manifests itself, whether at low-excitation energy the nucleus behaves like a few particles orbiting a closed inner core, if it acts similar to a quantum vibrational system, or if it acts more like a quantum rotor.

Serious breakdown of well-established models of nuclear ground-state properties is being encountered in the first studies of very neutron-rich light nuclei. The expected shell closure at $N = 20$ was shown to have been "replaced" by a strongly deformed structure through the observation of a very low-lying first excited state in ^{32}Mg. For this reason and the fact that a new shell closure arises at $N = 16$, the chain of oxygen isotopes terminates at ^{24}O with the conventionally expected doubly magic ^{28}O being unbound. This has been known for some time, but a full answer to "Why?" is only now, slowly, beginning to emerge in this very-difficult-to-study neutron-rich region. Studies of excited-state properties play a key role in understanding ground-state properties.

Two factors appear to be at work in these breakdowns. First, monopole shifts in shell model states are causing significant "migration" of shell gaps. A detailed study in the neutron rich Cu isotopes provides an excellent perspective of what is possible, through the interplay of experiment and theory, in exploring this issue [I. Stefanescu *et al.*, Phys. Rev. Lett. 98, 122701 (2007) and I.

Stefanescu *et al.*, Phys. Rev. Lett. 100, 112502 (2008)]. Possibly a tensor force plays a very important role in producing monopole shifts, as has been invoked to explain why the $N = 20$ shell closure disappears in the neutron-rich oxygen isotopes [Y. Utsuno *et al.*, Phys. Rev. C64, 011301 (2001)]. Secondly, shell model intruder states can become ground states in nuclei at and near singly closed shells when the other nucleon number is far from a closed shell. This is probably happening in ^{32}Mg and its neighbours, but the picture is very confused due to very little data suitable for answering these questions. If shell gaps weaken or correlations from residual interactions become strong, structure as we know it can undergo major change.

Unusual changes in structure can be heralded by unexpected ground-state properties such as mass measurements. This is epitomized by the discontinuity in S_{2n} values for the neutron-rich Na isotopes which signalled the onset of deformation in the "Island of Inversion" years before the first γ-ray was reported from decay studies in the region [C. Thibault *et al.*, Phys. Rev. C12, 644 (1975)]. TITAN, the on-line Penning trap at TRIUMF-ISAC, will provide the first information on nuclei produced at ISAC with as low as ~100 ions/second and $\tau_{1/2}$ ~ 50 ms. Additionally, this highly precise instrument, the only one of its kind using highly charged ions, enables greater precision than any other and can be used to achieve extraordinary sensitivity, ultimately employed to

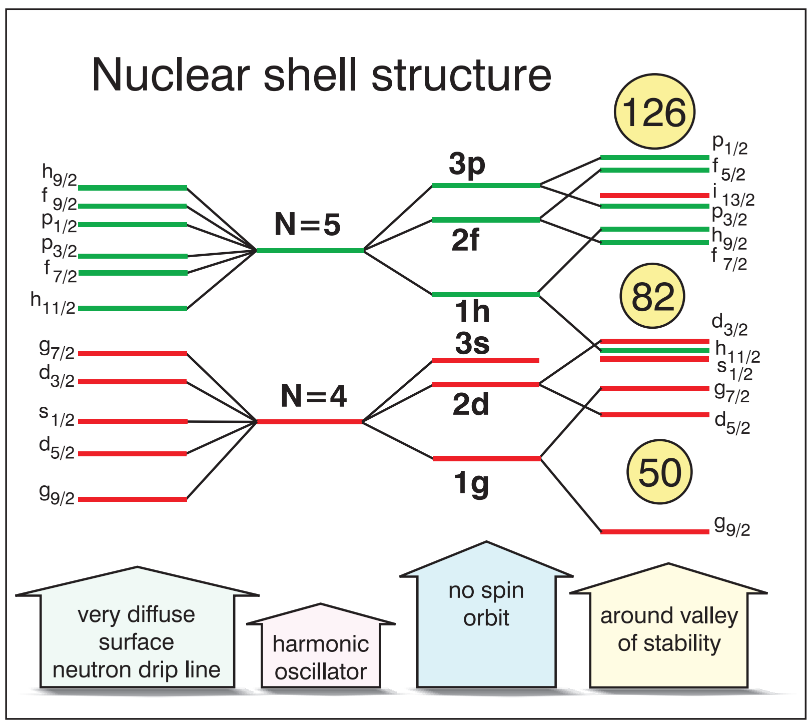


Figure 3: Shell structure as observed around the valley of stability (right), and that predicted for very neutron-rich nuclei. To probe shell structure, experiments such as transfer reactions, or those designed to extract transition matrix elements like Coulomb excitation or lifetime measurements, must be performed. For definitive results, systematic studies following the evolution of shells from stability are needed.

contribute to the probing of fundamental symmetries with precise ($\delta m/m<10^{-9}$) mass measurements for Fermi β-decay.

A number of theoretical calculations now predict that the familiar shell gaps that give rise to the "magic" numbers, or major shell closures, may change drastically in neutron-rich nuclei across the whole nuclear chart. Figure 3 shows one possible scenario, based on theoretical calculations, for how shell structure may be modified in heavy, very neutron-rich nuclei. The locations of the nuclear shells as a function of both proton and neutron number are critical data for testing and refining nuclear models that have had their parameters tuned from knowledge of nuclei at or near the line of stability. The locations of shells also have a profound impact on nucleosynthesis models, specifically on the location of the *r*-process path, and also on the nature of the excited levels (and the density of them) through which reactions, like (n,γ) and (p,γ), proceed.

New theoretical calculations incorporating interactions thought responsible for the modification in shell structure have become available and provide motivation for experimental tests. One such example is in the heavy Ca isotopes where at slightly higher masses the increasing energy of the $f_{5/2}$ orbital with neutron excess is thought to generate a new magic number at $N = 34$, making ^{54}Ca a doubly magic nucleus along with its stable partners ^{40}Ca and ^{48}Ca. As of yet, the data do not exist to test this prediction.

To map shell structure, extensive systematic studies of nuclear properties must be performed, starting with nuclei near the stability line, where the locations of the shells are, in general, known, and progressing outwards. The following key experiments must be undertaken:

1. Mass measurements, where evidence for major shell closures are found in deviations of the masses from smooth trends;
2. β-decay, which often yields the first crucial information on the locations, angular momenta, and parities of excited states and isomers, and tests key selection rules related to the underlying nature of the levels;
3. Coulomb excitation, measuring key matrix elements that depend on the state wave functions, specifically the collective properties;
4. Single-nucleon transfer reactions that probe the microscopic, single-particle, nature-of-state wave functions; and
5. Measurement of charge radii via precision laser spectroscopy.

Studies of the Evolution of Shell Structure at ISAC

A major experimental hurdle to studying very neutron-rich nuclei is the basic technical problem that for isotopes far from stability, yields go down and isobaric contamination goes up. In many cases, this problem has proven to be the limiting factor for the isotope-separator-on-line (ISOL) approach to studying very neutron-rich nuclei produced by fission and spallation of actinide targets with high-energy protons. The proposal herein to build a photo-fission driver offers a major advantage over protons through a significant reduction (and even in many cases elimination) of short-lived neutron-deficient isobars, as is shown in Section 6-2-1-2-3, Figure 8. Note, however, that high-current proton beams on an actinide target provides intense beams of neutron-rich isotopes in mass regions that are not in the "regular" fission fragment islands (see Section 6-2-1-2-3, Figure 7); and thus complement the photo-fission-driver capability.

All of the available spectroscopic tools will be used to access shell structure evolution with a number of experiments using TITAN, the 8π, GRIFFIN, and TIGRESS spectrometers, EMMA and DESCANT.

^{32}Mg Region and the "Island of Inversion"

Experiments on nuclei near ^{32}Mg, aimed at the study of the mechanism involved in the disappearance of the $N = 20$ shell closure and formation of the $N = 16$ shell closure have already begun using the 8π spectrometer to study the β-decay of ^{32}Na and TIGRESS to study the Coulomb excitation of ^{29}Na. When intense beams of the most neutron-rich nuclei become available from the ISAC actinide target, these studies will be extended. Experiments using β-decay observed with the 8π spectrometer, and later GRIFFIN, will be performed on the most neutron-rich nuclei near and beyond ^{32}Mg. The mechanism responsible for the modification of the $N = 20$ shell closure cannot be fully answered unless access is gained to nuclei beyond ^{32}Mg. With the upgrade of the γ-ray detection ability provided by GRIFFIN, spectroscopy could be performed with beam intensities as low as 0.01 ion/s. This spectroscopy will enable experiments on the crucial nuclei farther from stability, providing a more complete picture of shell structure evolution.

TIGRESS experiments will focus on measuring precisely *E2* transition matrix elements using Coulomb excitation for the $N = 16$-20 isotopes $^{26-30}$Ne and $^{28-31}$Na. Single-nucleon transfer reactions such as ^{24,25}Na(d,$p\gamma$) will also be used to probe the energies of the intruder orbital responsible for the island of inversion. These experiments will use TIGRESS for γ-ray detection and the segmented Si array SHARC for coincident proton detection.

Unique opportunities exist for the studies of nuclei at moderate to high spins in this region with fusion-evaporation reactions using the DESCANT+TIGRESS combination. The use of fusion-evaporation reactions would allow for the establishment of yrast and near-yrast states and would provide a test of the rotational properties of the levels. The $N = 16$ nucleus ^{30}Si can be reached with the reaction ^{9}Be(^{24}Ne,3n)^{30}Si; without light charged particles in the final state, events must be detected in DESCANT to indicate that a reaction has taken place. Indeed, ^{31}Si would be within grasp, and it may be possible to reach the $N = 18$ nucleus ^{32}Si with the reaction ^{13}C(^{22}O,3n)^{32}Si. Using a ^{14}C target would provide access to the $N = 20$ nucleus ^{34}Si. While experiments examining the latter nuclei would be low count-rate experiments, the use of tagging via the neutrons should eliminate very effectively the backgrounds from the decay of the beam particles scattered in the target chamber. In a similar vein, ^{32}Mg itself may be accessed via the ^{13}C(^{22}N,$p2n$)^{32}Mg reaction. In all cases, the identification of γ-rays to the channel can be accomplished by measuring the neutron multiplicity on an event-by-event basis.

The hypothesis of a new magic number at $N = 34$ will be tested through Coulomb excitations of neutron-rich ^{50,52,54}Ca and ^{48,50,52}Ar beams with TIGRESS.

Characterization of the Regions Near the Doubly-Closed Shell Nuclei ^{132}Sn and ^{78}Ni

The physics program proposed here focuses primarily on nuclear structure in the neutron-rich region beyond ^{132}Sn where the electron linac will have peak yields. A similar program that reaches beyond ^{78}Ni can be envisioned with a combination of the electron linac and the high-current proton beam line with an actinide target.

Currently, we have knowledge of ground-state masses in (most neutron-rich nuclei): ^{128}Cd, ^{132}In, ^{134}Sn, ^{135}Sb, ^{137}Te, ^{71}Ni, ^{76}Cu, and ^{78}Zn, and excited states in: ^{130}Cd, ^{132}In, ^{134}Sn, ^{135}Sb, ^{139}Te, ^{74}Ni, ^{76}Cu, and ^{77}Zn. These data are too few or too inaccurate for extrapolations and so we have little idea of what lies beyond. There is a growing body of literature that suggests fundamental ingredients of the shell model may change, for example the spin-orbit force as we know it may break down because of a more diffuse nuclear potential surface gradient in very neutron-rich nuclei. Possibly, with a more diffuse potential, many more states will lie near the Fermi surface and correlations will play a much more dominant role such as halo structure. (There is also the question of correlations involving configurations in the continuum if the Fermi energy is very close to the top of the well.)

The first experimental program will begin with studies of basic properties such as ground-state masses, single-particle states, and the first few excited states in the nuclei selected from ^{133,134,135,136,137,138,139}Sn, ^{131,132,133}In, ^{135,136,137}Sb, ^{130,131,132}Cd, ^{136,137,138}Te. The impact of such studies can be assessed by considering, for example, recent results reported for the excited states in ^{130}Cd [A. Jungclaus *et al.*, Phys. Rev. Lett. 99, 132501 (2007)] and for the mass of ^{134}Sn [M. Dworschak *et al.*, Phys. Rev. Lett. 100, 072501 (2008)], which show that $N = 82$ appears to be a good closed shell in a region where the possibility of "shell-quenching" had been raised to explain deficiencies in the predicted *r*-process abundances. (This has, for the moment, shifted the focus of *r*-process physics to the potential importance of neutron-induced fission "recycling" of actinides.)

Specific experiments will include precise ground-state mass measurements of $^{135-139}$Sn to permit extrapolation to infer the location of the neutron drip line. The recent discovery of an isomer, via a mass measurement of an excited (long-lived) state, in ^{65}Fe shows that isomer exploration, which can be expected to be fruitful in shell-model dominated regions, will be an attractive means for discovering simple, new structures [M. Block *et al.*, Phys. Rev. Lett. 100, 132501 (2008)]. A very important point in this respect is that excited state information for an isotope is obtained without having to produce the β-decaying parent for which yields drop precipitously in the regions very far from stability. An added bonus to the study of very neutron-rich nuclei by β-decay is that there is the appearance of two decay processes by which access to a given nucleus becomes possible: direct β^- decay and β-delayed neutron decay. These generally provide different spin distributions that are of enormous value in elucidating structure.

Complementary experiments to probe the ^{132}Sn region at TRIUMF-ISAC include the systematic precision binding energy measurements with TITAN along isotopic chains starting from ^{119}Pd, ^{122}Ag, ^{129}Cd, ^{133}In, and ^{135}Sn for $N =$ 82. The mass measurements will be followed up by systematic single-nucleon transfer ($d,p\gamma$) reactions using SHARC (Silicon Highly-Segmented Array for Reactions and Coulex), TIGRESS, and EMMA (ElectroMagnetic Mass Analyzer) extending from stable nuclei to ^{136}Sn, ^{122}Pd, ^{128}Cd, ^{142}Te, and ^{146}Xe. Combined with β-decay and β-delayed neutron decay studies with the 8π, PACES (Pentagonal Array for Conversion Electron Spectroscopy), and DANTE (Dipentagonal Array for Nuclear Timing Experiments) to determine spin-parity assignments and lifetime measurements of excited states for nuclei beyond ^{132}Sn, a comprehensive picture of the single-particle states will be obtained.

Similarly, in the $N = 50$ region, precision mass measurements starting with ^{73}Ni, ^{77}Cu, ^{82}Zn, ^{84}Ga, ^{86}Ge, ^{88}As, and ^{90}Se will be pursued. The presence of seniority isomers in the neutron-rich $A = 80$ region will be sought, and the validity of the $N = 50$ shell gap at large neutron excess will be probed through Coulomb excitation studies in the vicinity of ^{78}Ni. Deep-inelastic reactions with rare-isotope beams such as ^{81}Ga will be used to populate high-spin states in nuclei around ^{78}Ni. The high mass resolution of the EMMA spectrometer makes it a powerful device for an extensive program of ($d,p\gamma$) transfer reactions in conjunction with TIGRESS for γ-ray detection and SHARC for coincident proton detection. An extensive program of such inverse ($d,p\gamma$) studies at ISAC-II will map the evolution of single-particle states as a function of neutron excess and, in particularly favourable cases such as $d(^{100}\mathrm{Rb},p\gamma)^{101}\mathrm{Rb}$, will be performed on the *r*-process nuclei themselves. Such ($d,p\gamma$) studies will form an important part of the ISAC-II physics program and will establish ISAC as the world leader in this field.

Nuclear Structure near the $N = Z$ Line

The charge independence of the nuclear force has been a central concept in nuclear physics for more than sixty years. Once account is made for the Coulomb interaction, which is very weak compared to the strong nuclear interaction, charge independence states that the nucleon-nucleon force for the same relative state of motion and spin does not depend on whether one considers protons, neutrons, or a combination of the two. This symmetry, together with the fact that proton and neutron masses are nearly identical, prompted the isospin formalism wherein the two types of nucleon are treated as different states of the same particle that are distinguished by the projection of isospin onto a quantization axis. In reality, the nucleon-nucleon interaction has an isovector contribution (*i.e.*, the $nn \neq pp$ interaction) on the order of 1%, and an isotensor contribution (the average of the *nn* and *pp* interactions ≠ the *np* interaction) on the order of 2% of the strength of the isoscalar interaction. However, this causes only a minor perturbation, and the isospin concept is extraordinarily useful for nuclei near the $N = Z$ line.

The breaking of isospin symmetry has important consequences not only for nuclear structure but for the fields of nuclear astrophysics, where isospin partners are often used to predict the locations and natures of levels important in capture reactions, and in fundamental symmetry tests, where the isospin mixing is an important correction that must be applied to Fermi superallowed β-decay rates before the CKM matrix element V_{ud} can be extracted. TRIUMF-ISAC currently has the most intense beams of neutron-deficient nuclei near the $N = Z$ line, and an active program to exploit them, especially for the Fermi superallowed program, is already well underway. With the commissioning of the ISAC-II facility, new avenues of research into $N = Z$ nuclei are opened.

A program of Coulomb excitation, with the aim of investigating isospin symmetry breaking, is planned. These will include Coulomb excitation of heavy isospin $T = 1$, $N = Z$ nuclei such as ^{62}Ga, ^{66}As, ^{70}Br, and ^{74}Rb. The extracted $B(E2;2^+_1 \rightarrow 0^+_1)$ values will be compared to the isoscalar matrix elements from the neighbouring $T_Z = \pm 1$ nuclei. Beam intensities of ~10^3 ion/s are needed; the experiments will use the TIGRESS+SHARC combination, with the University of York Bragg detector to determine beam composition on an event-by-event basis.

It is well known that $T = 0$, $S = 1$ is the strongest channel of the nucleon-nucleon force. However, the pairing field appears to be dominated by collective $T = 1$, $S = 0$ pairs, rather than $T = 0$, $S = 1$ pairs, even in $N = Z$ nuclei where the latter might naively be expected to play a more dominant role. In heavy nuclei, a collective $T = 1$ pairing field develops and eventually forms a superconducting state. Evidence for a collective $T = 0$ *np* pairing field in nuclei, which until now has remained elusive, will be sought using the (^{3}He,*p*) deuteron-transfer reaction on a series of even-even nuclei into odd-odd $N = Z$ nuclei. Preliminary results using a ^{44}Ti beam at Argonne National Laboratory are promising; however, those studies are limited by the availability of short-lived radioactive beams. At ISAC-II, these studies will be pursued, with ^{72}Kr beams initially, and extended as other even-even $N = Z$ beams become available.

Using a LaC target, a program to probe the Sn nuclei approaching ^{100}Sn will be initiated. These measurements will include Coulomb excitation, where sufficient yields are expected down to ^{106}Sn, that will complement $B(E2)$ values extracted using intermediate-energy Coulomb excitation, and a series of single-nucleon transfer measurements, such as (*d*,*t*), to extract the locations of the single-particle strengths in the neighbouring odd-mass nuclei. These studies can also be complemented by the decay of neutron-deficient Sb isotopes using the 8π spectrometer, and later GRIFFIN. Fusion-evaporation reactions using the TIGRESS spectrometer combined with the EMMA recoil spectrometer will also be used to probe high-spin states near ^{100}Sn. The reactions using ^{56}Ni, ^{66}Ge and ^{63}Ga beams, obtained from a high-power ZrC spallation target, with a ^{40}Ca target, are particularly attractive.

What Are the Mechanisms Responsible for the Organization of Individual Nucleons into the Collective Motions that Are Observed?

In many complex systems, simple patterns may emerge. In nuclei, which may contain hundreds of individual nucleons, rather than displaying chaotic energy spectra, they often show remarkably simple excitation spectra at low energies. The emergence of the simple patterns is often related to underlying symmetries in the Hamiltonian. The phenomena of pairing, discussed above in the context of halo nuclei, is one example of this. Nuclei also organize (approximately) into different shapes and may possess surface vibrational modes. Spherical even-even nuclei away from closed shells are often labelled as vibrational because their low-lying spectrum can resemble that of a simple harmonic oscillator, while deformed nuclei are labelled as rotational since their spectrum resembles that of a quantum rotor. While models can account for some of the observables of these modes, a long-term challenge has been the transitional regions where the shape undergoes a rapid change. A prime example of this is the $N = 90$ region where there is a rapid change in the shape of the ground state as the neutron number increases from $N = 88$ to $N = 92$.

Since many nucleons participate in the development of collective phenomena, there could be a saturation effect. Nuclei near the mid-shell, which have the maximum number of valence protons and neutrons, would be expected to have the maximum collectivity. One may thus expect that a nucleus like ^{170}Dy, with $Z = 66$ and $N = 104$, would have the greatest degree of deformation. However, the lighter Gd isotopes have a greater deformation than their Dy isotones, prompting the idea that there could be a saturation effect.

Nuclei with well-deformed shapes typically possess a symmetry axis, and the projection of angular momentum onto this symmetry axis is the *K* quantum number. The degree to which *K* is conserved, *i.e.*, the "goodness" of this quantum number, gives a direct indication of the nuclear shape, and mixing effects, such as the Coriolis force. The most sensitive way to probe the degree of violation of *K* is the measurement of the decay of *K* isomers. These isomeric states result from a unique combination of single-particle orbitals that lie relatively low in excitation energy and that have large spin components projected onto the symmetry axis. One of the best regions of the nuclear chart to investigate *K* isomers is the mass 170–190 region.

Studies of Collectivity in Nuclei

A powerful spectroscopic tool that is beginning to be used in the study of collectivity in nuclei far from stability is multiple-step Coulomb excitation. An excellent recent example of the power of this spectroscopic tool is an investigation of the very neutron-deficient Kr isotopes [E. Clement *et al.*, Phys. Rev. C75, 054313 (2007)]: however, major issues of shape coexistence are unresolved. The problem is that coexisting structures mix and can give rise to complex and misleading patterns of excitations and decay. A powerful spectroscopic technique for identifying mixed, coexisting configurations is the observation of electric monopole transitions. These transitions afford a model-independent view of mean-square charge transition moments in nuclei, and these moments are strongly enhanced by the mixing of coexisting configurations with different shapes (which have different mean-square charge radii).

The combination of studies with the 8π-PACES array and with TIGRESS offers a multi-spectroscopic approach to the collective structure of nuclei away from the stability line that ranks among the very best spectroscopic capabilities currently available anywhere. The 8π-PACES array is able to provide detailed spin-parity information on excited states through γγ angular correlation studies and internal conversion electron studies with coincidence gating for γγ, γe^-, $e^-\gamma$, and e^-e^- combinations.

TIGRESS, in combination with BAMBINO or Super-CHICO and higher energy secondary beams will offer *E*2 matrix elements via multi-step Coulomb excitation, from which important constraints on the low-energy collective response of any given nucleus can be obtained. The β-decay studies with the 8π spectrometer and its auxiliary detection systems can be performed with beam intensities as low as ~1 ion/s. The new high-efficiency γ-ray spectrometer GRIFFIN will provide a 20-fold increase in absolute γ-ray efficiency, representing a 400-fold increase in γγ coincidence experiments. GRIFFIN will allow detailed structure studies for exotic isotopes produced with intensities below 0.01 ion/s.

The $N \approx Z$ nuclei in the region of ^{68}Se–^{80}Sr display rapid changes of nuclear structure associated with the coherent effects of proton and neutron wave functions, and Coulomb excitation with TIGRESS+SuperCHICO at ISAC-II of nuclei such as ^{68}Se, ^{70}Br, ^{72,74}Kr, ^{74}Rb, and $^{76-80}$Sr will probe shape co-existence in this region (in addition to probing isospin purities as outlined above). Using the high-power Nb target, fusion evaporation reactions such as ^{75,76}Rb+^{58}Ni will be used to populate high-spin states in the vicinity of ^{130}Sm. This particular region is predicted to have very large ground-state deformations with β_2 ~0.4 but is currently out of reach at stable-beam facilities due to their extremely low production cross sections. Deep-inelastic reactions with beams such as ^{81}Ga, ^{94}Kr, and ^{97}Rb impinging on ^{208}Pb or ^{238}U targets will efficiently populate even more neutron-rich systems and allow for studies of nuclear shell structure and deformation in the extremely neutron-rich $N = 50$ and $N = 60$ regions of the chart of the nuclides. These studies will require the fabrication of a large-acceptance, solenoid-based spectrometer to detect and identify the reaction products.

The Cd nuclei have been used as paradigms of vibrational motion, and the stable isotopes have been the subjects of many very detailed spectroscopic investigations. These have revealed the possible breakdown of the vibrational interpretation, but systematic studies must be extended into the neutron-rich region, including the neutron-rich Pd isotopes to fully map out the nature of the collectivity and influence of the intruder states. These systematic studies include the β-decay of neutron-rich Ag and Rh isotopes with the 8π spectrometer and its associated auxiliary detectors, and multistep-Coulomb excitation with TIGRESS and SuperCHICO. As $N = 82$ is approached, these studies will benefit from the high-purity beams provided by photo-fission driven by the e-linac.

An intensive program has been initiated to probe the shape transitional $N = 90$ isotones, and these studies will be extended to the neutron-rich ^{148}Ce, ^{146}Ba, and ^{144}Xe. Nuclei near $Z = 64$ and $N = 90$ have recently been suggested as examples of nuclei possessing tetrahedral magic numbers, with a signature of the vanishing of the $E2$ transitions near the rotational band heads, requiring their probing with multi-step Coulomb excitation. Regions of shape coexistence also include the neutron-deficient Pb and Bi isotopes. Although shape coexistence has been established in these nuclei, it is based on incomplete data; conclusive proof rests in the measurements of enhanced $E0$ transitions that can be measured with the 8π-PACES array. Other future studies include an investigation of the saturation of nuclear collectivity in well-deformed rare-earth nuclei near mid-shell by performing measurements to determine low-lying level schemes and lifetimes in the neutron-rich Gd and Dy isotopes. A search for high-K isomers in the neutron Hf, Tm, and Lu isotopes will continue, with the ultimate goal of discovering the long-lived $K = 18^+$ isomer in ^{188}Hf.

Nuclear Structure for Fundamental Symmetry Tests

A number of fundamental processes of nature occur in nuclei in a manner that permits high precision quantification. One of the first was the proof of parity violation by the weak interaction. A long-running topic of investigation has been the CVC theory of the weak interaction and the unitary of the CKM matrix, observed through precision measurements of superallowed Fermi β-decay. Indeed, a significant thrust in the physics program at TRIUMF-ISAC in the past seven years has been the characterization of a number of half-lives and branching ratios associated with superallowed Fermi β-decay.

Work remains to be done to fully exploit the unique capabilities at ISAC:

- Q-values measured with TITAN to a relative precision of 10^{-9} for ^{10}C, ^{66}As, ^{70}Br, ^{74}Rb, and ^{78}Y.
- High-precision branching ratio and $T_{1/2}$ measurements of ^{46}V, ^{50}Mn, ^{66}As and ^{70}Br
- High-precision $T_{1/2}$ measurements of ^{10}C and ^{14}O.

Two new lines of investigation into nuclear structure for tests of fundamental symmetries will become possible at TRIUMF-ISAC with the implementation of the actinide target with a second proton beam line and the electron linear accelerator. The first is the quest for the observation of a non-zero electric dipole moment in an atom. The second is extracting values for the masses of the neutrinos from neutrinoless double-β-decay (if neutrinos are Majorana particles).

Discovery of an Atomic Electric Dipole Moment

The electric dipole moment (EDM) quest focuses on a choice of atomic species most likely to exhibit a measurable effect. Heavy atoms that possess nuclei with large octupole moments are the best prospect. The best potential cases are in the very neutron-rich Rn isotopes (with A ~223).

The first step is to establish best cases of octupole deformation. This will need detailed spectroscopy of the most promising isotopes using multistep-Coulex with TIGRESS and detailed radioactive decay schemes of the astatine parent nuclei with the GRIFFIN-PACES arrays. To study $^{223,225}Rn$ with sufficient detail, rates of ~10^6 nuclei/s of the At parents are required. This will require currents on the order of ~10 μA on the proposed actinide target. When the best candidate octupole-deformed nucleus is identified, the atomic EDM measurement will follow with dedicated beam time for ~100 days of running.

Nuclear Matrix Elements for Extracting Neutrino Masses

The determination of neutrino masses from neutrinoless double-β-decay is fundamentally dependent on the calculation of the nuclear matrix element with sufficient precision. Low-precision calculations will indicate the mass regime in which the three-neutrino masses reside while high-precision calculations will determine the hierarchy of the three masses.

This undertaking will be one of the toughest challenges ever to nuclear theory because of the fundamental nature of the process. To do this will require very reliable theories of ground-state wave functions, and of excited states. The challenge is that the double-β-decaying parent-daughter candidate pairs are in mass regions where models of nuclear structure are not that reliable. A leading example is the $^{76}Ge/^{76}Se$ pair. This region has very complex pair structure and coexisting shapes [E. Clement *et al.*, Phys. Rev. C75, 054313 (2007)].

Such features render the commonly used collective-model theories questionable and the shell model approach too narrow (truncated).

The accessibility of intense beams of neutron-rich nuclei from the high-power photo-fission driver naturally match all the leading cases for investigation of neutrinoless double-β-decay from $^{76}Ge/^{76}Se$ to $^{150}Nd/^{150}Sm$, as the neutron-deficient isobars are not produced. In particular, very detailed studies of the collective behaviour of ^{76}Ge and ^{150}Nd will be undertaken via the radioactive decay of ^{76}Ga and ^{150}Pr using the 8π-PACES arrays. Recent studies have revealed that our knowledge of the structure of the candidate isotopes, is seriously lacking with respect to calculating double-β-decay matrix elements [J.P. Schiffer *et al.*, Phys. Rev. Lett. 100, 112501 (2008)].

Electron capture/beta (EC/β) branching ratios also provide a sensitive test of the theoretical calculations of the nuclear matrix elements need to describe neutrinoless double-β-decay. Currently, for most cases the electron capture branching ratios are poorly known due to their small value on the order of $\leq 10^{-3}$. Conventional techniques have reached a limit of sensitivity, so a new experiment using a novel approach is being set up at TITAN to determine these branching ratios [J. Dilling *et al.*, Can. J. Phys. 85, 57 (2007)]. Initial measurements for ^{100}Tc will allow a direct comparison between this novel method and conventional techniques. Ultimately, further EC/β branching ratio measurements are planned for other isotopes of relevance for neutrinoless double-β-decay experiments such as ^{110}Ag, ^{114}In, ^{150}Nd, and ^{76}As.

Conclusion

There are real opportunities to advance our understanding of the nuclear many-body problem and how it changes as we vary the number of neutrons and protons. TRIUMF has the talented people, award winners like Prof. C. Svensson. TRIUMF has the experimental facilities, world leading facilities like TIGRESS and TITAN. With the proposed upgrade to ISAC, TRIUMF will have the beams, an unparallel collection of rare-isotopes beams. The next decade at TRIUMF promises to be one of unequalled achievement in nuclear physics.

6.2.1.1.3

Nuclear Astrophysics

6.2.1.1.3.1

Introduction to Nuclear Astrophysics

One of the key motivations for the original ISAC facility was the exploration of nuclear astrophysics. In addition to the ISAC-I accelerators, major experimental facilities like DRAGON (Detector of Recoils And Gammas Of Nuclear Reactions), TUDA (TRIUMF UK Detector Array), and TACTIC (TRIUMF Annular Chamber for Tracking and Identification of Charged Particles) were constructed. Notable successes, which include the measurement of the ^{21}Na(p,γ) reaction cross section, the measurement of ^{26}Al(p,γ), and the measurement of ^{40}Ca(α,γ), have demonstrated that the combined capabilities of high-intensity beams and good instrumentation produce important physics results. Never the less DRAGON and TUDA have been negatively impacted by the general lack of beam time. However, TRIUMF remains firmly committed to the nuclear astrophysics program, and this Five-Year Plan proposes upgrades to the ISAC facility that will improve the level of productivity.

The main challenges facing the astrophysics program are the same as those of the rest of the ISAC program: lack of beam time and the lack of availability of the appropriate beams. The problem is especially acute with the DRAGON facility. It was designed to measure low-energy cross section reactions and, consequently, its experiments tend to be run significantly longer (from four to six weeks) and require the highest intensities of all the ISAC experiments. Some of the fundamental symmetry experiments share the same difficulties, and the long beam times these experiments require can only be met if an additional beam line and a target station are built.

The availability of the appropriate beams is also particularly acute for DRAGON because the most important beams for it require a lot of development work. For example, attempts by both TRIUMF and the Oak Ridge National Laboratory to develop a ^{25}Al beam for the reaction ^{25}Al(p,γ)^{26}Si have not been successful. ISAC is at the forefront of all ISOL facilities, so a lot of development work must be carried out and carried out in a novel regime. The search for the appropriate target materials and ion sources is partly trial and error and must be done at the high beam power only available at ISAC. It is important to try different materials and ion sources, and these attempts require experimenters to be able to change targets quickly, a property the current target stations lack.

The proposed new beam line, with the capability to change targets quickly, would significantly increase the productivity of the astrophysics program. First, the astrophysics program would benefit from the general increase in beam time. Second, higher currents on conventional, non-actinide targets in the new target station would be especially useful for the low cross section measurements typical of DRAGON. Third, the ability to change targets quickly would permit better beam development without as much disruption to the ongoing program.

In the next subsection, we present the science case for an extension of the current program in the region of neutron-deficient nuclei. This program will greatly benefit from the proposed upgrade of the ISAC facility, and its continuation is part of the justification for the upgrade. The subsequent subsection discusses a new astrophysics program that would be possible using the neutron-rich isotopes that will become available with an actinide target from either a proton or electron driver. Since the neutron-rich astrophysics program is new, more consideration is given to the general motivation for that program than for the ongoing astrophysics program.

6.2.1.1.3.2

Nuclear Astrophysics with Neutron-Deficient Nuclei

Introduction

The astrophysics program at ISAC utilizes rare-isotope and stable beams to investigate a variety of nuclear properties and reactions relating to processes on the neutron-deficient side of stability. In this area, TRIUMF is unique: we not only have the production capability for short-lived rare-isotope beams, but also the unique ability to accelerate intense beams up to and beyond astrophysical energies coupled to a variety of top-class experimental facilities ready to exploit them. The ongoing program can be split into several areas of importance for different astrophysical processes or stellar scenarios, such as explosive hydrogen and helium burning in novae and X-ray bursts, the *p*- and ν*rp*-processes in core collapse supernovae, and quiescent stellar burning or nucleosynthesis after the Big Bang. These areas of study are shared amongst these experimental facilities: DRAGON (Detector of Recoils And Gammas Of Nuclear reactions), TUDA (TRIUMF UK Detector Array), TACTIC (TRIUMF Annular Chamber for Tracking and Identification of Charged Particles), TITAN (TRIUMF's Ion Trap for Atomic and Nuclear Science), and DSL (the Doppler-shift Lifetime Facility). In addition, we have prospects for future work at facilities based at ISAC-II such as TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer), SHARC (Silicon Highly-Segmented Array for Reactions and Coulex), and EMMA (ElectroMagnetic Mass Analyzer).

Stellar Characteristic Gamma-Ray Emitters and Nova Grains

Space-based γ-ray telescopes such as the INTEGRAL satellite are attempting to probe astrophysical objects through the signatures of nucleosynthesis processes: either the flux of 511 keV γ-rays produced by annihilation from β+ decaying isotopes formed in stellar events, or via characteristic γ-ray lines from individual radioisotopes. Short-lived (on astronomical scales) nuclei that are predicted to be prolifically produced in certain stellar events, such as ^{13}N, ^{18}F, ^{22}Na, and ^{44}Ti, can become potential observables for individual sources, giving us a powerful look into the internal processes of explosive stellar events. Integrated signals from longer-lived diffuse galactic radioactivity such as ^{26}Al or ^{60}Fe can give us another observational constraint on models of stellar evolution, explosion, and galactic chemical evolution. So far, characteristic γ-rays from ^{26}Al, ^{60}Fe, and ^{44}Ti have been observed, for example, an individual supernova (Cas A) remnant containing detectable ^{44}Ti flux.

The reactions that create and destroy these radioisotopes in explosive scenarios are crucial inputs to astrophysics models that simulate these events and predict their observables. Eliminating the nuclear physics uncertainties in these nuclear reaction rates by laboratory measurement can give us a powerful direct link between the models and observation. This in turn can help us answer questions such as why we haven't seen any signal from ^{22}Na in classical novae yet, despite strong predictions otherwise, or why the ^{26}Al in the galaxy appears to be correlated with massive star production even though some models suggest a strong nova, Wolf-Rayet phase or an AGB star contribution.

The important nuclear reactions that play a role in determining the ejected abundances of these isotopes are usually proton- or alpha-capture reactions and are therefore prime targets for study using the DRAGON recoil separator. So far, the majority of DRAGON experiments have been oriented towards measuring the strengths of these important reactions such as ^{26g}Al(p,γ)^{27}Si, ^{21}Na(p,γ)^{22}Mg, ^{23}Mg(p,γ)^{24}Al and ^{40}Ca(α,γ)^{44}Ti; however, many unmeasured reactions remain. In particular, one high priority is the ^{25}Al(p,γ)^{26}Si reaction, the final unmeasured rate that affects ^{26}Al production in novae. Other reactions needed for the prediction of 511 keV γ-ray signals in novae are ^{13}N(p,γ), ^{17}F(p,γ), and ^{18}F(p,γ). In addition to the ^{21}Na(p,γ), ^{26}Al(p,γ), and ^{23}Mg(p,γ) studies already underway or completed at DRAGON, the measurement of these reactions will ensure that the abundances of γ-emitting radioisotopes in classical nova are based entirely on precision experimental measurement, rather than theoretical estimates of insufficient accuracy.

The quantity of the isotope ^{44}Ti, which is seen in supernova remnants, is sensitive to a network of nuclear reactions not firmly based on experiment. One example is the important ^{45}V(p,γ) reaction, which can be measured at

DRAGON and which complements the study of the direct ^{44}Ti production reaction ^{40}Ca(α,γ) already being measured at DRAGON. The important ^{44}Ti(α,p) reaction may also be measurable either directly at the TUDA facility, or via indirect or reverse reaction techniques. The experimental determination of all of these reaction rates is one of the highest scientific priorities of the DRAGON program and provides one of the strongest links between theory and observation in the field of astrophysics.

Several pre-solar grains have been identified that show isotopic ratios characteristic of the kind of nucleosynthesis that occurs in classical novae. It is speculated that these grains may have condensed out of material fresh with the imprint of explosive hydrogen burning nucleosynthesis in a classical novae. Crucial to the identification of these grains as nova candidates, and a potential powerful tool for constraining the physical models of novae, are particular isotopic ratios in these grains such as ^{28}Si/^{30}Si or ^{32}S/^{33}S. These ratios should bear the mark of nova nucleosynthesis with abundance ratios vastly different than seen in conventional grains borne out of bulk galactic nucleosynthesis. Only a few (p,γ) reactions contribute to these isotopic ratios, and their strengths are known either only partially by experiment, or almost entirely by theory, with considerable error in all cases. These reactions must be measured directly using the DRAGON facility to constrain the abundance ratios. Most important of these is the ^{30}P(p,γ) reaction, which determines the ^{30}Si/^{28}Si ratio in the nova ejecta and can give ratios of up to 40 to 100 times the solar ratio for some O-Ne nova models. Also of importance is the ^{33}Cl(p,γ) reaction, which complements the ^{33}S(p,γ) study already performed at DRAGON, and is needed to constrain the ^{33}S/^{32}S ratio in the models, which is a potential signature for nova grains.

CNO Cycles, Breakout, and Energy Generation in the *rp*-process

The CNO cycles and their subsequent breakout within explosive burning scenarios are crucially important for a variety of reasons. The cold CNO cycle generates energy within all more massive stars, and certain reactions have considerable influence on stellar evolution on the main sequence that is vital to the understanding of globular clusters and the age of the universe. The hot-CNO cycles are exited via breakout reactions which occur at high temperatures such as in X-ray bursts and which lead to the *rp*-processes, thus synthesizing some heavier elements and dictating the thermonuclear energy released in the process. The sensitivity of various global X-ray burst properties such as periodicity, amplitude and duration to individual nuclear reactions is astonishing and leads to the requirement of precise, direct measurements of these rates to constrain models and lead to a proper understanding of the underlying physics of these powerful cosmic events. Such reactions can be determined via direct measurement at the TUDA facility and also accessed using indirect techniques such as measurement of excited state lifetimes, reaction spectroscopy, or time-reversed approaches.

CNO Cycles

As previously mentioned, the CNO cycle is vital to the understanding of main-sequence stellar burning, in particular the main-sequence turn-off which is a critical parameter to understanding the relationship to the ages of globular clusters, which are often used as an indicator of the lower limit of the age of the universe. The transition from the hot-pp chain into the CNO cycle is also only partially understood experimentally. Measurement of the $^{11}C(p,\gamma)$ reaction, which is involved in this transition, is crucial for the understanding of the evolution of very low metallicity stars, a much discussed topic in astronomy at present. The $^{13}N(p,\gamma)$ reaction, dominated at these temperatures by a direct-capture component, is another important link in the CNO cycle that requires direct measurement. Lifetime measurements of the relevant excited states in some of the nuclei involved in the CNO cycle can provide a determination of resonance strengths if the state spin and parity are known, and the particle branching ratio can be derived from elsewhere. An example is the case of the $^{14}N(p,\gamma)$ reaction, where the extrapolations to stellar energies depend sensitively on *R*-matrix fits to resonances. Because of the importance of this particular reaction for the main-sequence turn-off, precision measurements of the ^{15}O excited states involved can help constrain the fits and provide extra confidence in the data.

Breakout from the Hot-CNO Cycle

The breakout from the CNO cycle in X-ray bursts is dominated by the $^{18}Ne(\alpha,p)$ reaction, in the sense that this reaction provides a bottleneck through which all mass is expected to flow. Although this reaction has been the focus of some limited study over the years, considerable disagreement exists between attempted direct measurements and reverse reaction techniques. With ^{18}Ne intensities improving annually at ISAC, the TUDA facility is uniquely poised to measure this reaction, complementing by reverse reaction techniques using the TIGRESS or TUDA facility at ISAC-II, and measuring alpha strengths of the relevant states via transfer reactions.

The most important reaction contributing to the breakout from the hot CNO cycle is $^{15}O(\alpha,\gamma)$, which drives the thermal instability in the accreting H/He-rich region that allows the $^{18}Ne(\alpha,p)$ reaction to take over. Thus, whether a given accreting neutron star results in a thermonuclear type 1 X-ray burst at all depends very sensitively on the strength of the $^{15}O(\alpha,\gamma)$ reaction. It has been shown in many theoretical studies that simple scaling of this rate can drastically affect the shape and periodicity of the generated X-ray luminosity curve (the primary observable), while theory also suggests that X-ray binaries with all accretion rates up to the Eddington rate should result in bursts. This theory is at odds with observation, in which bursts are only seen up to about 30% of the Eddington rate.

The DRAGON facility was built with this reaction in mind and is the only facility in the world poised to measure it. DRAGON will be able to measure this rate once a ^{15}O beam of sufficient intensity has been developed at ISAC. The presence of a new specialized actinide beam line at ISAC will enable faster development of such a beam. The direct measurement of this reaction will allow, for the first time, X-ray burst modellers and astronomers to disentangle the effects of nuclear physics and scenarios such as turbulent mixing, magnetic fields, and localized accretion on the bursts.

The αp- and *rp*-processes

After breakout from the hot-CNO cycle, nucleosynthesis up to tellurium and subsequent energy generation can proceed via a set of rapid proton captures and $\beta+$ decays: the *rp*-process. Because the accreting material also typically contains helium, these proton captures compete with a series of (α,p) reactions: the αp-process. The burst properties are sensitive to waiting points in the *rp*-process, specifically at points where small proton separation energies inhibit further net flow to heavier nuclei and where the path must wait for $\beta+$ decay before proceeding further. Such waiting points occur at ^{64}Ge, ^{68}Se, and ^{72}Kr.

The important nuclear properties required for laboratory measurement in the αp- and *rp*-processes are ground-state masses of nuclei right out to the drip line, their half-lives, and the rates of (p,α) and (α,p) reactions. For example the mass of ^{64}As is a critical parameter for this process. Although (p,γ) and (α,γ) reactions are less important at these high temperatures because of the quasi-equilibrium nature of the flow, they may become significant in certain cases near waiting points, for example, ^{57}Cu(p,γ), ^{65}As(p,γ), and ^{69}Br(p,γ). For cases where beams of sufficient intensity can be generated at ISAC, the (p,γ) rates can be measured at the relevant energies using DRAGON. Otherwise, a host of indirect techniques can be used to determine experimentally the rates using TIGRESS, EMMA, SHARC, or TUDA. The important (α,p) reactions can either be attempted directly at the TUDA facility using a gas target, if sufficient beam intensity is available, or attempted indirectly via the reverse (p,α) reaction combined with inelastic scattering and γ-spectroscopy studies at TIGRESS. Ground-state masses relevant to the *rp*-process are a prime target for the TITAN facility, and lifetimes can be measured via implantation using the 8π spectrometer.

Quiescent Stellar Burning and Big Bang Nucleosynthesis

Elements from carbon to calcium are formed in quiescent stellar burning, while elements from scandium to zinc are made in the statistical thermal equilibrium found both in core collapse and thermonuclear supernovae shortly before explosion. The quiescent burning does not (with a very few exceptions for longer-lived isotopes) involve radioactive isotopes because typical capture times are much longer compared to those of typical beta decays. Stable nuclei are also involved in some of the reactions occurring in novae. Typically, in quiescent stellar burning, the stellar burning temperatures are so low that the cross sections encountered are often not accessible to direct measurement. The DRAGON facility has been involved in the measurement of some of the reactions of quiescent stellar burning, most notably ^{12}C$(\alpha,\gamma)^{16}$O.

The sun is in a stage of quiescent hydrogen burning involving the *pp* chain because of its relatively low mass. The closeness of the sun allows the observation of the neutrino flux emanating from its core where the nuclear burning takes place. This observation has led to the discovery of neutrino oscillations and, as a consequence, the neutrino mass. TRIUMF is involved in the measurement of the most important reaction for the determination of high-energy neutrino flux from the sun, the ^{7}Be$(p,\gamma)^{8}$B reaction.

The isotope ^{7}Be is radioactive, with a laboratory half-life of 53 days. Therefore, either a radioactive beam or a radioactive target is required. For the measurement of the ^{7}Be(p,γ)^{8}B reaction, a target has been produced at TRIUMF; however, as very thin targets are required for the measurement of the elastic proton scattering, a ^{7}Be beam will be required. This measurement will determine the optical potential of ^{7}Be+p and will therefore improve the extrapolation of the ^{7}Be(p,γ)^{8}B cross section to the energies found in the solar burning. The elastic experiment experiment will be performed using the TACTIC detector.

During the first minutes of the Big Bang, a handful of light isotopes were synthesized, the most heavy one of any significant amount being ^{7}Li. The isotope ^{6}Li is, however, not expected to have been produced in any measurable amount. Nevertheless, there is stellar evidence that the primordial ^{6}Li amount may be around 20% of that of ^{7}Li. This evidence has renewed interest in the synthesis of ^{6}Li, and we plan to measure the ^{7}Li(^{3}He,α)^{6}Li and ^{3}He(t,γ)^{6}Li reactions at TACTIC or a similar set-up.

The Formation of the *p*-Nuclei

The *p*-process

The p-nuclei is the name given to the group of 35 neutron-deficient stable isotopes ranging from ^{74}Se to ^{196}Hg that stand separated, by short-lived isotopes, from the line of stability and remain unreachable by neutron-capture processes. The production of these isotopes was traditionally attributed to a so-called p-process, which is now sometimes called the γ-process. In this process, a medium already enriched by the s-process undergoes high-temperature and density conditions such as those in core-collapse supernovae, and the p-nuclei are reached via a series of photodistintegration reactions, in particular (γ,n), (γ,p), and (γ,α). These reactions allow the formation of lighter p-nuclei from the heavier s-process ashes, the crucial nuclear physics details being the branching points where the charged-particle reactions start to compete with the (γ,n) reactions. Models of the p-process can produce abundances only to within a relatively large factor of the observed abundances.

As in any quasi-equilibrium flow, the reaction Q-values and therefore masses of the relevant nuclei play an important role, but the details of the branching ratios remain mostly undetermined. In principle, the rates of the (γ,p) and (γ,α) reactions can be determined partially by measuring the reverse, (p,γ) and (α,γ) rates at the relevant energies, and applying the detailed-balance theorem, requiring knowledge of ground-state spin-parities for all nuclei involved.

Large compilations of (p,γ) and (α,γ) reaction cross sections that are required for experimental investigation for the p-process do exist, but these have focused on cases where the target nucleus is stable (although the final nucleus, which would be the target nucleus in the corresponding (γ,p) or (γ,α) reaction, can be unstable). Many international laboratories seek to attempt measurement of these radiative capture rates, or to determine the particle alpha potentials for input into statistical model codes which would lead to a tighter constraint on theoretical predictions for unmeasured reactions.

Many important reactions of interest will involve radioactive nuclei. When a large number of these and stable nuclei become available at ISAC from ISOL targets, many of the important properties pertaining to the *p*-process can be measured. The DRAGON facility can theoretically measure (p,γ) and (α,γ) cross sections in the region A_{target} = 80–90, providing the recoil charge state is boosted before entering the recoil separator, up to centre-of-momentum energies of 1 MeV. Energies higher than this can be accessed by making relatively small modifications to the bending magnets and electrode voltages in the separator. However, the facility can make a start on measuring some of the lighter important capture reactions on stable and radioactive targets such as ^{80}Se(p,γ), while properties of other relevant nuclei can be investigated at the higher energies available at ISAC-II using a variety of experimental techniques.

The ν*rp*-process

Another potential contributor to the creation of the *p*-nuclei has recently been shown to be a primary process, *i.e.*, one not relying on the previous formation of seed *s*-process nuclei, similar to the *rp*-process that may take place in proton-rich outflows at early times in a core-collapse supernova. Although the environment at this time is proton-rich, the key to this process has been realizing that a small abundance of free neutrons is produced by the effects of neutrino (and electron) interactions with protons. Thus, the traditional waiting points in the *rp*-process, at which the proton separation energies are sufficiently small so that net flow to higher masses is inhibited, can be bypassed by (n,p) reactions with characteristic timescales many times faster than the equivalent β^+ decay. This effect ensures that this ν*rp*-process can synthesize nuclei right up into the intermediate *p*-nuclei region, including the molybdenum and ruthenium nuclei that traditionally present problems for the *p*-process.

It has been shown recently that the abundances of individual *p*-nuclei, such as ^{92}Mo and ^{94}Mo, are critically sensitive to just a few proton separation energies in the ν*rp*-process flow, particularly in regions where forward flow is inhibited due to small proton separation energies and in which the path is diverted into neighbouring isotones. Some experiments have been performed in Finland and at Argonne, but these remain solely based on theoretical extrapolations with r.m.s. errors of the order 500 keV; mass measurements at the critical points are necessary to define the resulting abundances which are sensitive to individual proton separation energies at the level of 100 keV. This region of the nuclear chart is therefore a prime target for the TITAN facility. Because this process has only recently been considered, systematic studies of all the sensitive proton separation energies have not been fully explored.

As well as measuring masses, the strengths of the crucial (n,p) reactions at the critical waiting points have never been studied and require experimental attention, resulting in the prospect of a wide variety of structure and reaction spectroscopy prospects for the proton-decaying states of interest in the radioactive compound nuclei using facilities such as TIGRESS and EMMA, and a variety of available detectors.

6.2.1.1.3.3

Nuclear Astrophysics with Neutron-Rich Nuclei

The Origin of the Heavy Elements

The origin of the heavy elements is universally acknowledged to be one of the most important unsolved problems in all of science. The present evidence indicates that roughly half of the elements heavier than zinc (atomic mass number $A \sim 70$) are synthesized in a series of rapid neutron capture reactions interspersed with photodisintegrations and β-decays known as the *r*-process. This production mechanism involves highly unstable, neutron-rich nuclei that can't be found on Earth.

At least two distinct neutron capture processes are thought to be responsible for the production of nearly all the heavy elements ($A > 70$), the slow (*s*) and rapid (*r*) neutron capture processes. The adjectives slow and rapid describe the average pace of neutron captures in the processes relative to the β^- decay lifetimes typical of the nuclei involved. The *s*-process hews close to the valley of β stability and involves neutron captures that are slower than the β^- decay rates of the nuclei that participate. Hence the nuclei involved are stable or have relatively long β decay lifetimes and can be fashioned into targets and bombarded with neutrons to determine their capture rates and expected abundances. In contrast, the *r*-process is a series of rapid neutron captures that takes place in a hot environment with an extraordinarily high density of free neutrons ($> 10^{20}$ cm^{-3}), combined with a series of β^- decays that bring the newly formed, neutron-rich nuclei closer to the valley of β stability. The *s*-process has at least two distinct components, one responsible for producing light and another for heavy elements. Similarly, abundance differences between light and heavy *r*-process nuclei found in primitive meteorites led to the idea that there are at least two distinct *r*-process components or sites [G.J. Wasserburg, *et al.*, Ap. J. 466, L109 (1996)].

Recently, astronomical observations of the stellar halo of the Milky Way Galaxy have revealed the presence of stars that have infinitesimal yet measurable abundances of Fe and heavy neutron-capture elements compared to those of the Sun. As the formation of these heavy elements is associated with stellar evolution, these iron-deficient or metal-poor halo stars have hardly been enriched with the iron produced in supernova explosions and therefore are among the oldest observed stars in the galaxy. Nevertheless, the fact that they contain heavy elements such as U and Th that can only be produced in the *r*-process implies that an earlier generation of stars synthesized and ejected the *r*-process elements into the interstellar medium. Spectroscopic observations of these metal-poor stars reveal nearly identical abundance distributions for the heavy *r*-process elements with $A > 130$ [J. J. Cowan and C. Sneden, Nature 440, 1151 (2006)]. Hence metal-poor halo star observations support the hypothesis of two *r*-process sites, exhibiting a consistent *r*-process element abundance pattern for nuclei with $A > 130$ (the main *r*-process) but considerable variations for nuclei with $A \leq 130$.

Two astrophysical *r*-process sites, core-collapse supernovae and neutron star mergers, have been modeled extensively. The presence of heavy ($A > 130$) *r*-process nuclei in metal-poor stars that are at least 10 Gyr old represents strong circumstantial evidence that the main *r*-process nuclei were formed in a site associated with massive stars. This is because massive stars have short lifetimes of 10 Myr or less and would have been able to produce and disperse the heavy elements quickly enough to account for their presence in the oldest metal-poor halo stars. In contrast, neutron star mergers require sufficient time for both stars in a binary system to evolve into neutron stars and then spiral into one another. This scenario requires longer timescales, and the neutron star merger rate is small enough that they do not appear promising as an explanation of the *r*-process enriched halo stars. However, all the detailed astrophysical models constructed to date fail to produce conditions that lead to a robust *r*-process that can successfully account for the elemental abundances observed in old stars and the solar system. Given the uncertainty in the astrophysical site, experimental and observational constraints are crucial. Dynamical calculations of the core-collapse supernova scenario suggest that a wide range of correlated parameters such as neutron density and entropy can result in *r*-process nucleosynthesis, so it is presently impossible to uniquely specify the astrophysical conditions that obtain during the process.

For this reason, *r*-process calculations are typically performed in an astrophysical site-independent waiting point approximation [*e.g.*, K.-L. Kratz *et al.*, Ap. J. 662, 39 (2007)]. This approximation assumes that the temperature and neutron density are so high that, for a given element, neutron captures proceed rapidly until reaching an isotope whose neutron separation energy is so low that its neutron-capture rate is in equilibrium with the photodisintegration rate of its neutron-capture daughter. This (n,γ) – (γ,n) equilibrium implies that the neutron captures within an isotopic chain halt at waiting point nuclei that must β-decay before further neutron captures can occur, synthesizing heavier nuclei. Once the free neutrons are exhausted, or the temperature drops sufficiently, the neutron-capture reactions fall out of equilibrium with the corresponding photodisintegrations (freeze-out), and the remaining nuclei β-decay back toward stability. These waiting point nuclei are said to lie in the *r*-process path or be *r*-process progenitors since at the time of the freeze-out, the vast majority of the isotopes of a given element are the waiting point nuclei.

In addition to β-decay lifetimes, the identities of the waiting point nuclei depend principally on their neutron separation energies S_n, and the temperature and neutron density of the environment, which determine the abundances in an (n,γ) – (γ,n) equilibrium. Since the astrophysical site of the *r*-process remains unknown, the temperature is uncertain. Moreover, within any given scenario the temperature drops with time, implying that a range of different S_n values define the *r*-process path. In the core collapse supernova scenario, the path is defined by 2 MeV < S_n < 4 MeV. Since S_n is given by the mass difference between adjacent isotopes, nuclear masses determine the location of the *r*-process path and thereby have the largest influence on predicted *r*-process abundances. Nuclei with closed neutron shells (*e.g.*, neutron number $N = 50$, 82, and 126) are particularly tightly bound. Hence they have large S_n values and small neutron-capture cross sections relative to the neighbouring isotopes. Accordingly, they are disproportionately represented among the waiting point nuclei and contribute substantially to the final abundances, being responsible for the *r*-process abundance peaks at A ~80, 130, and 195.

Even if the neutron separation energy of the *r*-process path nuclei were known precisely, the waiting points would be extremely neutron-rich nuclei about which very little is known, including masses. For this reason, calculations rely on global nuclear mass models whose parameters have been adjusted to reproduce the masses of nuclei that have been measured with a root mean square deviation around 700 keV. It is clear from comparisons of these different mass models that there is a degeneracy between the astrophysical conditions and the nuclear masses, *i.e.*, the same final abundances can be produced by different combinations of physical conditions and the hypothesized masses of unmeasured neutron-rich nuclei. The behaviour of the mass trends near the closed neutron shells, *e.g.*, $N = 82$, has the most profound influence on the final abundances. Systematic studies of the masses and low-lying excited states of neutron-rich nuclei must be performed to look for deviations from theoretical predictions. Even where the *r*-process path cannot quite be reached, it would still be very helpful to precisely measure the masses of neutron-rich nuclei as far out along an isotopic chain as possible, seeking surprises. It will likely never be possible to measure the masses of all the relevant nuclei. Therefore, the nuclear mass models that must be relied upon to extrapolate to neutron-rich nuclei beyond the reach of present experiments will continue to be crucial; they must be tested and refined using data near the closed neutron shells, particularly $N = 82$.

To date, the masses of only about 10 *r*-process progenitors have been measured, most only via rather imprecise β^- decay Q value (Q_β) determinations. With neutron-rich beams produced by the fission of uranium, TRIUMF will be able to make important contributions to the understanding of the *r*-process through mass measurements. It will be possible to reach the *r*-process path in a number of places, but substantial coverage of the path near $N = 82$ represents the most exciting opportunity. The best option will be direct mass measurements using TITAN (TRIUMF Ion Trap for Atomic and Nuclear science). In some cases, the lifetimes of the nuclei will be too short (< 5 ms) to permit direct measurements of this kind. In these cases, other options are open such as production via a transfer reaction using a nearby neutron-rich beam followed by identification and isolation for Q_β study using EMMA (ElectroMagnetic Mass Analyzer) and TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer). Yield calculations indicate that we will be able to reach some of the most important *r*-process waiting point nuclei whose masses have not yet been measured or confirmed, including ^{126,127,128}Pd, ^{129}Ag, ^{131,132}Cd, ^{131,132,133}In, ^{134,136}Sn, ^{137,139}Sb, and ^{138,140,142}Te.

In addition to strongly influencing the progenitor abundances, β^- decay lifetimes determine the timescale of the *r*-process, particularly at and near the closed neutron shells at $N = 50$ and 82. TRIUMF will make an impact in this area by carrying out β^- decay lifetime measurements using the 8π array when it is possible to produce and ionize the nuclei of interest before they decay. In cases where the lifetime is too short for this, EMMA can be used to study the β^- decays of nuclei produced in secondary reactions. In the very hot environments capable of generating the huge free neutron densities required for the *r*-process, nuclei with low-lying excited states are likely to be thermally excited. Hence it is not only the ground state β^- decay properties that must be known in order to predict the final abundances, but also those of the low-lying excited states. It is not possible, in general, to create isotopes in short-lived excited states in the production target and then transport them for study before they decay. It is possible, however, to populate the excited states of these nuclei using transfer reactions and Coulomb excitation. In some of these cases, it will be possible to use EMMA to isolate the isomeric recoils for decay studies, allowing the study of the β^- decay properties of the low-lying isomers. In other cases we will have to rely on systematic studies of these nuclei using reactions capable of probing their low-lying excited states and characterizing them. In this context, TIGRESS will be instrumental when combined with EMMA and SHARC (Silicon Highly-Segmented Array for Reactions and Coulex), particularly for the study of $M1$ transitions to constrain Gamow-Teller strength.

Beta-delayed neutron emission probabilities P_n affect the final abundances in the *r*-process by shifting the mass of a decaying nucleus by one mass unit and liberating neutrons at late times far from thermal equilibrium. This has the effect of smoothing out the odd-even staggering present in the progenitor abundances to some extent. However, in the scenarios with high entropy, freeze-out occurs very quickly, and the capture of neutrons after the (n,γ) – (γ,n) equilibrium is broken is not very significant. Moreover, measurements indicate that the P_n values of the relevant nuclei that have been studied are not very large. If these assessments hold true as more measurements are performed, then the importance of non-equilibrium neutron capture is not great. But if not, the neutrons liberated following these decays will quickly be captured again by other nuclei, again shifting the mass distribution. In this case, the neutron capture rates on these nuclei, which lie closer to stability than those in the *r*-process path, are likely to influence the final abundances. Although direct (n,γ) measurements are not presently feasible on these radioactive nuclei, theoretical efforts to relate (d,p) and (n,γ) reaction cross sections have met with success and may allow a determination of some relevant bound state neutron capture cross sections using the powerful combination of TIGRESS, SHARC, and EMMA.

Experimental data on the β^- decay lifetimes and P_n values of *r*-process progenitors and daughters have been obtained for approximately 50 nuclei from ^{68}Fe to ^{140}Te. Since such experiments require lower beam intensities and can be performed with less pure beams than mass measurements, more progress has been made. Yet there are still a number of nuclei around the $N = 82$ shell closure for which lifetime and P_n values remain unmeasured. Some that will be within reach at TRIUMF include a number of nuclei in the Zr to Pd ($40 \leq Z \leq 46$) region. Among these, the most important ground state cases are ^{110}Zr and ^{128}Pd. While Zr is a highly refractory element that effectively resists ionization, its isotopes can be reached via proton transfer reactions with Y beams. Some of the nuclei with important low-lying isomers likely to be thermally populated in any reasonable *r*-process scenario that have not been definitively measured include ^{129}Ag, ^{131}In, and ^{127}Rh. Experiments with EMMA, SHARC, DESCANT (DEuterated SCintillator Array for Neutron Tagging), and TIGRESS will enable substantial progress on lifetime and P_n determinations.

An example of the type of precise study enabled by the powerful combination of these detectors and the pure, neutron-rich beams that will be available from photo-fission driven by the proposed electron linear accelerator is the study of the β-decay lifetimes and neutron emission probabilities of isomers in *r*-process progenitors around $N = 82$. The study of the decay properties of these isomers is rendered extremely difficult when the lifetimes of the isomer and the ground state radioactivity are comparable, as is often the case in this region. This situation implies that the contributions of the two states cannot be disentangled in the decay curves. However, by populating and identifying the isomeric state in a transfer reaction using a heavy beam in inverse kinematics, the recoiling isomer can be uniquely identified and its β-decay lifetime and β-delayed neutron emission probability measured, *e.g.*, the 300 keV isomer in ^{131}In could be studied effectively in this way. By carrying out a (p,d) reaction to populate the isomeric state using a ^{132}In beam, which is predicted to be very intense and pure, the deuterons could be detected with SHARC and used to tag the excitation energy of the ^{131}In recoil. The recoils themselves would be separated from the beam electromagnetically and isolated for β-decay study in the focal plane of EMMA. DESCANT would be used to ascertain the neutron emission probability following β decay. In this way one can achieve very precise and selective lifetime and branching ratio data.

The fission of heavy nuclei is important in some *r*-process models. In these scenarios, fission barriers and yields have a large influence on the final abundances. Calculations typically assume that all nuclei with $A > 256$ are produced in the *r*-process fission. Since the extremely heavy neutron-rich nuclei whose fission may terminate the *r*-process are unlikely to be produced in any laboratory anytime soon, systematic studies of fission are needed to improve theoretical models of fission in these unknown nuclei. TRIUMF can contribute in this area by carrying out systematic studies with lighter neutron-rich nuclei. Similarly, it will be difficult to produce the nuclei with $N = 126$ that are the progenitors of the third *r*-process peak around mass 195 in large numbers. Nevertheless, it may be possible to produce nuclei in this region in sufficient numbers to study their β-decays via the deep inelastic scattering of heavy, neutron-rich beams such as ^{132}Sn.

The Nuclear Physics of Neutron Stars

Neutron stars are the end states of massive stars. They are extremely exotic objects in that they are macroscopic, with radii of roughly 10 km, yet they have an average mass density almost as large as that of an atomic nucleus. Models indicate that the crusts of neutron stars exhibit a transition starting with stable nuclei at the surface, down through neutron-rich nuclei at high pressure and density, then moving towards the core through exotic phases of nuclear matter. Astronomers are now able to study the thermal emissions from neutron star crusts and infer their properties. Further, the crust plays an important role in Type I X-ray bursts, which are thermonuclear explosions arising from the accretion of matter onto the surface of a neutron star from a stellar companion in an interacting binary star system. The recently discovered X-ray superbursts, which are many times more luminous and longer lasting than ordinary X-ray bursts, are still poorly understood. To determine if superbursts have a thermonuclear origin, the thermal properties of the crust must be better known. To understand the neutron star crust, we need to understand neutron-rich nuclei and the nuclear equation of state at large neutron excess. The latter is significant in understanding the transition to new phases of nuclear matter as well as determining the neutron star mass-radius relation, and can be understood only through systematic studies of the structure and excitations of neutron-rich nuclei.

Recent calculations have explored the nuclear processes that take place in the crusts of neutron stars accreting material and undergoing X-ray bursts [S. Gupta *et. al.*, Ap. J. 662, 1188 (2007) and P. Haensel and J. L. Zdunik, Astron. Astro. 480, 459 (2008)]. As the ashes of an X-ray burst sink into the crust, being buried by more accreted material, electron captures drive the nuclei to a very large neutron/proton ratio. Once the nuclei reach the neutron drip line, they emit neutrons before undergoing further electron captures as the pressure and density increase. Finally, pycnonuclear fusion occurs as the nuclei approach depths at which the density is nearly nuclear. Both the electron captures and the pynonuclear fusion reactions heat the neutron star crust, affecting model predictions of astronomical observables such as the recurrence time of superbursts and the cooling of the crusts of the variably accreting neutron stars responsible for X-ray transients.

Only by improving our knowledge of the nuclear physics of neutron-rich nuclei will we be able to reliably describe the relevant electron capture Q values and properly interpret the astrophysical meaning of superburst and X-ray transient cooling observations. The nuclear data needs to include the masses and the properties of the low-lying excited states fed by the electron captures of neutron-rich nuclei with $20 < A < 160$, including Gamow-Teller matrix elements. Unfortunately, there are no substitutes for systematic studies as thousands of nuclei are involved. However, a large fraction of the ashes of X-ray bursts are predicted to be in the form of ^{104}Cd. So targeted studies of the electron capture products of these *rp*-process ash nuclei such as ^{104}Y and ^{104}Sr using TITAN would be particularly germane. The other experimental facilities at ISAC, including 8π, SHARC, TIGRESS, and EMMA, will allow β-decay and reaction spectroscopy of these neutron-rich nuclei that can't be done elsewhere. Finally, the nuclear symmetry energy dominates the baryonic contribution to the pressure of a neutron star, determining the mass-radius relation, the moment of inertia, and the thickness of the inner crust. The density dependence of the nuclear symmetry energy will be probed by comparing collisions of neutron-rich nuclei on a given target with those of neutron-deficient nuclei using the HÉRACLES facility at ISAC.

6.2.1.1.4

Fundamental Symmetries with Exotic Nuclei

Introduction

One of the great challenges in science is to explain the amount of matter we see around us. Evidence for some kind of Big Bang is overwhelming, but any cosmological model using the physics that we presently know produces a photon-to-baryon ratio much higher than the billion-to-one ratio observed. To correct the discrepancy requires processes that create a larger matter-to-antimatter asymmetry. The discovery and subsequent measurement of electric dipole moments (EDMs) potentially provides an experimental tool to constrain theoretical models that address this issue.

The world around us is governed by a series of fundamental laws and symmetries. The standard model has provided a precise framework for calculation and prediction, the results of which agree with experimental data remarkably well. Many extensions to the standard model have been proposed. TRIUMF has a long history of performing high-precision experiments that both test the standard model of particles and forces and look for physics beyond it. In recent years, this testing has centred on different aspects of the charged weak current as measured in the first generation of particles in nuclear beta decay. This program, centred on the TRIUMF Neutral Atom Trap (TRINAT), proposes to continue the pursuit of its objective of constraining physics beyond the standard model via measurements of right-handed currents, scalar bosons, and exotic massive particles.

To complement this existing program, as well as take advantage of TRIUMF's unique capabilities two new independent projects will probe time-reversal symmetries via a direct measurement. The first is a project to measure the permanent EDM in heavy, octupole deformed Rn nuclei and the second project is to measure parity non-conservation effects, both atomic and nuclear in the chain of Fr nuclei. A brief outline of these programs is discussed below.

New Programs at TRIUMF Utilizing High *Z* Atoms

In general, as the nuclear charge increases, the atomic electrons' overlap with the nucleus also increases. This overlap greatly increases the sensitivity of high Z atoms to short-ranged quark-lepton interactions. As an example, the magnitude of atomic parity-violating effects scale as Z^2N before relativistic effects are considered and nuclear anapole moments scale as $Z^{8/3}A^{2/3}$. To make full use of this enhancement, high-precision atomic physics techniques have to be combined with state-of-the-art nuclear detection methods as well as the world's most intense rare-isotope beams. These capabilities all come together at the ISAC-I facility where two new collaborations will utilize the unique capabilities of the facility.

Time-Reversal Violation

An electric dipole moment (EDM) changes sign under both parity and time reversal and, for an elementary particle, atom, or molecule, can only arise from polarization of the system by T- or, equivalently, CP- violating interactions. Measurement of a non-zero particle EDM would represent the detection of a new form of CP violation, distinct from the flavour-changing CP violation studied to date in the decays of neutral K and B mesons. This latter CP violation appears to be well described within the minimal electroweak standard model by a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM)

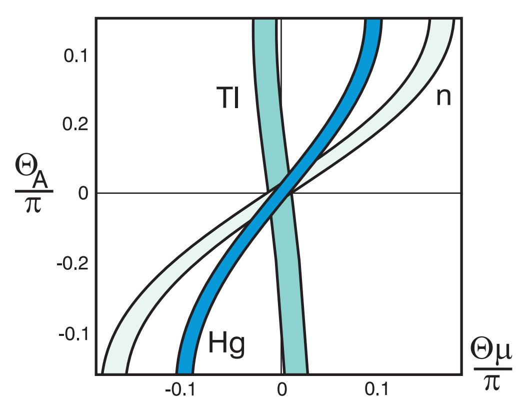


Figure 1: Example of complementarity of three EDM measurements in setting limits on two CP-violating parameters in a SUSY model.

quark-mixing matrix. However, it cannot account for the observed baryon asymmetry of the universe, strongly suggesting additional sources of CP violation. This additional CP violation is likely non-flavour-changing and could induce significant particle EDMs.

While the standard model predictions for particle EDMs are many orders of magnitude below current experimental sensitivity, virtually all extensions to the standard model, (*e.g*,. multiple-Higgs theories, left-right symmetry, and supersymmetry) generically predict EDMs within, or tantalizingly close to, the reach of current experimental techniques. The present limits on EDMs are given in Table 1. These have already ruled out significant portions of the parameter spaces of many models (see Figure 1 for an example). However, a substantial improvement on current limits would have profound implications for the spectrum of viable extensions to the standard model. The aim of this experimental program is to achieve such an improvement through the ability to select systems with enhanced sensitivity to underlying CP-odd physics. In particular, the work will focus on searching for atomic EDMs of certain radon isotopes where the large predicted enhancements stem from collective nuclear octupole deformation.

Parameter	Limits from		
	^{199}Hg	Neutron	Electron
θ_{QCD}	1.5×10^{-10}	4.1×10^{-10}	-
Down quark EDM	-	5×10^{-26} e-cm	-
Colour EDM	3×10^{-26} e-cm	-	-
ε_q^{SUSY}	2×10^{-3}	5×10^{-3}	-
ε_q^{Higgs}	$0.4/\tan\beta$	-	$0.3/\tan\beta$
χ^{LR}	1×10^{-3}	5×10^{-8}	-
C_T	1×10^{-8}	-	5×10^{-7}
C_S	3×10^{-7}	-	2×10^{-7}

Table 1: Limits on CP-violating parameters [Baker *et al.*, Phys. Rev. Lett. 97, 131801 (2006); Romalis *et al.*, Phys. Rev. Lett. 86 2505 (2001); Regan *et al.*, Phys. Rev. Lett. 88 71805 (2002); Cho *et al.*, Phys. Rev. Lett. 63 2559 (1989); from Pospelov and Ritz, *Ann. of Phys.*, 2005].

The presence, or absence, of octupole deformation in the odd-*A* Rn isotopes of interest, namely $^{219,221,223,225}Rn$, will be investigated by implanting beams of the Astatine isobars from ISAC-I at the centre of the 8π spectrometer. High-efficiency β, γ, X-ray conversion electron coincidence data will be acquired following the β-decay of these At isotopes and will be used to construct the decay schemes of the Rn daughters. These measurements aim to establish the energy splitting of the parity doublet states predicted to accompany octupole deformation, a key parameter in the enhancement of the atomic EDMs, and one that is unknown in all of the previously mentioned Rn isotopes. In addition to the nuclear structure interest of achieving a better understanding of octupole deformation in this mass region, these measurements will identify the best candidates for EDM searches at ISAC-I.

We propose to perform the experiment by a measurement of the free procession rate of a sample of polarized Rn atoms suspended within a well-defined magnetic and electric field environment. If an atom has electric and magnetic dipole moments, d and μ respectively, then its interaction with externally applied electric and magnetic fields will result in the Hamiltonian:

$$H = \vec{J}.(\mu\vec{B} + d\vec{E})$$

resulting in a precession frequency of:

$$h/\omega = 2(\mu B \pm dE)$$

where the arises from the electric field being either parallel or anti-parallel to the direction of the magnetic field. Therefore, a comparison of the change in the observed precession frequency when the electric field is reversed will result in a direct measurement of the atomic EDM.

The precession rate will be observed by utilizing the angular distribution of γ-rays emitted by the decaying Rn nuclei using a ring of high purity germanium detectors from either TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer) or GRIFFIN (Gamma-Ray Infrastructure for Fundamental Investigations of Nuclei) (see Figures 2 and 3).

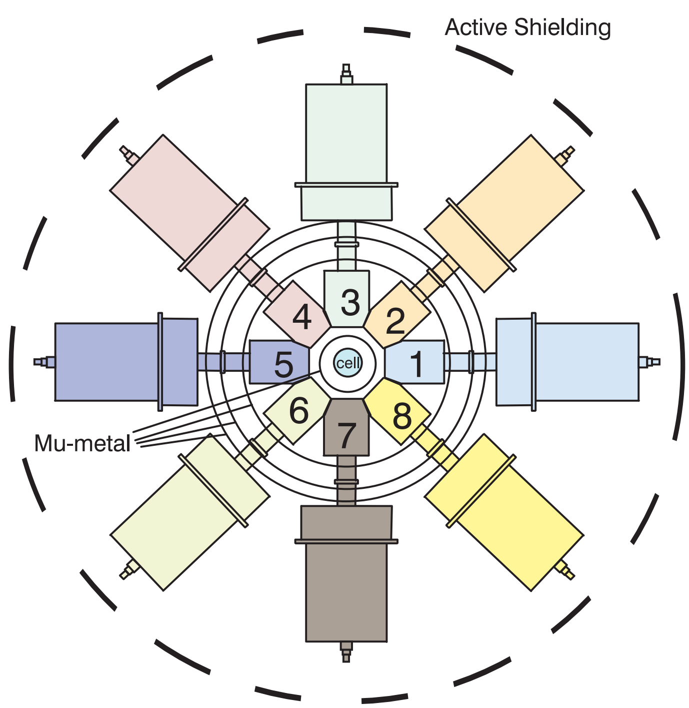


Figure 2: A schematic of the experimental set-up for the Rn EDM experiment.

Systematic effects will be considered by the introduction of a co-magnetometer, which is an isotope with known magnetic moment, μ, and predicted negligible EDM alongside the Rn isotope of interest.

Parity Non-Conservation

The study of weak interactions between individual nucleons allows us to extract unique information about the short-ranged interactions that exist within the nuclear medium. We propose to bring together expertise from nuclear structure, weak interactions, and atomic physics to study a parity-violating electromagnetic nuclear moment to gain conclusive information on how these nucleon-nucleon interactions change within nuclear matter. The main source of parity violation within atomic transitions arises from the exchange of weak neutral currents between the electrons and nucleons. These interactions can be grouped within the Hamiltonian into those that have nuclear spin dependence and those that do not. In general, the nuclear spin independent terms will dominate; however, for the studies proposed at ISAC using transitions between the hyperfine levels of the atomic ground state of francium, the heaviest of the alkali elements, these nuclear spin independent terms vanish. The vanishing of the spin independent term gives a unique handle on the spin dependent interactions.

Bohr-Weiskopf Effect

As the weak neutral charge arises mostly from the neutrons, it is important to have an independent test of the neutron distribution along the chain of isotopes of interest. One of the approximations often used in atomic spectroscopy is that the electron wave functions are constant across the full extent of the nucleus. While true for almost all nuclei, this approximation breaks down

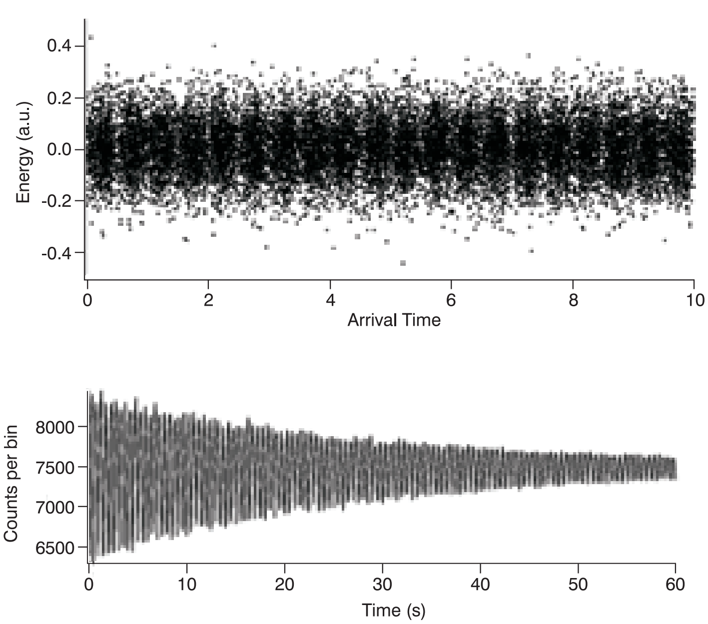


Figure 3: Simulated, time correlated signal from a single detector.

when the heavier nuclei are observed. In 1950, Niels Bohr and Victor Weiskopf showed that the extended nuclear magnetization has observable consequences on atomic spectra as the hyperfine structure is modified. This modification arises from an electron creating a non-uniform magnetic field over the region of the nucleus, providing an interaction dependent not only upon the size of the nuclear magnetization but also on its distribution.

Detailed measurements of the Bohr-Weiskopf effect usually require knowledge of both the hyperfine structure constants and magnetic moments of the given nucleus. High-precision measurements of the hyperfine structure of two states with different radial distributions across the nucleus can give information about the hyperfine anomaly. This anomaly was first investigated at Stony Brook by combining precision measurements of the $7P_{½}$ hyperfine splitting performed in house with $7S_{½}$ splittings carried out previously at CERN's ISOLDE for the chain of isotopes from ^{208}Fr to ^{212}Fr. The results are sensitive to the spatial wave function of the valence neutron in the odd-*N* francium isotopes. The splittings will be measured along the entire available chain at ISAC-I.

Nuclear Anapole Moments

We propose to start this program of study by measuring the nuclear anapole (*not a pole*) moment along a series of francium isotopes. The nuclear anapole moment is a parity-violating, time-reversal, conserving electromagnetic moment first postulated by Zel'dovich in 1957. The moment arises from the weak nucleon-nucleon interactions and is the result of the chirality acquired by

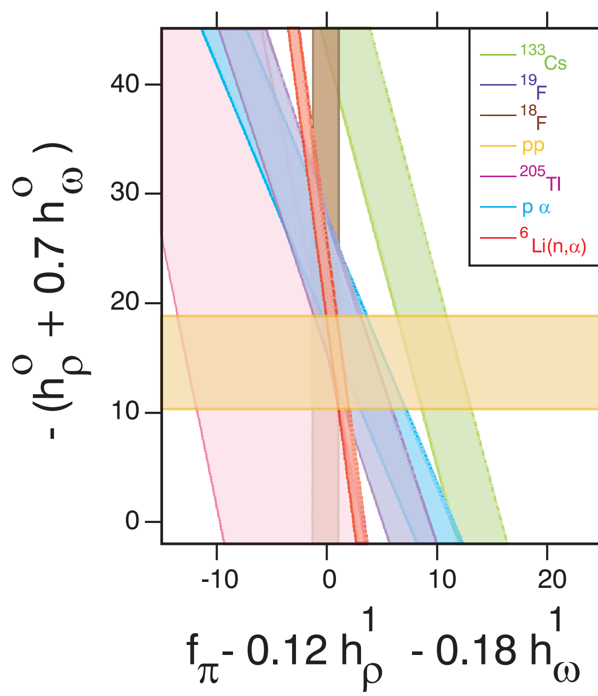


Figure 4: One standard deviation constraints on isovector and isoscalar weak *N-N* couplings from measurement. As can be seen, the Cs measurement is hard to reconcile with other experiments.

the nuclear current. This moment can naïvely be viewed as a dipole moment and a toroidal current that generates a magnetic field only within its interior.

Anapole moments can arise from a number of different effects; however, recent calculations by Haxton *et al* suggest that it is dominated by nuclear core polarization caused by valence nucleons [W.C. Haxton and C.E. Wieman, Ann. Rev. Nucl. Part. Sci. 51, 261 (2001)]. If this is the case, then a systematic measurement of the anapole moments along a chain of isotopes would result in an odd-even effect dominated by the single unpaired neutron which would, in turn, allow for studying the modification of the *N-N* interaction parity-violating interaction in the nuclear medium. The current constraints on the isovector and isoscalar weak *N-N* coupling are given in Figure 4.

To study the nuclear anapole moment along the chain of francium isotopes, its interaction with the atomic electrons will be probed. An $E1$ transition between hyperfine levels is parity forbidden; however, this restriction can be relaxed by anapole-induced mixing of states with opposite parity. The general approach is then to measure the strength of this anapole-induced mixing. Many atoms will be initially trapped and cooled in a magneto-optical trap before being transferred to and held in the centre of a microwave Fabry-Pérot cavity by a blue, detuned dipole-force trap. These state-of-the art techniques would allow for the cloud of atoms to be precisely held within a node of the magnetic microwave field (an anti-node of the electric field) while being within a static magnetic field and a Raman field generated by a pair of intersecting laser beams (see Figure 5). This will ensure that the microwave field will only drive $E1$ transitions. The atoms will all start in the lower ground-state

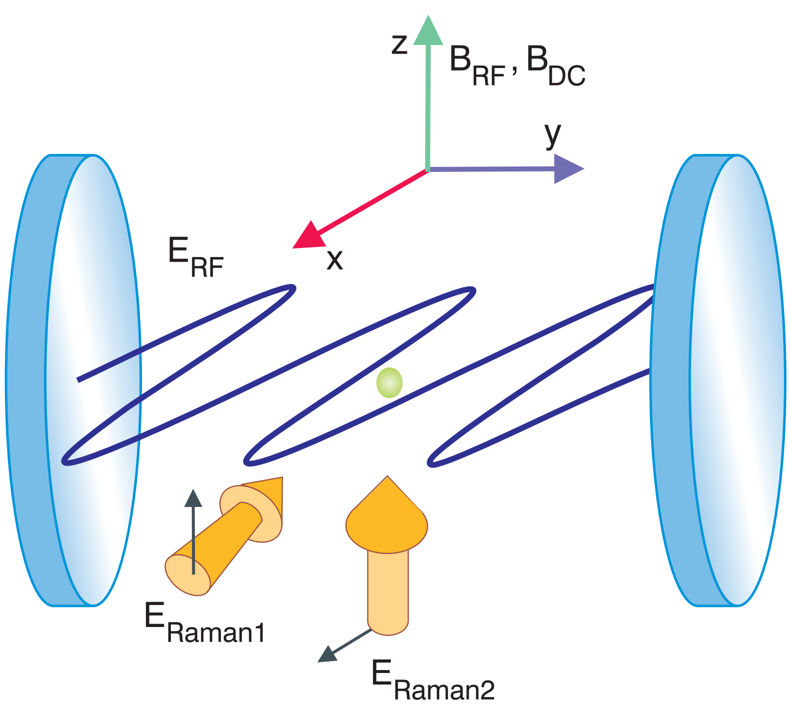


Figure 5: Schematic of the proposed set-up for measurement of the anapole moment of francium atoms. From Gomez *et al.* Phys. Rev. A75 033418 (2007) .

hyperfine level while the observed signal will be proportional to the population of the upper state probing the strength of the induced transition.

Atomic Parity Non-Conservation

Atomic parity violation measures the strength of the weak neutral current at very low momentum transfer. Within the atom, the weak interaction is dominated by the weak charge of the neutron, as the proton weak charge is significantly smaller due to an accidental cancellation of terms. Atomic parity non-conservation results in Cs are therefore naturally complementary to parity-violating electron-electron and electron-proton scattering experiments at the Standard Linear Accelerator Center and the Thomas Jefferson National Accelerator Facility. The contribution of the weak charge is not consistent across all standard model extensions; however, its measurement will provide a benchmark for other possible departures of other low-energy standard model observables because it is almost insensitive to corrections of one-loop order from all SUSY particles.

The weak interaction induces a mixing of atomic states with different parities. The mixing allows transitions that would otherwise be forbidden to occur because the mixings, and therefore transition strengths, are generally very weak. They are most readily viewed as an interference with a stronger, allowed transition. A typical observable can be represented as:

$$\left|A_{PC} + A_{PNC}\right|^2 = \left|A_{PNC}\right|^2 + 2\,\mathrm{Re}\left(A_{PC}A_{PNC}^*\right) + \left|A_{PNC}\right|^2,$$

where A_{PC} and A_{PNC} are the parity conserving and parity non-conserving amplitudes, respectively. In general, the $|A_{PC}|^2$ term of negligible magnitude can safely be ignored whereas $2\mathrm{Re}(A_{PC}A^*_{PNC})$ is the interference term that

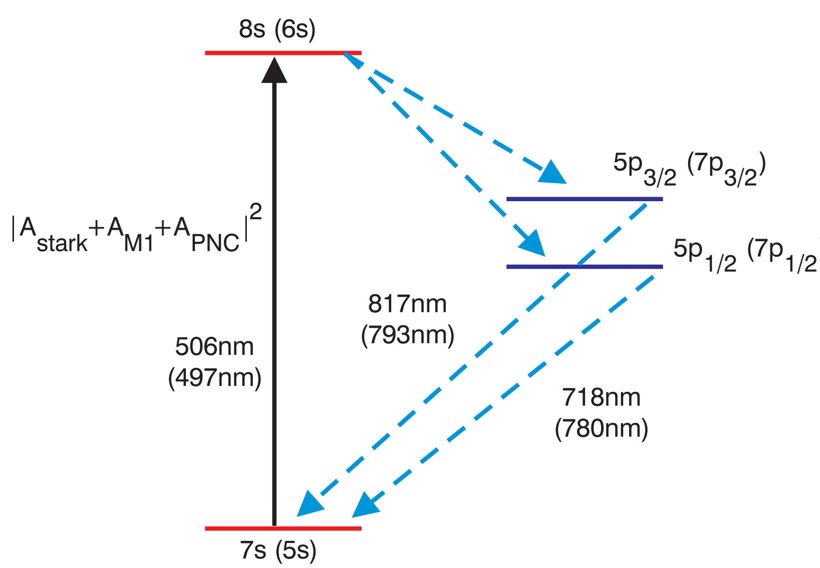


Figure 6: The relevant atomic levels and associated transition wavelengths of Fr (Rb) for an atomic parity non-conservation experiment at TRIUMF.

can be experimentally isolated as it changes sign under a parity transformation.

To date there has not been an atomic parity non-conservation measurement carried out in neutral atoms utilizing the relatively new technologies of laser cooling and trapping of high Z, radioactive species. We will work towards this measurement in Fr, first by developing techniques that measure the $M1$ strength in Rb for the analogous transition (see Figure 6), then later by measuring a highly forbidden transition rate in Fr, where the high Z gives a significant enhancement. This procedure follows one of the two main strategies outlined in the recent review [Bouchiat *et al.*, Eur. Phys. J. D15, 5 (2001)]. The transition of interest is the ground state to first excited *s*-state in atomic Fr (see Figure 6). Here, the application of a large electric field will result in interference between the parity non-conserving amplitude and the Stark effect that is proportional to the weak charge.

A collaboration is mounting an experiment at the Lawrence Berkeley Laboratory using a caesium atomic fountain that could eventually improve electron EDM searches by two orders of magnitude. Through a TRIUMF letter-of-intent, the collaboration has declared that if successful in caesium, it will mount an experiment at ISAC-I to improve further the sensitivity by an additional factor of nine by using francium atoms.

Summary

TRIUMF has a tradition of careful, high-precision measurements that require extended periods of gathering data. The above program would extend this tradition into the weak neutral sector via a series of complementary experiments focused on stringent tests of physics both within and beyond the standard model.

6.2.1.2

Major New Initiatives

6.2.1.2.1

Cyclotron Refurbishing and Specialized Actinide Beam Line

Introduction

Space charge forces limit the maximum intensity available from the TRIUMF cyclotron to approximately 500 μA. In 1988, and again in 2003, peak currents of 420 μA were demonstrated in pulsed mode to reduce the average current to 200 μA. Proton beam dump capacity and development time limited testing to achieve slightly less that 300 μA of average proton current extracted from the cyclotron for a few hours. Significant in this result is that the cyclotron operating temperatures and internal beam spills (to minimize activation) scaled well with the increase in circulating current indicating good beam quality through the injection and accelerating systems.

The development program in conjunction with the refurbishing program has made significant progress increasing the cyclotron output over the past ten years. The increase in output current has not had a negative impact on the beam quality or the serviceability of the machine. At present, 220–245 μA is accelerated and routinely extracted.

The 300 μA upgrade will address the need to deliver higher operational intensities of quality beam reliably and provide the groundwork to allow subsequent upgrades towards the 500 μA ultimate intensity. This upgrade is compatible with the anticipated construction of BL4N, which is part of the TRIUMF ten-year vision.

Key components to achieving higher operating currents include: higher intensity beam that will maintain or improve on the existing characteristics of good quality, reproducibility, and reliability. While beam stability for the three existing beam lines is acceptable, the additional operation of the new proton beam line, BL4N, will require further stability improvements. Lastly, higher operating currents cannot significantly add to activation that impacts serviceability.

Beam Intensity, Quality, Reproducibility, Reliability, and Serviceability

Approximately 300 μA average current has been successfully demonstrated under development conditions that optimize all systems parameters. Operationally, these optimal conditions are not necessarily easily or quickly reproducible. Over time, better tunes have been developed to make routine operations at increased currents easier to achieve. Additional beam dump capacity would allow this process to continue as well as provide the ability to ascertain and test improvements. From experience, we know that higher currents can cause heating in the central region and induce inflector sparking. We have successfully dealt with the heating problem in the past, so believe that there are no insurmountable problems in this regard.

The spiral inflector, which consists of two uncooled insulated electrodes, directs the H^- ion beam from a vertical trajectory into the horizontal plane of the cyclotron. Typically, beam is skimmed at the entrance to the inflector with losses less than 1 W. Though the nominal ion-source emittance is small enough to fit through the inflector system easily, the energy spread halo increases with increased injected current. This increase is because the injected beam needs to be increasingly bunched with increasing intensity. Because the inflector is highly dispersive, the energy spread halo leads to beam losses in the centre region.

While ~300 μA operation has been demonstrated, it is difficult to project whether operating in the present configuration routinely at 400 μA will or will not damage the inflector. A spare is being built to provide the contingency that will allow for further development. To move to higher currents, a fundamental design change is proposed, although it would not preclude the use of a third buncher in the injection line for 1 mA bunched beam. This proposal incorporates existing TRIUMF ion source technology to produce 5 mA H^- ion beam with a no- or weak-bunching regime. The anticipated injected current is 5 mA to achieve an extracted current of 450 μA. This option has not been explored with the present injection line because the ion source is only capable of 1 mA.

Naturally, the effective emittance is larger at higher current, but the injection element aperture sizes are sufficient: 0.3 μm normalized emittance is 12 μm at 300 keV. The maximum beam diameter, which is defined here as 4 times the rms size, is 9.2 mm at 0 mA rising to 11 mm at 5 mA. The periodic section transport has 90° phase advance per cell at zero current, but is depressed to 55° at 5 mA. However, the injection line quadrupoles have an aperture of 51 mm with aperture clamps ("skimmers") of 38 mm; these are more than adequate to handle the increased beam sizes at 5 mA.

The ion source and injection are very reliable and reproducible for the present beam production of approximately 225 μA. To achieve higher extracted currents, the cooled variable slits are opened, and tuning is required in both the injection line and the cyclotron. This process is reproducible but challenging. Required upgrades to deliver high quality, high intensity beam are:

- High current TRIUMF cusp ion source;
- Vacuum upgrade to ~3 × 10^{-8} torr to keep stripped beam below the 5 μA level;
- The 300 kV power supply and other electrostatic power supplies will need to be upgraded for higher current;
- Slits, beam stops, and cooled apertures will need to be installed in the injection line to have the potential to absorb the 1.5 kW injected beam power; and
- The vertical injection line upgrades scheduled for 2009 must be compatible with either the bunched or unbunched modes.

Optimal H^- production from the present ion source is not achievable due to physical space constraints. The high output source will be located in the existing third ion source terminal in the next year or two. Beam quality is expected to improve in either the unbunched or bunched mode with the high-output cusp source. In the bunched mode, cooled variable aperture slits are used to define the emittance of the beam transported to the cyclotron. As the high current ion source is brighter than the existing source, more quality beam will be available within the acceptance of the cyclotron. In the unbunched mode, ion source instabilities will not be amplified by the bunchers, and phase control is simplified. Better injected beam quality translates directly to less average spills in the cyclotron thereby preserving serviceability (activation) and is further discussed in Section 4.2.4.

The first turn in the cyclotron needs to absorb about 1.5 kW, so cooled apertures will be required. Intuitively, the expectation is that beam coming out of the inflector and traversing the first acceleration gap would be "messier" at this high current but, because of the zero-energy spread, it will be cleaner and more easily collimated. A water-cooled beam absorber was installed at the centre post a few years ago. This, in combination with the existing radial flags and the use of the existing ion source to inject 500 μA unbunched beam, will allow us to make measurements to ascertain the losses and extrapolate cooling requirements.

The vertical focusing limit at the cyclotron centre is approximately 100 μA per 10° of phase acceptance. To gain the required phase acceptance, the radiofrequency (RF) voltage will be raised by about 10–15%. In late 2007, the RF voltage was successfully raised by 10% for test purposes. This, and the increased required RF power needed to routinely accelerate higher currents, requires approximately 40% more RF power, which is well within the range of the existing system with a few minor engineering upgrades.

Beam losses must be significantly reduced if machine serviceability is to be maintained during the high-intensity upgrade. This objective can be achieved by reducing the extraction energy for major proton-beam users from 500 to 475 MeV. Electromagnetic stripping of the electrons is the dominating beam-loss mechanism at energies above 450 MeV. Thus, limiting the extraction energy at 475 MeV would reduce the losses by about 50% compared to a 500 MeV extraction energy.

Stability

A huge advantage of an H^- cyclotron is that the extracted beam is not sensitive to the RF voltage. A stripper foil at fixed radius always sees the same beam energy; if the RF voltage fluctuates (increases/decreases), it simply takes more/less time for particles to reach this radius. For this reason, TRIUMF has not had or needed the RF voltage stability to be better than a few parts in 10^{-3}.

This stability criteria changes if there is more than one extracted beam at energies above 430 MeV. Operating BL1A and BL2A at comparable extracted current requires BL2A to "catch" a sliver of the circulating distribution that is only about 1 mm wide. The beam on BL2A (ISAC-I) target is required to be stable to 1% for steady RIB production; this requires the width of this sliver to be stable to the level of 10 μm. The radius gain per turn is small compared with the betatron turn width so, if the cyclotron conditions are ideal, such a tiny width is not a problem because the radial density is uniform in the outer portion of the cyclotron. However, the cyclotron traverses the $\nu_r = 3/2$ resonance at 430 MeV which causes the circulating beam to become mismatched. This mismatch precesses as ν_r departs from 3/2 causing radial density modulations, which create fluctuations in BL1A/BL2A extracted current ratio as the RF voltage fluctuates.

Presently the ion source pulser is used in a feed back loop to maintain the stability of the BL2A beam, albeit at the expense of the other on-line beam lines. The problem will become more complicated with three simultaneously extracted high-energy beams (BL1A, BL2A, and BL4N). There are two relatively straightforward solutions: stabilize RF voltage to better than 10^{-4}, or correct the 3/2 resonance.

Experiments have shown that this resonance can be either exacerbated or reduced using existing "harmonic coils" mounted on the cyclotron vacuum tank lid [R. Baartman *et al.*, Proc. Int. Conf. on Cyclotrons and their Applications (1984) p.40]. These coils are in 6 azimuthal segments and generate a first harmonic, so the third harmonic cancellation is not exact. Orthogonal pairs of coils may be contemplated to provide phase correction if necessary.

Specialized Actinide Beam Line

A number of lessons have been learned from building and operating the beam line (BL2A) that supplies protons to the current ISAC-I target:

- The matrix used to describe the beam exiting the cyclotron was incorrect in the vertical direction.

- Most of the BL2A tuning time is devoted to handling the few ηA that are in the beam halo to avoid tripping the spill monitors.
- An achromatic design would have facilitated tuning, especially when switching from one target to another.

A beam line has been designed (see http://lin12.triumf.ca/text/2008-AAC/beamline4n-071122.doc) to address all three of the above points. This line is achromatic, includes a collimator in the cyclotron vault section, and uses the new extraction matrix.

Most of the beam halo comes from large angle scattering at the stripper foil. Traditionally, foils of 5 mg/cm^2 thickness have been used. In 2007, foils in the 2–3 mg/cm^2 range were successfully run in routine operation. GEANT4 calculations confirm that there is sufficient scattering from such thick foils to exceed the "hands-on maintenance" level of 1 ηA/m that is used as a trip level. Further foil calculations, which include the fraction of neutrals coming from a too-thin foil, find an optimum thickness of 800 μg/cm^2. The existing BL1A and BL2A stripper cassettes are not designed to handle such thin foils, but the new BL4N stripper will. A recent simulation of the stripping foil indicates that the foil temperature is lower with a thinner foil. Experiments to test this finding and to establish a baseline μAh lifetime are planned during the 2008 running period. The thinner foils are expected to reduce total spills by a factor of 2.5. New stripper cassettes designed to handle thin foils will be installed on BL1A and BL2A as part of the 300 μA upgrade. BL4N will be capable of transporting 200 μA of proton beam and will be equipped with a beam dump to provide flexibility for cyclotron tuning and tests during the high-intensity upgrade.

Conclusion

Significant development results and operational experience provide confidence that the proposed upgrades to the injection system, RF systems, and stripper foils will culminate in routine extraction of 300 μA from the cyclotron with no serviceability issues. These upgrades are required for, and compatible with, possible future upgrades to 400 μA.

6.2.1.2.2

Electron Linear Accelerator: e-linac

TRIUMF proposes to build an electron accelerator at the TRIUMF laboratory. The accelerator will significantly advance national capabilities in science and technology, while fostering new international partnerships. Fundamental science, such as the study of how the chemical elements in the Universe were made, as well as applied science, such as the technique of β-NMR for detailed investigations of the magnetism in materials, will benefit from this facility. Through this project, the technology of superconducting acceleration, an emerging global industry, will be developed in Canada. This technology opens a new avenue for the production of medical isotopes and will form the basis for next generation light sources that are used for materials and biomolecular research. International partners from India and Japan wish to participate in the construction of this facility and the knowledge gained will allow Canada to participate in future international facilities such as the CERN SPL, the European Spallation Source, and the International Linear Collider.

Motivation

The TRIUMF electron linear accelerator (e-linac) proposal represents a unique opportunity in the history of TRIUMF: an ostensibly internal infrastructure project that furthers both the internal and external physics programs in almost equal measure. In addition, it brings the benefit of introducing new technology to Canada and the vehicle for transferring it to an industrial partner.

Introduction

This section describes a megawatt-class electron linear accelerator (e-linac) proposed as a driver for γ-ray induced fissioning (photo-fission) of actinide targets with rates up to 10^{13} to 10^{14} fissions/sec depending on nuclide species. The particular emphasis would be on neutron-rich isotopes for nuclear structure physics, and $^{9}Be(\gamma,p)^{8}Li$ production for β-NMR studies of material properties. The e-linac will also benefit users of proton-rich isotopes (*e.g.*, nuclear-astrophysics) by reducing the competition for proton beams at the existing, and planned, ISAC facilities.

The 50 MeV, 10 mA, continuous wave linac (CW-linac) is based on existing superconducting radio-frequency (SRF) technology in the GHz range. Though high-power and/or high-current e-linacs are a mature technology proposed elsewhere for applications ranging from coherent light-sources (at a few tens or hundreds MeV) to linear colliders for exploration of fundamental particle physics at the TeV scale, TRIUMF is the vanguard[1] for applying this technology to the copious production of rare-isotope beams (RIBs).

This proposal calls for a factor of ten increase of power handling at the targets, compared with the best that is presently available at ISAC and a commensurate rise in neutron-rich nuclide production rates. This increase will give complementarity with the proton-rich nuclei produced with 500 MeV protons extracted from the TRIUMF cyclotron 4-north beam line (BL4N). This proposal also calls for radio-frequency (RF) power handling per accelerating cavity near the present technological limits of SRF CW-linacs. With these choices, the proposed electron driver and its photo-fission based actinide target station represent a major infrastructure initiative that will be a major contributor to maintaining the pre-eminence of Canadian nuclear physics programs for at least a decade.

Relationship to Broader Canadian Research Community

E-linac will draw upon TRIUMF's existing capability to design and operate 100 MHz, 4K and $\beta = v/c \ll 1$ SRF systems and expand the expertise to 1 GHz, 2 K and $\beta = 1$. As a result, TRIUMF will become a unique multi-regime centre for SRF science and accelerator physics. The Canadian university-research program has its sights set firmly on the Large Hadron Collider (LHC) and its upgrade path, the SPL and PS2 and on precision Higgs physics at the International Linear Collider (ILC). Both the CERN superconducting proton linac (SPL) and ILC rely on SRF accelerating structures, at 0.7 and 1.3 GHz respectively, and infrastructure for e-linac could facilitate Canadian contributions to either of these high-energy physics frontier projects.

The proposed linac has much in common with the SRF technology proposed for the ILC and could act as a springboard for commercialization of this technology in Canada. Whatever the precise fortunes of ILC, GHz SRF technology is here to stay. The linac also has features in common with designs for ERL

1 The abandoned electron linac proposal for SPIRAL-II at GANIL was for a mere 25 kW beam power.

drivers of free electron lasers (FELs) that are used for studies in condensed matter physics, materials science and biochemistry. TRIUMF's e-linac infrastructure could be expanded to serve those needs.

Diversification: Next Generation Light Sources

Electron linacs are in operation or proposed around the world as drivers for so-called fourth generation synchrotron light sources.[2]

Future reconfiguration of e-linac as a recirculating linear accelerator (RLA) or energy recovery linac (ERL) opens the door to such a possibility. A shortcut to high-energy X-rays is proposed via Compton scattering (CS) of optical photons off hundreds of MeV electrons. CS sources have applications in materials science and medical imaging where the high 6D brilliance and easy tuning of photon energy out-compete synchrotron light sources. E-linac could serve as a testbed for the enabling technologies of a CS source at the Canadian Light Source (CLS). At the other end of the light spectrum, the infrared FELs can provide capabilities that make them competitive with laser-based sources. They are easily tunable by adjusting the undulator field, and their range extends down to terahertz. In addition, their enormous photon power makes possible near-field imaging with resolution considerably below the diffraction limit.

These properties alone provide excellent tools for structural analysis. When combined with conventional laser sources and in-pump probe experiments, they will give the means to understand how these structures function in systems as diverse as cell organelles and quantum dots. Although the expansion path to a CS Source or IR-FEL is not costed in the e-linac baseline, we have gone to some pains to assure that e-linac is inclusive of future options: no part of the e-linac design will preclude such a future expansion.

Broader Impacts

E-linac will transform Canada from a purchaser of SRF technology to a nation with the capability to construct, process and sell niobium cavities and their attendant components. Presently, there are only a few vendors of SRF technology. Through collaboration with a BC-based engineering company, e-linac will enable Canadian industry to join this elite group. The e-linac project will provide many opportunities for the training of highly qualified personnel, particularly in the fields of cryogenic and radio-frequency engineering and accelerator science, including particle beam and electromagnetic field modeling; etc. Research and development (R&D) for e-linac may also have direct impacts on the disciplines of accelerator engineering; *e.g.*, megawatt (MW)-regime facilities will all benefit from improved input coupler design.

Facility Overview

The photo-fission source has two major components: a 0.5 MW e-linac, to be housed in the existing Proton Hall and a 0.5 MW-capable target station, to be located in the western extension of the ISAC Target Hall, connected by a 60 m long electron beam line that parallels the proton beam line 4 north (BL4N).

2 JLab IR FEL & UV FEL, Cornell ERL, Daresbury ERLP & 4GLS, ARC-EN-CIEL at Soleil, BINP (Novosibirsk) THz FEL, JAERI ERL-FEL, PKU-ERL-FEL, KAERI EAF, BESSY-FEL, etc.

The target concept is described elsewhere, as is the justification for 50 MeV as the optimal electron beam energy.

E-Linac Design Overview

Three main goals have shaped the conceptual design of E-linac: (1) CW operation at high average power; (2) the utilization of existing technology wherever possible; and (3) flexibility toward operation and configuration. For easy reference, the beam characteristics and main RF system parametres are tabulated below. These are followed by an explanation of the choices that led to these values.

Bunch charge (pC)	16	Bunch vital statistics	inject	eject
Bunch repetition (GHz)	0.65	Normalized emittance (μm)	<30π	<100π
Radio frequency (GHz)	1.3	Longitudinal emittance (eV.ns)	<20π	<40π
Average current (mA)	10	Bunch length (FW), inject (ps)	<170	>30
Kinetic energy (MeV)	50	Energy spread (FW)		<1%
Beam power (MW)	0.5			
Duty factor	100%			

The beam power, duty factor, beam energy, and average current are all set by the fission-driver application. The production target sets no requirement on beam emittance, and the given values are representative of thermionic sources and anticipated blow-up.

Number of cryomodules	2, injector & main
Number of cavities	5 total
Number of cells/cavity	9
Type of accelerating structure	Standing wave
Accelerating mode	TM_{010}, π mode
Fundamental frequency	1.300 GHz
Quality factor	$Q_0 \geq 10^{10}$
R/Q per cavity	518 ohm
Active length	1.04 m
Tuning range	± 300 kHz
Input coupler/cavity	2
HOM absorber/cavity	1

With the exception of input coupler and a higher order mode (HOM) absorber, these RF system parameters reflect the selection of the Tesla Test Facility (TTF) cavity technology as the baseline.

	Fission driver	ERL
Accelerating gradient	10 MV/m20	MV/m
Q external of input coupler	10^6	2.6×10^7
Beam power/cavity	100 kW	50 W
2 K heat load/cavity	12 W	62 W
5 K heat load/cavity	8 W	9 W
80 K heat load/cavity	180 W	150 W

These power and heat-load values reflect the choices of CW operation and 10 mA beam current. In the case of the possible ERL expansion, which is not costed in the baseline, numbers assume about 20 mA current and energy recovery inefficiency of 10^{-4}.

Relation of E-Linac to TTF Cavity Unit

From the outset, we have opted to base the e-linac design around technology developed for TESLA, XFEL, and ILC for two reasons: to benefit from the extensive SRF development for these electron accelerators, and to prepare TRIUMF and Canada for participation in ILC if that project proceeds beyond the Technical Design Review (TDR) stage. However, if given free rein from the start, we would have come to very similar conclusions: five 1.3 GHz SRF cavities housed in two cryomodules.

For a 50 MeV e-linac, high duty factor or CW operation is inconceivable with normal conducting (NC) cavities: depending on the details of the cavity shunt resistance 2–4 MW of RF power (*i.e.*, 4–8 MW of wallplug power) are required in addition to the 0.5 MW of beam power. Contrastingly, implemented in SC-cavity technology, the wallplug power, including cryogenic cooling, is less than 1.5 MW—a dramatic reduction resulting in enormous savings in operational costs.

Theoretical considerations arising from the temperature and frequency dependence of SC cavities built from bulk niobium point to a cost minimum at ≈1.8 K and ≈1.3 GHz. This result, known for 40 years, has impelled SRF R&D on a 30-year course of discovery culminating in electric field gradients up to 40 MV/m. During those decades, the impediments of multi-pactoring, inadequate material purity, and poor metallic surface preparation have been overcome; and with impetus from work on TESLA in the 1990s, 20 MV/m is almost becoming routine. TESLA has metamorphosed into the ILC, which hopes to achieve an accelerating gradient in excess of 31.5 MV/m.

The ILC cavity unit (consisting of a 9-cell cavity, liquid helium vessel, mechanical tuner, RF input coupler, HOM coupler, and 2-phase He pipe) has become the standard building block for SRF linac design. Although it is the starting point for the e-linac design, commonality with the ILC stops at the cavity unit (see Figure 1) and does not extend to the cryomodule level.

E-Linac HLRF Building Block

The e-linac and ILC have very different cryomodule specifications; indeed e-linac has far more in common with designs for ERL injectors. The ILC design is gradient limited, whereas e-linac is power limited, the limitation arising from input coupler design and cryogenic heat loads. A single ILC cryomodule produces almost GeV acceleration, and the per-cavity peak power is 300 kW; but because of the 5 Hz machine repetition rate and the < 1 millisecond beam pulse length, the average values are much lower. For example, the ILC cavity input coupler sustains an average power less than 16 kW. In the fission-driver linac, 500 kW of CW RF power has to propagate through the input couplers and cavities into the electron beam; for that reason, we have chosen the 60 kW CW coupler developed by Cornell (see Figure 2). Two such couplers, per cavity, push the power limit to 100 kW.

Basing the design on existing technology, the e-linac adopts a high-level RF

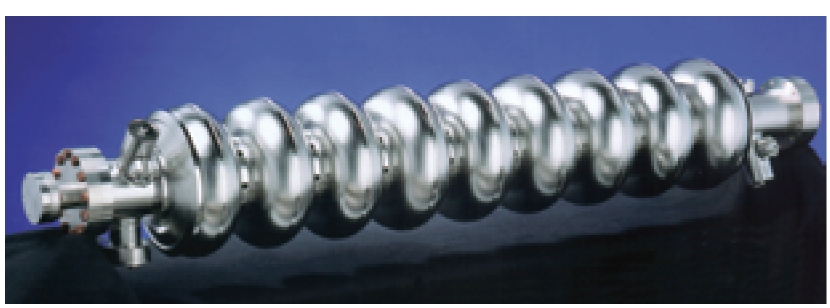


Figure 1: TTF-style 9-cell cavity. Courtesy DESY.

(HLRF) building block of one 130 kW klystron, two 60 kW couplers, and one 9-cell cavity. The power values refer to the equipment ratings; the devices would be run at slightly lower values so that each building block delivers 100 kW of beam power. Choosing the number of cavities is then simply a matter of enumerating combinations of beam current and accelerating gradient that consume 100 kW/cavity and also result in a beam energy around 50 MeV.

Beam current	Cavity gradient	# cavities	Beam energy	Beam power	Cost or length
5 mA	20 MV/m	3	60 MeV	300 kW	×0.6
10 mA	10 MV/m	5	50 MeV	500 kW	Unit
20 mA	5 MV/m	5	25 MeV	500 kW	Unit
20 mA	5 MV/m	10	50 MeV	1 MW	×2

The first option does not have the required reach of power on target. The third option, although credible, is sub-optimal regarding the γ-photon spectrum and fission cross section, and profits little from the high gradients which are a feature of SRF. The fourth option probably exceeds the available extension in the Proton Hall, less than 20 m. We have confined the range of gradient options to ≤ 20 MV/m because this is the limit of what is achievable with chemical polishing of the niobium surfaces. Electro-polishing allows higher gradients to be achieved, but the necessary infrastructure is not available at TRIUMF in the present scenario.

The second option, 10 mA beam current and 10 MV/m accelerating gradient has been chosen as the baseline; it furnishes a useful electron beam and relies on a conservative expectation for the gradient. We are now in a position to tabulate the broad specifications for the e-linac and ILC cryomodules, and emphasize their differences.

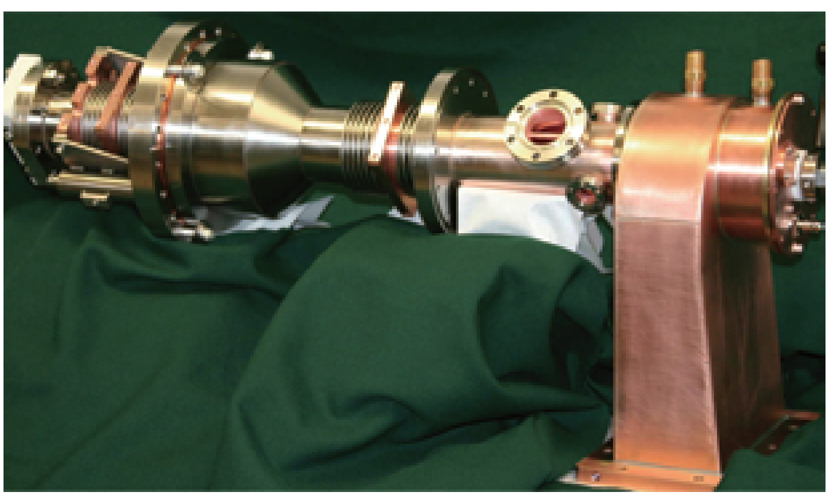


Figure 2: 60 kW CW input coupler. Courtesy Cornell University.

ILC		Fission Driver	
9 cavity/ cryomodule; 9 cell/cavity	Average current 0.04 mA	2,3 cavity/ cryomodule; 9 cell/cavity	Average current 10 mA
1 input coupler/ cavity; 31 MV/m gradient	Average power 16 kW/cavity	2 input coupler/ cavity; 10 MV/m gradient	Average power 100 kW/cavity
2 HOM coupler/ cavity	Duty factor 0.5%	1 HOM absorber/ cavity	Duty factor 100%

CW Operation: Challenges and Benefits

CW operation of e-linac has challenges beyond a limited choice of input couplers and klystrons. There are higher heat loads in all RF components. Indeed, the heat loads in the 5-cavity e-linac at 10 MV/m are 5 times higher than the loads in the 12-cavity TESLA cryomodule at 23.4 MV/m. This thermal challenge, which requires a departure from the TTF cryomodule, is starting to be met by the designers of FEL drivers.

Several parties are working on higher duty factor or CW variants of the TTF unit as drivers for FELs, some with energy recovered (*e.g.*, Cornell, 4GLS) and some without (DESY-XFEL, BESSY-FEL). The Daresbury 4GLS proposed to use the CW two-cavity cryomodule designed by Forschungszentrum Rossendorf and marketed by ACCEL, which is operated up to 8 kW/cavity. The BESSY FEL, utilizing a 16-MV/m gradient, is pulsed at 1 kHz with an average current of a few μA. Neither design, ACCEL or BESSY, is appropriate to fission driver needs. More promising is the Cornell ERL Injector, in which no energy recovery is performed. ERL injectors must be optimized for high current and low energy. The Cornell injector will provide complementary combinations of current and energy ranging from 100 mA and 5 MeV to 30 mA and 15 MeV that result in ½-MW beam power. Despite its unusual RF configuration (five 2-cell cavities operating at up to 14 MV/m), this injector provides an existence proof for a CW-½-MW cryomodule that could well form the basis of the e-linac cryovessel design. Because of the fewer cells, the RF heat load per cavity in the Cornell design is about 2 watts at 2 K.

Nevertheless, CW operation does afford some benefits when compared with a pulsed machine. There are: (i) no periodic beam-load transients; (ii) no periodic Lorentz-force detuning of the cavity; (iii) little or no need for piezo actuators; and (iv) the low level radio-freuqency (LLRF) is, in principle, simpler. In these respects, the e-linac specification is more relaxed than that of ILC. In addition, CW operation implies lower bunch charge for the same average current, and this leads to lower HOM excitation; CW operation is ideal for production targets because it avoids thermal cycling or shocking of the target.

Two–Three Cavity Split

The baseline configuration splits the five HLRF building blocks between a two-cavity injector linac, and a three-cavity main linac. This choice gives us the opportunity to prototype some components in the injector before employing their designs in, or modifying them for, the main linac. This same choice would allow the linacs to be reconfigured at some later date by the insertion of return arcs, as a testbed for ERL (20 mA, 70 MeV) or RLA (2 mA, 160 MeV) technology. Little additional cost is incurred by this 2–3 split. Neither the return arcs nor the photo-cathode gun are costed in this proposal, but HOM absorbers, variable coupling ratio, and piezos (but not their drivers), form part of the baseline design. The additional cryoplant capacity to run at 20 MV/m is not included in the baseline; however, 20 MV/m could be achieved by running at reduced duty factor.

Electron Source

It transpires that the fission-driver specification is more relaxed than for a comparable ERL injector, as the table below clearly shows. FEL-based light source at ERLs need 6D high-brilliance beams and careful emittance preservation. In practice, this implies photo-cathodes and small emittance and high bunch charge, which leads to extreme space-charge forces that must be overcome by rapid acceleration in high-voltage DC or RF guns. By contrast, the fission driver eliminates its beam on target and has no requirement for brilliance; and so a much simpler, low-maintenance thermionic electron gun is employed.

	Daresbury ERLP	**JLab IR-FEL (1.5 GHz)**	**Cornell ERL**	**ILC**	**Fission driver**
Charge/ bunch (pC)	80	135	80	100	16
Bunch length (ps)	1-2	0.2-2	2	2	30
Emittance (μm) normalized	1-2	< 30	1	3,0.03	30-100
Bunch rep. rate (MHz)	81.25	75	1300	3	650
Macropulse rep. rate (Hz)	20	CW	CW	5	CW
Beam energy (MeV)	40	80-200	10	300/ cryo	50

Higher-Order Modes

The ERLs are driven to lower bunch repetition rates by the desire for high bunch charge because the FEL lasing varies as the charge squared and because of limitations to the repetition rate of the laser driving the photo-cathode. This results in a dense spectrum of beam frequency components extending to many tens of GHz and strong interaction with the cavity HOMs, necessitating strong counter measures such as ferrite ring HOM absorbers or waveguide HOM couplers. By contrast, HOM excitation in the fission-driver linacs will be minimal due to the long bunches and widely spaced frequency components.

Staging

Staging is more an issue of implementation than design. In principle, the ½-MW capable e-linac could be completed by the end of 2014; however, it is proposed to stage the linacs: providing 5 mA, 30 MeV in mid 2013, and 10 mA, 50 MeV in mid 2015. This staging aligns e-linac with the RIB target staging and provides a useful beam at the earliest possible date. In this scenario, all e-linac components, with the exception of 60% of the HLRF power sources and distribution components, will be purchased between 2010 and 2015. The remaining klystrons, etc, would be purchased and installed early in the subsequent Five-Year Plan.

Conclusion

E-linac will be an exemplar CW, high-power, high-current linac. Due to the intrinsic power efficiency of SRF technology and the compactness and high-accelerating gradient of L-band structures, their adoption provides a cost effective approach to a MW-class fission driver. There are cell, cavity, input coupler, klystron, mechanical tuner, HOM damper, and cryostat designs either pre-existing or close to the e-linac requirements; and this eliminates substantial R&D cost. CW operation poses some challenges compared with TESLA/ILC design, for instance, the higher thermal loading of the cryomodule and the limited choice of klystrons and input couplers, but these challenges are already being met in some FEL light source designs. Indeed, some of the fission-driver specifications are more relaxed than for ILC and/or FEL drivers. For example, the bunch parametres selected for e-linac simplify the source design and provide a degree of immunity against cavity HOM effects.

E-Linac Staging

Whether or not the e-linac construction is staged, the 50 MeV accelerator would naturally be split into two shorter linacs. When staging is an imperative, the question arises “what is the optimal split of cavities between the cryomodules?”

A cryomodule consists of its insulating cryovessel and the interior cold mass of RF cavities and their ancillaries. The baseline design must select the number of modules and the number of cavities each contains. The choice of cryomodule configuration is influenced by technical issues, and by external factors: the science program and RIB targetry needs. At an early stage, it was recognized that the full acceleration would be split between an injector and main linac. The division allows:

- the injector to prototype some components for the main linac;
- the possibility of staging the construction;
- better control over the beam optical properties;
- measurement of beam properties at an intermediate energy;
- greater flexibility in tuning of machine performance; and
- possible expansion path to a testbed for ERL-RLA-based light source.

Having chosen two modules, one must next decide how to split the five RF cavities between them. Purely technical issues, particularly the first and last listed above, would favour a (1+4) configuration of one-cavity injector and four-cavity main linac; but there are other considerations.

In parallel with e-linac design activity, progress has been made on a conceptual design for the new target station and improved understanding of the feasibility and challenge of target designs with >100 kW power handling. As a result of that analysis, a staged approach has been adopted for target operations: 50–100 kW in the 2010–2015 Plan, ramping to ½ MW late in the subsequent plan.

In March 2008, TRIUMF's proposed science programs were the subject of two reviews: the Policy and Planning Advisory Committee (PPAC) provided a Canadian university-oriented prioritization of possible Five-Year Plan components, and a Special Experiments Evaluation Committee (SEEC) gave an international review perspective of the science program and schedule. Both committees underscored the need to "get the science out early."

The e-linac operation must align with the foreseen staging of high-power targets; it would be wasteful of resources to complete a ½-MW-capable linac in the present plan if the corresponding target capacity is not available until the following plan. In addition, the scenario of when the e-linac delivers the first useful electron beam must play in concert with the desired schedule of experiments beginning by mid-2013. These two external imperatives, particularly the second, favour a (2+3) configuration of 2-cavity injector and 3-cavity main linac because this configuration is capable of producing a beam of useful energy and intensity a full year earlier than the 1+4 layout.

The ability to deliver multiple beams (electron and proton) to multiple users as soon as possible helps clear the backlog of planned experiments, and gives the opportunity to win from nature some of its scientific prizes a year earlier. This is an overriding consideration that governs the e-linac choice of a 2+3 cryomodule configuration. Both layouts, 1+4 and 2+3, have the same ultimate reach. A detailed, quantitative analysis of the trade-offs between the 1+4 and 2+3 layouts, in support of these conclusions, is provided in the e-linac technical design below. Here we state precisely what is delivered in each phase of the staged approach.

The e-linac has been cost estimated in 1+4 and 2+3 layouts; there is no difference between the two machines built complete. The 2+3 layout has also been costed in a staged scenario. In the first stage, the entire electron beam line and a complete 2-cavity cryomodule is delivered, with one klystron driver per cavity. This first stage, which is completed mid-2013, includes the entire cryogenic capacity for the eventual 2+3 machine.

In the second stage, ending late in 2014, an additional Mark-II cryovessel is delivered, but neither the three extra cavities nor their klystrons. (One can imagine developing variants on that precise mix of equipment as the project evolves.) The Mark-II vessel benefits from lessons learned from the 2-cavity module and the planned R&D on high-power input couplers. Funds to complete the first 2 stages are requested in this plan. In the final stage, additional cavities and klystrons would be installed making the full beam energy and power available. Funding for the final stage, approximately C$4 million dollars, will be requested in the 2015–2020 plan, or solicited from other sources.

At an early stage, it was realized that the cryogenic plant and the high-power RF sources are the main cost drivers for e-linac. Both these items are to some degree discretized. Cryoplants come in standard ratings, and it is cheaper to source one large unit rather than combine two smaller units to achieve the equivalent cooling capacity. Similarly, vendors of klystrons charge a substantial overhead for single units. On balance, the project total cost will be impacted less if we add incrementally to the RF power rather than the cryogenic capacity. Hence, the decision to install the additional klystrons in the final stage.

E-Linac Technical Design

Fission driver

The major components of the fission driver are a 20 MeV injector, followed by a main linac section accelerating from 20 to 50 MeV. The linacs will be located in the Proton Hall, which provides ample space for the baseline machine and a small ring, if so desired.

Injector Section

The injector is composed of a 100 keV electron source, a first buncher cavity, a 0.5 MeV capture section, followed by a 0.5–20 MeV linac containing two 9-cell SRF cavities. The injector linac terminates in an electron-beam energy analysis section containing a 30° spectrometer magnet and Faraday cup, etc. In addition, there are optics-matching sections between these components and steering magnets upstream and downstream of the linac tank for aligning the beam trajectory with the cavity axis. A short dogleg (2 dipole magnets) is envisioned immediately downstream of the injector linac for compatibility with later options (ERL or RLA).

RF cavities are driven with sinusoidal waveforms. The purpose of bunching is to make the electron pulses short enough so that all particles receive (almost) equal acceleration on the crest of the wave. The buncher cavity is used to prepare the beam for efficient acceleration and additional bunching in the capture section. One takes advantage of the fact that, while the beam is not yet relativistic, a small voltage modulation can achieve a significant bunching action. Once the beam becomes relativistic, very large energy spread and/or a magnetic chicane are needed to produce bunching in a short length of beam line.

Electron Source

The source is a 100 kV DC thermionic gun, with a gridded cathode producing >10 mA (average) electron current. The modest extraction voltage, 100 kV, is chosen to avoid the inconvenience of an SF_6 bath to avoid arcing, as occurs at higher voltage. The source outputs 170 ps FW bunches each of 16 pC with a bunch repetition rate of 650 MHz. The grid electrode converts the gun from diode to triode operation. Modulating the grid causes the gun to be conducting for 45° (or less) of the RF cycle allowing the beam to emerge pre-bunched at the anode. Designs of this sort have been pursued successfully at NIKHEF-FELIX and the Mitsubishi Electric Corp. Microtron. The transverse emittance typical of a thermionic gun at this current level is some 30 μm (normalized).

Buncher Cavity

The buncher is a normal conducting RF cavity excited at 650 MHz with an amplitude of approximately 15 kV and phased at 90° with respect to the beam. The buncher produces no net acceleration, but rather imposes an energy modulation from head to tail of the bunch; and so its power requirements are modest and are met with a commercial solid-state amplifier.

Capture Section

The capture section performs two functions: modest acceleration and additional bunching. Injecting a 100 keV beam ($\beta = 0.55$) directly into a $\beta = 1$ RF structure results in very inefficient acceleration because of the mismatch in transit time; for example, injection into a 10 MV/m 9-cell structure would result in ≈ 8 MeV energy gain, rather than 10 MeV. There are also deleterious transverse effects, leading to apparent emittance growth, associated with such low-energy injection into a high-gradient SRF structure.

The capture section accelerates the beam to ≥ 500 keV ($\beta = 0.863$). In addition, the first cell of the capture section imposes further energy modulation to improve the bunching throughout the remainder of the linacs. The capture section could be implemented either through an NC-graded-beta structure or four independently phased NC cells each operating at ≈ 150 kV and driven by inductive output tubes (IOTs); or two SC low-gradient single cells within the entrance of the injector linac. Costing favours the latter, but beam dynamics favours the former lower-gradient option. A detailed analysis will be performed leading to a final choice between these options.

Injector Linac

In final operation, running at 10 MV/m gradient, the injector will produce a 10 mA electron beam at 20 MeV. In the proposed staging, the injector is the only module completed by mid-2013. Using the available headroom in the cryogenic cooling capacity, this linac can be run at 15 MV/m and apply a 30 MeV beam to the RIB production target. The 15 MV/m operation is a conservative estimate based on $Q_0 = 10^{10}$; if the low-field Q_0 attains 2×10^{10} and there is no Q-droop at the higher field, then 20 MV/m operation and 40 MeV beam energy is possible without exceeding the heat load limitation.

Main Linac

The main linac consists of three 9-cell TTF-style SRF cavities housed in a single cryomodule. The cavities operate at 10 MV/m, and each has an active length of 1 m. Each cavity is fed by a single 120 kW klystron via two 50 kW coaxial input couplers. The rate of photo-fissioning drops from 7 to 6×10^{13}/s, if the beam energy is reduced from 50 to 40 MeV, which is almost negligible. Consequently, there is no strong imperative to consider a fourth cavity to improve the fault tolerance of e-linac to events such as malfunction of a cavity tuner. In any case, tuner failure is very rare.

Electron Beam Line

The electrons are transported from the output of the main linac to the target station by a magnetic focusing channel, or beam line. An electron beam of 50

MeV is quite easy to manipulate. The low rigidity, Bρ is only 0.17 Tm, implies we can transport it with relatively inexpensive focusing elements, but the corollary is that the beam is easily perturbed by outside influences such as stray magnetic field from the cyclotron and the Earth's field. We can minimize these effects either with good shielding or sufficiently strong periodic focusing. The economical optimum is to do some of each.

We propose to shield the beam pipe with mu-metal or similar, to a level of less than 0.1 gauss. Then an average Courant-Snyder beta-function of 3 m is sufficiently small. With a phase advance per cell of 90°, this requires 15 focusing cells for the 60 m beam line length. For nominal emittance, this results in an average beam radius (2σ) of near 1 mm. The cells can be solenoids or FODO quadrupole doublets. For the solenoid option, 15 are needed, with, for example, a field of 0.5 T and length of 0.25 m. For the quadrupole option, 30 magnets are needed, but the integrated strength (gradient times length) is only 0.12 T. This latter case is the one we have costed.

Beam Spot on Target

The small emittance means that the beam size is naturally small, about 1 mm. The desired beam size on target is around 1 cm diameter to spread the thermal load. One could devise a large-beta section to expand the beam optically, but this also expands any problematic halo. A better solution is to focus to a naturally small size on target and raster the beam over the required size at a rate that is fast compared with thermal time constants. Dual horizontal and vertical AC steering magnets operating at, for example, 12 and 120 Hz located just upstream of the final matching quadrupole will allow us to customize the beam distribution over the 1 cm^2 spot size.

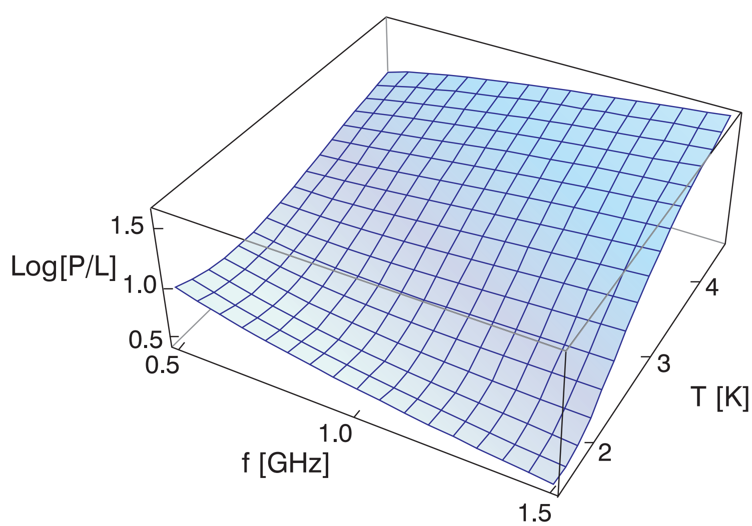


Figure 3: Three-dimensional surface in temperature, frequency, and power-per-length space.

Superconducting Linacs

Introduction

The chief difference between the injector and main linacs is merely the number of cavities within the cryomodule; hence their common RF design features can be reported together.

SC Versus NC

We have chosen superconducting (SC) linacs because high duty factor and high field gradient operation is only possible with SC cavity structures. Typically, linacs are pulsed with RF power supplied for only a fraction of the time, referred to as duty factor. The enormous power requirement of normal conducting (NC) cavities has limited their use to duty factors of a few percent or less. Both NC and SC cavities can produce high gradients, tens of MeV/m, but only in the SC case can this be sustained in continuous operation.

For CW operation, the power dissipated in the walls of a NC structure is potentially enormous, but not so for SC cavities. The power is $P = V^2/[2(R/Q)Q_0]$. The ratio of shunt resistance to quality factor (R/Q), which depends on cavity geometry, is not vastly different between NC and SC cases; and so the formula is dominated by the bare quality factor Q_0. The microwave surface resistivity of Nb at 2–4 K is 10^{-5} smaller than for Cu at 300 K; thus $Q_0^{SC} \approx 10^5 \times Q_0^{NC}$.

For the Cu cavity, the AC power must include the efficiency of the RF power source, typically 0.5. For the Nb cavity, the AC power must include the Carnot efficiency F_C to remove heat at liquid He temperature, and a refrigerator efficiency of about 0.25. Overall, SC operation reduces the wallplug power (to establish the electric fields) compared with NC, by a factor 200, thus reducing power consumption from MWs to kWs.

Frequency and Temperature Choice

The superconducting niobium cavities will be operated at 1.8 K and excited at a microwave frequency of 1.3 GHz. The true figure of merit for an accelerating structure is the power-per-unit length (P/L) at constant gradient (E_0) removed at room temperature (T_{sink}):

$$\frac{P/L}{F_C} = \frac{E_0^2}{\eta^2}\frac{c}{f}\left(R_{dc} + R_{BCS}\right)\frac{\left(T_{\text{sink}} - T\right)}{T}$$

Here f is the frequency, T is the liquid He operating temperature, and η is a structure factor. The resistivity has two components: the direct current value R_{dc}, and the Bardeen-Cooper-Schrieffer (BCS) component:

$$R_{BCS} = 90\times10^{-6}(f^2/T)\exp(-1.76T_c/T)\,.$$

For niobium, with T_c = 9.2K, R_{BCS} at 1.3 GHz is about 800 nΩ at 4.2 K, and drops to 15 nΩ at 2 K. The logarithm of power-per-unit length is plotted below, Figure 3. The merit figure clearly shows that at sufficiently low temperature, P/L is minimized at higher frequency. The optimum is around 2 K and 1.3 GHz (see Figure 3).

Some 40 years ago, Schwettman pointed out that the cost minimum occurs at 2 K and 1.3 GHz [H.A. Schwettman, IEEE Trans. Nuc. Sci. (1967)]. The first L-band SRF linac (the 27 m long, 50 MeV SCA) was built at Stanford 30 years ago; however, there were three impediments to high-Q and gradient that had to be conquered: (1) material purity, (2) multipactor, and (3) surface quality. With major impetus from CESR, LEP, CEBAF, TESLA and ILC, etc, all these problems have been overcome. The advent of so-called high-RRR material by zone refining solved the material purity problem. Multipactoring, an electron-avalanche phenomenon, was not remedied until the early 1990s. The solution was to make a spherical cavity. Given their superior mechanical stability, elliptical cavity shapes are now universally adopted for $\beta = 1$ SRF cavities. Finally, the third problem is addressed by a variety of procedures (clean room assembly, high-pressure water rinsing, chemical etching, and electro-polishing) that are available in combination for the preparation of almost defect-free Nb metallic surfaces.

Although the gradient planned for the fission driver is a modest 10 MV/m, it is intended both to leave an upgrade path to an ERL operating at 20 MV/m and to have an intermediate stage of 15 MV/m running of the injector linac. Thus, the 20 MV/m promise of 1.3 GHz structures is further appealing on that account. It is therefore proposed that the fission driver be based on 1.3 GHz technology, whereby maximum benefit can be gained from the years of development for the TESLA, TTF and subsequent ILC accelerators. This frequency choice has provoked industry worldwide to facilitate the manufacture of high-power RF devices and low-level RF control systems so that fission drivers are now in a position to reap the rewards.

RF Power Source

Once the frequency is chosen, the pivotal choices are the power source and the input coupler. For CW operation of e-linac, these choices are contingent rather than free. Each 9-cell cavity will be driven by a 130 kW CW klystron through two 60 kW coaxial input couplers. These are rated values; routine operation will be at slightly lower values. There are a total of 5 TTF cavities, 5 klystrons, and 10 input couplers.

Possible Power Sources

Vacuum tubes suitable for particle accelerators are triodes, IOTs, and klystrons. Klystrons and triodes have been the traditional power source because they produce high power and offer high gain (50 dB) with efficiencies exceeding 50%. Presently, in L-band, IOTs offer only a few tens kW CW. Although appropriate for ERLs, they are not adequate for the fission driver. A variety of manufacturers offer pulsed klystrons rated at up to 5 MW peak and 100–250 kW average power, but the reduced duty factor means they are not applicable to the fission driver. Although several manufacturers have the capability to build a 120 kW CW klystron, only *e2V* (a UK supplier of electron tubes, sensors, and semi-conductors) has such an item in its standard-model data sheets, and their offering has been selected for the baseline design.

Klystron General Specification

The RF system will utilize 120 kW CW klystrons, K3415LS, manufactured by *e2v*. This is a 7-cavity, factory-tuned, high-efficiency, high-gain, broad-band, water-cooled klystron amplifier, with designed saturated output power of 135 kW CW. Because of the high gain, the maximum required RF drive power is ≤ 15 W in any operating condition. The klystron is designed to allow rebuilding up to three times during its operating life, thus reducing the need for a large spares inventory. The klystron efficiency must be high to minimize the operating costs of the linear accelerator and is equal to 68% when operated in saturation mode of 135 kW.

Input Couplers

At the present time, the highest power-rated commercially available CW input coupler at 1.3 GHz is the 60 kW Cornell-designed coaxial coupler available from CPI-Eimac. This coupler has been chosen for the baseline (see Figure 3).

Input couplers convert power from the waveguide mode used to transport RF to the cavity fundamental EM-mode. The main requirements for the e-linac coupler(s) are to deliver 100 kW CW RF power to the beam (per cavity), provide strong and variable coupling, minimize cryogenic heat leaks, provide a multipactoring-free geometry, and minimize transverse kicks to beam. The last requirement pertains to a possible expansion to an ERL. The feature of variable coupling allows us to operate the cavity as a matched load at high- or low-beam power (traveling-wave mode), or for energy recovery (standing-wave mode), which avoids wasteful power reflected to the isolator and resistive load.

There are two possible design options: a waveguide coupler or a coaxial coupler. Both have a large set of (differing) merits and demerits; however, only the coaxial type can provide a large, variable coupling range. Additional advantages of the coaxial coupler include lower chance of multipactoring, compactness, and smaller penetration of the cryomodule resulting in lower heat load.

RF Distribution Scheme

The klystron power is delivered via a circulator and RF load, followed by a waveguide, a splitter and RF load, two waveguide-to-coaxial transitions and, finally, the two equal input couplers delivering 50 kW each. The design will be modeled on the Cornell ERL injector.

The choice of the distribution architecture is inherently linked to the choice of RF power source. Typically, the choice is between (i) a single high-power source whose output is divided between the cavities via a network of splitters, or (ii) multiple lower-power sources each dedicated to single cavity. This choice amounts to a compromise between cost economies of a high-power source versus the cost and complexity of the distribution scheme. The single-source configuration usually offers less flexibility in the cavity phasing and in amplitude regulation.

Because there is no CW, MW-class klystron available at 1.3 GHz, multiple 100 kW klystrons (one per cavity) is the only option for the fission driver. Multiple klystrons have the virtue of redundancy: if one fails, you can still run the facility. indeed, by raising the gradient in the remainder cavities, there is little or no change in the beam energy.

HOM Damping

The HOMs are the cavity resonances above the fundamental mode, and they may be longitudinal (monopole) or transverse deflecting (dipole), or other modes. The HOMs provide an opportunity for additional ohmic losses and heating at 2K, and for collective beam instability, both deleterious. The HOM power varies as the bunch charge squared. The fission driver principal line of defense against HOM effects is avoidance: the bunch charge is low; the beam frequency components are widely spaced compared with the spectrum of cavity resonances; and the bunches are long, so their power spectrum does not extend to very high frequency. These measures alone are probably not sufficient to overcome the HOM effects and will be supplemented by HOM absorbers.

The cavity HOMs will be damped to safe levels by opening up the beam pipe to 90 mm diameter, thus allowing (almost) all damaging modes above ≈ 2.6 GHz to propagate to a ceramic absorber; the absorber design is intended for the DESY XFEL. Dedicated loop couplers, targeted at particular groups of modes will be installed as needed; again XFEL designs are available. To preserve the option of an ERL and short-bunch operation, sufficient longitudinal space is allocated to replace the ceramic absorbers with the Cornell ferrite design at a later date.

The bunched beam break up (BBU) instability describes a multitude of possible effects: single- and multi-bunch in single-pass linacs, and regenerative multi-pass effects in ERLs. For e-linac, the most severe constraint would come from ERL operation and the transverse BBU current threshold arising from a single HOM—leading to the requirement that HOM quality factors must be damped below 10^4.

Because the cavity has 9 cells, each monopole mode is split into a passband of 9 frequencies, and each dipole mode is split into passbands of 18 frequencies. This dense spectrum of resonance frequencies is problematic for linacs with low bunch repetition frequency. Of course, cavity modes that do not coincide with bunch Fourier components are irrelevant, and that is the beauty of having a high bunch repetition frequency: in the e-linac there are components only at multiples of 650 MHz.

Cavity modes inherit their nomenclature from the single-cell modes, which are enumerated by their indices ϕ,r,z. Generally, cavity modes with frequency above the cut-off frequency of the corresponding waveguide mode will propagate into the beam pipe.

Monopole Modes

The beam is accelerated by the fundamental mode, TM_{010}, at 1.3 GHz. The second harmonic TM_{011} at 2.4 GHz is well separated from nearest beam harmonic at 2.6 GHz and does not pose a problem. The other TM_{01} modes (*e.g.* TM_{012} at 3.8 GHz) are above their cut-off (2.55 GHz) and unlikely to pose a threat.

Dipole Modes

The lowest dipole bands are the TE_{111} (1.62–1.79 GHz) and the TM_{110} (1.8–1.89 GHz). Both are well separated from nearest beam harmonic at 1.95 GHz and do not pose a problem. The other TE_{11} modes are above their cut-off (1.95 GHz) and unlikely to pose a threat. However, there may be problematic TM_{11}

modes below their cut-off frequency of 4.06 GHz. A more comprehensive analysis, using electromagnetic modeling software will be used to isolate these and higher modes, and to devise dedicated means of mode damping, if required.

HOM Damper Choices

There are typically three different means of HOM damping: coaxial loop coupler, waveguide, and beam pipe absorber.

Beam Pipe Absorbers

The beam pipe is widened and used as a circular guide that allows the HOMs to propagate out of the cavity into a wideband load that is cooled either at 5 K or 80 K. The coupling to the HOMs is improved over the waveguide approach, and the layout is simplified. In e-linac, we have chosen to increase the beampipe radius to 45 mm, as compared with the TESLA and ILC standard of 36 mm, to propagate more cavity modes.

There are two variants of the absorber design: the Cornell ferrite absorber, with a bandwidth up to 100 GHz and maximum dissipation of 200 W cooled at 80 K, and the XFEL ceramic absorber good for a few tens of watts, which is a near CW adaptation of the TESLA design. The latter is a factor eight less costly, is completely adequate for the < 1 Watt/cavity HOM losses anticipated for the fission driver, and has been selected for the baseline costing.

Cavity Frequency Tuning Systems

The INFN coaxial type mechanical tuner was adopted for the cost estimation purposes of the baseline design of the fission driver. This design has been chosen for ILC, and its adoption would afford any technology spin-offs from the e-linac greater synergy with ILC. The coaxial tuner is wrapped around the cavity and takes up less longitudinal space inside the cryostat, which is an important consideration for the ILC. There is no such concern in the fission driver "real estate". The recent development at DESY of the Saclay lateral tuner, which has been operated successfully for many years, for application to XFEL and the imminent mass-production of >800 units, will yield significant cost reductions. Therefore, the final choice of tuner has yet to be made. Both tuner designs are available with piezos for fine-tuning, and both meet or exceed the specification for e-linac.

Requirements

Tuners are employed to mechanically alter the shape of the cavity to set the resonance frequency in coincidence with the drive frequency. The tuning system must compensate for perturbations to the cavity geometry such as: (1) mechanical fabrication tolerances, (2) contractive forces during cool down to 2 K, (3) Lorentz force detuning as the cavity is electrically energized, and (4) acoustical vibrations (microphonics).

The dominant detuning contribution is the length contraction during cooldown, which results in a static 600 kHz rise in the resonance frequency. Because the fission driver is operated truly CW, with no macro-pulsing of RF power, the Lorentz detuning (of 50 Hz) is also a static effect, and its compensation is simpler than in pulsed linacs. The fission driver is heavily beam loaded, and the microphonic detunings all lie within the loaded bandwidth of the cavity. For operation as an ERL, a fine-tuning resolution of 1 Hz would be required. The incremental cost of incorporating piezo actuators, but without their drive or control systems, is small when implemented early, and has been included in the costing to allow an expansion path to an ERL. Retrofitting would be more costly.

Cryomodule Configuration

Though it is conceivable to place all five cavities in a single cryomodule, it is preferable to split them between two modules: an injector and main linac. The injector serves as a prototype for the cryogenic, vacuum, and mechanical systems of the later main module. The split of injector and main cryomodule gives a natural place to incorporate the return arcs of the ring in the event of an expansion to an ERL or RLA, and it provides a natural opportunity to stage the construction. Thus, the precise division of cavities between modules is influenced by two factors: (1) expansion to light-source applications by reconfiguration of the linacs as an ERL or RLA; and (2) what beam capability can be provided to the proposed RIB experimental schedule in early 2013.

It is standard practice to split an ERL or RLA into injector and main linacs. In particular, for an ERL, it is desirable to have the lowest energy injector because there is no energy recovery in this part and the highest current since this has almost no impact on the RF power consumption of the main linac, although it does influence beam losses. The following table compares possible assignments of cavities to modules for three linac applications.

Application	1+4 configuration	Power (kW)	2+3 configuration	Power (kW)
Fission driver reach	10 mA, 50 MeV	500	10 mA, 50 MeV	500
ERL reach	20 mA, 85 MeV	100	20 mA, 70 MeV	200
RLA reach	2.5 mA, 180 MeV	500	1.9 mA, 160 MeV	475

The ERL/RLA scenarios are based on 20 MV/m accelerating gradient. Excepting the ERL, the power rating is both the RF power consumed and the beam power. For the ERL, the value is the power consumed in the injector; the instantaneous beam power is 170 kW and 140 kW, respectively, for the 1+4 and 2+3 cavity assignments. Evidently, the 1+4 configuration gives better opportunity for component prototyping and has slightly stronger expansion potential for an ERL or RLA.

We turn now to project staging and compare which of two possible cavity assignments will provide the most useful beam for RIB production in 2013.

	1+4 configuration	Power (kW)	2+3 configuration	Power (kW)
E-Linac reach in 2013	5 mA, 15 MeV	75	5 mA, 30 MeV	150

Both options are based on a conservative projection of the maximum achievable gradient with $I_0 = 10^{10}$ and the planned cryogenic capacity; the 2 K heat load at 15 MV/m is more than double that at 10 MV/m. Both options have the same ultimate reach of ½ MW. Clearly, from the table, the configuration of 2-cavity injector and 3-cavity main cryomodule has several advantages.

- Better match to the requirements of its immediate nuclear physics and materials science user community: ≥ 30 MeV is guaranteed for mid-2013.
- Beam power capability will, literally, drive the target development program for several years.
- Not prohibitive for expansion to testbed for fourth generation light source.

Two-Cavity Cryomodules

The preferred division into two almost equal two- and three-cavity cryomodules places them in juxtaposition to a commercially available two-cavity cryomodule, based on the Forschungszentrum Rossendorf design, from the European vendor ACCEL with a guaranteed field gradient of 15 MV/m. Inevitably, it will be asked “Why not buy rather than build?” The product offered is TTF technology upgraded to CW operation, but for low power applications, up to 8 kW/cavity. This design does not meet the e-linac specification of 100 kW/cavity and would require substantial redesign for the higher anticipated heat loads. Moreover, one of the motivations of the e-linac is to transfer SRF technology to a Canadian fabricator and end the reliance on purchases from overseas.

Cryoplant and Expected Heat Load

The cost estimate for cryoplant is based on the purchase of a Linde LR280 helium refrigerator with a capacity of 900 W at 4.5K with liquid N_2 pre-cooling.

The starting point for a heat load calculation is the TESLA TDR for a 12-cavity cryomodule. Scalings appropriate to the 10 mA fission driver or 100 mA ERL are applied for beam currents, duty factor, and number of cavities, and where different component designs are selected. The table below gives the heat load for the sum of all cavities (5), input couplers (10), bellows (5), etc. For comparison, the table shows the combined static and dynamic heat load of the 12-cavity TESLA cryomodule operating at 23.4 MV/m. In all cases, an intrinsic $Q_0 = 10^{10}$ is assumed. In addition, the heat load to the three-cavity main linac in ERL-mode is provided.

	Fission driver, 10 MV/m 5 cavity	ERL 20 MV/m 3 cavity	TESLA TDR 23.4 MV/m 12 cavity
2K RF Load (W)	52	124.8	4.95
2K Sum (W)	55.5	188.6	9.05
5K Sum (W)	36.4	25.9	15.94
80K Coupler load	890	198.8	80.9
80K Sum (W)	897	450.9	183.02

The e-linac 2 K and 80 K heat loads are roughly 5 times the TESLA values, despite having 40% of the number of cavities. The severity of the 2K load is ascribed to establishing CW, rather than pulsed, RF electric fields, and scales quadratically with gradient; while the large 80 K load is mostly due to the 500 kW of beam power that must first flow through the input couplers. Refrigeration for the ERL option is not included in the baseline cost estimate.

Budgeted Heat Loads

It is customary to prepare from the estimated loads above a budgetary load. There are two reasons for this practice: (1) A larger budget allows upgrading to higher gradients without installing new refrigeration. Plant and cost are heavily discretized, which means that adding incremental cryo capacity is costly. Therefore, it is better to overspecify in the first place.

(2) Cavity quality factors and peak gradients typically have a spread, so one should leave some overhead in case many Qs are lower than design.

The 2 K budget for injector and main linacs is 100 W (the estimated load is 60 W). This represents a load of 400 W at 5 K, to which must be added the direct 5K cavity load of 40 W and loads from transfer lines and valve boxes, etc, of 170 W for a total of 610 W. Introducing an engineering margin of 50% implies a budget of 900 W cooling at 5 K.

Cryovessel Design

Currently, there exist two proven designs, with different relative merits, that may be used as a basis for the e-linac cryomodule: (1) the TTF/TESLA/ILC, and (2) the CEBAF and SNS modules designed at Thomas Jefferson Laboratory (TJNAF). It will be an engineering exercise to choose between these designs, as both are viable starting points for the E-linac design. The cost estimation is largely independent of the design, because for single modules the development cost will dominate. The estimate was prepared from the SNS high-β design, with a small-quantity overhead factor of 3 applied.

CW High-Power Cryomodule

Cornell has made strong progress in developing a high average-power CW cryomodule design, The Cornell ERL injector design is a derivative of the TTF cryovessel. In addition to a redesign of the cold mass, the Cornell cryovessel incorporates the following modifications required for CW operation.

- Increased diameter of 2-phase 2 K He pipe for CW cavity operation;
- Direct gas cooling of chosen 5 K and 80 K intercept points with He-gas flow through small heat exchangers;
- No 5 K shield, only a 5 K cooling manifold and intercepts;
- New end-cap and feed-cap concept with reduced length;
- Three layers of magnetic shielding for high Q_0;
- HOM absorbers between cavities; and
- *In situ* bake for input couplers, no further atmosphere exposure, no pre-conditioning.

Technical Systems

Vacuum Systems

The vacuum system of the linac facility, which has an overall length of 80 m, can be divided into three parts with different vacuum requirements and volumes: the 5-m long source area operated at 10^{-9} torr, the 15 m cold section composed of the two cryomodules (injector and main linac) with pressure 10^{-11} torr, and the 60 m beam line-to-target operated at 10^{-8} torr. These requirements are standard ultra-high vacuum (UHV) practice at accelerator laboratories and will all be met with commercially available equipment. Indeed, the 10^{-11} torr in the cold section is a consequence of operation at 2 to 4 K and not a requirement. However, extreme cleanliness is a requirement. To limit the possibility of particulates migration into the cold section, the room temperature upstream and downstream sections are separated by gas flow restricting diaphragms.

Generally, the vacuum pipe size is chosen consistent with molecular conductance and the non-interception of beam halo. The residual pressure is chosen consistent with minimal losses from residual gas scattering, and the cryomodule requirement for extreme cleanliness against contaminants. The 37 mm diameter pipe is consistent with halo losses below 10^{-4} in the source region and below 10^{-7} in the beam line, assuming an emittance $\leq 100\pi$ μm normalized. The vacuum pressure in these regions is consistent with fractional loss per metre (of beam line) from out-scattering below the 10^{-6} level.

Vacuum Pumps and Valves

The UHV system is brought to the nominal pressure in stages: rough pumping, pumping to high vacuum, and pumping to UHV. The roughing from 1 atmosphere to 10^{-3} torr is done by a dry mechanical (scroll) pump. The pumping down to 10^{-6} torr is performed by a turbo pump backed by the scroll. A turbo-scroll assembly with appropriate gauging and valves is called a turbo pumping station. Ion pumps are commonly used to create the UHV of 10^{-8} torr or lower. These pumps are characterized by cleanliness, ability to pump different gases, and maintenance- and vibration-free operation.

The electron gun, buncher, and capture cavities will each have one turbo station and ion pump. Each of the cryomodules has two turbos and two ion pumps, while the beam line has two turbos and five ion pumps.

Electron Beam Diagnostics

The e-linac beam diagnostics measures several key quantities:

- the beam positions along the linear accelerator chain and along the transport line to the target station;
- the transmitted beam current through these same components;
- the beam emittances after the source, buncher and capture cavities, and after passage through the injector and main linac;
- the beam momentum and spread immediately after passage through the two linacs as a means to adjust the cavity phasing for on-crest acceleration; and
- the beam RF phase compared with LLRF and some measure of bunch length.

Instrumentation has been identified to perform all these measurements.

Dynamic Range

The diagnostic strategy will foresee that initial commissioning of the linacs and set up of the beam line will be conducted with perhaps 10 µA while operations will run up to 10 mA.

Thus, as is common in high-power accelerators, the diagnostic strategy must encompass a large dynamic range of order 10^3. There are two aspects to this problem: (i) how much to turn up or down the "source", and (ii) how to instrument the electron beam at various average intensities. Typically, equipment is limited from both ends. At too low intensity, signals are weak and noisy; and at too high intensity intercepting monitors are destroyed by the beam.

The present concept is to adjust the average beam intensity by a combination of throttling back the electron gun and implementing means to macro-pulse the beam, including control over the repetition rate and pulse length. This allows us to avoid either very low bunch charge, or the full beam power. A key feature of this procedure is that the RF system is not pulsed, and there are no Lorentz-detuning transients; however, some periodic beam-loading must be accepted.

Each of the various beam monitoring devices has a finite dynamic range. Consequently, the recommended strategy is to align and characterize the electron beam based on low current position and other measurements, and then to bring the beam to operations level based on beam current measurements. The position will hardly change, but the losses may, so loss monitoring is an important tool.

Beam Position Monitors

The electron beam position system is the backbone of the diagnostic system and will provide the beam horizontal and vertical positions at each magnetic element, and at the entrance and exit of each cryomodule. The desired measurement accuracy is 0.1 mm, with a resolution of 25 µm, over the linear range of the BPM, ±5 mm.

Each beam position monitor (BPM) is composed of four buttons, feedthroughs, and head electronics to perform the sum and difference of the two signal pairs to provide horizontal and vertical information. The BPM system should have the largest possible dynamic, and baseband processing with a log demodulator will be performed.

Acquisition Frequency

BPM signal acquisition and processing at 1.3 GHz is a costly business: signal attenuation in cables is relatively large, and processing electronics is not commercially available at reasonable cost. Furthermore, as a general principle, it is recommended not to acquire beam signals at the same frequency that is broadcast by the HLRF system because inadvertent RF leakage will contaminate the beam-induced signals. These problems all disappear if the acquisition is moved to 650 MHz; and for that reason, the bunch repetition frequency has been set at 650 MHz. This has the side effect of doubling the bunch charge (from 8 pC at 1.3 GHz) to 16 pC, with a minor impact on the HOM losses.

Beam Transmission

During initial commissioning at low energy and modest beam currents, an intercepting device such as a 10 kW Faraday cup will be used to verify beam transmission and losses. At higher beam power, non-intercepting devices will be employed. Commercially available Bergoz DC current toroids have a variety of range options including 10 μA to 10 mA and offer high precision.

Beam Transverse Profiles

Beam "profiles" are a valuable tool: the beam spot from a scintillator (nA-μA) or fluorescent screen (μA-mA) instantly verifies that the electron beam has been threaded through the accelerator and beam line during commissioning. Detailed profile measurements allow the estimation of emittance growth. Profiles will be measured before the capture cavity, after the injector and main linacs and before the target station. The baseline is to use a fluorescent screen before the injector linac, and OTR screens before and after the main cryomodule, and possibly wire scanners in the transfer line and close to the photon converter due to the high radiation level.

Momentum Analysis

The phasing of the cavities is optimized based upon maximizing the beam energy gain as measured by the deflection in a spectrometer magnet. Two analysis stations, each equipped with a 30° bend, slits, and 10 kW Faraday cup, are each placed immediately after the 20 MeV injector and the 50 MeV main linac. The desired resolution is ≈ 0.5%.

Longitudinal Beam Structure

The diagnostic system will provide the bunch RF phase compared with the LLRF signals and bunch longitudinal profile, *i.e.*, bunch shape. The bunch phase is crucial to optimizing the accelerating cavity phasing, and will be measured, with an accuracy of 1^0 at 1.3 GHz, immediately prior to the capture section and the injector and main linacs. The beam phase can be measured from the sum signal of BPMs. It can also be read back from the cavity field probes with HLRF turned off.

Personnel Radiation Protection System

In all cases that personnel are present in the e-linac vault, the Radiation Safety System (RSF) will ensure dose rates below the low occupancy limit, 10 μSv/hr. Conditions which exceed this limit, proton spills in the 4-North beam line, will result in alarms and immediate evacuation. Residual activity exceeding the 10 μSv/hr limit in the e-linac vault will result in denied access to this area. By prescription and design, such events should be exceedingly rare.

ISAC-II Experience

The ISAC-II SRF accelerator operators have chosen to designate the accelerator vault as an exclusion zone: no personnel are permitted whenever the RF systems are energized or the particle beams are present. This restriction was occasionally inconvenient during the accelerator commissioning but has the merit of greatly simplifying the Radiation Safety System. The balance of the ISAC-II experience has been positive, and this exclusion-zone principle will be applied to the e-linac in the Proton Hall.

No personnel will be admitted to the Proton Hall whenever the high-power RF systems are energized or if there is accelerated electron beam present. However, to avoid scheduling conflicts, personnel will be permitted in the e-linac vault while there is a proton beam in the 4-North beam line; this will allow maintenance to be performed on e-linac without interrupting proton-beam delivery to the target station. Thus, while the majority of the e-linac components will be unshielded, the proton beam line will be heavily shielded.

Shielding from Proton Losses

The requirement for shielding the e-linac vault from the 110 μA, 500 MeV proton beam line is two-fold: shield for chronic loss, and shield for rare catastrophic loss. Catastrophic loss is defined as point loss of the full beam sustained for up to an hour. Based on experience from the BL2A proton beamline, the chronic losses can be kept below 1 watt per metre (≈1 nA/m), which is the widely accepted limit for hands-on maintenance of a proton facility.

We have chosen layouts for the e-linac and BL4N shielding consistent with the philosophy that passive means of protection, *i.e.,* more shielding, are preferred over active methods such as double layers of instrumentation. Six meters of shielding in the form of 3.5 m of steel and 2.5 m of concrete lead to dose rate below the low-occupancy limit, < 10 μSv/hr (1mR/hr), given the expected chronic losses, and to dose below 50 mSv/hr in the forward direction from a catastrophic loss. Steel and concrete are preferable to concrete alone, as the heavier nuclei provide effective attenuation through spallation. In this case, only neutron monitors outside the shielding are required and the proton-related component of the Radiation Monitoring System becomes an extension of the existing safety system, and will use TRIUMF's standard neutron monitoring hardware and techniques.

Activation from Electron Losses

The activation from 50 MeV electrons comes about from the photo-neutron and photo-spallation reactions when the beam is stopped. There will be both air activation and activation of the accelerator components. The stopped beam will come about from low-level chronic losses throughout the accelerator and from the beam dump and targets where the beam is directed.

Air Activation

It will be important to fully shield the tuning dump and target(s) to minimize air activation by high-energy neutrons. Air activation from chronic losses cannot be so easily mitigated. For comparison, the table below shows the saturation air activation[3] for the 500 MeV cyclotron at 200 μA average current. The vault ventilation rate, an air exchange every 45 minutes, results in releases of the short-lived positron emitters (C-11, N-13, and O-15) corresponding to 1% of the derived release limit (DRL) for the site. The regulatory limit for operation of a nuclear facility is 5% DRL. The table also shows the values per kW for the electron linac. To limit the increase in air activation to less than double current site emissions, the chronic losses for the e-linac and electron beamline would need to be limited to 5 kW (≈1μA/metre) or less.

Saturation Air Activation Concentrations		
	500 MeV cyclotron	50 MeV e-Linac
Radionuclide	Bq/m^3	Bq/m^3-kW
H-3	8.0×10^5	5.5×10^3
Be-7	2.7×10^5	8.5×10^2
C-11	5.3×10^5	8.5×10^3
N-13	2.7×10^5	8.5×10^4
O-15	2.1×10^5	4.3×10^4

Activation of Accelerator Components

The production of energetic neutrons is significantly less for a 50 MeV electronic shower than for a spallation reaction of a 500 MeV proton. Most of the photo-neutrons from the shower come from excitation of the giant dipole resonance, producing neutrons of energy less than 5 MeV. The neutron yield on an intermediate mass target, such as Cu, is 1×10^{12}/kW-sec for 50 MeV electrons as compared to 2×10^{13}/kW-sec for 500 MeV protons. Correcting as well for the smaller activation yield for the lower energy neutrons, means that e-linac losses of 100 watts/meter (2μA/meter @ 50 MeV) can be tolerated and still maintain permissible dose rates for hands-on maintenance. Over a total length of 50 meters, this would amount to 5 kW.

Radiation Safety System

The Radiation Safety System for the e-linac will consist of two subsystems: an Access Control System (ACS) to keep people away from the high-radiation fields inside shielding that are expected during normal operation, and a Radiation Monitoring System (RMS) to measure dose rates outside shielding and

3 The released quantities for tritium and ^{7}Be are significantly less than the saturation values, $< 1 \times 10^{-4}$, as the equilibrium concentrations for these long half-life species never have a chance to build up to saturation.

terminate facility operation if they rise above acceptable 10 μSv/h levels. As noted above, the RMS is based on neutron monitoring. The ACS will use standard features that TRIUMF incorporates in all areas where dose rates inside shielding can be high.

Machine Protection System

The machine protection system is designed to keep chronic beam losses below a few μA total and below 1 mA/m, as is consistent with maintenance and minimized air activation, and to prevent catastrophic loss of the full beam.

At full power, the electron beam is capable of melting engineering metals in a few milliseconds and of producing temperature rises capable of opening vacuum seals, etc., in a few hundred microseconds. The "charge" to machine protection has two components: (1) inhibit catastrophic events such as loss of the full beam, and (2) monitor chronic low-level beam losses and, by suitable interventions, reduce them to a level consistent with hands-on maintenance (a few μA total). The philosophy here is not to respond to catastrophic loss but to prevent it. In fact, machine protection reduces to a single imperative: keep the chronic loss below 1 μA and respond to incremental beam loss of ≈ 1μA within about 100 μs. A system which trips-off the linac at losses of 1 μA, will also trip at losses of 10 mA, and, of course, if beam loss of 10 μA is detected, you do not wait for it to rise to rise to 1 mA before taking action.

Machine protection will be implemented by two strategies: (1) monitoring of equipment conditions with a refresh rate of about 100 Hz, and (2) direct monitoring of beam loss with a response time of 100 μs or less. Interlocks for valves, magnets, RF, temperatures, coolant flow etc., are monitored for "out of acceptable range" conditions to terminate facility operation should potentially unsafe configurations occur. Beam losses can be measured directly with DC current transformers on a time-scale of 100 μs with a precision of 10 μA in 10 mA, and two such devices are installed in the beam line. To achieve faster response and lower the resolution to < 1μA, one must measure the complement of beam loss: beam appearance in a suitable particle detector. For example, the e-linac vault and beam line could be instrumented with a series of photomultiplier tubes housed in light-proof boxes. Losses greater than 1 μA anywhere along the linac or beam lines will trip off the electron beam, with the conclusion that total losses cannot exceed a few μA and average levels would be much below 1 μA/m.

Fourth-Generation Light Sources

Introduction

The e-linac stands on its own merits as a photo-fission driver for nuclear physics and materials science and enjoys strong connections to SRF accelerator projects worldwide, connections which are advantageous to the HEP community. Nevertheless, it is tempting to point out that e-linac, potentially also has connections to the next generation of light sources, connections that could be explored in the far future with incremental expenditures but large benefits.

Third-generation electron-synchrotron light sources, such as the Canadian Light Source, have become part of the key national scientific infrastructure of most developed countries. The research using these beams has expanded from initial applications in materials research and physical chemistry to almost all areas of science, including biology, geology, agriculture, archaeology, and medicine. These synchrotron-based facilities provide multiple photon beams with high flux and brightness from the far infrared to hard X-rays. At both ends of this spectrum, a case may be made for investigating linac-based sources.

Hard X-rays

Most of the recent third-generation sources have an operating energy of about 3 GeV, which is the optimum energy for maximizing the range of scientific research at the facility. A consequence of this choice is that the maximum useful X-ray energy from a bending magnet source is about 30 keV. X-ray energies up to 100 keV are available using high-field wiggler magnets, but the high average power in the X-ray beam (up to 25 kW) presents significant technical challenges to X-ray optical components. Light sources with 6 to 8 GeV electron energy (ESRF, APS, and SPRING-8) can produce these higher energy X-ray beams much more easily, but each of these facilities costs a billion dollars. FELs are even more expensive for achieving a specific X-ray energy. The LCLS at Stanford and XFEL at DESY both will produce X-rays of about 12 keV with a brightness 10^{10} times higher than ring-based sources, but at a capital cost up to a quarter-billion dollars.

Thus, it is interesting to explore other possible techniques to produce X-rays with sufficient flux and brightness to do interesting research or exploit potential industrial or medical applications, but which have substantially lower costs especially for higher X-ray energy and/or short X-ray pulse lengths. One attractive approach is the Compton scattering source (CSS), which capitalizes upon the immense performance increases in lasers that have also been developed over the past two to three decades.

Compton Scattering Source

The concept of CSS is based on the scattering of photons from an intense laser by a relativistic electron beam. Using the laser as an effective undulator with a much shorter period than the commonly used magnetic undulators in synchrotron light sources, a much less energetic electron beam can be used. Proof of principle has been demonstrated at Duke University, UCLA, Lawrence Livermore National Laboratory, Brookhaven National Laboratory, Frascati, and other CCS are under development at MIT, the University of Tokyo, and the University of Hawaii.

Photons, which are backscattered in head-on collisions with the electron beam, are Doppler-upshifted in energy by a factor of $4\gamma^2$. Consequently, the combination of a modest 75 MeV, 1 mA electron linac and a modern table-top pulsed laser system with ≈1 eV photons could produce X-rays up to 90 keV. However, the scattering cross section, 6.7×10^{-29} m^2, is very small. To get reasonable flux from the collisions, the peak electron current (typically 1 nC in a sub-picosecond bunch), and the peak photon flux (at least 1 J in a few picosecond-long pulse) must be very high, and the cross section (10 μm^2) of both beams must be small at the collision point.

These conditions present significant technical challenges that any design for a CSS must address. A non-exhaustive list of R&D would include:

- photo-cathode intense pulsed electron sources;

- high-quality electron linacs;
- electron pulse compression;
- focusing both laser and electron beam to required spot size;
- stability of electron and laser beam at interaction region;
- reproducibility of electron and laser beam pulses;
- electron and photon beam diagnostics; and
- X-ray beam optics tailored to CSS characteristics.

Retro-fitted with a photo-cathode electron gun, piezo controllers, and equipped with a bunch-compression magnet chicane and low-beta beam optics insertion, and run at reduced duty factor, the e-linac provides a 100 MeV capable electron source for this R&D effort.

Applications of CCS

Applications of the CSS technology are currently emerging [Proc. Synchrotron Radiation Instrumentation (SRI2007), Baton Rouge, Louisiana, 25-27 April 2007]. Various groups (MXISystems, Lyncean Technology, MIT, and so on) are advocating these sources for monochromatic X-ray therapy of cancers. Because these sources have a much narrower X-ray spectrum than conventional hospital-based sources, there is increased lethality for the tumour cells. Other medical applications include high-contrast, low-dose diagnostic examinations, such as low-dose 3-D mammography; and a new kind of radiation therapy for cancers called Auger Cascade Radiotherapy, for example the treatment with iodine-125 (or I-127) of the thyroid.

Current third-generation light sources are exploring potential applications of hard X-rays to novel biological and medical imaging techniques, such as K-edge subtraction and diffraction enhanced imaging, which require high X-ray energy for adequate penetration of large biological samples. CSS also opens up experiments at X-ray energies above 100 keV that are not currently available at most third-generation facilities. The potential applications include nuclear fluorescence spectroscopy and isotopic imaging, time-resolved positron annihilation spectroscopy, and MeV flash radiography.

Infrared Radiation

For narrow band studies, the IR FEL is in competition with relatively conventional tabletop lasers. However, the wide range tunability and scanability, particularly in the far IR, favours the FEL. The FEL is easily tuned, for example by simply changing the beam energy or the undulator field strength over an energy range which, by the standards of conventional lasers, is extraordinarily wide. The FEL source has other capabilities beyond those of current tabletop IR lasers, particularly in terms of its ten times higher power and its long wavelength capability extending to THz.

The high power opens the door to image resolution below the diffraction limit. The so-called near-field microscopy relies on exponentially decaying evanescent waves, and so high-brilliance illumination is essential. With high-power also comes the ability to collect sufficient photons to produce an image in so-called time-resolved microscopy with very short illumination pulses. In combination with other radiation sources, the IR FEL offers fascinating possibilities, for example, two-colour experiments and pump and probe experiments. Whereas the third-generation synchrotron light sources provide the means to determine structure with high precision, these fourth-generation tools enable us to understand how these structures work.

IR FEL

Configured as a 20 mA × 70 MeV ERL by the addition of return arcs and boosted cryogenic capacity, and coupled to a suitable high-Q cavity FEL, the e-linac could produce hundred-watt-levels of infrared radiation in the range 2–200 μm (near IR to far IR). The superconducting RF-linac offers the advantage of highly stable operation and high average power. Applications of IR FELs are starting to become mature, and we have selected two examples that exploit the photon-power advantage.

Near-Field Microscopy

Near-field microscopy is rapidly evolving from a novel technique to a powerful instrument for the nano-imaging of materials and biological systems. The use of IR FELs is an important ingredient in this evolution. For example, collaborators at EPFL, Switzerland, ISM-CNR, Italy, and Vanderbilt University, USA, have created "spectroscopic" images of microcircuits with resolution beyond the diffraction limit. In another example, researchers from ISM-CNR, Italy and Vanderbilt have used scanning near-field techniques to analyze the distribution of functional groups in a single cell with a resolution of 100 nm for spectroscopic images and 50 nm for topographic images, which corresponds to ≈ 1/60 of the diffraction-limited resolution.

Materials Processing

The Thomas-Jefferson National Accelerator Facility (JLab) IR FEL provides two examples of materials processing. Carbon nano-tubes are increasingly utilized in various technologies. Current commercial applications include motor vehicle fuel system components and specialized sports equipment. Worldwide demand is currently a few metric tones/year, while current production techniques produce about 0.2 gm/hr. Using the IR Demo FEL and delivering an average power of 300 W onto the target, researchers obtained yields of 1.5 gm/hr.

Functional or smart surfaces and coatings play an increasingly decisive role for the applicability and performance of all modern materials. An example that is familiar to many is the application of titanium nitride (TiN) on tool bits. TiN is also used to improve the biocompatibility and wear characteristics of replacement joints. University of Gottingen researchers have used the IR FEL for the nitriding of Ti metal. Compared to other types of laser nitrided Ti, the FEL-produced material had a thicker and harder coating, due to the formation of oriented dendrites.

Terahertz Radiation

Electromagnetic radiation in the frequency range from 0.3 to 20 THz, sometimes called the THz gap, is a frontier area for research in the physical sciences, biology and medicine. Terahertz sources of high quality and high average power are scarce, and as a result the community of users is presently much smaller than the potential based on scientific opportunities. Accelerator-based sources of THz radiation with high peak and average power will illuminate new realms. Here we focus on two classes of experiments that require characteristics which can be delivered by linac-based THz sources, either Free Electron Lasers (FEL) or Coherent Synchrotron Radiation (CSR) sources. In FELS, the wavelength is related to the wiggler period; whereas for CSR produced in a bending magnet, the radiation occurs on the scale of the bunch length which must be exceedingly short.

Narrow-Band THz Radiation

A typical FEL source is composed of a single-pass 10–50 MeV electron linac (NC or SRF) driving a wiggler placed inside an optical cavity. There are three FEL user facilities of this type operating in the THz gap: FELIX in the Netherlands, the Stanford Subpicosecond FEL Center, and the University of California at Santa Barbara (UCSB) FELs. Research at the latter emphasizes how the properties of semiconductors can be manipulated by the application of strong THz fields. The Stanford FELs are driven by an SRF linac and, as a result of the lower RF losses, are capable of 10^3 times higher macropulse durations than an NC facility such as FELIX. Compact CSR sources in this regime have so far been proof-of-principle experiments, but they have great potential and are being actively explored.

Broad-Band THz Radiation

Other experiments require coherent half- or few-cycle THz pulses of high peak and average power which enable applications in the areas of high-field physics and ultrafast (50 fs) time-domain experiments, usually performed using a "pump-probe" technique. These experiments require tunable (0.1 to 50 THz), ultrafast THz pulses, with synchronized ultrafast pulses from mid-IR to X-rays.

The NSLS/SDL at BNL is an example of an NC linac-based THz source, while the JLab FEL is an SRF-driven FEL and THz user facility that produces half-cycle THz light. Experiments at BESSY have produced stable CSR in a storage ring, while experiments at LBNL-ALS have demonstrated intense THz CSR pulses from laser-slicing. In all cases, THz radiation is produced through CSR. To produce a single or half-cycle coherent THz pulse, the entire electron bunch must be short (<1 ps). Linacs using photo-cathode electron guns offer distinct advantages with respect to production of high brilliance and short pulse electron beams, and intrinsic synchronization of an ultrafast laser to the electron beam. Furthermore, SRF linacs allow operation at high repetition frequency, resulting in up to kilowatts average power of THz radiation. Finally, linac-based sources offer flexibility in their mode of operation.

A 10–20 MeV e-linac is sufficient to produce THz radiation. With a number of modifications, the e-linac could be configured as a THz radiation source: either FEL-based similar to FELIX, or CSR-based similar to the JLab THz facility.

User Community

The Canadian community of laser and synchrotron light sources is a diverse group conducting research at home and abroad. Presently, this community is engaged in exploiting, to maximum potential, the existing facilities, including the CLS at Saskatoon. For the next few years, it is believed that improvements in instrumentation, automation, and detector technology will be a more cost-effective investment than new accelerator infrastructure. Moreover, the concepts presented here are entirely complementary to the CLS in their parameter reach and scientific possibilities.

Against this argument serving the *status quo*, must be set the enthusiasm of the wider community for alternative accelerator-based sources. For example, there are numerous FEL user facilities: six operational in the United States, six in Europe, and two in Japan [www.lightsource.org]. In addition, there are about 30 research machines and 24 other FELs proposed [Colson, Blau, Kampouridis, Proc. of FEL 2006, BESSY, Berlin, Germany]. The fourth-generation sources offer exciting new reach for the physical and biological sciences. Enthusiasm for them in Canada should be expected to grow, and they should be part of the ten-year horizon. Indeed, it is CLS personnel who have proposed a Canadian initiative to develop CCS-based hard X-ray sources, and any development at TRIUMF would have to rely on strong collaboration with CLS scientists.

With marginal incremental investments, e-linac could serve as a testbed for CCS technologies or a staging post to an IR or THz FEL or CSR source. E-linac provides a source of future possibility and opportunity to broaden light-source based research in Canada. For those reasons, we have gone to some pains to assure that e-linac is inclusive of those future options: no decisions made in the e-line design will preclude diversification of the facility to a demonstrator of fourth-generation light source technology.

Conclusion

The e-linac promotes access to some exciting science by allowing high yields of certain neutron-rich species with lower isobar contamination. These neutron-rich rare isotopes are a niche region and complement the proton-rich rare isotope program. E-linac can also be used to expand the β-NMR program and explore the production of novel medical isotopes. As illustrated, this "driver" is new for TRIUMF and will hone the skills of Canada's accelerator community and open future windows of discovery. The choice of L-band SRF technology will develop a new core competency and make Canadian industry one of only 5 in the world able to do this type of work. In the longer-term, the science and technology of the e-linac positions TRIUMF well for advanced accelerator R&D involvement on the world's next global science project, the ILC which truly works at the edge of technology. Finally, this project will grow domestic expertise in 4th generation light source technology.

6.2.1.2.3

Conceptual Design of New Target Station

The development of ISAC into a multi-beam facility requires that TRIUMF build a new independent target station that will accept either protons from a new cyclotron beam line or electrons from the new linear accelerator. For future expandability, it is desirable to leave open the option of subsequently installing an additional target station. These new stations, combined with the existing ISAC target station, will allow TRIUMF to deliver, simultaneously, initially two, and subsequently, with the additional target station, three, rare-isotope beams (RIBs) to ISAC users. This capability will allow TRIUMF to triple its scientific output. The new target station will be compatible with operating actinide targets using a proton beam at 500 MeV or an electron beam at 50 MeV for photo-fission. It will employ a modular approach similar to that used for the present ISAC target stations. An entrance module will be equipped with diagnostics for the incident beam. A target module will be equipped with a hermetic containment box that will house the target/ion source assembly. A beam dump module adjacent to the target module will stop the incident beam. Two exit modules will contain the optics to prepare the heavy ion beams for the mass separator.

After analysis of the present ISAC target station operation, we found that the major drawback is the non-hermetic sealing of the target box; this represents a risk of contamination and makes operation of air sensitive material such as uranium carbide a potential hazard. The second issue is the fact that the mechanical and electrical services have to be connected and disconnected manually, which creates delays for the target exchange. In the new ISAC design, we will address these issues by having a completely hermetic containment box that will house the target/ion source assembly. The new ISAC target modules will be equipped with a hermetically sealed containment box, and the services will be provided remotely. Considering that in this configuration we will be able to condition a fresh target on the test stand in advance and have it ready for on-line operation, we could change targets within two days instead of the three to four weeks presently required.

Two new hot cells are also proposed. One hot cell will be instrumented specifically for target/ion source assembly and exchange, while the second one will be used for maintenance and repair.

Exotic Beam Production with Protons

Protons at high energy ($E \sim 500$ MeV) incident on a high Z thick target are used to produce rare isotopes. There are three principal reaction mechanisms taking place: spallation, fission, and target fragmentation.

Spallation Reaction

This mechanism is a two-step reaction, which involves protons at 500 MeV interacting with high Z target material. The emission of charged residues follows the evaporation of neutrons. This reaction mechanism leads to a large mixture of different nuclei mainly situated on the neutron deficient side of the nuclear chart. The exoticity of the isotopes produced in this reaction mechanism is roughly proportional to the energy deposited during the nuclear interaction. The more energy deposited in the interaction, the more neutrons will eventually evaporate from the highly excited compound nucleus.

Target Fragmentation Reaction

Depending on the impact parameter and proton energy ($E > 400$ MeV), the incident particle breaks the target nucleus in two smaller residues, one close to target mass and the other a light nuclei. In this case, the energy deposited is not large, and the residues will subsequently evaporate a few neutrons. This mechanism produces neutron-rich rare isotopes. The neutron-to-proton ratio of the light fragment depends on the neutron-to-proton ratio of the target. Hence, if neutron-rich light fragments are required, it is desirable to use ^{238}U as the target material.

Fission Reaction

At relatively high incident energy, the fission mechanism produces a symmetric fission that creates a peak in isotope production in the medium-mass region. By going higher in proton energy, this symmetric peak becomes wider and eventually disappears around 3 GeV where the production is nearly flat for all residues.

With fissile target such as Th or U, there are asymmetric fission peaks on top of the products from the other reaction mechanisms. These fission peaks are induced either by secondary slow neutrons or by fast protons and neutrons. Together, the fission fragments will broaden the usual mass distribution toward the neutron-rich isotopes while the neutron deficient remains similar.

Exotic Beam Produced with Photo-Fission

An electron linear collider (e-linac) is proposed at TRIUMF as a test bench for the international linear collider (ILC) initiative. TRIUMF wants to acquire the high frequency 1.3 GHz super-conducting technology by building a 50 MeV electron machine. This e-linac can be used to produce exotic nuclear ion beams via the photo-fission of the ^{238}U nucleus. This process was proposed by Diamond as a means to produce RIB and expanded on by Oganessian in the late 1990s [W. T. Diamond, Nucl. Instrum. and Methods V 432, 471, (1999) and Y.T. Oganessian, Nucl. Phys. A 701, 87 (2002)]. The fission is typically induced by electron beam interacting with a fissile nucleus. The photo-fission threshold is 5.4 MeV. Furthermore, the excitation of the giant dipole resonance yields a large fission probability, 160 mb around 15 MeV. The energy range of the atoms produced by the GDR is between 10 and 20 MeV [J. T. Caldwell, *et al.*, Phys. Rev. C21, 1215 (1980)]. For large electron beam powers, it is not practical to impinge the electrons directly onto a thick U target. It is preferable to use a converter that produces photons by braking radiation (bremm-strahlung). The photon energy distribution is a continuous spectra from zero to the maximum energy of the electron. The optimum energy for the electrons to produce photo fission is approximately 50 MeV.

The bremstrahlung photons are emitted in a sharp cone around the electron direction. Taking into account the angular dispersion of the electron with respect to the original direction and the photon cone angle, one can calculate the number of photons that will interact with the target. The result is the convolution of the two processes. Once we have the distribution of the photon with respect to its energy we can find the number of photo-fissions by integrating the braking radiation spectrum and the giant dipole resonance cross section.

It is important to take into account the fact that high-energy photons ($E_\gamma > 5$ MeV) are easily converted into electron-position pairs. This process will attenuate the photon intensity, and the resulting effect will be a lower yield. A Monte Carlo simulation shows that we can expect a photo-fission rate of around 4.6×10^{13} /s. The release mechanisms of the RIB from the target are similar to those for proton production. To optimise RIB rates, the same type of development as proton-irradiated targets will be required.

ISOL Method: Release Mechanisms and Processes

Once the incident particle (proton or electron/photon) interacts with the target nucleus, the reaction products are stopped in the bulk of the target. To reach the ion source where an ion beam can be formed, these atoms have to undergo two release processes, the diffusion and the effusion, respectively. The rare isotopes form atoms that have to diffuse to the surface of the granule or foil. Then they have to undergo absorption de-sorption from the surface every time they collide with the walls of the target container, *i.e.*, effusion process.

In this method, if we want to produce beams of very short-lived elements, the release process has to be very fast. A rapid release of the reaction products embedded in the target material implies that the diffusion process brings the desired element to the surface, The diffusion rate in solids can be obtained by solving the Fick's equation for the diffusion. The key parameters driving this process are: the operating temperature, the size of the granule or crystal composing the target (d), the activation energy for the diffusion into the target material (E_A), and the self-diffusion parameter (D_0).

Parameters D_0 and E_A depend on the element of interest and the target material. The major role of the development of new exotic nuclear beams is to find the best target material for the specific beam. Operating at high proton intensity can significantly change this picture. At ISAC, we observed a non- linear increase of the RIB intensity with the incoming proton beam intensity. This can be related to the fact that, at high power density, the number of voids created by the incident proton beam in the crystal lattice increases faster than the repair mechanisms or self-annealing process. Since the impurities will migrate preferentially toward those voids, the increase in concentration will speed the diffusion process. For ^{11}Li and ^{21}Na, we can observe that the diffusion is enhanced and the yield is non-linear. In fact, the diffusion goes with the square of the proton beam intensity. Because of this process, we are less and less limited by the diffusion process if we can operate ISAC at proton beam intensity larger than 50 μA and with a beam spot of the order of 4 mm FWHM on target [M. Dombsky *et al.*, Nucl. Instr. and Meth. B204 (203) p. 191].

The second release mechanism deals with the surface desorption and subsequent effusion from place to place until the atom reaches the ion source. Once the atom has reached the surface of the target granule or foil, it has to gain enough energy to overcome the surface desorption enthalpy of the material or of any other surface material encountered on its way to the ion source. The release efficiency for pure effusion depends on the mean number of collisions with the surface of the target material and the target container before leaving the enclosure. The sticking time t_0 per collision, which depends essentially on the temperature of the crystal and on the absorption enthalpy ΔH_a of the surface in the enclosure:

$$p_\nu(t) = \nu e^{-\nu t}$$

and the mean free flight time t_f between two wall collisions. The profile is given by:

$$\frac{1}{\nu} = t_\nu^{delay} = x_c(t + t_f)$$

where,

$$t = t_0 e^{-\Delta H_\alpha / kT}$$

and t_0 can be related to the lattice vibration frequency; the higher temperature, the smaller this term will be. From these equations, we can see that the limiting factor is the time the atom sticks to the surface of the enclosure and the absorption enthalpy. If the absorption enthalpy is large, there will be huge decay losses. This means the atoms will decay before they can reach the ion source. When dealing with effusion-limited release, it is important to limit the number of wall collisions. This implies a need for a small volume target container.

Refractory elements, even if long-lived, are not released from target material even at the highest operating temperature because most of the time this is due to chemical affinity between the refractory species and the target material or target container. If the element of interest makes alloys or compounds that are even more refractory than the target material, the release will be very inefficient. To overcome these difficulties, we can inject a gas that will react with the element of interest and the resulting compound will be volatile. Several groups have successfully used the high volatility combined with the thermodynamic stability of the metal chlorides or fluorides [U. Köster, *et al,* European Physics Journal, V 150, 285 (2007)]. Unfortunately, with the non-hermetic containment box of the present ISAC target module, it is not advisable to use this method. The risk of contamination during transport from the target station to the hot cell is too large.

And, finally, once the atoms have effused from the target to the transfer tube that connects the target volume to the ion source, they must be ionized and extracted to form an ion beam. The importance of the ion source cannot be neglected in the isotope separation on-line (ISOL) method; an inappropriately designed ion source may not produce the intensity we want even though the initial production of the required isotope in the target is significant.

Target and Ion Sources Development

Experience at the operational ISOL facility clearly shows that there is not a universal target/ion source combination for the production of all required isotopes for the physics program. Thus, several types of ion sources are required at the ISAC facility. The initial TRIUMF-ISAC target module design was done with this idea in mind, and flexibility has been provided in the system to allow their successful implementation. This flexibility has been retained in the new target station design. To maximize the yield of a desired species, we have to reduce the transmission losses. This means that the ion source has to be closely coupled to the target oven. This fact has enormous implications on ion sources. The hostile environment also dictates that the ion source be both simple and small for sake of economy and to minimize surface area in order to avoid decay losses.

Target Ion/Source Assembly

The target module houses an assembly comprising both the target container and ion source. This assembly is changed on a regular basis, every three to five weeks on average to satisfy the requirement from the scheduled physics program. In addition to the target container, transfer tube and ion source, the assembly includes an oven to heat the target material, an extraction electrode, beam-optics correction bender, and the ground electrode.

The ISAC Target Stations

The present two ISAC target stations have been in operation for a good number of years. Each comprises five modules that house the primary beam diagnostics (entrance module), the target/ion-source assembly (target module), the beam dump (dump module), and the optics for beam matching for the mass separator (exit modules 1 and 2). Each module has a service cap, a service duct, and a containment box housing functional components (target/ion source, optics, or beam dump). These five modules are inserted into a large vacuum box. Differential pumping avoids collapse of the containment box and limits the spread of the contamination from one vacuum entity to the other. In this design, the regions requiring the use of radiation-hard materials are limited by shielding and distance.

The proposed new ISAC target stations are designed based on lessons learned from the operation of the existing ISAC target station concept. Three advantageous features of the modular design have been borne out in practice:

1. The non-radiation resistant components, such as O-rings, turbo pumps, actuator, and cable insulators, are protected by the module-shielding plug. This allows maintenance-free operation at the specified proton beam intensity of 100 μA.
2. The dose to staff is kept to a minimum.
3. The two stage mass separator concept, a pre-separator combined with a high-resolution separator, satisfactorily limits the contamination spread through the ISAC beam lines.

Routine operation has also revealed the following areas for improvement in the design:

1. The target box housing the target/ion source assembly is not hermetically sealed.
2. Thus, the transfer of the spent target from the target station to the hot cell is done in the open atmosphere of the target building. This introduces a risk of volatile radioactive gas or dust escaping the target box during transfer from the target station to the hot cell. The open configuration of the target box also means that vacuum and high-voltage conditioning must be done *in situ*, once the new target module is installed in the station. This takes an additional one to two weeks depending on the target material and extraction voltage.
3. All mechanical and electrical services for the target/ion source assembly are connected and disconnected by hand. The required cool down period for access to the service cap to undertake these operations is presently one week.
4. Since the target change time is about three or four weeks, the target/ion source system in the other target location has to remain operational for the same period to avoid beam time loss. This is quite demanding on target assemblies when running at high proton beam intensity. Radiation damage is clearly visible; in post-mortem inspections, we can see cracks developing on the target container. This damage is not merely superficial, it also manifests itself as degrada-

tion in exotic ion yield. Optimizing scientific output requires that we run our targets for shorter periods. In turn, this requires faster target module turn around. Figure 1 shows the sequence to change a target/ion source assembly.

5. In the present ISAC pre-separator, the focal plane slits and the laser window port require manual maintenance and replacement. The dose rates for these operations are quite large. This is especially problematic for regular cleaning of the laser window port on the pre-separator magnet vacuum chamber.

New ISAC Target Station Specification

To address the issues mentioned above, the new ISAC target station design will implement a hermetically sealed containment box on the target module and on the two exit modules.

A sealed containment box on the target module virtually eliminates the risk of contamination spread, allows the use of air-sensitive target materials, and provides the ability to pre-condition the module. On this last point, target/ion source assemblies in this new design undergo vacuum and high-voltage conditioning off-line prior to installation, so that they may receive primary beam immediately after installation. This modification will address deficiencies 1 to 3 listed above. To address the other issues, which are related to personnel radiation dose, we will have remote connect and disconnect of the target/ion source services. This feature will eliminate the need for cool down time before

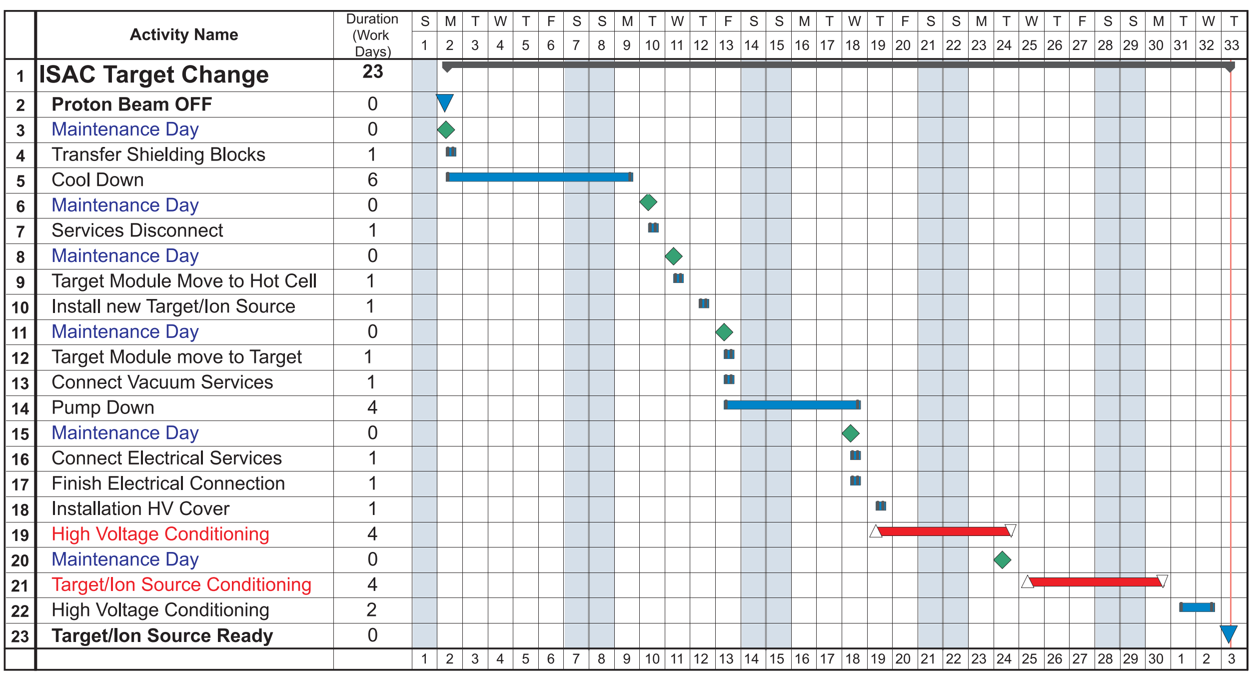


Figure 1: The target/ion source exchange sequence. This shows that each new target/ion source assembly takes about four weeks before it becomes operational. The main issue is the fact that the target/ion source conditioning and high voltage conditioning has to be done *in situ.*

removing the target to the hot-cell. With these modifications to design and operating procedures, we will be able to change a used, spent target with a fresh, ready-to-run target in two days (see Figure 2).

To accomplish this task, we will need to develop an all-metal seal system that connects the containment boxes, target, and exit module. Each containment box will be equipped with all-metal radiation resistant gate valves. The VAT® company offers a DN250 all-metal gate valve with a compact actuator that is suitable for this application. The connection between the containment boxes will be made with an all-metal C-seal joint.

The remote handling crane coverage in the new ISAC target hall will include the pre-separator slits (object and image) and the laser mirror, which includes the entrance laser window. A similar all-metal-seal system will be used to satisfy the remote services.

Hot Cells

The new ISAC target facilities will include two new hot cells. One hot cell will be fitted with specialized instruments for the target/ion source assembly exchange, and a second will be fitted with general-purpose equipment primarily for maintenance and repair.

The target/ion source assembly exchange hot cell prerequisites are:

1. Rapid target exchange turnaround,
2. High target exchange reliability,
3. Improved contamination control, and
4. Efficient module transfer.

To achieve a rapid target turn around, target/ion source conditioning will be done before the new assembly is installed for on-line beam production. The target/ion source assembly will be maintained under vacuum or control atmosphere so that it remains ready to receive beam. Because this hot cell will be specialized to perform only the target/ion source exchange, it will be specifically designed to limit the exposure of the module to the target contamination

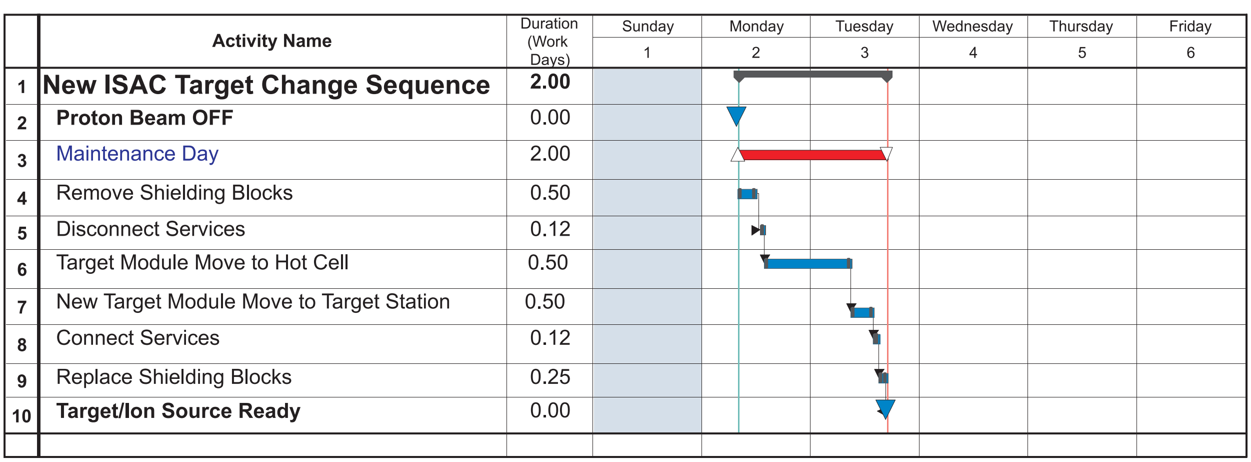


Figure 2: Target/ion source exchange sequence for the new ISAC target station.

volume. The module exterior will be isolated from the target containment volume. The hot cell will have a sealed transfer portal for target/ion source assemblies and tools. Spent target/ion source assemblies will be transferred directly to a shipping containment vessel.

The second hot cell will be more universal and dedicated to maintenance and repair of the modules, diagnostics, etc., and we see it being similar to the existing one; we anticipate adding a decontamination facility into this hot cell.

Target/Ion Source Conditioning Station

The present ISAC target/ion source assembly is not ready for beam when it is installed in the target station. Since it is exposed to air during the transfer into the station, it must then be baked, pumped, and high-voltage conditioned prior to receiving primary beam. To essentially eliminate this conditioning time, we will build a separate, off-line conditioning station for the new ISAC target/ion source assemblies. Preferably, this station will be equipped with a mass separator (R ~1000 for ε ~ 10 π mm mrad at 50 keV) for a complete evaluation of the new target/ion source assembly before on-line operation. Once the fresh target/ion source assembly is ready, it can be stored under vacuum while waiting to go on-line. The conditioning sequence is shown in Figure 3.

New Proton Beam Dump

At present, we are routinely operating the H^- cyclotron at 245 μA. For all existing facilities to operate at full capacity, the cyclotron would have to deliver 350 μA. The limitation on demonstrating an average current in excess of 295 μA has been a shortage of beam dump capacity. A beam dump capable of 200 μA is required to be able to develop the high cyclotron beam intensity required for operating all the targets simultaneously at full intensity. We are thus planning to install a new beam dump at the end of the new BL4N capable of 200 μA at 500 MeV (see Figure 4).

RIB Development at the New Target Station

Development of new exotic beams is essential for successful scientific exploitation of ISAC. Most of the scientifically interesting beams are created in very small amounts and require the full intensity beam. In general, each new element requires a different target material and optimum target design. Fur-

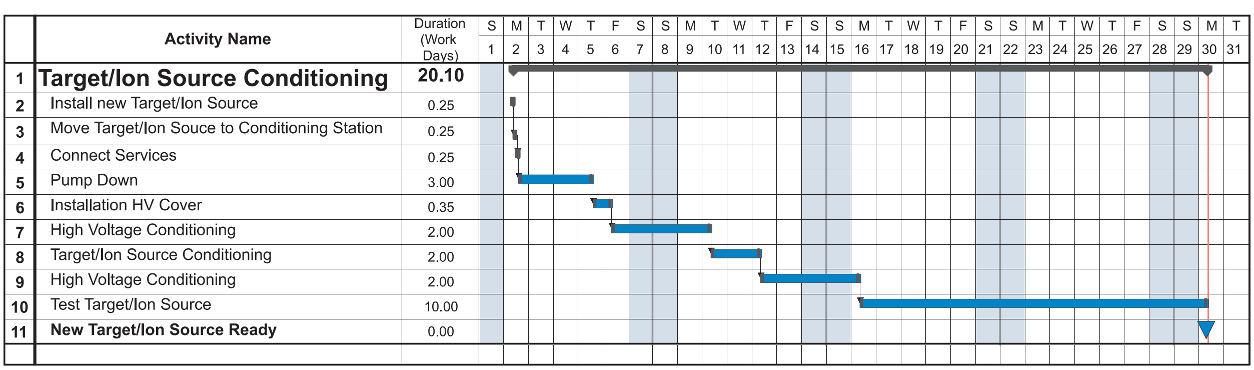


Figure 3: Target/ion source conditioning sequence in order to have a target ready for beam.

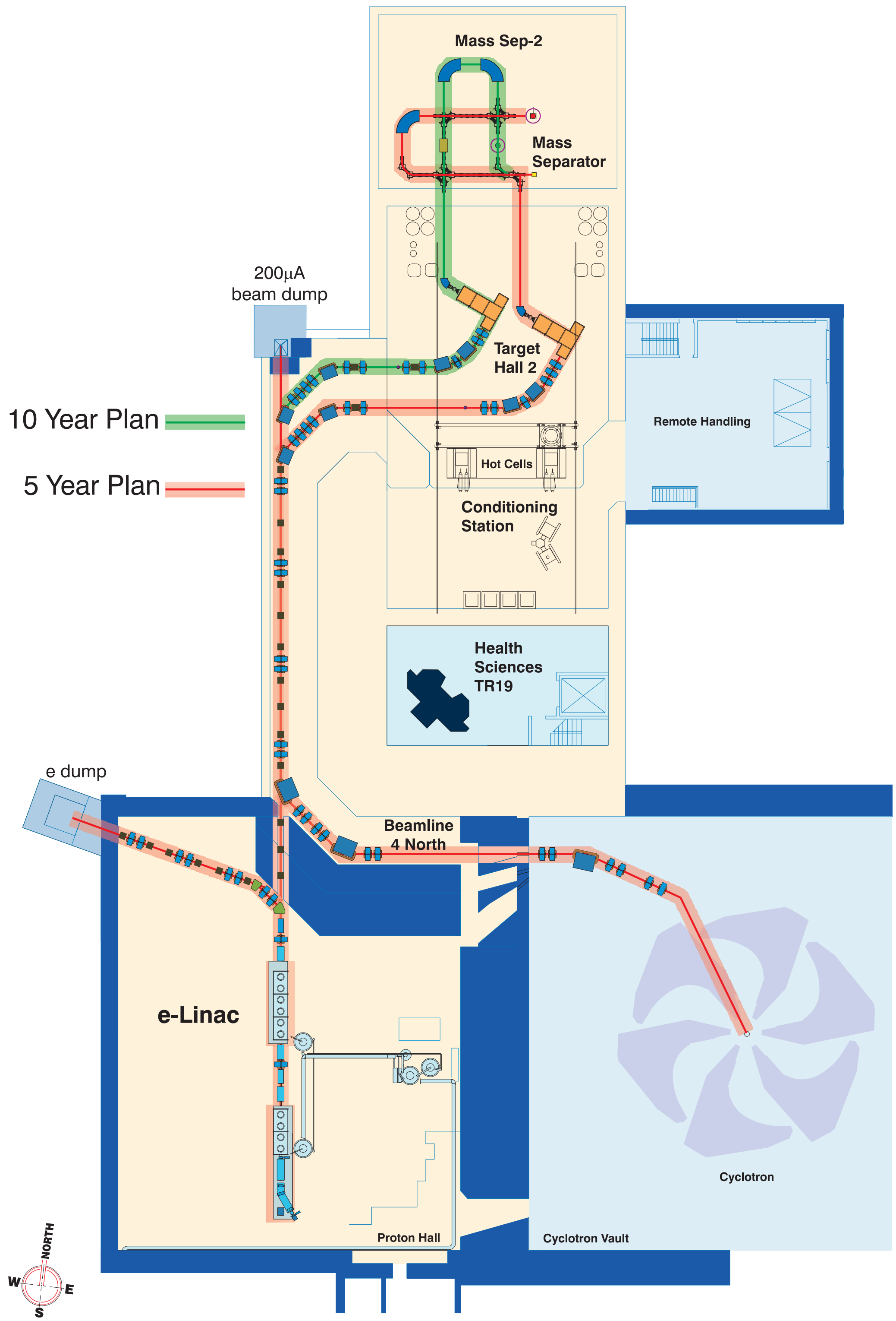


Figure 4: Plan view of the proposed layout to accommodate the new e-linac (to the right hand side of the cyclotron), two new target stations and their associated front-end optics, mass separator, and vertical section that will bring the RIB to the experiments.

thermore, many different types of ion sources are needed to cover the periodic table. As such, target and ion source development is an essential task in any ISOL facility and must be actively pursued at ISAC to ensure a successful long-term scientific program.

At the present time, ISAC has only one beam line (BL2A) for the transport of protons from the TRIUMF cyclotron to the target and two target stations (designated East and West). With careful scheduling of the two target stations, the actual interruption in isotope production can be kept to a minimum when beam production changes from an old target in one target station to a new pre-conditioned target in the other target station. However, for a given target station, each target change requires about a three to four week turn around from "beam off" to "beam on." Target development and on-line ion source development are not directly compatible with RIB delivery operation and are difficult to schedule with the long changeover times between targets. This has created the situation where about 25% of potential proton beam time is not available for scientific experiments while essential new targets are being developed. With the faster target changes at the new target station, target development can more easily be scheduled, and time wasted on resulting target changes significantly reduced. We foresee that by increasing these efficiencies as well as the number of targets operating at the TRIUMF-ISAC facility, by 2020 target development time will drop in percentage terms to about 12.5% while the available time for target development will increase from about 650 hrs/year to 1500 hrs/year.

Shielding Considerations for the New ISAC Target Station

The shielding for the new ISAC target station will be similar to what is in place for the existing ISAC target stations, because the proton beam energy and the maximum beam current are the same. A combination of steel and concrete will be used as it is with the shielding for all high-energy proton targets and beam dumps. The steel provides effective attenuation and moderation of the neutron

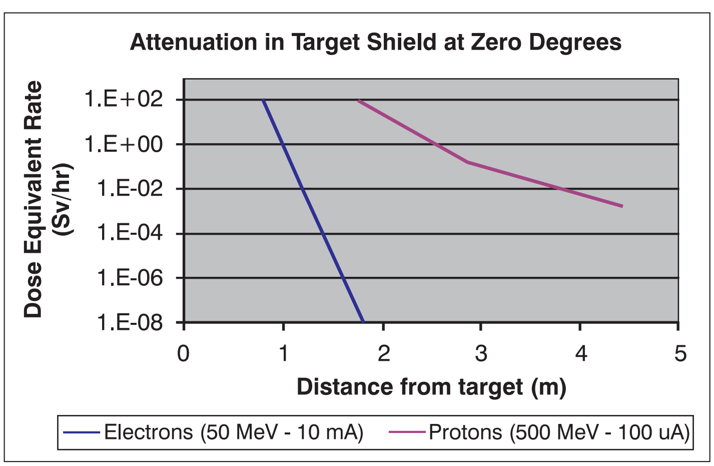


Figure 5: A comparison of the attenuation for a 500 MeV, 100 μA proton beam and a 50 MeV, 10mA electron beam at zero degrees.

energy down to a few MeV. Below that energy, elastic scattering dominates, and the lighter mass concrete is effective in providing attenuation. The shield transmission has been estimated using the Moyer model. The attenuation for a 500 MeV, 100 μA proton beams at zero degrees is shown in Figure 5. The change in the effective attenuation length from the inner steel shield to the outer concrete is seen at a target distance of about three meters.

Also included in the figure is the attenuation of the steel and concrete shielding for the bremsstrahlung production from a 50 MeV, 10 mA electron beam incident on a heavy production target at zero degrees. The energetic gammas will also give rise to neutrons from photonuclear reactions; however, the dose rate from these is two to three orders of magnitude less than that from the bremsstrahlung. Ultimately, it is the energetic neutrons from the high-energy proton beam that drives the requirements for the target shielding.

In addition, with the operation of actinide targets one can expect a potential maximum flux of fission neutrons of 1×10^{13} sec^{-1}. The outer layer of the target shield consists 1.2 to 1.5 metres of concrete. This thickness will be sufficient to moderate and attenuate the fission neutron spectrum to a dose rate of a few μSv/hr, in keeping with the TRIUMF limit for low occupancy areas.

Other considerations for the shielding will need to include:

- A reduction of the dose rate at the shield boundary to tens of mSv/hr to keep activation of the infill soil from the residual neutron flux well below

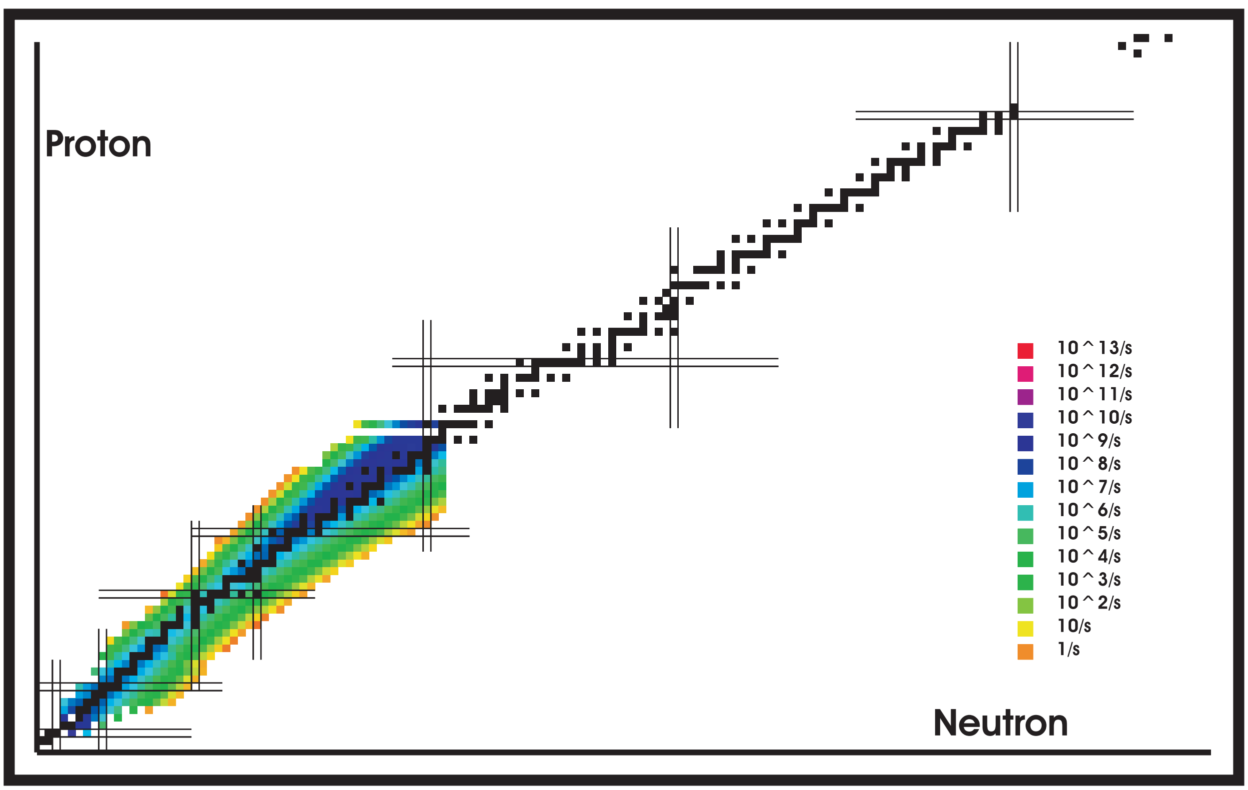


Figure 6: Production in target assuming 100 μA proton beam on a 10 g/cm^2 Nb foil target from Silverberg-Tsa parametrization.

the natural background activity in the soil.

- Hybrid steel and concrete blocks will need to be used above the target stations to effectively attenuate energetic neutrons streaming through the small solid angle of the service chase in the side of the target module.
- Use of low sodium concrete of approximately 0.06% by weight combined with the addition of boron carbide, approximately 0.2% by weight, to suppress the thermal neutron flux and, hence, the production of ^{24}Na in areas where personnel access.
- Prompt radiation fields in accessible areas will be kept below 10 μSv/hr and, ideally, the shielding will be designed to achieve 1 μSv/hr in these areas.
- Shielding for accessible areas in the proximity of the proton beam line will be adequate to keep dose rates below 1 μSv/hr in the event of an accidental loss of the full beam current. In addition, the area would be equipped with redundant Safety Critical Radiation Monitors to provide a fast shut-off for the proton beam and to keep potential doses below regulatory limits.

Safety and Radiation Monitoring System for the New ISAC Target Stations

The proposed operating configurations for BL4N to dual target stations and the target hall above those stations will influence the design of new radiation safety systems and the required modifications to existing radiation safety systems. The amount of shielding and desired operational flexibility will play a key role in determining the complexity of these systems. However, the following general assumptions can be made:

- Additional prompt radiation monitors will be required both inside and outside target shielding. These monitors must be interfaced to the existing 500 MeV Radiation Monitoring System and trip off the 500 MeV accelerator should radiation levels exceed acceptable levels.
- Additional accelerator interlocks will be required in the 500 MeV Central Safety System to ensure beams are being directed to the correct target station and that BL4N is off for access to beam line tunnels.
- A new safety system will be required to control access to the new Target Hall for local target movements under crane control.
- Information from residual radiation monitors for new targets, water packages, and hot storage areas will be required by multiple user groups, as will information from new local and nuclear ventilation air monitors.

Services for the New ISAC Target Stations

The nuclear ventilation in the new ISAC Target Maintenance Hall will be designed to have laminar flow across the hall to provide optimum airflow to all areas of the hall, eliminate dead zones, and facilitate monitoring for potential airborne radioactivity.

Shielding for the activated water package will be sufficient to accommodate the short-lived activation species such as ^{14}O and ^{16}N that have energetic gamma rays. In addition, shielding will be provided around the whole active cooling water package.

The volume of the primary exhaust in the new target station design will be limited to minimize the volume of exhaust gases generated from the primary vacuum. Several operating storage tanks will be provided for storage of the exhaust gases. These tanks will be connected in series to allow optimum decay before transfer to a series of decay storage tanks and eventually up the stack. With the smaller volume, the intent is to provide sufficient storage to allow residual activity to decay one year before releasing to the nuclear exhaust.

Expected Yield at the New ISAC Target Station

The new target station will allow us to use a proton beam with intensity up to 100 μA on a non-actinide target and up to 10 μA of protons or up to 10 mA of electrons on a ^{238}U target. Figure 6 shows the exotic nuclear beam intensity produces

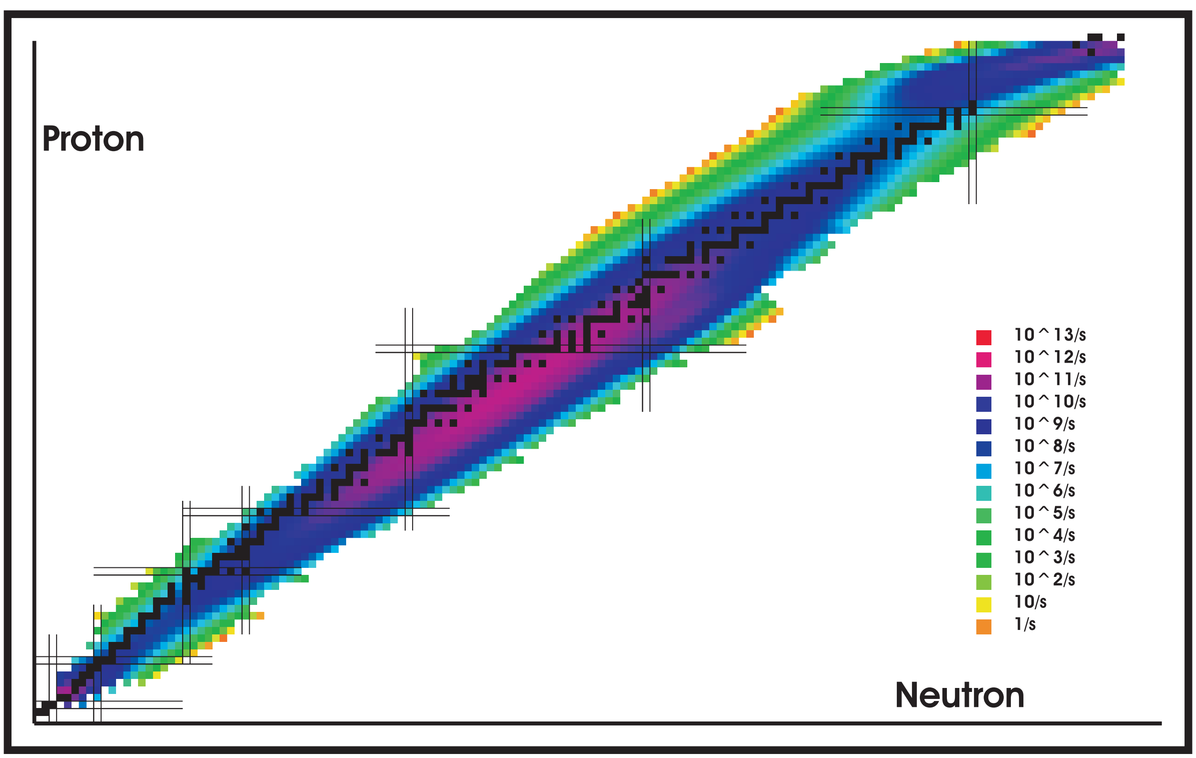


Figure 7: Production yield in target assuming a 10 μA proton beam onto a 25 g/cm^2 UC$_X$ target using FLUKA.

in target, assuming a 100 μA 500MeV proton beam on a 10 g/cm^2 Nb target. Figure 7 shows the in-target production using 10 μA on a 25 g/cm^2 ^{238}U target.

A Monte Carlo simulation of the photo-fission expected from a 50 MeV 10 mA electron beam has been performed. We used multiple electron scattering convoluted with the angular distribution of the emitted braking radiation. The photon beam is attenuated via various attenuation mechanisms: photo-electric effect: $E_\gamma < 0.1$ MeV; Compton scattering: $0.1 < E_\gamma < 5$ MeV: and pair production: $E_\gamma > 1.022$ MeV. Only the Compton and the pair production are taken into account because at low photon energy the contribution to photo-fission can be neglected. Figure 8 shows the photo-fission products distribution using 50 MeV 10mA electron beam onto a 15 g/cm^2 ^{238}U target onto a Hg converter.

Conclusion

The TRIUMF Five-Year Plan for 2010–2015 proposes to expand the ISAC capability to deliver two beams simultaneously with the possibility of extending this to three beams in the following five-year period. At the moment, only one RIB can be delivered at a time, creating a long list of experiments waiting for beam time. Between 2010 and 2015, we plan to build one new target stations allowing the delivery of two simultaneous RIBs to users. In addition to the existing ISAC target station, we will have one more target station in ISAC, compatible with either 100 μA of proton beam from the new cyclotron beam line or 10 mA of electron beam from a new electron superconducting linac.

The proposed new target stations use a similar target design as the one devel-

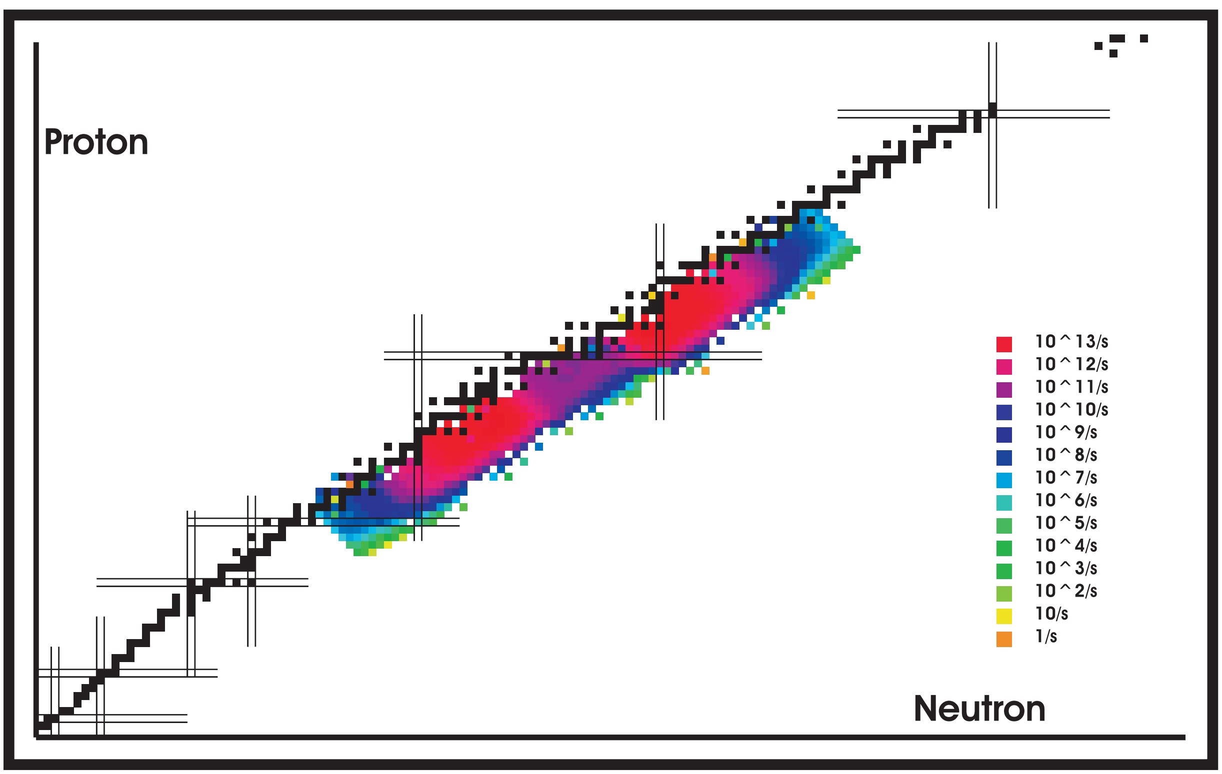


Figure 8: Production in target assuming 4.6×10^{13} photo-fission induced into a 15 g/cm^2 UC_x target.

oped at ISAC over the last 10 years of operation. This design can accommodate proton beams up to 100 μA on non-actinide targets and 10 μA proton beams and up to 10 mA electron beam on actinide targets. The proposed project is compatible with the ISAC scientific program.

6.2.1.2.4

Front End

Introduction

In the ISAC-I facility, 500 MeV protons at up to 100 μA can be steered onto one of two production targets to produce short-lived isotopes. The isotopes pass through a heated tube to a source where they are ionized, accelerated off the source high voltage platform at up to 60 kV, and sent through a mass separator to select the ion beam of choice. The beam is transported in the low-energy beam transport (LEBT) electrostatic beam line and sent via a switchyard to either the low-energy experimental area or to a series of room temperature accelerating structures to the ISAC-I medium-energy experimental area. For high-energy delivery, the DTL beam is deflected north along an S-bend transfer line to the ISAC-II superconducting linear accelerator (SC-linac) for acceleration above the Coulomb barrier.

The current isotope production facility has a number of strengths and weaknesses. They are:

Strengths

1. The cyclotron provides the highest power driver beam (50 kW) of any operating isotope separation on-line (ISOL)-based facility. High-power targets have been developed to fully utilize this beam power and have the potential to produce high intensities of exotic nuclei.

2. Two 50 kW target stations are available to help reduce the switchover time between targets.

3. The present facility is strong for nuclear astrophysics in the ISAC-I hall. The mass range of interest for this physics tends to be in the lighter masses so the radio-frequency quadrupole (RFQ) accelerator limitation of $4 \leq A/q \leq 30$ is high enough that charge state booster (CSB) operation is not required and efficiencies of the order of 20 to 25% can be attained dominated by the charge-state distribution after stripping at 150 keV/u. The flexibility and reliability of the accelerators coupled with excellent beam quality provide the capability for a successful user program.

Weaknesses

1. The present facility has nine major experimental infrastructures but only one rare-isotope beam (RIB) available at any given time. With the cyclotron typically shut down for four months each year, there is less than one month of beam time per experimental facility annually.
2. The beam time is further reduced due to target preparation and beam development for future experiments because there is no on-line target test area. The present target design and hot-cell arrangement, coupled with hall access restrictions, demands a four- to five-week turnaround time for target replacement and periodic vault access is required during the switchover. The vault access reduces the beam delivery time from the other target.
3. Other programs are pushing for actinide target use; however, the use of actinide targets is problematic with the present target design because the targets are craned to the hot-cell after use, and there is no provision for containment of any loose contamination.
4. The present accelerator layout is not advantageous for nuclear physics of heavy ions in ISAC-II due to the $2 \leq A/q \leq 6$ limitation. For masses with $A > 30$, the CSB is used but for ions with $A > 120$, the most probable charge state results in ions with $A/q > 6$ and the efficiency is sharply reduced for heavier ions. This limitation can be partially addressed in the short term by the addition of new power supplies in the ISAC-I medium-energy beam transport (MEBT) section to expand the ISAC capability to $2 \leq A/q \leq 7$ and $A > 150$.

Proposal

The aim of the proposal for a new ISAC front end is to get more RIBs on target to produce more physics. Fundamental to the plan is the eventual delivery of three simultaneous RIBs to three experimental areas. The expansion requires the addition of two new driver beams, one from a second cyclotron proton beam line and one from a new electron linac (e-linac), and two new independent actinide target areas plus a flexible front end capable of delivering the new beams to the experiments. The proposal addresses the key weaknesses inherent in the present ISAC facility and can be implemented in a staged way.

Features

1. Three simultaneous beams will at least triple the beam time on target. In addition, the electron driver beam could be available during the cyclotron shutdown periods either enhancing the beam time even further or augmenting development time.
2. Three target stations will facilitate target and source development. The new target stations will be designed for actinide target use with self-containment and will be engineered for a turnaround of only a few days.
3. The new installation will be designed with independent separators that allow simultaneous operation.
4. A new accelerator path will be created to be compatible with beams up to $A/q = 9$ so that all CSB-produced beams, including the existing ECR PHOENIX breeder, can be used at the most probable charge state for all masses.

Stages

1. The first stage proposed for this Five-Year Plan includes the additions of:
   a. The e-linac to 50 MeV, 1 mA (50 kW) capability; 30 MeV by the end of 2012;
   b. The completion of BL4N to a capability of 500 MeV, 200 μA (100 kW) by the end of 2014;
   c. One new target station with 50 kW electron/proton capability by April 2013;
   d. A new medium-resolution mass separator (MRS) and low-energy beam transport (LEBT) to deliver beams from the new target station to the low-energy area by April 2013; and,
   e. A new CSB and LEBT to allow the acceleration of beams from the new target area by the end of 2014.
2. The second stage proposed for the next Five-Year Plan would include the addition of:
   a. The upgrade of the e-linac to 50 MeV, 10 mA (500 kW);
   b. A second new target station with 500 kW electron and 50 kW proton capability;
   c. An expanded low-energy section with high-resolution separator (HRS) allowing simultaneous beams from the two new target areas; and
   d. A new accelerator front end to allow two simultaneous accelerated beams.

Components

Pre-Separator/Mass Separator

General Comments

The isotope production methods at an ISOL facility are not generally very selective: spallation, neutron-induced fission, or photo-fission produce a huge variety of elements. Therefore, to deliver an isotopically pure beam to the experimental areas, an efficient separation method has to be used. The mass-separator performance specification is determined by the beam quality, the mass range of interest, and the desired transmission. The required performance is set by the mass difference along isobaric lines and the relative abundance of the various isobars. The mass resolution is the minimum relative mass difference $\delta m/m$ that can be resolved with a given system. The mass resolving power is the reciprocal of the resolution.

Three distinct goals of the separator system are:

1. Elimination of most of the radioactivity to avoid activation in the downstream transport or accelerator.
2. Elimination of the stable contaminants produced in the source system (stable isobars, isotopes with the same mass-to-charge ratio, and molecules), which can dominate the desired radioactive ion beam by several orders of magnitude.
3. Separation of all radioactive ion species.

The first goal is achieved by incorporating a low-resolution pre-separator magnet just downstream of the target/source. A resolving power of only ~100 is sufficient to remove most of the radioactivity at the image slit of the pre-separator. For light ions, the elimination of most of the contaminants requires a resolving power in the range of 1,000–2,000. In some particular cases, a resolving power of 20,000 could be needed. The selectivity of the source system could help to suppress these specific elements. As well, the use of experimental techniques to reject some unwanted components at the experiment can relax the separation requirements, resulting in a better transmission and reduced tuning time. In general, with heavier ions, the mass difference between isobars become smaller, and a mass-resolving power of 10,000 or more would be useful in many cases. There are some ions (*i.e.*, ^{8}Li for materials science investigations) where the resolution of the pre-separator is sufficient to separate the ion of choice, and a method of bypassing the mass separator would reduce tuning time significantly.

The beam quality is important in determining the resolving power of a certain magnetic system. The resolving power is given by the ratio of the magnet dispersion and the beam width at the focal point, $R_m = D_m/x$. Thus, beam emittance is an important criterion that affects the achievable spot size for a given tune. For example, the use of an RF cooler to reduce significantly the emittance of the beam entering a mass-separator system can significantly improve the resolving power.

Concept

For these reasons, it is useful to consider a switchyard that is, depending on the experiment, capable of low-resolution, medium-resolution, or high-resolution separation schemes. In general, the reduced resolution schemes are desired because it will reduce the tuning time required. The proposed configuration is shown in . Here, each of the two-target/source units has a pre-separator and individual transport lines directing the beams to a mass-separator Figure 1 switchyard. The beams after separation are directed to either one of two new vertical sections VS-2 or VS-3 for delivery to the upstairs experimental area. The pre-separator, associated optics and object and image slits would be housed in a shielded cave where the main radioactivity would be contained and key elements engineered for remote handling. Standard ISAC LEBT electrostatic components would be used to deliver the beam to either a medium-resolution spectrometer (MRS) or a high-resolution spectrometer (HRS). The medium-resolution leg would have a resolution of ~2,500 while the high-resolution leg would have a resolution of >15,000. The high-resolu-

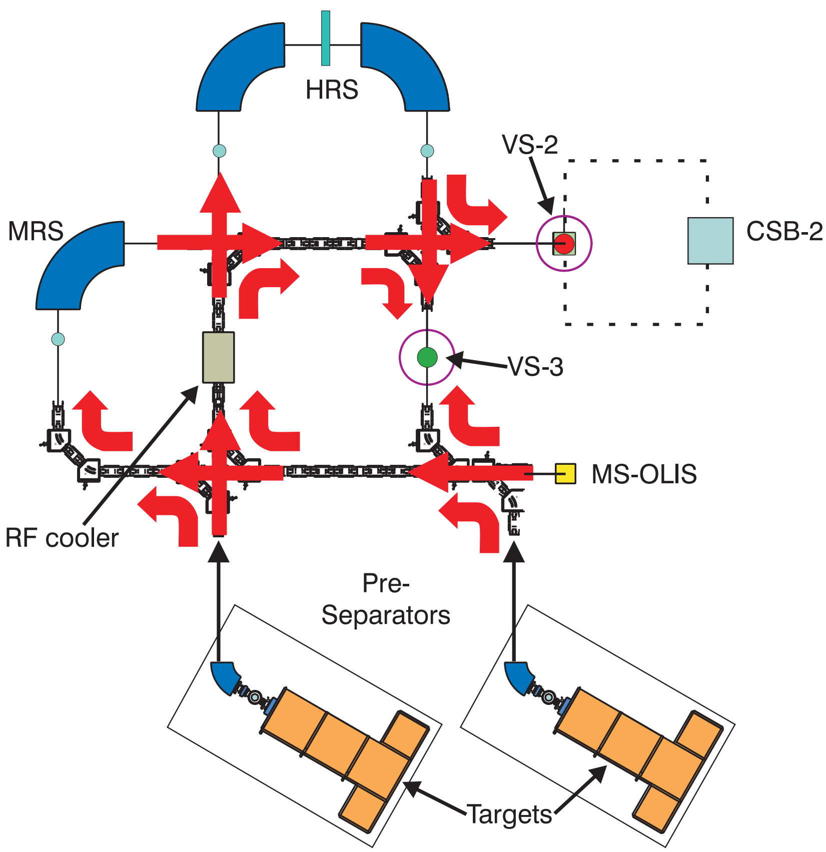


Figure 1: New target stations and downstairs mass-separator switchyard. The red arrows indicate possible beam paths. The MRS and HRS are accessible from either target via a flexible LEBT switchyard. The separated beam is sent upstairs via VS-2 or VS-3 to deliver beam to the accelerators or to the low-energy experimental area respectively. An off-line source (MS-OLIS) is available for separator tuning.

tion leg would be equipped with an RF cooler to reduce the emittance of the beam before separation. The switchyard is designed with sufficient flexibility that each of the targets can pass beams through the HRS while the beam from the other target can be sent to the MRS. In addition, a bypass line is available so that, if not required, a beam with pre-separation only could be sent to the experimental area.

The front-end-complex will be installed in stages. A first stage will see the e-linac being installed to produce RIBs from one new target station. This first target would require only one mass separator and vertical section to transport the new RIB beam upstairs. The proposed first stage of the mass-separator switchyard is shown in Figure 2. A bypass line allows beam delivery independent of the mass-separator.

RF Cooler for New Front-End Complex

To improve the performance of the high-resolution leg of the new facility, an RF cooler will be installed to reduce the incoming beam emittance before separation. An RF cooler offers reduced transverse emittance and energy spread, along with beam-bunching capability, for a wide range of masses on a timescale (< ms) appropriate for radioactive ion beams. Such radio-frequency quadrupole coolers have been under development for many years at several facilities worldwide and, at ISOLDE-CERN, one has recently been tested on-line. Other proposed facilities plan to make use of an RF cooler to improve mass-separation abilities, *e.g.*, SuperCaribu at ANL and ISF at the NSCL.

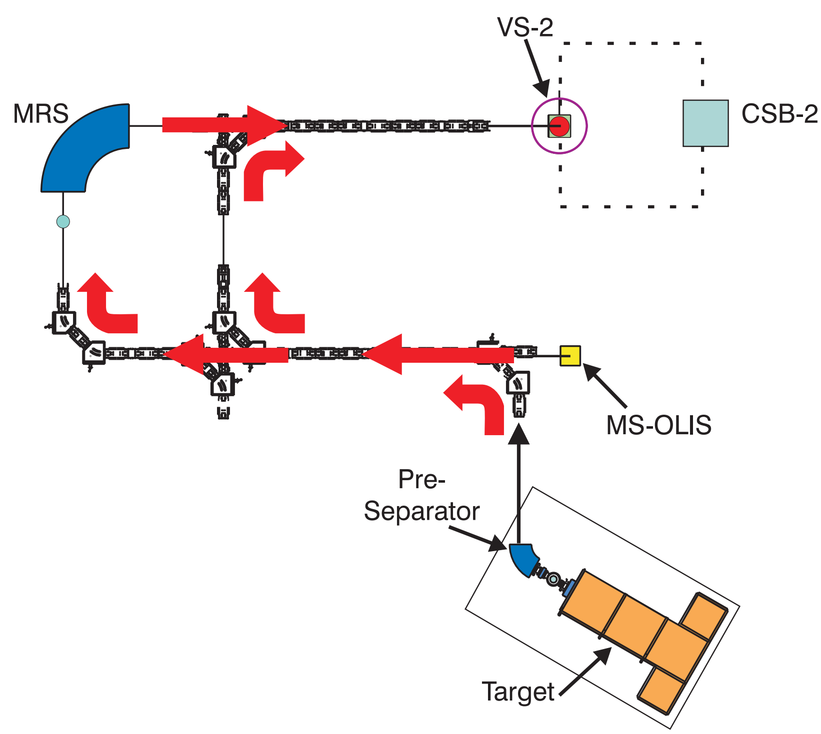


Figure 2: First stage of the mass-separator switchyard coinciding with the installation of the new target station.

At ISOLDE, the ISCOOL RF Cooler has been designed to be a general-purpose ion trap for the preparation of cooled and, if desired, bunched isotope beams. It is composed of three elements: an RFQ field for radial confinement; DC potentials for controlling extraction in bunched or continuous mode; and He buffer gas for ion-motion cooling. While the transmission through the RF cooler depends on the emittance of the target/ion source used, the resulting emittance is typically a factor of 10 better. For the few elements tested, transmission ranged from 20–30% for masses below 40, and up to 70–80% for higher masses when operated in continuous mode.

At ISAC-I, beams extracted from a surface ion source have emittances of about 10π mm mrad, whereas, from plasma sources, emittances are in the range of 20–30π mm mrad. With an RF cooler at the new front end, beam emittance could be reduced down to better than 3π mm mrad, enhancing the capabilities of the mass-separation system by at least a factor of three with a proportional increase in resolving power. Local expertise already exists at

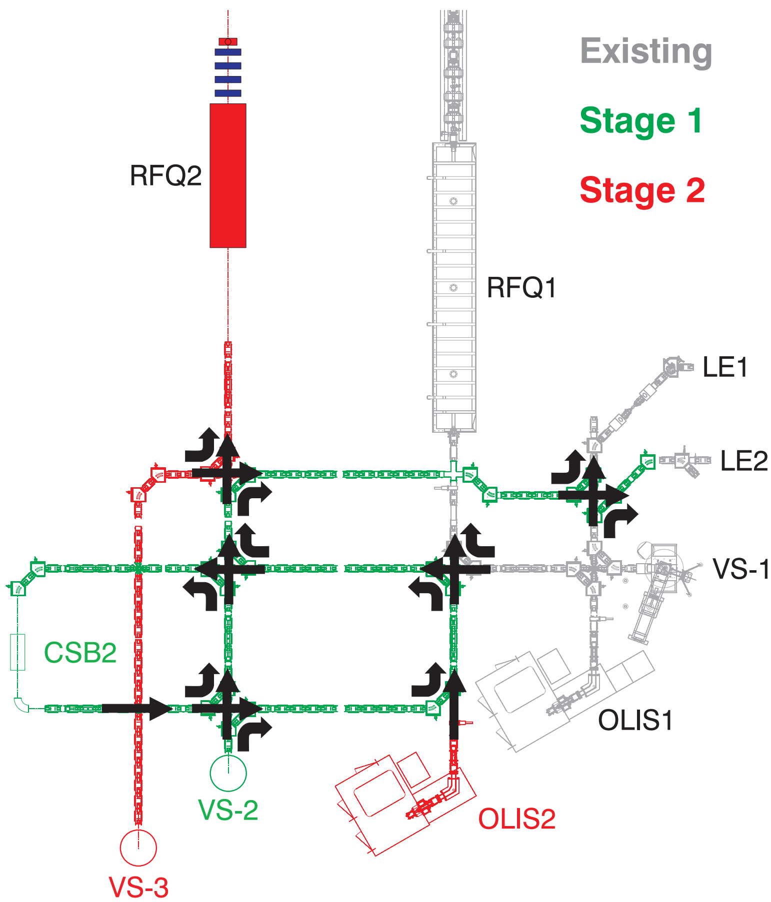


Figure 3: The new ground level LEBT for the new front end. The existing section appears in grey. The first stage installation is shown in green and the second stage is shown in red. The beam is delivered to the ground level from the target level through three vertical sections; VS-1 (existing beam), VS-2 (Stage 1) and VS-3 (Stage 2). The black arrows indicate the available beam paths.

TRIUMF as the TITAN facility has an RF cooler and buncher at the beginning of the ion-trap system.

Low-Energy Beam Transport

General Comment

The low-energy beam transport (LEBT) is the all-electrostatic transport that takes the beam at source potential (≤ 60 kV) from the downstairs target/separator area to the upstairs experimental floor for delivery to the low-energy areas or to the accelerators. Substantial LEBT transport has already been installed in ISAC-I. The design of the new installation will copy the standard building blocks that comprise the present installation. In the case of the LEBT downstream of the charge state booster (CSB), some modifications to the components will be required for it to be compatible with achieving a vacuum ($< 5 \times 10^{-8}$ torr) to transport high charge state beams with low loss. A design goal of the new installation is to provide enough flexibility that any of the target stations, existing or new, can deliver beams to any of the three experimental areas, low energy, medium energy or high energy, so that the RIB beams from each target can be optimized for a given experiment. Another goal is to provide a second path to the low-energy experimental area where there is the largest buildup of experimental infrastructure.

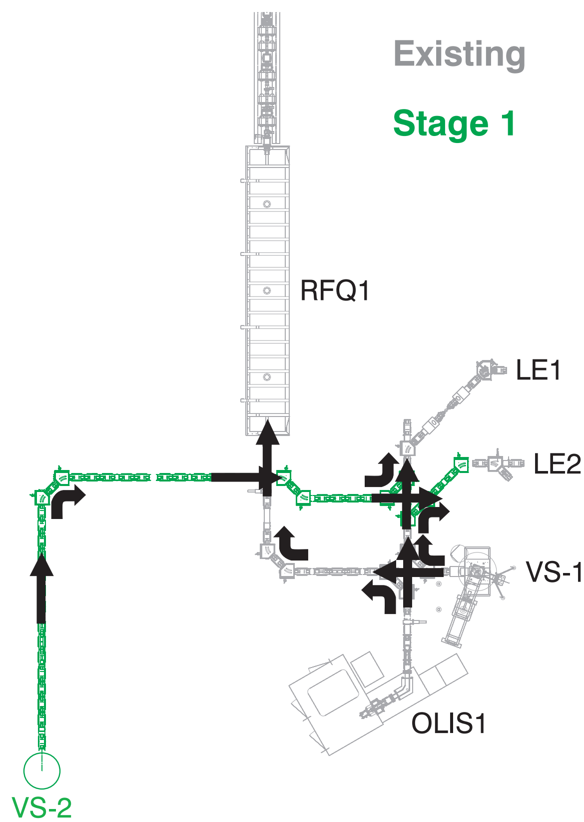


Figure 4: The first stage of the new front-end EBT.

Concept

The ground floor LEBT for new front end is shown in Figure 3. Two new vertical transport lines VS-2 and VS-3 bring RIBs from the new downstairs target area, adding to existing RIB line VS-1 to provide three simultaneous RIBs in the fullness of time. The new LEBT switchyard adds a new line to the low-energy experimental area that splits the area into two halves: LE1 feeds 8π, the general-purpose station and the future electron dipole moment (EDM) facility and LE2 feeds TITAN (TRIUMF Ion Trap for Atomic and Nuclear science), β-NMR, and Osaka. A switchyard is used to select which of the low-energy feeds goes to which experimental area. A second charge state booster (CSB-2) is added in Stage 1 to increase the charge state of beams selected for acceleration. An extra line is added so that beams from the existing target area can also be boosted in CSB-2 if preferred. In Stage 2, a second accelerator path is available with the addition of RFQ-2 positioned beside the existing ISAC RFQ-1. The new LEBT switchyard will deliver beam from any target to either accelerator front end for simultaneous delivery. A second off-line ion source (OLIS-2) allows tuning of either accelerator line while delivering RIBs to the other. The LEBT vacuum normally reaches 2 x10^{-7} torr. It should be noted that transporting the higher charge states from the CSBs would demand a better vacuum to reduce transmission losses ($< 5 \times 10^{-8}$ torr).

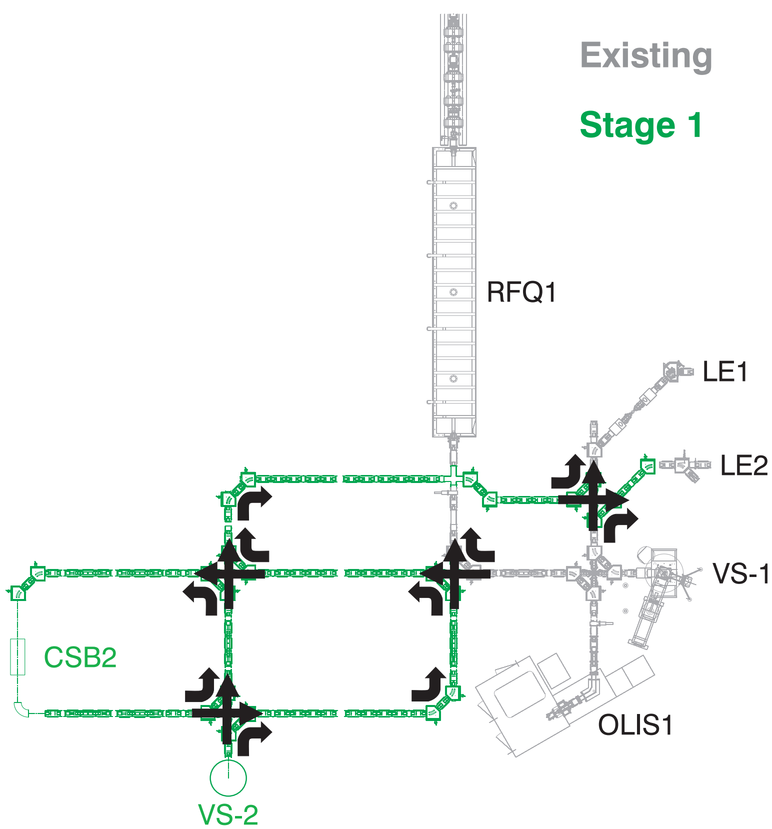


Figure 5: The continuation of Stage 1 will see the installation of CSB-2 to prepare both the ISAC-I and new front-end beam for acceleration.

Staging

The new front-end LEBT would be installed in stages as required by the target installation schedule and the experimental program. A first stage (see Figure 4) would see a low-energy transport line go from VS-2, fed from the new e-linac on Target 2 to the low-energy area. A new switchyard in the low-energy area will divide it into two equal halves: LE1 and LE2. The switchyard allows delivery of VS1 to LE1 and simultaneous delivery of VS2 to LE2, or vice versa. The LE1 transport feeds 8π, GPS, or the new EDM area. The LE2 transport feeds TITAN, β-NMR, and Osaka. The accelerated beam program is only fed from Target 1 coupled with CSB-1.

The Stage 1 installation would continue in Stage 1b with the installation of the CSB-2 and transport lines to allow charge boosting of beams and subsequent acceleration from Target 1 (ISAC-I) or Target 2 in the new target area (see Figure 5). With the planned installation, the new CSB-2 would be reachable from either the new Target 2 or the existing Target 1, with a common delivery to the existing RFQ. The last stage of the installation, Stage 2, would coincide with the installation of the second target station in the new front end, Target 3 (see Figure 1).

Charge State Booster (CSB-2)

Increasing the charge state of ions is done to reduce the total voltage required to accelerate ions to a particular energy. Common techniques to increase the charge state are: stripping the beam in a thin foil or charge breeding in either an electron beam ion source (EBIS) or an electron cyclotron resonance ion source (ECRIS). The former technique is used in ISAC-I for ions with mass $A \leq 30$. Here a 1+ beam is accelerated to 150 keV/u and passed through a stripping foil to achieve beams with $A/q \leq 6$. In the new front end, the specification will be expanded to include all masses ($A < 240$), and the requirements on the initial 1+ acceleration would be more demanding.

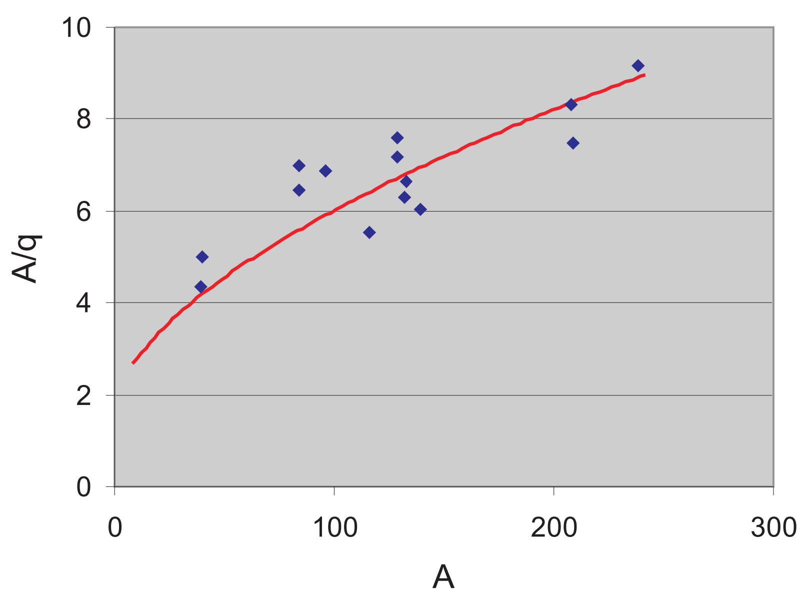


Figure 6: Expected *A/q* value for most probable charge state from CSB-1.

The technique of accelerating the 1^+ beam to a gas stripper at an intermediate energy was analyzed but abandoned as impractical due to the high accelerating voltage required. Of the charge breeding techniques, only the EBIS at ISOLDE is routinely used for on-line production. The EBIS source is presently operated as a pulsed device where a 1^+ beam bunch is injected and step-wise ionized in an electron beam axially focused by a strong solenoid. The REX-ISOLDE installation includes a combination of a Penning trap (REXTRAP) for ion cooling and bunching, and an EBIS (REXEBIS) for charge breeding. With the ECRIS, 1^+ ions are fed into a magnetically confined plasma region. Plasma electrons are heated resonantly in an RF field at their cyclotron frequency to allow them to strip the ions to higher charge states. The source operates in continuous mode with 1^+ ions continuously injected and n^+ ions continuously removed after some confinement or breeding time. The existing TRIUMF ECRIS charge state booster is a PHOENIX source with a confinement field provided by a room temperature solenoid and the RF field supplied at 14.5 GHz.

The charge state achieved is a function of the plasma density and confinement time. These values are determined by the magnetic field, RF frequency, and RF power. For the TRIUMF PHOENIX source, experiments have shown that the most probable charge is dependent on the mass of the ion with roughly the relationship shown in Figure 6. This shows, for example, that the present ISAC-I accelerator limit of $A/q = 6$ is exceeded for ions with a mass of $A >$ 100. This sets the present mass limit in the facility to $A < 120$. A modest upgrade to the ISAC MEBT would increase this limit to $A/q = 7$ and extend the mass range to A ~150. Typical production efficiencies in the most probable charge state from the PHOENIX source are in the range of 5%.

Based on the REXEBIS and PHOENIX developments, some comparisons of the two methods can be drawn. As mentioned, the EBIS is now a pulsed device with a pulse rate given by the breeding time while the ECRIS operates in continuous mode. The EBIS has better performances in terms of the final charge state, of breeding time, and of beam purity with several orders of magnitude lower background. In addition, the method is not species dependent; the charge breeding of any element is possible. Short-lived heavy isotopes can be bred in reasonably short periods with an EBIS breeder. On the other hand, the

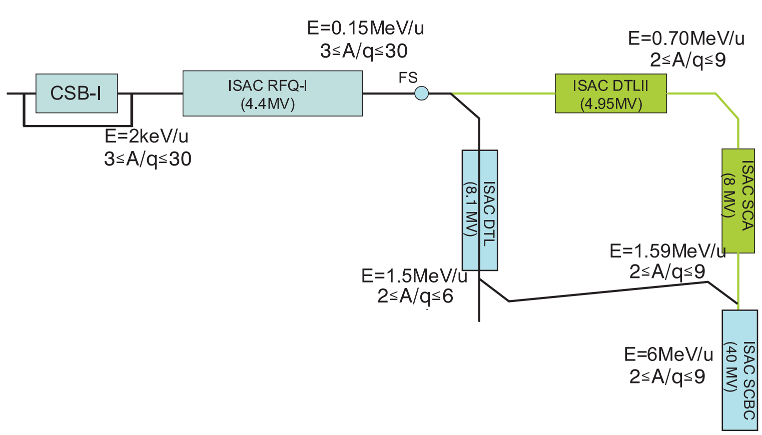


Figure 7: The existing ISAC-I and ISAC-II accelerator chain in blue and the initial upgrade of the new accelerator system in green.

ECR charge breeder has much higher intensity capabilities, operates CW, and is robust. Operating an EBIS will also require bunching and cooling in front of it. In principal, this can be done with a cooler in between the separator magnets, but it may be beneficial to have a dedicated one directly in front of the EBIS.

Parameter	REX-EBIS	PHOENIX
Efficiency	4-15%	2-10%
Breeding Time	13-500 ms	100-300 ms
A/q	2-4.5	4-8
Mode	pulsed	Cw
I max	Few nA	>1 micA
Emittance (20q keV)	15-20 mm mrad	15-20 mm mrad
Background	<0.1 pA	<2 nA
Complexity	High	Robust/simple

The technology choice for the new front-end charge state booster between EBIS and ECRIS sources will be made by 2010 after the on-line performance of CSB-1 (ECRIS) with rare-isotope beam delivery can be evaluated. TRIUMF also has a working EBIS on site with the TITAN experimental installation. The second accelerator path in this proposal uses an upper mass to charge ratio of $A/q = 9$ that is compatible with the existing CSB-1 source and either the EBIS or ECRIS choice for CSB-2.

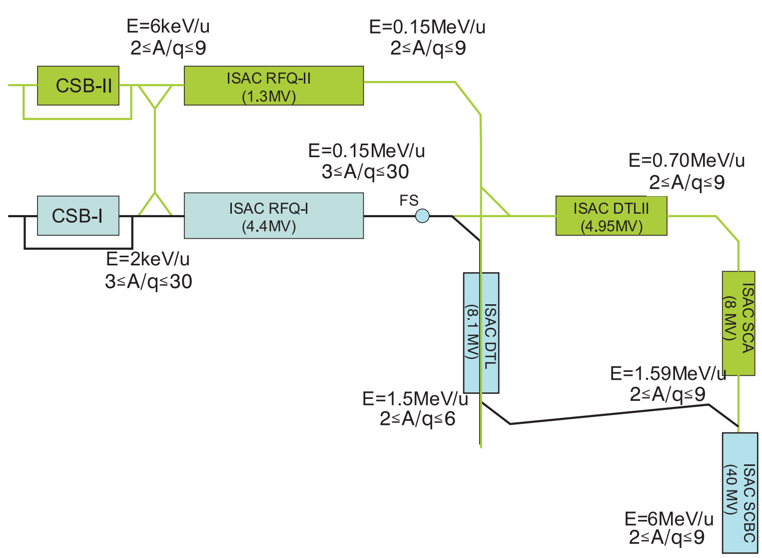


Figure 8: Schematic of the Stage 2 accelerator installation in green.

New Accelerator Path

The upgrade to the accelerator to allow two simultaneous accelerated beams is part of the second stage of the ISAC-II upgrade and so is not a part of this Five-Year Plan. The present ISAC-I RFQ-I can accelerate ions with mass to charge ratio of $4 \leq A/q \leq 30$ to 150 keV/u. The beam is then stripped to a charge state up to $A/q = 6$ for acceleration by the ISAC DTL. Beams from the ISAC-DTL are either sent to the ISAC-I medium-energy area ($0.15 \leq E \leq 1.8$ MeV/u) or sent to the ISAC-II SC-linac through an S-bend transport line at $E = 1.5$ MeV/u (see Fig 7).

To accelerate two beams simultaneously it is necessary to add a new accelerator front end fed from the new LEBT switchyard (see Figure 8). A new RFQ compatible with accelerating ions up to $A/q = 9$ takes the beam to 150 keV/u. The A/q limit is set by the most probable charge produced in CSB-I and II for heavy masses. A new beam line running north of the existing RFQ into the ISAC-I vault will provide separate paths for ISAC-I and ISAC-II accelerated beams avoiding the ISAC-DTL bottleneck of $2 \leq A/q \leq 6$. A new medium-energy transport section, MEBT-II (see Figure 9) incorporates a switchyard that allows sending either of the RFQ beams to either of ISAC-I or ISAC-II simultaneously. The new beam line to ISAC-II will include a room-temperature drift tube linac (DTL-II) to boost the energy from 0.15 MeV/u to 0.7 MeV/u for beams up to $A/q = 9$ and a low-β section of the SC-Linac to boost the energy of the ions to at least 1.5 MeV/u for injection into the rest of the SC-linac. A magnetic switchyard would enable beams from RFQ-I or RFQ-II to be sent to either ISAC-I or ISAC-II as required.

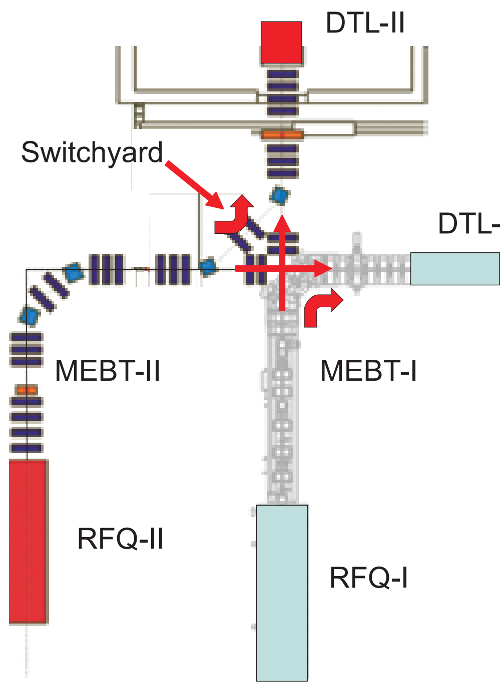


Figure 9: RFQ-II, MEBT-II, MEBT switchyard and matching into DTL-I.

6.2.1.2.5

Complementarity of Using Electrons and Protons for Neutron-Rich Isotope Production

Nature has an excellent way of producing a wide range of neutron-rich radioactive isotopes: fission of the uranium nucleus. Using a uranium target, short-lived isotopes can be produced using either a high-energy proton or an electron beam.[1] When an electron beam is used, the isotope production is dominated by exciting the giant dipole resonance, which then decays by fission to produce two intermediate mass isotopes. When a proton beam is

1 High-energy here means MeV, not the TeV of elementary-particle physics.

used, spallation, fragmentation, and fission processes all contribute to isotope production, with spallation contributing significantly more than the other two processes. The electron beam generating isotopes by a single process produces a limited range of isotopes, albeit in large quantities. Because a limited range of neutron-rich isotopes near the fission-mass peaks is produced, the beams are cleaner (*i.e.*, fewer isobaric contaminants). By contrast, the proton beam produces a wider and broader range of neutron-rich isotopes. This larger range leads to beams with significantly more isobaric contaminants. Thus, the strengths and weaknesses of the two targets are coupled. If the electron beam produces the isotope of interest, it would be the preferred production method. On the other hand, many isotopes of interest can only be produced using a proton beam on an actinide target. In particular, the production of radioactive actinide elements required for the fundamental symmetries program and the neutron-rich isotopes of elements below the light fission mass peak, required for nuclear structure studies of halo nuclei and neutron skins, can only be produced using high-energy protons."

The spallation process with ~500 MeV protons produces a spectrum of isotopes peaked at $Z = 45$, $N = 68$ with an approximate Gaussian shape of width $\sigma_Z \sim 11$, $\sigma_N \sim 4$. The photo-fission process produces two much narrower peaks centred at $Z = 38$, $N = 58$ and $Z = 54$, $N = 86$, respectively. The calculated isotope production yields in a uranium target from both production mechanisms are shown in Figure 1. Note that the rare-isotope beam intensities will be considerably lower than the in-target production yields because of losses in extracting the isotopes from the target and delivering them to experiments. This problem is severe for Z between 40 and 46,which are refractory elements not released by the target. Outside this range, measurements can usually be made when the in-target yields are above 10^3-10^5, depending upon the half life of the isotope and the ionization efficiency of the element.

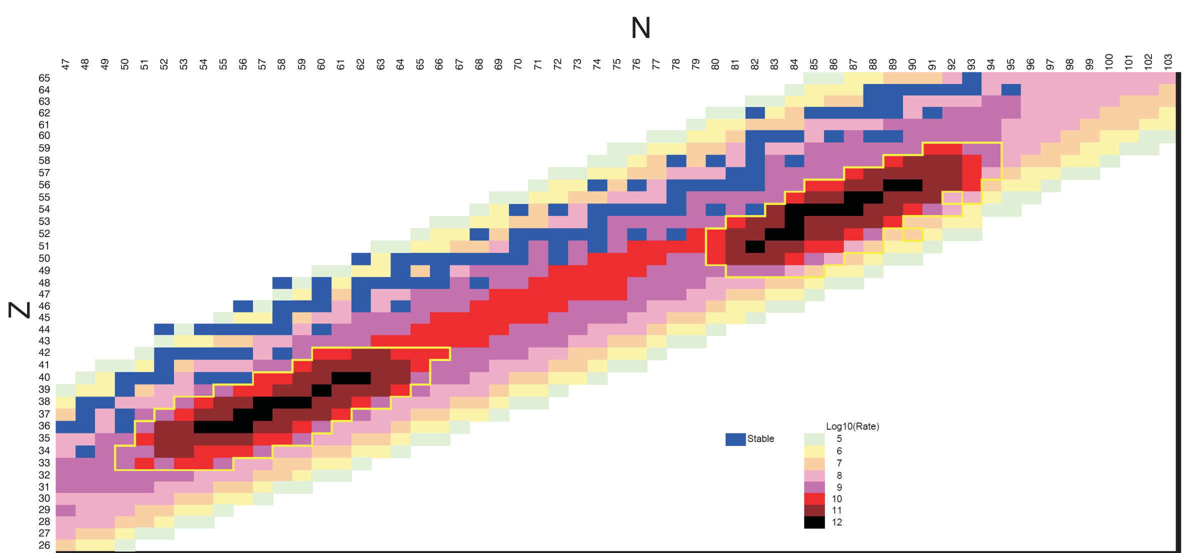


Figure 1: *Z* versus *N* plot of isotope production rates in a uranium target. The regions outlined in yellow are where the photo-fission dominates. Shown is the rate from the optimum of two production methods: 1 μA of 500 MeV protons in the majority of the diagram, and photo-production from 0.2 mA of 5 0MeV electrons in the two GDR peaks. The proton production rate peaks at 5×10^9 s^{-1} and the electron rate at 2×10^{12} s^{-1}.

The in-target production yields shown in Figure 1 were calculated for 1 μA of 500-MeV protons and 0.2 mA of 50-MeV electrons. These beam intensities are lower than the full intensity design limits by factors of 10 and 50 for protons and electrons, respectively. At these beam intensities the yield of neutron-rich isotopes near the fission fragment mass peaks produced by photofission exceed those obtained with high energy proton by nearly a factor of 400. However, the protons produce a large number of neutron rich isotopes that cannot be studied with a photon fission driver. The availability of both production processes at a single facility enhances the neutron-rich isotope reach of experiment. Furthermore, because the two techniques use different drivers, and maintenance of the drivers are normally scheduled at different times, rare-isotope beams can be available for longer than with a single driver. Figure 2 illustrates the reach of this combined facility for neutron-rich isotopes whose masses are unknown.

Isobaric Contamination

Practically all experiments at the on-line isotope mass separator (ISOLDE) facility at CERN that seek to go as far as possible from stability are limited, not from the low production of the most exotic nuclides, but rather from over-

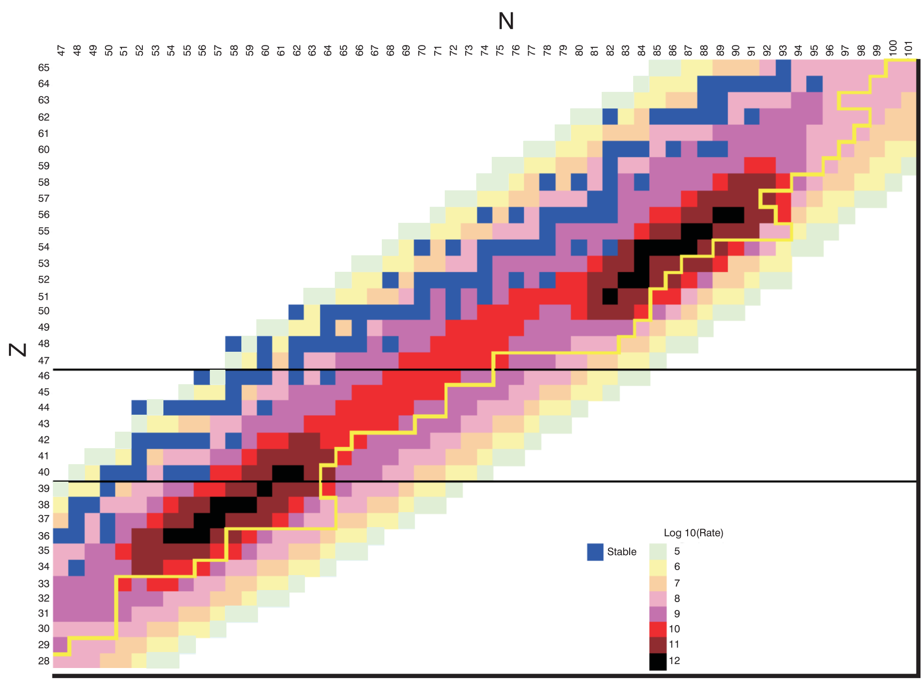


Figure 2: Rate of production of isotopes in the target. The masses of nuclides to the right of the yellow line are unknown (from: Nucleus-AMDC 2003). Between $Z = 40$ and 46, shown by black lines, the ion beam rate is suppressed due to the elements sticking to the target. Outside this range, mass measurements can be made when the in-target rate is above 10^5 per second. Thus, over 200 nuclides on this graph are potentially available for a first mass measurement. Significant improvements are also possible for hundreds more.

whelming isobaric contamination. Because ion traps have a limited space-charge capacity, they can easily be saturated with contamination, leaving no room for the isotope of interest. In the case of nuclear spectroscopy, the radioactivity from contamination causes too much dead time.

Resonant laser ionization has been a great help in reducing the density of isobaric contamination. However, surface-ionizable species are not suppressed so the result is often the same. Some success has been achieved with a special quartz transfer line that traps alkali atoms before the ionization region, but this technique, which is still in its infancy, makes for complicated and fragile target-ion source units.

Proton-induced fission is clearly unbeatable for certain regions: the light, neutron-rich species of interest for halo studies, the actinide region of interest of fundamental interaction studies, and the medium-mass ($A < 100$) proton-rich species. While photon-induced fission production may decline more rapidly far from stability on the neutron-rich side, it does possess one strong advantage in its comparative cleanliness. In the end, this advantage will probably prove to be decisive in forays towards the neutron drip line.

Some Specific Examples

One of the important "benchmark" nuclides is ^{132}Sn. Measurements of tin isotopes are thwarted by isobaric contamination from cesium and barium isobars that are surface ionized and three to four orders of magnitude more abundant. A recent mass measurement experiment of tin isotopes [M. Dworschak *et al.*, Phys. Rev. Lett. (2008)] uses a chemical sideband technique that tries to move the tins out from under the alkalis by making sulphur molecules. Unfortunately, alkalis also make molecules, and the experiment could not go beyond ^{134}Sn, despite a yield of over 10,000/s. This work was a continuation of the work in which, despite laser ionization of ^{132}Sn, it was impossible to overcome the Cs/Ba isobars [G. Sikler *et al.*, Nucl. Phys. A (2005)]. A glance at the photon-induced fission yields shows the Cs/Ba contamination to be lower than the yields of Sn.

The neutron rich beams for $28 \leq Z \leq 34$ should be much cleaner for photon fission than for proton fission because the intensity contours follow isobaric lines (rather than $N = Z$). While some contamination will still be present, it is at least not overwhelming.

Finally, for the lanthanide elements (for example, from Pm to Dy), the same argument holds: almost equal-intensity beams along isobaric chains for photon fission. These equal-intensity beams are in great contrast to proton fission where the situation is aggravated to the point of impossible experiments by a ridge of very high-intensity, proton-rich isobars.

In conclusion, given that experience shows isobaric contamination to be the bane of neutron-rich exploration efforts, any effort at increasing intensities must be accompanied by efforts in reducing contamination. The very mechanism of photon-induced fission is cleaner and would perfectly complement other areas of the chart where proton-induced fission is superior. With proven capabilities in mass separation and laser ionization, a combined arsenal of proton- and photon-induced fission, along with spallation, would make TRIUMF a truly unique facility, at the forefront of nuclear science.

6.2.1.2.6

International Competitiveness

First-generation rare-isotope beam facilities are operating in Europe, North America, and Asia and several laboratories are undertaking significant upgrades to prepare second-generation facilities. The first-generation facilities continue to produce important results, and ambitious experiments are planned with them in the next few years. However, the second-generation facilities are where breakthroughs, which will significantly increase our understanding of atomic nuclei, are most anticipated.

The research on rare isotopes is receiving global interest, and many countries are gearing up to engage in this exciting field (see Figure 1 and Table 1). Through TRIUMF, Canada has a unique opportunity to "strike first" in this high priority science endeavour.

In the report by the Working Group of Nuclear Physics of the Organisation for Economic Co-operation and Development (OECD) Megascience Forum, published in January 1999, one of the major recommendations stated:

> "The Working Group recognizes the importance of radioactive nuclear beam facilities for a broad program of research in fundamental nuclear physics and astrophysics, as well as applications of nuclear science. A new generation of radioactive nuclear beam facilities of each of the two basic types, ISOL and in-flight, should be built on a regional basis."[1]

1 OECD Megascience Forum, "Report of the Study Group on Radioactive Nuclear Beams to the Working Group on Nuclear Physics," Paris, France: OECD Megascience Working Group on Nuclear Physics, 1999, p. 39.

In-Flight and ISOL Facilities

The rare-isotope beam facilities are categorized as in-flight facilities and ISOL-type (Isotope Separation On-Line) facilities. In the ISOL facilities, the rare isotopes are produced inside a thick target at rest. They effuse out of the target matrix as neutral atoms and are ionized by a method that depends on the chemical element. The ions are then electrostatically accelerated to several keV and formed into a beam, mass separated, and delivered to the experiments or post-accelerated. With in-flight facilities, the primary heavy-ion beam hits a thin target at energies of some tens to hundreds of MeV/u. Rare isotopes are produced in the target and immediately recoil out at a similar energy to the primary beam. The rare-isotope beam is formed independently of the chemical element and can be separated using a combination of electric and magnetic fields. The beam is then delivered to the experiments at the same high energy.

The two different production processes are complementary as they provide access to different beams for different applications. ISOL production allows the production of many different isotopes but is limited in the chemical selection (refractory elements don't diffuse out of the target matrix) or the half-life of the isotope (if the extraction process is too long compared to the half-life, in reality the half-life limit is about 5 ms). The advantages of ISOL-type beams are the high intensity, excellent beam quality, and variable beam energy for experiments with stopped or post-accelerated beam.

Figure 1: Worldwide overview of leading rare-isotope facilities. The location for (US) FRIB has not yet been selected; therefore, it is placed arbitrarily in the middle of the country. (Note that this figure also appears in Chapter 2.)

In-flight production provides rare isotopes of all chemical elements (no target or ion source selectivity) and can reach very short half-lives (sub-ms). Ultimately, in-flight facilities will have a larger range of produced isotopes available for experiments. The secondary beam, however, is less mass resolved (different charge states are simultaneously produced, hence no unambiguous identification) and has poorer beam quality (higher longitudinal and transversal energy spread). It has discovery potential but will not provide for most of the science scope aimed for at TRIUMF. For example, the high-energy beams (50–1000 MeV/u) of rare isotopes are not suitable for probing the relevant regime for nuclear astrophysics. To provide partial access and to take advantage of the inherent beam properties of ISOL-type facilities, recent programs have started (RIKEN, MSU, ANL, GSI) to couple in-flight facilities to a low-energy program by injecting the rare-isotope beam into a gas-stopper cell, where the beam is brought to rest. It can then be extracted and formed into a low-energy beam for use with stopped or post-accelerated beams. The gas-cell stopping systems are still undergoing technical development, but none of the existing systems can operate fast enough to take full advantage of the half-life range of in-flight facilities (gas-cell extraction takes about 20–100 ms). Once fully developed, such systems will be able to provide the good beam quality needed for efficient post-acceleration, however, they are still limited in yields of rare isotopes.

Next-Generation Facilities

As Figure 1 shows, the global interest in rare isotope science has spawned many facilities. There are major facilities being built or already in operation that comprise second-generation technologies. European facilities are: GSI Darmstadt, Germany which has the approved upgrade to their international facility FAIR (Facility for Anti-proton and Ion Research); the SPIRAL facility at the GANIL National Laboratory in France which plans to upgrade to a hybrid ISOL and in-flight facility SPIRAL II; and the ISOLDE facility at CERN, Switzerland which plans to upgrade to HIE-ISOLDE. American facilities are: the Argonne National Laboratory ATLAS facility; the Holifield facility at Oak Ridge National Laboratory; and the MSU National Superconducting Cyclotron Laboratory (NSCL). In Asia there is one facility, RIBF (Rare-Isotope Beam Factory), at RIKEN (Rikagaku Kenkyūsho meaning "The Institute of Physical and Chemical Research") in Japan.

GSI, GANIL, ISOLDE, Holifield, NSCL, and ANL are first-generation facilities all in operation. The funded $US1.5 billion FAIR upgrade will be operational sometime between 2013 and 2015. GANIL plans to start operation of the SPIRAL II facilities in 2012, with stable beam, and, later, once regulatory issues have been resolved, with rare isotopes. The HIE-ISOLDE upgrade is envisioned for 2017. The US just announced the funding opportunity for a $540 million second-generation facility, with potential operation starting as early as 2017. The RIBF facility in Japan started operation in 2007 and uses the newest in-flight technology.

As indicated earlier, the largest range of isotopes can be produced at in-flight facilities, although the calculated intensity rates are as low as 10^{-6} ions/s. While at ISAC, experiments have been performed at intensities as low as 1 ion/s, the in-flight facilities only provide these beams (and rates) directly after production, hence at very high energy (between 50 and 1,000 MeV/u (depending on the facility).

The physics scope probed at these facilities is complementary to what is aimed for at ISAC and hence, as shown in Table 2, no in-flight facility has physics programs that include all of the four research pillars of nuclear astrophysics, in particular, those using post-accelerated beams, nuclear structure, test of fundamental symmetries (such as EDM or APNC) and molecular and materials science. Only ISOL-type facilities will be able to compete with ISAC on these science goals; however, the unique state-of-the-art experimental devices already available at ISAC will provide an enormous competitive advantage over all the new facilities. All the new facilities incorporate the multiple beam option as a critical component, a component that is also key to the TRIUMF plans.

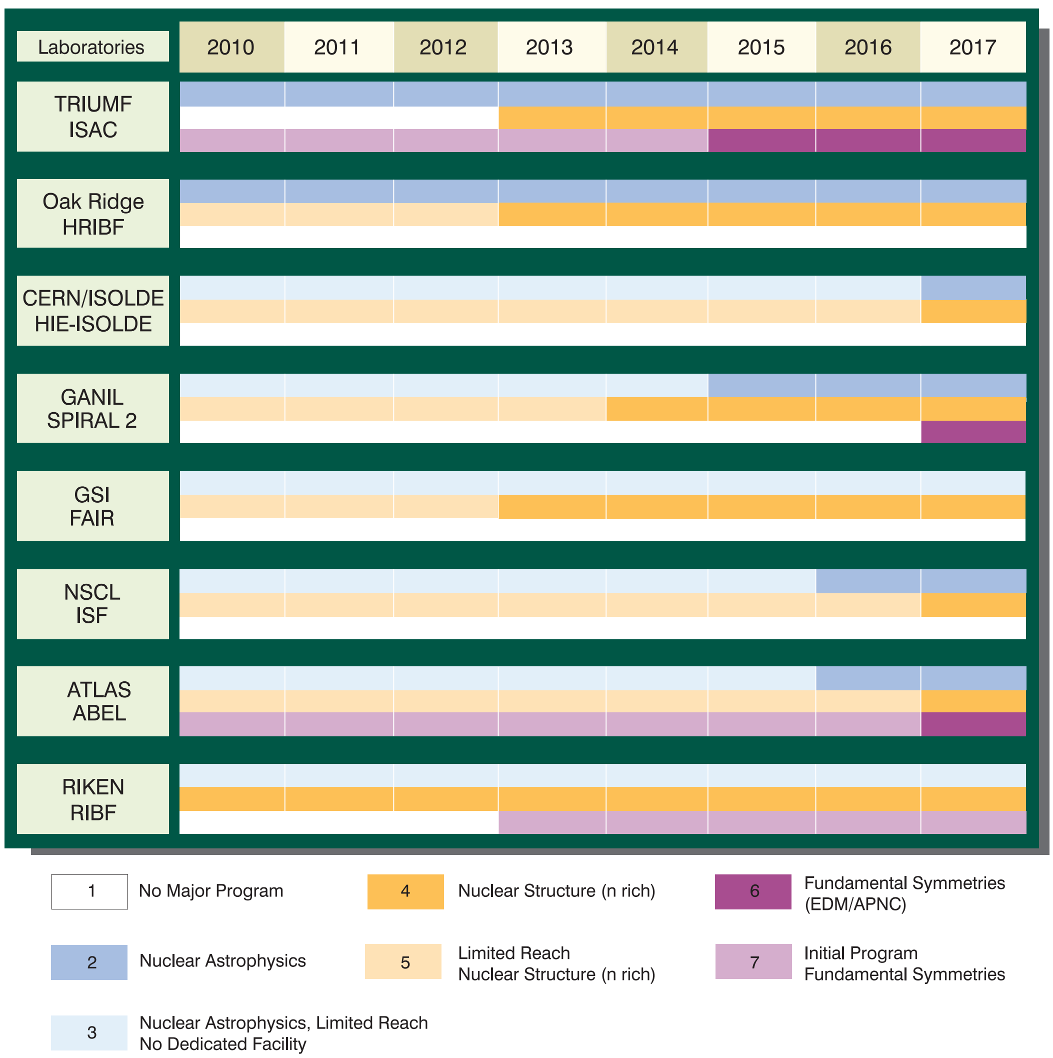


Figure 2: Comparison of key science programs addressed at present and future rare-isotope facilities. The three rows for each facility correspond to Nuclear Astrophysics, Nuclear Structure, and Fundamental Symmetries.

The window of opportunity presented by TRIUMF'S ISAC program and the next-generation upgrade is shown in Figure 2. This figure shows a comparison of key science programs addressed at present and future rare-isotope facilities. The figure displays the projected/proposed participation in physics fields for the years 2010 to 2017. The rare-beam facilities and their proposed upgrades are given on the left and the science areas are divided into: (1) No major program in the relevant field, possibly single experiments; (2) Nuclear Astrophysics, direct reaction rate measurements at astrophysical relevant energies; (3) Nuclear Astrophysics, with limited intensities, or no dedicated facilities, or no access to relevant energy range; (4) Nuclear Structure of neutron rich (medium or heavy) isotopes; (5) Nuclear Structure of neutron-rich isotopes, however, with limited reach; (6) Fundamental Symmetry studies such as EDM or APNC using rare-isotope beams; (7) Initial Program on Fundamental Symmetries including first measurements on Rn, Fr, and Ra isotopes.

The TRIUMF Five-Year Plan has a diverse program using neutron rich rare-isotope beams to study nuclear structure, nuclear astrophysics, and fundamental symmetries. As Figure 2 illustrates, this program is timely and internationally competitive.

Facility	Location	Operation	Plans
ISOL Facilities			
ISAC	Canada (TRIUMF)	Since 1999	e-linac (2013) 2nd p-line (2015)
Holifield	US (Oak Ridge)	Since 1997	e-rhodotron (2013)
ISOLDE	Switzerland (CERN)	Since 1968	HIE-ISOLDE (2017)
SPIRAL	France (GANIL)	Since 2001	SPIRAL II (2012)
In-Flight Facilities			
GSI	Germany	Since 1993	FAIR (2013-15)
NSCL	US (MSU)	Since 1990	FRIB-ISF
ATLAS	US (ANL)	Since 1996	FRIB-AEBL
RIBF	Japan (RIKEN)	Since 2007	

Table 1: An overview of the worldwide efforts involving rare-beam facilities. There is a clear complementary aspect in the different facilities, all having their own strengths and advantages.

Facility	Type	Max target time	Multi Beam ops	Expt at rest	Expts. at High-energy (~ 50 Mev/u)	Post-accel.	Nuclear Astro in inverse kinematic	Nuclear Structure	Fundam. Sym. (EDM APNC)	Atomic Physics	Material science
ISAC -I & II	ISOL p (up to 50 kW)	Up to 6 weeks	No	Yes	No	Yes (up to 12 MeV/u)	Yes	Yes	No	No	Yes
Next-Generation ISAC	p (up to 100 kW) photo-fission (up to 500 kW)	Up to 6 weeks	Yes (3)	Yes	No	Yes (up to 12 MeV/u)	Yes	Yes	Yes	No	Yes
ISOLDE	ISOL	Up to 6 days	No	Yes	No	Yes	No	Yes	No	No	Yes
HIE-ISOLDE	ISOL (*p* up to 9 kW)	Up to 6 days	No	Yes	No	Yes (up to 10 Mev/u)	Yes	Yes	No	No	Yes
Holifield	ISOL (up to 5 kW)	Up to 3 weeks	No	Yes	No	Yes (neg. ions up to 25 Mev/u)	Yes	Yes	No	No	No
Holifield e-rib	ISOL/ photo-fission (up to 25 kW)	Up to 3 weeks	No	Yes	No	Yes (neg. ions up to 25 Mev/u)	Yes	Yes	No	No	No
SPIRAL	ISOL (HI up to 6 kW)	Up to 3 weeks	No	Yes	No	Yes (up to 20 Mev/u)	No	Yes	No	Yes	Yes
SPIRAL II	ISOL (HI and *d* up to 200 kW)	Up to 12 weeks	Yes (5)	Yes	No	Yes (up to 20 Mev/u)	Yes	Yes	Yes	Yes	Yes
SPIRAL II	In-flight		Yes (5)	Yes	Yes	No	No	Yes	No	Yes	No
GSI	In-flight		Yes (2)	Yes	Yes	No	No	Yes	No	Yes	No
FAIR	In-flight		Yes (5)	Yes	Yes	No	No	Yes	No	Yes	No
NSCL	In-flight		No	Yes	Yes	No	No	Yes	No	No	No
ISF (FRIB)	In-flight		Ye (2)	Yes	Yes	Yes (up to 12 Mev/u)	Yes	Yes	No	No	No
ATLAS	In-flight		No	Yes	No	No	No	Yes	No	Yes	No
ABEL (FRIB)	In-flight (400 kW)	Yes (2)	Yes	Yes	Yes (up to 15 Mev/u)	No	Yes	No	Yes	No	
RIBF	In-flight (1 kW)		Yes (4)	Yes	Yes	No	No	Yes	No	Yes	Yes

Table 2: Overview of worldwide activity in rare-isotope beam physics. The shadings of the table group together facilities at a common locations.

6.2.2

Particle Physics

Science

The driving motivation behind particle physics experiments is the desire to uncover the true nature of fundamental forces and particles. Our current standard model is believed to be an effective theory, which has a deeper underlying theory reachable in the next generation of experiments. In the electroweak sector, where great successes of the past decades have predicted and verified the unification of the electromagnetic and weak nuclear forces, precision measurements at the CERN large electron positron collider (LEP) and the Fermilab proton-antiproton collider (Tevatron) demand that there be either a light Higgs particle with a mass less than about 200 GeV or a physical system mimicking its interactions. At the same time, the requirement that the theory be stable even with a Higgs, as well as the observation of cold dark matter in the universe, compellingly point to new physics at the Terascale.[1]

In the flavour sector, a decade of increasingly precise measurements of the properties of heavy quarks has shown remarkable agreement with the standard model predictions, and we are now moving into an era of precise investigations of the neutrino sector. The demonstration by the Japanese Super-Kamiokande and Canadian SNO experiments that neutrinos flavours oscillate but that their masses are likely much smaller than those of the other elementary particles suggests that there are critical phenomena in particle physics which cannot be

1 The "Terascale" refers to energies of one trillion electron volts, or 1 TeV, where 1 electron volt is the energy an electron gains when accelerated across 1 volt. 1 TeV corresponds to 1000 proton masses. Viewed in terms of length scales, 1 TeV corresponds to probing distances of 10^{-19} metres, about 10,000 times smaller than an atomic nucleus.

explained by the standard model. This physics likely had a very significant role in cosmology. There are some hints that this new physics might be accessible to upcoming experiments. In the strong sector, the theory of quantum chromodynamics (QCD) has been successfully used to predict the behaviour of quarks and gluons at high energies observed at the HERA collider at DESY Hamburg as well as LEP and the Tevatron, but the lower energy regime, where they are bound into particles such as protons and neutrons, remains theoretically and experimentally challenging and requires further investigation.

While the case for physics beyond the standard model is strong, there is no clear indication of what form the new physics will take. There is no substitute for directly probing the energy regime where the physics lies, so Terascale colliders are the highest priority in international particle physics. The two projects directly relevant to the 2010–2015 timescale of TRIUMF's new Five-Year Plan are the Large Hadron Collider (LHC) at the CERN laboratory, and the International Linear Collider (ILC). One of the critical areas that might be probed by Terascale colliders is the connection of electroweak physics to dark matter; experiments at the SNOLAB laboratory in Sudbury, including the DEAP and PICASSO collaborations, seek to detect the remnant dark matter directly in the low-background, deep underground facility. A direct observation of remnant dark matter in the laboratory would be a spectacular confirmation of its existence. The intriguing nature of the neutrino makes experiments that measure its properties compelling, and precise measurement in long baseline neutrino beams of oscillations in the parameter range suggested by atmospheric and solar neutrino experiments is another high priority in international particle physics. Another top priority is the investigation of the possibility that neutrinos act at least partially as their own anti-particles, which could enable neutrinoless double-beta decays. The upcoming projects in the 2010–2015 timeframe include the Tokai to Kamioka (T2K) long-baseline neutrino project in Japan and the SNO+ experiment at SNOLAB seeking neutrinoless double-beta decays. Experiments at the JLAB facility in Virginia are designed to measure the properties of hadrons precisely, in the range of a few times the mass of the proton, providing direct experimental probes of hadron properties in regions difficult to predict with theory and also to perform precision symmetry tests in nuclear physics to search for physics beyond the standard model.

We are poised on the edge of a new era in our understanding of the most fundamental constituents of matter and their interactions. Canadians, with the support and leadership of the TRIUMF laboratory, are at the forefront of this international scientific endeavour.

Experiments

ATLAS Physics at the CERN LHC

The Large Hadron Collider will define energy frontier physics for the next decades. Discoveries and measurements made at the LHC will determine whether higher energies or precision measurements of the new physics are needed as the next step. Canadians have been heavily involved in the construction and commissioning of the ATLAS detector at the LHC, and are well positioned to lead its physics studies. TRIUMF is a natural focal point for physics analysis in Canada for particle physics experiments. The laboratory can host faculty and students from Canadian universities, support meetings and workshops, and provide computing resources to Canadians. TRIUMF is also able to support a critical mass of user analysis support personnel. The anticipated LHC data accumulation profile, along with potential physics signatures observable with those data, is shown in Figure 1.

ATLAS physics analysis will require access to petabytes of data, CPU for analysis and simulation, and visualization tools. Physicists will access data using the Worldwide LHC Computing Grid (WLCG), including significant resources secured in Canada for Canadian ATLAS use beyond our commitment to shared WLCG resources. This will be a complex environment for performing physics analysis. Canadian coordination and user support beyond that typical of previous experiments will be essential. TRIUMF employs two ATLAS user analysis support people, funded currently from the CFI award for the Tier-1 centre. A TRIUMF scientist is also the ATLAS-Canada physics coordinator and hosts weekly Western Canadian ATLAS-Canada physics analysis phone meetings and coordinates the organization of tri-annual Canadian ATLAS physics workshops.

Maintaining a critical mass of scientists, faculty, post-docs, and students doing ATLAS physics analysis at TRIUMF will be key to the success of TRIUMF as a Canadian ATLAS analysis centre. TRIUMF is increasing the number of its ATLAS scientists with a primary focus on physics from one to three and is hiring a phenomenological theorist who will work with the ATLAS group. With this critical local mass in place, TRIUMF should naturally form a nucleus for ATLAS physics analysis in Canada. Providing office space and conference facilities to accommodate visiting Canadian ATLAS members will allow TRIUMF to provide this essential local support, enabling

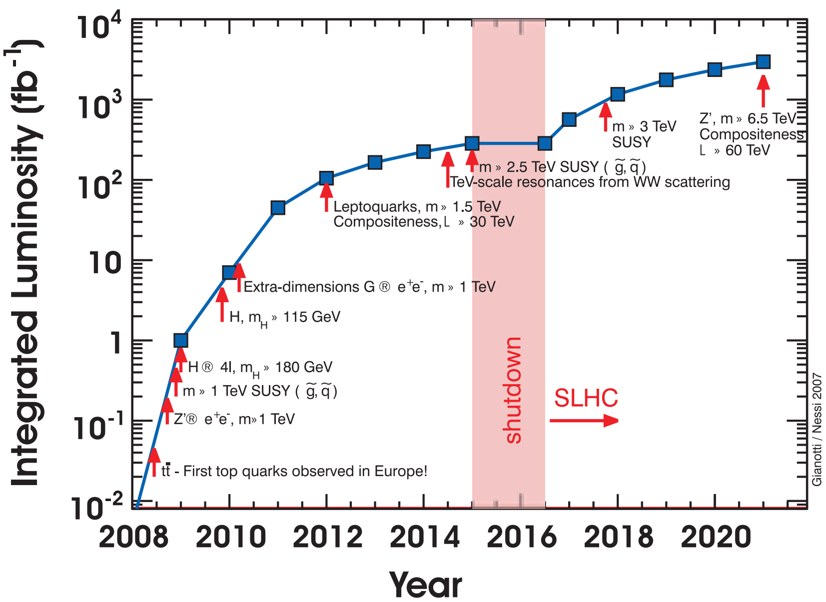


Figure 1: The anticipated integrated luminosity (data sample) ATLAS will accumulate for the next decade. Also shown are the thresholds where possible physics signals could be first observed. New physics signatures are particularly speculative, since we do not know which, if any, model is correct.

a major Canadian impact in the context of a globally distributed effort.

The ATLAS computing model uses a tiered system, allowing for scalability and distribution of resources around the world for the analysis of several petabytes (1 PB = 1,000,000 GB) of data accumulated by ATLAS each year. Data from the detector are first processed at a Tier 0 centre at CERN, and are then distributed to ten Tier-1 and about 50 Tier-2 centres for further processing and physics analysis. The Tier-2 centres are also used for detector and physics simulation, a critical part of all particle physics analysis.

The TRIUMF laboratory hosts the Canadian ATLAS Tier-1 computing and data analysis centre, which is part of the WLCG. Funding for the centre until 2011, including both hardware and personnel, was secured by ATLAS-Canada through the Canada Foundation for Innovation (CFI) Exceptional Opportunities program. In the 2010–2015 period, hardware renewal, personnel, and other operations tasks will be integrated into the TRIUMF program. While the annual hardware resource needs will grow steadily as the LHC acquires new data, the annual cost of these resources, including hardware renewal, will be approximately flat.

The TRIUMF resources required for ATLAS physics can be split into two categories:

- Canadian ATLAS Physics Analysis Centre:
  - Visitor desk space for a minimum of ten people, beyond TRIUMF staff. This will allow visiting faculty, post-docs and students to take full advantage of the opportunity of working with TRIUMF scientists and user support people, making TRIUMF a true centre of ATLAS analysis activity in Canada.
  - Meeting room space equipped with video conferencing ability is extremely limited at TRIUMF. In practice, it is difficult to use space for many ATLAS meetings, and impossible to host a few-day long workshop that requires teleconferencing ability. A dedicated meeting room equipped for teleconferencing would enormously increase the potential for TRIUMF both to host and engage in ATLAS physics activities.
  - A Tier-3 computing cluster for both TRIUMF personnel and visitors. These resources are not easily funded by either NSERC or CFI, and most universities are funding such facilities from other sources (including startup and other university funds). A minimal initial facility for TRIUMF personnel use would cost about C$25,000, and a facility for visitors would double that to C$50,000. The facility would need renewal over time.
  - The recent TRIUMF scientist hires will make a significant improvement in the local physics effort, more than doubling the TRIUMF scientist commitment to ATLAS physics. Adding two TRIUMF-funded contract-limited research fellows to support the regional analysis centre would make a significant increase in the physics output of the TRIUMF laboratory ATLAS group and its ability to lead Canadians in ATLAS. This would also provide a significant opportunity for TRIUMF to engage in the training of excellent physicists between the graduate student and faculty stages.

- Tier-1 Data Analysis Centre:
  - The precise computing requirements needed for the ATLAS Tier-1 centre are very difficult to estimate many years in advance. The computing resource needs are increasing approximately linearly with time, while the costs per unit are dropping. Personnel costs remain approximately constant. The current CFI Exceptional Opportunities Fund (EOF) award will provide sufficient funds to support the ATLAS Tier-1 centre through 2011. During the 2010–2015 period, the Tier-1 hardware estimated cost is C$8.2 million, including renewal of older systems, if we maintain our full ATLAS Tier-1 centre including resources dedicated to Canadian use.
  - Appropriate space with cooling and accessible electric power is also required. Room refurbishment to house the computers until 2015 will cost C$1.5 million.
  - The centre's operations costs for consumables, including power, will be about C$1.6 million.
  - In addition to computing hardware, the operations costs of the centre include personnel. These range from technical personnel such as system administrators, database and network experts to user analysis support personnel. Ten highly qualified technical experts are required to operate the Tier-1 centre, in addition to physicist managers.

T2K at J-PARC

The Japan Proton Accelerator Research Complex (J-PARC) accelerator will provide high-intensity neutrino beams to the T2K experiment starting in 2009, ramping up to full initial intensity using a 0.75 MW proton beam. During the following 5 years, the accelerator will continue to increase intensity while the experiment searches for $\nu_\mu \rightarrow \nu_e$ oscillations and measures the neutrino mixing angle θ_{13}, which is not known from solar and atmospheric neutrino measurements. If θ_{13} is sufficiently large, it may be possible to make a meaningful search for charge-parity (CP) symmetry violation by measuring the conjugate process with anti-neutrinos using an upgraded-intensity proton beam of 4 MW.

T2K construction is expected to be completed by the end of the current TRIUMF five-year planning cycle. Ongoing resources will be required from TRIUMF physicists for data acquisition support. The top priority for T2K during the 2010–2015 period will also be the extraction of physics. While the global distribution of data will not make distributed analysis coordination as severe for T2K as for ATLAS, it is still critical for TRIUMF to provide an infrastructure base for Canadians leading T2K physics analysis. Maintaining a critical mass of physicists at TRIUMF will also be a key for keeping a Canadian base for T2K physics analysis. TRIUMF will also become the analysis centre for T2K Canada, storing about 100 terabytes of data. While smaller than the Tier-1 centre, the scope is similar to the LHC physics analysis centre at TRIUMF.

SNOLAB Detectors

SNOLAB's ultra-low background places it centre stage in two quests: on the cosmic scale for interstellar dark matter and on the microscopic scale for neutrinoless double-beta decay. Astrophysical measurements indicate that 80% of the matter in the universe is "missing," that is, we can see its gravitational effects but it does not emit any heat or light. This "dark matter" is hypothesized to be the stuff that shapes the destiny of the universe, and yet we have no idea what it really is.

Experiments at SNOLAB will search for hypothesized rare interactions between dark matter and normal matter. On the microscopic end of the spectrum, neutrinoless double beta decay probes the very nature of antimatter. Advanced theories of particle physics and the Big Bang suggest that the neutrino particle may have a special nature: it might be its own antiparticle. Answering this question about the neutrino could reveal new insights into why the modern universe is predominantly occupied by matter (including dark matter!) rather than anti-matter. The initial program of SNOLAB will likely include experiments that focus on direct detection of dark matter (DEAP/CLEAN, PICASSO, Super-CDMS) and neutrinoless double-beta decay (SNO+, EXO).

SNOLAB was constructed with C$50 million from CFI for capital costs; a series of negotiations with NSERC, CFI, and the Ontario provincial government have secured annual operating costs of $C6M through 2009 and even to 2012 assuming federal investments continue. DEAP/CLEAN, SNO+, EXO and PICASSO have received NSERC funding for advanced prototyping, and all three are preparing CFI or NSERC proposals requesting construction capital.

In the near term, there are several projects for SNOLAB that would benefit enormously from on-hand TRIUMF expertise. The highest priority items include:

- Engineering and finite element analysis of the rope hold-down system for SNO+, and ensuring that the acrylic vessel is able to withstand the external pressure without buckling;
- Design and installation of electronics for the DEAP/CLEAN detector;
- Engineering and construction of the glove box and calibration manipulator system for SNO+;
- Liquid argon cryostat and cryogenic engineering for DEAP/CLEAN;
- Design, construction and qualification of the Alberta Low-Radon Laboratory (for DEAP/CLEAN and SNO+);
- Temperature control and hydraulic pressurizing system for PICASSO;
- Readout electronics for PICASSO;
- Shielding, pressure vessel design, for EXO; and
- Electronics/DAQ design for EXO.

At this stage of SNOLAB experiments, the primary need is for engineering and physics design expertise. As the experiments move into a construction, commissioning, and operating phase additional support in the form of shop time and technical expertise will be required. Estimates have been made of the amount of effort required on an ongoing basis. For the main Canadian efforts (PICASSO, SNO+, DEAP/CLEAN, EXO, CDMS) this will require the full-time equivalent of three scientists, three engineers/draftsmen and six technical support people.

ATLAS Upgrades, ILC R&D and other compelling projects

ATLAS Detector Upgrades

The initial ATLAS detector, set to begin collision data-taking in 2008, has largely completed installation and is being commissioned. It is expected to operate until approximately 2015, accumulating significant data sets for measurements of standard model processes at high-energy scales and searches for physics beyond the standard model. By about 2015, some parts of the LHC and the ATLAS detector will have suffered significant radiation damage and will need replacement; even with a fully working detector, the gain in experimental statistics from continued running at the same rate would be modest. What we foresee is an increase in the LHC interaction rates by an order of magnitude and corresponding upgrades to ATLAS to handle these higher radiation doses and detector occupancies. The primary upgrades for the LHC itself will be in the final focus region, achieving smaller beam spots by redesigning the collision optics, including adding magnets inside the experiments themselves. The ATLAS upgrades for the Super LHC (SLHC) will likely take place at the same time as the accelerator work to keep the period without physics data-taking as short as possible.

The upgrades needed to continue ATLAS operations in the SLHC era will be extensive. The entire tracking system near the beam intersection point will need to be replaced, including both the detector particle sensors and their readout electronics. This is particularly challenging because the new systems will need approximately an order of magnitude more active elements in order to cope with the extremely high occupancies expected at the SLHC, but the services (cooling, front-end readout electronics, cables) will have to fit into the same space. In addition to the tracking upgrades, the energy-measuring calorimeter systems nearest to the beam axis may see rates beyond their maximum operational values, and new detector systems and readout electronics may be required. The outermost ATLAS muon system will be difficult to operate due to large numbers of interactions from the increased numbers of low energy neutrons created at the SLHC, and technologies for either reducing the number of neutrons or coping with the high rates will be required. It took about five years of research and development (R&D) to develop technologies for the initial ATLAS detector, and another ten years to construct and install the full system. Taking advantage of our expertise from building ATLAS, we plan to compress that time frame to about three years of R&D and five years of construction and installation for ATLAS upgrades in order to be ready for ATLAS operation in the SLHC era.

Canadian groups made leading contributions to the design, construction, installation, and commissioning of the ATLAS liquid argon (LAr) calorimeter system, with critical leadership from the TRIUMF laboratory and the support of TRIUMF infrastructure for the contributions made from Canadian university groups. For ATLAS upgrades for the SLHC, several Canadian contributions are being considered, all of which require strong support from TRIUMF. NSERC has provided an initial one-year grant for R&D leading towards ATLAS upgrades, supporting, in particular, R&D for new technologies for high-rate calorimetry and high-rate pixel tracking detectors.

The LAr endcap calorimeters operate in a region with intense radiation and high particle fluxes. At the SLHC, the liquid argon itself may boil, critically reducing the effectiveness of these Canadian-built detectors. One option being considered is placing a very-high-rate calorimeter in front of the LAr endcaps. This could effectively shield the LAr endcaps from the highest particle rates while recovering some of their measurements needed for ATLAS physics. The TRIUMF group is actively engaged in studies of the environment in this detector region during SLHC running, and in R&D for technological alternatives for a very-high-rate calorimeter. The ATLAS Hadronic Endcap Calorimeters (HEC) have preamplifiers located in a high-radiation area. It is not known if they will survive to SLHC fluxes. TRIUMF is also studying new technologies that could be used to replace these electronics.

Canadian groups are also strongly interested in efforts to upgrade the ATLAS inner detector tracking systems, which will need complete replacement after about three years of full-LHC-luminosity running. R&D is ongoing on the use of chemical vapour deposit (CVD) diamonds in the ATLAS pixel detector upgrade, led by Canadian groups. CVD diamonds have radiation and thermal properties that may allow the most radiation hard detector using the least material of any of the current options. Canadians are also engaged in efforts to build new front-end readout electronics for the ATLAS upgraded silicon tracker (SCT) system. Critical to this effort is the development of the expertise for ASIC microchip design and development at TRIUMF.

The total infrastructure support for ATLAS detector upgrades that will be requested from TRIUMF depends on the technologies chosen and the Canadian involvement. If all currently foreseen projects proceed, about four engineers and four technicians (half mechanical, half electronic) plus about three designers would be required at a relatively constant activity level from 2010–2015.

International Linear Collider Detector R&D

Research and development for detectors for the ILC have been ongoing for more than a decade. Experience from the Large Electron Positron Collider (LEP) provides considerable guidance for the physics exploitation of a high-energy e^+e^- collider, but the goals set for ILC detectors are much more ambitious. The ILC detectors need to have ten times better momentum resolution, two times better jet energy resolution, and superb vertex resolution using much less material. For many years, the worldwide ILC detector R&D effort focused on individual detector subsystems (vertex detector, large volume tracker, electromagnetic calorimeter, hadronic calorimeter, and muon detectors). More recently, four detector concept groups have formed to develop optimized full detector systems, and the preliminary designs were included in the reference design report for the ILC. To be in step with the accelerator planning, a process has begun to prepare two engineered detector designs by 2010. A call for letters of intent to produce an engineering design report for an ILC detector has been made. From the submissions, two detector concept groups will be asked to go forward to the engineering design phase.

Canadians have made significant contributions to the ILC detector R&D over the past decade. The initial efforts focused on improving the intrinsic precision of time projection chambers (TPCs) necessary for ILC detectors to achieve their momentum resolution goals. The key element was to replace wire grids with micropattern gas detectors (MPGDs) such as gas electron multipliers and Micromegas devices. Prototype TPCs were built in Canada with MPGD readout and were operated at TRIUMF, DESY (Germany), and KEK (Japan). These were the first tests that demonstrated that the precision goals can be reached with this technology in strong magnetic fields. The MPGD TPC is now a leading candidate for the central tracker for the ILC detectors. Canadian ILC TPC efforts have been growing; today they include calibration systems, chamber gas systems, readout electronics, and overall system integration and engineering. Canadians are recognized international leaders in the ILC TPC design groups, including global coordination roles at the highest levels.

Canadians have more recently become involved in hadron calorimetry for the ILC. The requirement for fine segmentation in the hadron calorimeter to have good particle flow jet energy resolution is challenging. Canadian efforts are currently focusing on the readout of fine-grained scintillators for ILC hadronic calorimetry using silicon photo-multipliers (SiPMs).

The total infrastructure support for ILC detector work that will be requested from TRIUMF depends on the ILC timescales, technologies chosen, and the Canadian involvement. If all currently foreseen projects proceed, and the ILC construction proceeds according to a technically limited schedule, about five engineers and five technicians (half mechanical, half electronic) plus about four designers would be required at a relatively constant activity level from 2010–2015.

JLAB, SuperB and other projects

In addition to large-scale projects, TRIUMF has a strong history of providing infrastructure for particle detector R&D and construction for projects of smaller scales. The experience of TRIUMF engineers, designers and technologists has made contributions by university researchers to detectors at other labs possible at levels beyond those by the universities alone. Small contributions from TRIUMF can have a significant impact.

One such recent project was the central tracking chamber for the BaBar experiment at the Stanford Linear Accelerator Center B-Factory. TRIUMF provided a large clean room and experienced technical staff making the project possible. Canadians have led the physics output of several BaBar areas, including seminal results in tau-lepton physics and searches for new physics in rare *B*-meson decays. In 2010–2015, a strong team of Canadian researchers from the University of Victoria, UBC, Carleton University and McGill University may be involved in the construction of the detector for the "Super B-Factory" in Italy. While this project is not yet approved, its relatively short time scale would require detector construction to be completed during the upcoming Five-Year-Plan period. The Super B-Factory would probe to several orders of magnitude higher sensitivities than BaBar, possibly into the regions where new physics might be observed.

Canadian physicists have also played leading roles in the U.S. Thomas Jefferson National Accelerator Facility (JLab) program since its inception. In the coming decade, the JLab program will be centred on a significant enhancement of its capabilities through the "12 GeV Upgrade". Canadian subatomic physicists are already in leadership roles in this program, including:

- GlueX: a search for hybrid mesons predicted by QCD (Regina, Alberta);
- Experiments in Hall C to study QCD scaling (Regina);

- Gep-15: the measurement of the proton form factor to $Q^2 = 15$ GeV^2 (St. Mary's); and the
- 11 GeV Möller experiment (Manitoba, TRIUMF, UNBC, Winnipeg).

The first three are fully approved parts of the JLab 12 GeV scientific program, while the fourth will occur over a longer time, with a letter of intent now being written. TRIUMF infrastructure resources will be critical to the success of this effort, as they have been for the ongoing JLab program discussed in Section 4.2.2.5. Relatively modest contributions from TRIUMF will enable the continued leadership of Canadians in this program.

The total infrastructure support for other detector projects such as SuperB and JLab experiments that will be requested from TRIUMF will be relatively modest. Support levels around 2 FTE per year including engineers, designers and technicians, similar to previous periods at TRIUMF, will be typical.

Accelerators

Super LHC

The LHC will collide counter-rotating proton beams at centre-of-mass energies of 14 TeV, probing well into the Terascale regime. The LHC accelerator has been under construction for more than a decade, and first proton collisions are expected during 2008. The LHC takes advantage of the existing CERN accelerator infrastructure for its initial acceleration and injection chain, and the collider itself is built inside the existing 27 km circumference tunnel from the LEP facility. The LHC makes extensive use of superconducting magnet technology, which is used to generate the extremely large magnetic fields needed to bend the high-energy proton beams and steer them through the accelerator ring. The LHC bending dipole magnets have magnetic fields over 8 Tesla, about an order of magnitude stronger than the strongest permanent magnets. By circulating the proton beams, it is possible to use the same radio-frequency cavities over and over again to accelerate the bunched beams to high energy and, once full energy is achieved, repeatedly collide the same bunches of protons.

Once the LHC has begun physics operation, there will be a strong focus on exploiting the facility and extracting physics at the Terascale. The highest priority for the accelerator will be to consolidate and upgrade the reliability of its injection chain, some of which is 50 years old. The CERN European member states allocated 240 million Swiss Francs of new funds in June 2007, with a top priority of starting these upgrades. Combining those resources with international contributions, CERN plans to replace the earliest parts of the LHC injection chain including the linear accelerator (LINAC), booster accelerator, and the proton synchrotron (PS). These upgrades have begun and will continue through about 2015 and will allow, together with upgrades to the LHC itself, significant increases in the data-taking rate of the facility, eventually reaching an order of magnitude higher rates than the nominal LHC levels. The LHC and upgraded facility, referred to as the "Super LHC" or SLHC, will have the highest direct energy reach of any currently planned project. A sketch of the LHC injector system is shown in Figure 2.

Canada, through the TRIUMF laboratory, has made significant contributions to the LHC. The expertise of the TRIUMF accelerator group in radiation-tolerant magnets, fast electrostatic kicker systems, and power supplies made it possible to develop and construct the Canadian LHC contributions in Canada, fostering Canadian industry and training Canadians in these high-technology areas. For the SLHC, TRIUMF's developing expertise in superconducting radiofrequency (SRF) technology and close collaboration with PAVAC Industries Inc. makes key contributions to the SLHC possible. In particular, the upgrades to the LHC injection chain will include a high-intensity superconducting proton linear accelerator (SPL) with components well matched to TRIUMF's SRF group. The expertise of the TRIUMF accelerator group in the dynamics of high-intensity proton accelerators is also well matched to optimizing the new CERN Proton Synchrotron design, PS2.

SLHC-related accelerator contributions will require about one to two FTE per year of time from accelerator physicists, with contributions from three to four different people. TRIUMF would also work with PAVAC to design, fabricate, and supply a significant fraction of the superconducting RF cavities in the lower energy (so-called "β<1") section of the SPL. The expected capital costs for the cavity construction depends on the number of cavities produced in Canada; for scale, half the SPL β<1 cavities could be constructed in Canada for about C$4 million.

Superconducting RF development for the ILC

The ILC is a planned next-generation electron-positron (or anti-electron) collider. Unlike the LHC proton collider, the ILC will accelerate the electrons in a straight line. This is necessary because the much lighter electrons lose large amounts of energy due to synchrotron radiation when steered by magnets, and a very high-energy electron beam in a circular accelerator will lose more

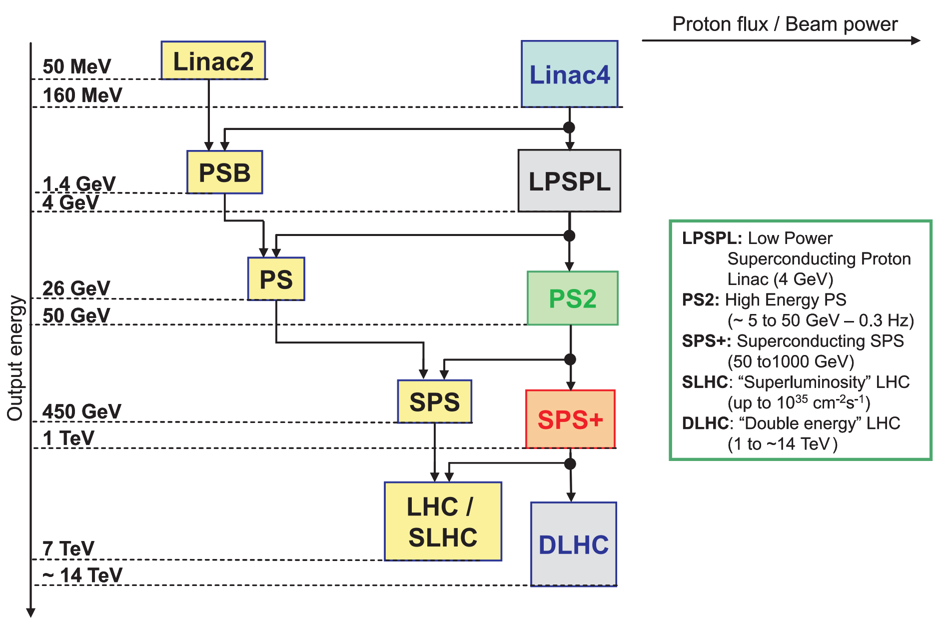


Figure 2: The current LHC injector chain is shown on the left, and the progressive new accelerators planned to consolidate the operations are shown on the right. The superconducting SPL and high intensity PS2 are ideal candidates for TRIUMF.

energy than can be practically replaced. The linear accelerator is a one-shot device, and large electric field gradients are required to accelerate the particles to energies that will allow probes of Terascale physics using a facility with a practical length. The baseline ILC design uses Superconducting Radio-Frequency (SRF) accelerator cavities with electric field gradients in excess of 30 million volts per metre (MV/m). The ILC will initially have centre-of-mass energies of about 500 GeV.

There is now a reference ILC design, and a detailed engineering design will be completed by 2010. Following this, the ILC funding, site selection and international construction partnerships will be clarified, and construction will start. A realistic success-driven schedule places first ILC particle collisions at the end of the coming decade. The period 2010–2015 will see the completion of R&D for the ILC component fabrication, particularly the superconducting RF acceleration cavities, and hopefully the start of major construction. While Canada is a full member of the ILC global design effort, the contribution to ILC accelerator R&D has so far been limited to a few small projects. With the adoption of SRF technology for the ILC baseline design, expertise from TRIUMF could allow Canadians to be strong contributors to this effort. The acceleration of charged particles in the SRF cavities being developed for the ILC is shown in a computer simulation in Figure 3.

The ILC is likely to be focused on R&D through most of the 2010–2015 period, although a technically limited schedule allows construction to start in the later part of the period. There are significant synergies across the TRIUMF and Canadian e-linac, SPL and ILC R&D efforts, including the collaboration with PAVAC. ILC accelerator efforts at TRIUMF will require an additional effort of about one to two FTEs per year from accelerator physicists.

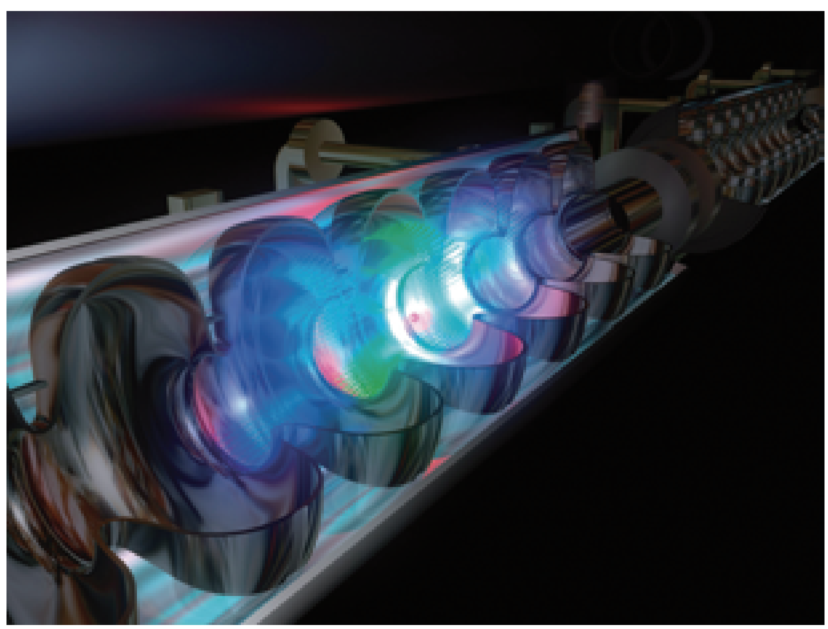


Figure 3: A computer simulation of the RF fields accelerating a charged particle in an ILC SRF cavity is shown. Figure courtesy DESY Hamburg.

6.2.3

Nuclear Medicine

TRIUMF's nuclear-medicine program is unique. The availability of outstanding accelerator (cyclotron) physics and chemistry, an outstanding ligand chemistry group, excellent PET scanning and imaging expertise, combined with established collaborations with high-quality programs in neurology with the University of British Columbia (UBC) and oncology at the BC Cancer Agency (BCAA), result in a program that has few, if any equals. The TRIUMF five-year vision proposes to provide vigorous support to the program as it unleashes its full energies on a multi-partner initiative in nuclear medicine.

Introduction

Medical imaging allows physicians and biomedical researchers to examine non-invasively the living human body in health and disease. Traditional imaging techniques such as computed tomography (CT) and magnetic-resonance imaging (MRI) are widely used to monitor human disease; however, many diseases do not cause disruption of macroscopic physical structure but instead alter functional relationships within and between organ systems. Functional imaging enables metabolic change to be visualized. Current PET ligands allow for the quantitative visualization of non-specific functions such as cerebral blood flow and glucose metabolism, neurotransmitter synthesis and storage, and neurotransmitter receptors. While extremely useful, such techniques are limited by the relative paucity of well-characterized specific ligands. There are very few tools to image cellular processes downstream to neurotransmitter receptors. Such processes, including induction of immediate, early genes or of transcriptional regulation, may play a key role in central nervous system disorders.

The Five-Year Plan proposes a major initiative at TRIUMF in nuclear medicine. This initiative will build on TRIUMF's strong points in molecular

DEAN KARLEN

R.M. Pearce Professor of Physics, University of Victoria

Dean Karlen, completed his B.Sc. at the University of Alberta in 1982 and Ph.D. at Stanford University in 1988. His Ph.D. thesis,"A Study Of Low Q2 Radiative Bhabha Scattering," described a new calculation and measurement of electron-positron scattering undertaken with the Mark-II detector at SLAC. In 1988, he returned to Canada to join the team at Carleton University, led by Robert Carnegie, building the vertex detector for the OPAL experiment at the Large Electron Positron (LEP) collider at CERN.

In 1989, Dr. Karlen joined the Faculty and moved to Geneva for the first three years of the LEP program. At CERN, he served as physics coordinator for the OPAL experiment, a collaboration of more than 400 physicists. After the great success of the LEP program, Karlen began participating in studies for the successor to LEP, the International Linear Collider (ILC).

In 2002, Karlen moved to the University of Victoria to become the R. M. Pearce Professor of Physics, a joint appointment with TRIUMF, and lead efforts to develop precision time projection chambers (TPCs) for the ILC. In 2003, he joined the T2K-Canada group.

Dr. Karlen has led the T2K TPC project since its inception, drawing on the many talents and resources of the detector group at TRIUMF, along with other faculty, staff, and students at the University of Victoria, UBC, and many collaborators in Europe. In addition, he is leading the Canada Foundation for Innovation funding application for the proposed electron linear accelerator at TRIUMF. ■

imaging, radionuclide research, and radiotracers; catalyze a national network for the development of cyclotron-based medical isotopes and radiotracers; and strengthen existing partnerships with TRIUMF's partners in life sciences. The nuclear-medicine initiative has the following elements.

- Upgrade and transformation of infrastructure
- National network for radiotracer development
- Focused research and development of microfluidics
- Expanded cyclotron targetry for PET isotopes
- Innovative techniques for mining novel radionuclides, especially from the new e-linac accelerator proposed at TRIUMF
- Strengthened existing partnerships.

This combined initiative will meet the demands of the existing program that is growing rapidly with strong, externally-funded projects with a need for facilities that meet regulatory oversight. It will also allow TRIUMF to address the needs of emerging programs wanting access to molecular imaging. Finally, it will support the national effort to work cooperatively in molecular imaging.

Major Initiatives

There is growing evidence that Parkinson's disease and other major disorders may result from impaired cellular protein handling. To better understand such processes, there is an urgent need to visualize gene and/or protein expression *in vivo*. Imaging of protein expression would essentially depend upon labeling of specific antibodies. While numerous technical hurdles may be associated with the development of agents designed to image gene expression, there is ample evidence of feasibility. The Nuclear Medicine Program will therefore pursue an approach in which oligonucleotides labeled with a positron emitter can be used to assess the degree of mRNA expression. This approach is essentially *in situ* hybridization performed *in vivo* and takes advantage of skills and experience already in place within the research group. The approach can theoretically be applied to the study of any gene of interest and will allow unrivalled diversity and specificity.

While the infrastructure provided by the collaboration between TRIUMF and the Canadian research community will focus on the labeling of functionally specific markers such as oligonucleotides and peptide fragments, new small molecule development will also be extended to take advantage of their ability to serve as surrogate markers for other processes. To enhance throughput for production of short-lived radioactive tracers, researchers will develop lab-on-a-chip technology. This technology will increase production efficiency by reducing the amount of starting materials and the time for chemical synthesis. Removal of impurities by chemical separation, which will lead to enrichment of the radiotracers, will also be accomplished on the same microchip, resulting in high integration capability. This lab-on-a-chip technology will allow for many production runs of different markers to feed into the scanning schedule to address a variety of biological questions on the array of scanners across the Network's community.

Upgrade and Transform Infrastructure

TRIUMF's role in the Canadian nuclear medicine community is different than its role in the subatomic physics community. In partnership with the Pacific Parkinson's Research Centre (PPRC) and the British Columbia Cancer Agency (BCCA), TRIUMF's Nuclear Medicine Program represents a research output at the forefront of nuclear medicine techniques. There is growing national interest in medical isotopes as evidenced by the proposal submitted to the Canada Foundation for Innovation (CFI) concerning cyclotron-produced radiotracers as well as the public debate surrounding the operation and possible upgrade to the Chalk River nuclear reactors used for isotope production. An expansion of the TRIUMF infrastructure in this area will allow the lab to take a leadership role in this wave spreading across Canada.

TRIUMF's involvement in the production of radiotracers for human experimentation requires an upgrade to meet Health Canada's Good Manufacturing Practices Guidelines for operation beyond the near term. This upgrade will allow for an expansion of TRIUMF's partnerships with the both PPRC and BCCA. Recognizing that radiotracer development in many ways mirrors the complexity of pharmaceutical development, a facility is needed that will streamline and speed the development pathway by pursuing a key innovation in process optimization rather than seeking to focus simply on developing a new narrow line of tracers. To exploit fully this opportunity, a new clean room facility containing six hot cells and a laminar flow hood is proposed. The present TR-13 cyclotron will be relocated to the basement of a new chemistry laboratory that would include a dedicated vault for the cyclotron.

It is proposed that these new facilities will be housed in new laboratory space within the Health Sciences Building under discussion with the province of British Columbia. This infrastructure upgrade will transform TRIUMF's nuclear medicine program and allow it to drive the development of the next generation of radiotracers for use in functional imaging for both basic and clinical research, with a focus on neuroscience and oncology.

Radiotracers

The development of new biomarkers for functional imaging will focus on the synthesis of radiotracers based on large molecules such as peptides, peptide fragments, oligonucleotides, and antibodies. Attaching a radionuclide to an organic entity requires the proper conditions to be rapid and high yielding. New approaches are being tested that will be used to fast track the development of a range of radiotracers that can be evaluated in a clinical setting. These radiotracers will not only address medical needs that have been defined within existing clinical research programs, but also serve to drive the development of a platform process for radiotracer development that will be equally applicable to the next generation of novel radiotracers targeted at other diseases.

The idea is to generate an imaging agent precursor (*e.g.*, peptide, folate, oligonucleotide) that can be labeled in a single step using aqueous ^{18}F to provide for high specific activity with minimal post-labeling work-up, much like with ^{64}Cu wash-in labeling of DOTA-linked conjugates. The novelty of this approach to labeling biomolecules with ^{18}F involves the formation of either boron-fluorine bonds or silicon-fluorine bonds instead of the hard-to-generate carbon-fluorine bond.

To exploit these opportunities, a proposal is being submitted to the Canada Foundation for Innovation (CFI) New Initiative Fund. With UBC-TRIUMF serving as lead, the proposed Pan-Canadian Network (The Network) will capture all of the cyclotron-based radiotracer facilities and take advantage of their capabilities in a synergistic manner. The funding requested for TRIUMF will provide the infrastructure for the functional imaging programs at UBC and BCCA to be further developed and augmented. In particular, it will provide the infrastructure for development of a platform for high throughput generation and production of highly selective, targeted radiotracers that can be tested for proof-of-principle in a research setting. The aim is to identify candidates suitable for clinical evaluation in important human diseases, such as Parkinson's disease, cancer, and heart disease. The Network will address an internationally recognized need for the establishment of a comprehensive functional imaging program that integrates basic research on medial isotope production with precursor molecule identification and synthesis, as well as clinical-grade small scale manufacture for the assessment and clinical testing of resulting novel radiotracer candidates. We propose an innovative approach whereby microfluidics technology will be applied to the development of the next generation of radiotracers for functional imaging.

There are few places in the world where both the expertise and the facilities exist to facilitate the establishment of a fully integrated functional imaging program. The Network is poised to become one of them. TRIUMF will be a unique, comprehensive facility for radiotracer development combining the radiochemistry research and production expertise at TRIUMF with the translational and clinical expertise of the PPRC, BCCA, the Brain Research Centre (BRC), and other basic and clinical research departments. The Network will use TRIUMF's core facility, which is composed of multi-disciplinary researchers focused on the discovery, development, evaluation, and application of novel, relevant radiotracers and their production in a cost-effective and reproducible way to support basic research and clinical applications in nuclear medicine. Along with the rapid development and assessment of fundamentally important new radiotracers, these researchers will produce technical innovations with a high degree of commercial potential, provide wide ranging health benefits to a broad sector of the population and further the establishment of Canada as a world leader in functional imaging technology.

The Network is proposed to include the following partners with UBC and TRIUMF as the lead:

- Active cyclotron-based programs
    - McMaster University
    - Cross Cancer Institute
    - Montreal Neurological Institute
    - Ottawa Heart Institute
    - Université de Sherbrooke
- Emerging cyclotron-based programs
    - BC Cancer Agency
    - St Joseph's Health Care (London, ON)

- Sunnybrook Hospital (Toronto)
- Thunder Bay (ON)
- University Health Network (Princess Margaret Hospital)
- University of Calgary
- Dalhousie University
- University of Manitoba
- Université de Montréal

- Terry Fox Research Institute
- Centres of Excellence for Commercialization and Research
  - Advanced Applied Physics Solutions, Inc. (AAPS), Vancouver, BC
  - Centre for Drug Research and Development (CDRD), Vancouver, BC
  - The Prostate Centre's Translational Research Initiative for Accelerated Discovery and Development (PC-TRIADD)), Vancouver, BC
  - Centre for Probe Development and Commercialization (CPDC), Hamilton, ON
- Private-sector companies
  - MDS Nordion
  - Siemens Medical
  - GE Healthcare
  - Edmonton Radiopharmacy Centre

As molecular biology unravels the various pathways for signal transduction and protein interactions, the targets for specific tracers has increased dramatically. The challenges the radio chemist faces are enormous. The development of a new probe (radiotracer) is akin to what large pharmaceutical companies deal with in their quest for new and better drugs. Canadian research centres are few and, in general, small, so our proposed new Network will help foster collaboration that will help each group benefit from the efforts of others. TRIUMF is the natural leader of this Network because of its strong connections to biomedical programs at UBC via both PPRC and BCCA. In addition, TRIUMF's expertise in accelerator science and technology and radiochemistry make it a crucial partner in any such national effort.

Microfluidics

The miniaturization of the radiochemistry that is used to prepare radiotracers has the advantage of higher yields, shorter reaction times, and higher purity, all of which provide for a more rapid translation from animal studies to human studies. This miniaturization, called a lab-on-a-chip, will initially focus on bringing our existing boutique of tracers to a scale that will allow simple, rapid production with minimal intervention. Chips will be designed to take advantage of the operations approach to labeling so that we can continue to exploit the advances made in preparing new compounds as they appear in the literature.

The required equipment will be used to microfabricate the chips for conducting microscale chemical synthesis. After microfabrication, the chips will be tested for various mixing, chemical reaction, and separation steps. Subsequently, the chips will be tested with radiotracers.

The regional team of TRIUMF, PPRC, and BCCA will work with Simon Fraser University, University of British Columbia, and the University of Alberta's nanotechnology centre to lead Canada and the world in the development of microfluidic capabilities. Microfluidics has been widely recognized as a barrier to broad distribution of nuclear medical capabilities because laboratories traditionally require trained chemists, wet labs, and hot cells. TRIUMF's role in developing microfluidic technology is therefore driven by its broader program in nuclear medicine and the interests of its partners to develop and deploy a set of tools for national impact.

Targetry

The need for improved yields and specific activity for radionuclides used in PET imaging has always been a continual battle. Recent developments have pointed to the benefits of using ultra-high specific activity. The existing TR-13 cyclotron at TRIUMF was designed to operate at 19 MeV with >100 μA of protons circulating; however, it was situated in a public area with localized shielding that was not capable of providing the necessary radiation safety at the machine's design parameters. At present, operation is restricted to 13 MeV with target beam currents of less than 25 μA. While this situation is adequate for a narrowly focused program, the new program will require greater capacity for routine production as well as for the development of new target-chemistry systems. This greater capacity will be especially important for developing highly concentrated high specific activity ^{11}C where we would like to have multiple curies in very small volumes.

The Canadian nuclear-medicine community is typically situated at teaching hospitals, but there is increasing recognition of the need to couple members of this community with accelerator and radiochemistry experts found at physical science research centres. Relocating the present TR-13 cyclotron would allow TRIUMF to take the lead in this evolution of the Canadian nuclear medicine community. Canada has traditionally been a world leader in the development and supply of radionuclides for medicine, but there are indications that, if Canada does not redouble its efforts in medical isotope production, in a few years the United States, a long-timer customer of Canadian medical isotopes, will simply replicate the Canadian program and render the Canadian advantage obsolete (see Appendix F for more information).

Mining Radionuclides

The spallation/fission targets developed for the actinide-target program at ISAC provide the possibility of producing large quantities of radionuclides that may have therapeutic potential both as α-particle emitters and β-particle emitters. These radionuclides can have powerful therapeutic value based on their half-lives, decay-spectrum energetics, and particle type. For instance, alpha particles travel only a short distance in human tissue and deliver enough ionizing energy to break both strands of DNA and thereby ensure cell death. One futuristic vision proposes to deploy PET-labeled target molecules in the human body with alpha-particle emitters as "seek and destroy" assassins for cancer. Pursuing this line of research requires access to radioisotopes produced from the actinide targets, both proton and photo-fission. Initial studies can explore the isotope mix produced in the spallation mix once the target has been removed. Once promising candidates are identified, the exploration can turn to assessing feasibility in terms of on-line extraction versus off-line chemical separation approaches.

This program would fit naturally into the nuclear medicine focus of the TRIUMF Nuclear Medicine Program. It would play to TRIUMF's strengths in this area and, in partnership with BCCA, would develop world-unique capabilities.

Strengthening Existing Partnerships

TRIUMF's nuclear medicine team is focused on continuing the existing collaboration with PPRC and building on the emerging collaborations with both BCCA's cancer biology research program and British Columbia's Centre for Drug Research and Development's (CDRD) burgeoning program on incorporating functional imaging into drug discovery research.

PPRC and Neurology

PPRC has an international track record of using state-of-the-art PET imaging techniques to study Parkinson' s disease. The research with the PPRC has been funded by grants from the Canadian Institutes of Health Research (CIHR), the Michael Smith Foundation for Health Research, the Pacific Alzheimer's Research Foundation and the Natural Sciences and Engineering Research Council of Canada (NSERC). Overarching the multiple specific projects that are incorporated into the PPRC team's applications are the following three basic questions:

1. What causes Parkinson's disease?
2. What are the underlying mechanisms that contribute to complications of advanced disease and long-term treatment?
3. How can we use Parkinson's as a model to understand better the neurobiology of dopamine and other monoaminergic systems in the brain, in health, and in disease?

1. What causes Parkinson's disease (PD)?

The TRIUMF Nuclear Medicine Program uses positron emission tomography (PET) to study the origin and progression of both sporadic PD and PD caused by dominantly inherited mutations. Compensatory changes in the dopamine (DA) system are being studied during early and preclinical stages of the disease using multiple tracers of the presynaptic dopamine system. In addition, we assess occupational risk factors for PD using a population-based, case-controlled design and investigate the contribution of potential risk-modifying genes.

2. What are the underlying mechanisms that contribute to complications of advanced disease and long-term treatment?

We are studying changes in dopamine turnover and their relationship to alterations in dopamine transporter (DAT) expression in PD patients with fluctuations in motor function as well as in a rodent model of PD and levodopa-induced dyskinesias. The aim is to determine whether changes in DAT expression are related to different dopaminergic therapies. Using PET, we assess the dopaminergic basis for depression in PD by assessing DA release in response to methamphetamine and compare depressed PD to non-depressed PD subjects, as well as depressed PD to non-PD patients with major depression and controls. We are assessing the effects of expectation on DA release and the placebo effect, and are assessing DA release and prefrontal cortical activation in PD subjects with pathological gambling. Alternate therapies that may have non-DA effects, such as retinal-pigmented epithelial cell implants and ECT, will be assessed in non-human primates.

3. How can we use PD as a model to understand better the neurobiology of dopamine and other monoaminergic systems in the brain, in health, and in disease?

Experimental studies on the role of DA in incentive motivation and its relationship to depression and expectation are being conducted using *in vivo* microdialysis and, related to human studies on depression, the placebo effect, and pathological gambling. The UBC-TRIUMF team will be pursuing methodologies to label oligonucleotides with positron emitters to study gene expression *in vivo* as described above.

In addition to the CIHR team grant activities, the UBC-TRIUMF nuclear medicine team works with the Mayo Clinic in Jacksonville, Florida to study dementia. Dementia is the commonest symptom of neurodegeneration and is estimated to affect approximately a half million Canadians. The major causes of degenerative dementia are Alzheimer's disease, Parkinson's disease, Lewy body dementia, and frontotemporal dementia. Although the clinical features and histopathology of these conditions are different, there is increasing recognition of clinical and pathological overlap. Individuals with one condition may develop both clinical and pathological features of another. Overwhelming support for the concept of overlap between syndromes and pathological heterogeneity is derived from the example of Parkinsonism due to mutations in the gene-encoding, leucine-rich repeat kinase 2 (LRRK2), in which the Lewy bodies typical of Parkinson's disease may or may not be present, and which may be associated with the pathological hallmarks of other forms of neurodegeneration, including progressive supranuclear palsy, frontotemporal dementia, and Alzheimer's disease.

The UBC-TRIUMF collaborative program will undertake a comprehensive examination of the relationship between cognitive impairment and motor dysfunction, using clinical, genetic, pathological, and neuroimaging approaches. We are studying two different familial forms of Parkinson's as well as frontotemporal dementia. In all three cases, both cognitive impairment and Parkinsonism occur, but the neuropathological and genetic substrates are different. The overarching hypothesis is that insights derived from understanding the genetic bases for these disorders will lead to the elucidation of a common pathway underlying neurodegeneration. Thus, the findings obtained from these studies will have an impact on other neurodegenerative dementias, including Alzheimer's disease and will provide insight into mechanisms underlying sporadic neurodegeneration. Focus areas of the next few years will be:

- Presynaptic dopaminergic integrity can be assessed using [^{11}C]dihydrotetrabenazine (DTBZ; a marker for the vesicular monoamine transporter type 2 [VMAT2]) and [^{11}C]*d-threo*-methylphenidate (MP; a marker for the membrane dopamine transporter [DAT]), as well as 6-[^{18}F]-fluoro-L-dopa (FD). FD uptake is usually used to assess the decarboxylation of levodopa to dopamine. However, we have utilized longer than usual (four-hour) scan times to estimate dopamine turnover, and this approach will continue to be applied to the study of asymptomatic subjects with the conditions considered here.
- Dopamine receptors can be assessed using [^{11}C]raclopride (D2 receptor) or where appropriate [^{11}C]SCH 23390 (D1 receptor). While either study may be useful to determine integrity of post-synaptic receptors, the more common application here is to use a change in [^{11}C]raclopride binding to estimate dopamine release in response to medications or other stimuli, such as expectation of reward/therapeutic benefit. The TRIUMF-UBC team has extensive experience with this approach.
- Cholinergic activity is assessed in all demented subjects or subjects at risk for dementia using the acetylcholinesterase substrate N-[^{11}C]methylpiperdin-4-yl propionate (PMP) and shape analysis, appropriate for regions with low to intermediate levels of cholinesterase activity. The team has considerable experience with the use of this tracer in preliminary studies on PD with dementia and related disorders.
- Neuroinflammatory responses can be assessed where appropriate using the peripheral benzodiazepine ligand (*R*)-[^{11}C]PK 11195 that images activated microglia.
- The team will image amyloid/aberrant protein deposition using the ^{18}F labeled analog of the Pittsburgh B compound (PIB). ^{18}F is better suited than ^{11}C because of the kinetic properties of this ligand, which is a thioflavin analog. Although most published literature to date suggests that this compound is selective for fibrillar -amyloid, this is somewhat controversial, with unpublished claims that it may bind to other misfolded proteins. The other PET ligand that has been developed for amyloid imaging is 2-(1-{6-[(2-[F-18]fluoroethyl) (methyl)amino]-2-naphthyl} ethylidene) malononitrile ([F-18]FDDNP). This agent appears to bind to both plaques and neurofibrillary tangles. This compound has somewhat different properties from PIB and is likely to bind to at least some protein aggregates in disorders other than Alzheimer's disease. To date, there has been no direct published comparison of the properties of these two relatively recently developed tracers.

An important component of the PPRC-related research is the investigation of small animal models of disease with a dedicated small-animal imaging camera and related imaging expertise. The expansion of the TRIUMF nuclear-medicine program will be able to take advantage of these skills when establishing its small animal imaging program dedicated to radiotracer development.

BCCA and Oncology

Leveraging TRIUMF's established skills and expertise, BCCA launched a highly successful clinical program in functional cancer imaging. Currently, approximately 3,000 patients per year benefit from PET scans using ^{18}F-FDG produced by BCCA staff at TRIUMF. BCCA has purchased a cyclotron which will be housed in its own facility and should be commissioned in approximately one year. With BCCA's recent creation of a research chair in functional cancer imaging and its purchase of a small animal micro-PET/CT scanner, TRIUMF sees the collaboration with the BCCA as a unique opportunity to expand the scope of its own life sciences program into cancer research. To achieve this, TRIUMF will kickstart a joint research program with the BCCA by providing isotopes for pre-clinical and clinical research, such as ^{18}F-Fluoroestradiol (for breast cancer imaging) and ^{18}F-EF5 (to image hypoxia). The addition of a cyclotron at the BCCA will provide greater capacity for isotope production, an alternate supply for some research isotopes, and another site for radiochemistry development in collaboration with TRIUMF.

Through joint grant-funded projects, the BCCA-TRIUMF team will expand ongoing initiatives to radiolabel organic macromolecules (peptides, proteins and oligonucleotides) of interest in basic and pre-clinical cancer research. Both institutions intend to maintain a close collaboration and to leverage each group's strengths (genomics, cancer biology and clinical imaging research at BCCA and target chemistry, radiochemistry and instrumentation research at TRIUMF) to build a world-class program in cancer imaging. As an example, BCCA has an active program to identify key genes associated with breast cancer, using high-throughput genome-wide siRNA screening. By selectively inactivating individual genes through thousands of iterations, researchers at BCCA are identifying key genes that are essential for breast cancer growth and proliferation. The proteins associated with these genes can then be identified and characterized, and complementary radioabelled probes can be designed to interact with these proteins for diagnostic or therapeutic purposes. Beyond additional opportunities to enhance the understanding of cancer biology through imaging probes, the expertise in target design and radioisotope production developed at TRIUMF will also be highly valuable to identify novel therapeutic isotopes to treat cancer.

The combination of world-class expertise in basic target research, radiochemistry, instrumentation research, molecular biology of cancer, preclinical expertise in imaging, advanced cancer therapeutics and clinical imaging research is unique in Canada and perhaps even in the world in terms of geographical and intellectual proximity.

Conclusion

TRIUMF's nuclear-medicine initiative requires specific human and technical resources. Three research chemists focusing on novel chemistry developments, large molecules, and microfluidics will be needed. A nuclear chemist will work with existing TRIUMF experts to explore innovations in radionuclide production methods. A molecular biologist or biochemist will focus on the development of direct tracers. An imaging physicist will lead innovations in small-animal imaging. Supporting this team will require five technicians. It is expected that the expanded team will engage many more graduate students and up to six postdoctoral fellows, all supported by the external research grants of the investigators.

The fastest growing part of TRIUMF's program in the current five-year vision is the Nuclear Medicine Program. The opportunity to drive the nuclear medicine revolution sweeping Canada and, indeed, the world is too important to pass up. TRIUMF's combination of technical expertise, physical infrastructure, and enthusiastic partners make it a powerful player in Canada's efforts to improve the health and well-being of its citizens and to ensure a continued Canadian role in the global market for medical isotopes.

6.2.4

Molecular and Materials Science

Over the time span of the next Five-Year Plan (2010–2015), as detailed below, we will consolidate major expansions in the μSR facility, and, by implementing a second production target at ISAC, we will build on the success of β-NMR by significantly increasing available beam time and opening nanoscience opportunities to a wide pool of potential users.

Introduction

Almost every innovation in the history of humanity has been enabled by an advance in the understanding and control of materials, from the advent of metallurgy that heralded the Bronze Age to the development of solid-state electronics based on the properties of semiconductors such as silicon. The systematic scientific study of materials over the past several centuries has been a key aspect of modernization. At the dawn of this millennium, we face enormous global challenges due to overpopulation and overconsumption of energy and other limited resources. Central to our response to such challenges is the development of new technologies to improve efficiency and reduce the production of dangerous byproducts (including greenhouse gases such as CO_2), technologies that push the limits of our ability to control materials. Thus, more than ever before there is an urgent need for fundamental research into the physical and chemical properties of materials, and for methods of controlling their deployment in devices.

Although TRIUMF's principal focus has been the study of nuclear and particle physics, one of its major achievements has been the development of the muon spin rotation (μSR) facility and, more recently, the beta detected NMR (β-NMR) facility at ISAC, for materials research. These techniques use beams of light spin-polarized particles as ultra sensitive magnetic probes for fundamental studies of matter at the atomic (rather than subatomic) scale. With its Centre for Molecular and Materials Science (CMMS), TRIUMF is the only laboratory in the world to offer a broad community of chemists and materials scientists, with diverse research interests, the complementary tools of μSR and β-NMR in one integrated facility.

The use of radiotracers is well known in chemistry. Here the pathway of a radioactively labeled chemical species is followed through a chemical reaction to elucidate the reaction mechanism, for example, bringing to light important rate-determining steps. The use of the muon as a chemical radiotracer is based on its ability to mimic hydrogen by forming a special hydrogen-like atom called muonium with the positive muon (μ^+) playing the role of the atomic nucleus. Hydrogen is a very simple, common and extremely important atom in chemistry, particularly organic and aqueous chemistry. Moreover, its simplicity, stemming from its single electron, makes it highly amenable to accurate theoretical calculations. The information available by μSR is, however, much greater than from traditional radiotracers. This is because the radioactive decay of the muon is used not just to register the presence of the radiolabeled species but through a special property of the β-decay called parity violation, to obtain information about the state of the muon's spin at the time of decay, yielding information similar to nuclear magnetic resonance (NMR). NMR is a technique that uses the magnetic moments of stable nuclei with nonzero spin and is the basis of the medical diagnostic tool known as MRI (magnetic resonance imaging). The ability to extract magnetic resonance information via a "nuclear" detection scheme, *i.e.*, detecting the emitted high-energy β particles, yields an extremely high sensitivity. Together with its short lifetime (2.2 μs), this sensitivity makes μSR an ideal probe of short-lived transient species that are key intermediate players in critically important chemical reactions. These range from simple gas phase reactions that test our detailed fundamental mechanistic understanding, to organic reactions relevant in combustion and atmospheric chemistry; to the study of chemistry under the extreme, but highly industrially relevant, conditions such as nanoconfinement in zeolite cages, and the high temperature and pressure conditions of hydrothermal synthesis and supercritical fluids. Supercritical fluids present a particularly interesting example as the solvent media for chemical reactions. Unlike conventional solvents, their properties are continuously variable via temperature and pressure, leading to their wide industrial application as environmentally safe alternatives to conventional solvents (see Physical, Green and Materials Design Chemistry in Section 4.3.1).

Solid materials are the basis of all technology. A strong fundamental understanding of materials enables them to be engineered into devices. This is perhaps best illustrated by the research into the fundamental properties of formerly little known and little used materials known as semiconductors. This research led remarkably quickly to the 1947 invention of the transistor, a simple device that is at the heart of modern computer technology.*

* See
http://download.intel.com/pressroom/kits/events/60th_anniversary/TransistorAnniversaryBackgrounder.pdf

Our knowledge of the materials science of semiconductors like silicon is now extremely well developed; however, there are an enormous number of other materials that are substantially less well understood, including a large number whose electronic and magnetic properties are qualitatively different from materials used in current technologies.

The possibility of using the properties of novel materials in radically new technologies, such as quantum computers and magnetic spintronics, has provided significant motivation to study materials that currently seem exotic, but may turn out to be tomorrow's "silicon." Such materials are structurally and compositionally more complex than simple elemental semiconductors, and to be considered for mass-produced technology, their properties must be well understood, and consequently controllable, before they can be considered for the engineer's material palette.

In this connection, one of the major streams of modern materials research is the problem of strongly correlated electron materials, where the electrons exhibit a collective behaviour, which in general is very different than for a system of independent electrons. There is currently no general understanding of such materials and our ability to predict their remarkable properties is quite limited. One particularly fertile class of unconventional materials is the transition metal oxides, where small interatomic overlap and localized *d* atomic orbitals lead to strong Coulomb interactions between electrons and a plethora of electronic ground states including: high-temperature superconductors; colossal magnetoresistive metals; insulating, conducting and semiconducting magnets; multiferroics (materials that combine the magnetic properties of ferromagnets with the dielectric properties of ferroelectrics), etc. A system of strongly correlated electrons is notoriously difficult to treat theoretically, so it is extremely important to use state-of-the-art experimental methods to guide theorists.

Scientists using the CMMS μSR facility continue to make key contributions in this global effort, using the extraordinary sensitivity of the muon as a local magnetic probe to study novel strongly correlated magnetic and superconducting materials (see Superconductivity (HTSC): Definitive Measurements and Tests; Strongly Correlated Systems and Quantum Phase Transitions in Section 4.3.1).

The sensitivity of μSR also makes it ideal for studying certain subtle, but critically important, problems in materials, such as the behaviour of hydrogen in semiconductors, where it is a common and very important impurity, and in potential hydrogen storage materials that can store high concentrations of hydrogen fuel in the relatively safe and convenient form of a solid solution (see Hydrogen–Materials Interactions in Section 4.3.1).

While still in its infancy, the β-NMR technique, as implemented at TRIUMF, has been shown to be an effective probe of nanostructured materials, where interfaces between dissimilar materials play a crucial role. There are very few other techniques capable of studying the depth-dependent phenomena that occur at heterointerfaces in solids.[1] Recent progress indicates there is significant potential in this regard: to use the unique capabilities of this new depth-resolved technique to study many phenomena at buried interfaces and

1 There are some competing probes, *e.g.* L. Giovanelli *et al.*, Appl. Phys. Lett. 87, 042506 (2005); T. Shigematsu *et al.*, Phys. Rev. Lett. 45, 1206 (1980); see also the reviews: G. Srajer *et al.*, J. Magn. Magn. Mat. 307, 1 (2006); M.R. Fitzsimmons *et al., ibid.* 271, 103 (2004), but the only other general-purpose depth-resolved local probe is LEμSR, see P. Bakulé and E. Morenzoni, Contemp. Phys. 45, 203 (2004).

near free surfaces that are of both fundamental scientific interest as well as of crucial practical importance in new generations of technological applications.[2]

The TRIUMF Centre for Molecular and Materials Science

The TRIUMF CMMS is one of four μSR facilities currently operating worldwide.[3] It has maintained its edge despite its lower proton intensity and significantly less support for its μSR facility than its principle competitor, the Paul Scherrer Institute (PSI), through continuing flexibility and innovation.

TRIUMF and its CMMS infrastructure and facility enable a wide range of users from around the world to carry out research in materials science and chemistry, yielding high scientific output (see Table 1). For example, between 2003 and 2007, containing 27 months of μSR beam time, TRIUMF μSR research generated 211 refereed articles (including 29 Physical Review Letters), 20 graduate theses, and 9 book chapters, including some of the most highly cited papers based on experiments carried out at TRIUMF.[4]

Through TRIUMF, Canada plays a leading role in the development of μSR and has reaped substantial scientific benefits and wide recognition for this success.

	Users	Spokespersons
Canada	100	111
USA	59	38
Japan	114	54
Europe	55	11
South America	5	0

Table 1: Profile of the CMMS users from 2003–2007, distinguishing users and experiment spokespersons.

The β-NMR facility at the CMMS is unique in the world. Only a few labs are capable of β-NMR, and none have a dedicated facility to study materials science with depth-resolved capabilities, nor with the beam intensities and spectrometer capabilities of the CMMS.[5]

At the present time, the only scientific competition is the low-energy muon facility at PSI because both methods can be used to probe the local properties of materials on a nm scale. However, the much longer-lived nuclear probes generated at ISAC are also complementary to the short-lived muon when it

2 See section 5 below

3 The others are the Paul Scherrer Institute (PSI) in Switzerland and the two-pulsed facilities: ISIS at RAL in the UK, and the KEK facility that is currently being relocated and expanded at the new J-PARC accelerator in Japan.

4 Thus far, in the 2003–2008 review period, there are 12 (μSR) and 4 (β-NMR) papers in Physical Review Letters. In the same period, there are 28 from the other 3 μSR facilities combined.

5 Other β-NMR labs include: ISOLDE, see http://ssp.web.cern.ch/ssp/experiments.htm for a list of experiments underway in materials science; Julich, see http://www.fz-juelich.de/iff/wns_nmr/; the NSCL in Michigan, see http://www.cem.msu.edu/~mantica/equip/bnmr.html.

comes to studying nanostructures. It is worth noting that the proposed RIA project in the United States, motivated by the ISAC model, includes a β-NMR facility for the study of materials. Other planned radioactive ion beam facilities (such as GSI-FAIR) are also considering implementing such facilities.

The CMMS is a user facility that provides infrastructure and support to the large number of scientists who come to TRIUMF to perform μSR and β-NMR experiments. It operates as other large-scale reactor/accelerator-based user facilities for neutron scattering,[6] synchrotron X-rays,[7] or high magnetic fields.[8]

Teams of researchers typically bring samples to TRIUMF for an experiment that consists of 6 days operating 24 hours a day, necessitating a very efficient, reliable, standardized, and user-friendly facility. A major role of the CMMS is thus to provide a specific, operating and fine-tuned spectrometer to the user at the start of each experiment, supporting the experimenters in carrying out their measurements.

Currently, the CMMS has 2 TRIUMF-supported scientists, 2 scientists supported through NSERC's Major Facilities Access (now MRS) grant and 3 technical support staff also funded by the latter. The MFA/MRS grant is obtained from NSERC by a consortium of 11 of the major Canadian users of the CMMS facility and is obtained independently of TRIUMF.

The CMMS is composed of two parts: a mature μSR program with a large international group of users and a newly developed β-NMR program. Plans for each of these streams are given in the following sections.

β-NMR

TRIUMF's ISAC facility represents a major recent success for the lab. It uses the primary proton beam from the cyclotron (BL2A) to produce beams of a wide range of radioisotopes. While ISAC works remarkably well, it can produce only a single beam at any given time. This presents a severe bottleneck with too many users competing for too little beam time. As such, this is the most important limitation to the exploitation of ISAC's unique capabilities. For example, over the period 1999–2006, β-NMR has received about 4 weeks of beam per year. This period is in sharp contrast to its main competition, the low-energy muon facility at PSI, which is now served by a dedicated high intensity muon beam line (μE4) with about 30 weeks of beam per year![9]

With such limited beam time at TRIUMF, there is no chance for β-NMR to grow into a broad-based research tool like μSR, serving a large user community with diverse interests. Moreover, there is little or no time for development of the technique that could optimize its use, and potentially enable new types of experiments. This situation is becoming particularly frustrating as the potential of β-NMR is revealed by the CMMS research team. If Canada is to exploit this unique scientific opportunity, a steady ^{8}Li beam is needed.

6 See the Canadian Institute for Neutron Scattering at AECL Chalk River, http://www.cins.ca/ or the Institute Laue-Langevin at Grenoble, http://www.ill.eu/.

7 See the Canadian Light Source, http://www.cls.usask.ca/, the Advanced Light Source at Berkeley http://www-als.lbl.gov/, or the Advanced Photon Source at Argonne http://www.aps.anl.gov/.

8 See the High Field Lab at Tallahassee, http://www.magnet.fsu.edu/ or the pulsed field facility in Toulouse, http://www.lncmp.org/.

9 The low-energy muon facility website is http://lmu.web.psi.ch/lem/

To make the leap to user facility, it is essential for TRIUMF to implement a parallel source of rare-isotope beams for ISAC such as the proposed photo-fission source. As β-NMR uses exclusively light isotopes, like ^{8}Li, a duplicate mass separator for such beams would not need the resolution required for higher masses and would thus be much simpler to realize. Lithium-8 is also convenient because it is produced readily via a thermal ionization source, so designing a new production target will pose few problems. β-NMR isotopes may be produced directly by photodisintegration, for example, using a beryllium target, via a ^{9}Be(γ, p)^{8}Li reaction. Using known cross sections, it is estimated that this process will yield at least as much ^{8}Li as the conventional ISAC target, even with a safe margin for uncertainties in radiation-enhanced diffusion of ^{8}Li [Haslam *et al.*, Can. J. Phys. 31, 210 (1953); Clikeman *et al.*, Phys. Rev. C 126, 1822 (1962)]. Alternatively, more beam time on the standard proton-driven ISAC target will become available as the load is spread between the two parallel operating targets. The new source will interface with the existing low-energy beam lines at ISAC, eliminating the need to duplicate the laser polarizer system and the β-NMR spectrometers (see Section 5.2.1.2).

With the proposed new source, we anticipate that the beam time available for β-NMR would quadruple before the end of the five-year planning period. Together with advances in the reliability of beam delivery and the implementation of the fast kicker that allows nearly simultaneous operation of the two β-NMR spectrometers, the available beam time will easily exceed the threshold for β-NMR to operate effectively as a user facility instead of a development project.

For a number of practical reasons, effort in β-NMR at TRIUMF has exclusively used ^{8}Li, which is abundantly produced in high yield at ISAC's simplest surface ionization production target. There is substantial motivation for developing other β-NMR beams. For example, the spin 1/2 isotopes ^{11}Be, and ^{15}O, having zero electric quadrupole moment, are pure magnetic probes like the muon. Thus, unlike ^{8}Li, the β-NMR spectra for these nuclei are free of complicating quadrupolar effects. In April 2008, a beam of ^{11}Be was produced and polarized at a readily usable intensity of about 10^{6}/s at the β-NMR spectrometer. In contrast to the muon, with its short lifetime of 2.2 μs, the β-NMR probes have much longer lifetimes, making them sensitive to timescales comparable to conventional NMR. Development of other probe beams is also currently limited by the lack of beam time.

The Science of Metamaterials with β-NMR

When materials are combined to form a layered heterostructure, the resulting properties may differ substantially from those of each of the pure bulk starting materials. Such metamaterials have important applications in electronics and sensors, and newly developed metamaterials can have unprecedented properties, which may form the basis of entirely new technologies, such as quantum computers or spintronics. In a similar way, the properties of materials differ at a free surface. For example, in surface reconstruction, the crystal structure of atoms at the surface is different from that of a simple truncation of the bulk. In fact, all structural, magnetic, and electronic properties of metamaterials and crystals near a free surface are depth-dependent. The only issue is the length scale over which the bulk properties are recovered. Remarkably little is known about such phenomena, for the simple reason that there are only a very few depth-resolved techniques. There are a number of “surface” methods, for example, scanning tunneling microscopy and photoemission (of electrons), but these are limited to the topmost atomic layers.

In β-NMR (as in μSR), properties of the probe spin polarization are detected via the anisotropy of the weak β-decay. This “nuclear” detection scheme enables measurements using many fewer probe spins than conventional magnetic resonance experiments. Together with the low beam energy at ISAC (typically 30 keV), and electrostatic deceleration, β-NMR can be used as a sensitive depth-resolved local probe of metamaterials and near surfaces.

Previous uses of β-NMR in materials science have been focused on studies of point defects in semiconductors. In contrast, the CMMS β-NMR experiments are aimed at using the implanted probe to investigate intrinsic properties of materials, and in particular depth-dependent phenomena on the nanometre scale in thin film heterostructures. As in the case of μSR, we have recently established that β-NMR can be used effectively to study intrinsic local electronic or magnetic properties, and thus provide information similar to what a host nuclear spin would reveal. Of course, conventional NMR is not possible in a nanostructure due to the limited sensitivity of that technique.

The CMMS team has developed this technique over the past few years, and that investment is now paying off with exciting new science. For example, the use of nanoscale magnets for technological applications such as information storage or quantum computing requires monodisperse magnets that can be addressed individually. A major step towards achieving this goal came recently with the discovery of molecules that function as identical magnets, and the ability to deposit a monolayer of these molecules on a suitable substrate. At low temperatures, these single-molecule magnets (SMMs) exhibit fascinating quantum mechanical behaviour that dramatically affects macroscopic properties such as magnetization. These include the observation of quantum tunneling of the magnetization (QTM), topological quantum phase interference, and quantum coherence. However, the small quantity of magnetic material present in a monolayer (or sub-monolayer) means that it is virtually impossible to accurately determine magnetic properties with conventional bulk techniques. Researchers at CMMS used β-NMR to investigate the magnetic properties of SMMs in a two-dimensional lattice [Nano Lett. 7, 1551 (2007)], measuring the temperature dependence of the magnetic moments of a monolayer of the prototypical SMM, Mn_{12}, grafted to a silicon substrate. Intriguingly, the magnetic properties of the SMMs in this low dimensional configuration differ significantly from the bulk. With tantalizing prospects such as the above example, the wider μSR community is keen to apply this new probe to study highly topical and technologically relevant problems in the study of materials.

The SMM experiment is one example of a more general approach that the CMMS team has been developing, that of proximal detection [J. Magn. Reson. 191, 47 (2008)], *i.e.*, implanting the probe ions, not into the material of interest but into a simple inert adjacent layer. Other examples include studies using Ag / high-T_c superconductor heterostructures.

Another recent advance was the first ever beta detection of a pure nuclear quadrupolar resonance in zero applied field [Phys. Rev. B 70, 104404 (2004)]. Because the spin two ^{8}Li has a small electric quadrupole moment, its spin is coupled not only to internal magnetic fields in a material, but also to the local electric field gradient, *i.e.*, to the local structure of the surrounding atoms. This coupling can complicate the spectrum when the Li is in a site of less than cubic symmetry, compared to a pure magnetic spin one-half probe like the muon. However, it has also proven useful in the study of the structural phase transition in $SrTiO_3$ [Phys. Rev. Lett. 96, 147601 (2006)], where it was used to monitor the distinct near-surface behaviour of this prototypical soft-mode structural transition. Since then, this work provided strong motivation for the 2007–2008 completion of the deceleration capability on the second (low-field) β-NMR station, now known as the β-NQR spectrometer, to study the depth dependence of this phenomenon. More recently, it also spawned depth-dependent grazing incidence synchrotron X-ray diffraction experiments, using this complementary "reciprocal space" probe.

Low- and zero-field capabilities have been extremely useful in μSR studies of weak magnetism, and it is anticipated that they will be similarly useful in β-NMR. For example, in the search for weak magnetism that may exist at some interfaces of high-temperature superconductors (see TRIUMF experiment M1041). Another low-field phenomenon that will prove both interesting and useful is the recent observation that at sufficiently low fields the implanted ^{8}Li is sensitive to the dynamics of the host nuclear spin system, which allows β-NMR to monitor the host nuclear spin dynamics (and hence the low energy excitations of the system) under conditions (thin layer, depth-resolved, and small nuclear moments) where conventional NMR is impossible. The first use of this has been to make absolute measurements of the magnetic penetration depth in superconductors [M.D. Hossain *et al.*, submitted to Phys. Rev. Lett (2008)].

Newly proposed experiments focus on superconducting and magnetic proximity effects in heterostructures, for example, involving magnetic semiconductors such as Mn-doped GaAs and EuO, which have been intensively studied for developing semiconductor spintronics.

In the context of so much progress in establishing the power of this new method and the discovery potential, it is frustrating that progress is severely limited by access to beam time.

μSR

Starting in 2008, the μSR facility will enter a period of unprecedented expansion with the upgrade to the surface muon beam line M9A and to the M20 beam line, which will be split to serve two experimental areas simultaneously. The former project was funded in the previous Five-Year Plan and the latter, in 2006–2007, by a large Canada Foundation for Innovation Grant.[10] The increasing availability of muons for materials research will provide the flourishing community with much needed beam time. The excess of user demand for beam time over available time is illustrated by the current backlog of more than 60 weeks or approximately two beam line years. In the coming five-year period, the beam line expansion will necessitate the development of new spectrometers and new capabilities that continue to push the forefront of the technique.

10 Details of the CFI award: "Muon Beam Line for Molecular and Materials Science at TRIUMF", P.W. Percival, Simon Fraser University, Principle Investigator, can be found at the CFI website http://www.innovation.ca/projects/index.cfm. The award was \$2.4 million (CFI, approved Nov. 2006) + \$2.4 million (BCKDF, approved June 2007) + \$1.2 million (TRIUMF), see section 4.3.1 for more details.

With an ample supply of new beam lines providing high luminosity beams to five experimental stations, and a guaranteed supply of cryogens (see section on helium liquefaction below), the focus of facility development will shift to experimental capabilities, expanding the parameter space for experiments, for example, with applied pressure, optical illumination, applied electric fields, or the combination of high pressures and ultra-low temperatures. Emphasis will also be placed on increasing the reliability and ease of use of the spectrometers, for instance, using a new generation of reconfigurable electronics. It will also be important to promote facility capabilities and develop new users, particularly nonexpert users whose central research expertise lies in other areas.

Above all, new people are required to support these major expansions. By any reasonable measure, the CMMS is already understaffed. For example, the LMU muon facility at PSI currently has a staff of 14 scientists plus technical support. In 2008, TRIUMF hired another scientist whose time is divided between the M20 upgrade, β-NMR, and general μSR support. With the current and planned expansion, understaffing will become critical. Thus, we plan to hire three new scientists in addition to the current positions. Two of these will support the expanded demands due to the new muon beam lines and will be included in the next user-based NSERC MFA/MRS application. We request that TRIUMF support the remaining position, a scientist responsible solely for β-NMR, and who will be charged with the significant technical challenges of maintaining and expanding the β-NMR capabilities as well as managing the transition to a user-friendly system required for a user facility.

With the new beam lines currently underway, TRIUMF will continue to be the leading facility for innovative experimental science with μSR, provided there is sufficient support to fully utilize this capacity. In particular, this requires infrastructure investment in new spectrometer capabilities, and most importantly the support personnel to develop and maintain them.

Materials Science and Chemistry with μSR

The basic themes of the science of μSR are summarized in the section above and Section 4.3.1.

The development of new beam lines and spectrometers will supply the vibrant research programs of CMMS users in areas of traditional strength, *i.e.*, superconductivity, magnetism, hydrogen in semiconductors, gas phase chemical kinetics, and free radical chemistry. However, it will also foster newly emerging research focused on functional materials design, environmental chemistry in supercritical and ionic fluids, in materials for energy storage and transmission, such as hydrogen storage and battery applications. It will also provide opportunities for new users to embark on a μSR research program that is currently limited by the oversubscription of available beams. In the past three years, there have been 105 experimental proposals and reports vetted by the Molecular and Materials Science Experiments Evaluation Committee. The pool of experimenters is typically broad with 36% of spokespersons local BC users, 15% from elsewhere in Canada, 12% from the US, 31% from Japan, and 6% from Europe.

Some notable new capabilities that continue to develop, opening up more parameter space for the study of materials, are the ability to do μSR experiments under high pressure and under optical excitation. The increasing availability of muon beams currently underway, together with new capabilities, will enable significant new scientific opportunities in many areas.

The newly emerging research from the CMMS μSR facility is well illustrated by the program of Prof. K. Ghandi of Mt. Allison University on the application of muon science to probe "green chemistry" at the microscopic and fundamental level. His research group focuses on three areas:

1. The development of laser-controlled muonium chemistry to study the effect of selective excitation on free radicals. The idea is to use photon absorption, instead of chemical reactions. Their first report of laser excitation on muonium chemical dynamics was published as a cover article [K. Ghandi, I. P. Clark, J. S. Lord, S. P. Cottrell, Phys. Chem. Chem. Phys., 9, 353-359 (2007)].

2. The study of free radical chemistry in supercritical CO_2 as a "green solvent". A supercritical fluid (SCF) is any substance above its critical temperature (T_C) and pressure (P_C) but below the pressure required to condense it into a solid. As the temperature increases, the liquid becomes less dense, due to thermal expansion, and as the pressure increases, the gas becomes denser. At the critical point, the densities become equal, and the phase distinction between liquid and gas disappears. SCFs have a host of properties not found in conventional solvents, such as gas-like diffusivities and liquid-like densities, and the ability to be "tuned," meaning that their solvent properties can change significantly as a function of temperature and pressure. Supercritical CO_2 has been used as a solvent for a wide variety of chemical applications, including free radical polymerization and photochemical reactions. Carbon dioxide is not classified as a volatile organic chemical solvent by the Environmental Protection Agency. In addition, CO_2 is inexpensive and nonflammable. It is an energy-conserving, selective, and waste-reducing alternative to organic solvents. Moreover, the use of supercritical CO_2 doesn't add to the greenhouse effect because it can easily be conserved during the industrial processes. The focus of the Mount Allison University group is to investigate, at the fundamental level, the tunability of free radical reactions in supercritical CO_2.

3. The study of free radical reactions in ionic liquids (ILs), another class of "green" solvents. ILs are two-component systems composed of equimolar amounts of anions and cations. The contrasting nature of cations and anions, specifically, close sites of high electron deficiency and high electron richness, suggests that ionic liquid solvents could enable chemistry that is not possible in normal molecular solvents. Experiments are designed to investigate significant coulomb interactions of cations and anions with free radicals and free radical precursors. It has been found that there is significant local ordering in ILs, and that this has significant effects on both the generation and structure of radicals. Information on the electronic structure of radicals as well as the effect of solvent interactions is gained by measurement of hyperfine coupling constants, while information on free radical reaction dynamics in green solvents is obtained by the measurement of spin relaxation rates.

Further examples can be found in Section 4.3.1.

Proton Driver Beams for β-NMR and μSR

Currently, both β-NMR and μSR depend on proton beams from the TRIUMF cyclotron to produce muon and radioactive ion beams. To make full use of the new muon beam lines and to continue the current β-NMR program while the new production target is designed, built, and commissioned, it is essential that the cyclotron be maintained, and in the context of increasing demands from the overall ISAC program and radioisotope production, it is essential that the cyclotron's operating current be upgraded significantly.

Aside from the intensity of the proton beam, the primary technical constraint to maximizing the luminosity (and usefulness) of both the new and existing muon beam lines is the nature of the production targets on BL1A. These targets were not designed to optimize muon flux, and the T2 target in particular has a poor geometry, with the consequences of low luminosity and short target lifetime. A substantial fraction of the proton current from the cyclotron is now delivered to ISAC, necessitating a reduction of BL1A current from the pre-ISAC 140 μA down to the current maximum 100 μA. With the increasing demands of ISAC, this trend will only continue. Thus, it is imperative to redesign and rebuild the muon production targets now and to upgrade the cyclotron for higher operating current (see Section 6.2.1.2.1) to make the most of the new μSR infrastructure in the Meson Hall.

Helium Liquefaction

Liquid helium is used as a cryogen throughout the CMMS facility for the operation of superconducting magnets and for controlling the experimental temperature. Temperature is a critical experimental variable in all μSR and β-NMR experiments, and the low temperatures are particularly important to reveal properties of the lowest energy "ground" state of the system, free from the effects of thermal fluctuations. Recent worldwide shortages of helium are currently limiting the supply available to CMMS users to about 60% of requirements, and the price is increasing rapidly.[11] This situation is expected to continue and even worsen for the near future. Helium is a non-renewable resource found in the Earth's crust (released as a by-product of natural gas extraction). It poses no environmental threat if released into the atmosphere, but once released it is not recoverable. The helium shortage will rapidly become a serious limitation on the research productivity of the facility; therefore, a TRIUMF-wide helium recycling and liquefaction system must be implemented in the next five-year period. This will involve an airtight collection system, collecting helium vapour from each experiment, that will supply a liquefier, to be operated in conjunction with existing and planned liquefiers dedicated to existing ISAC-II and planned Nb cavity superconducting RF accelerators. With an efficient He recycling system, the input of He from external sources will be limited to a sustainable amount.

11 See Karen H. Kaplan, Physics Today, June 2007, p31 online at
http://ptonline.aip.org/journals/doc/PHTOAD-ft/vol_60/iss_6/31_1.shtml

Summary

The CMMS is an extremely productive component of TRIUMF's research, and with the current expansion of μSR beam lines, it will continue this output as well as expand into new areas of fundamental and applied research in materials science and chemistry. However, it will require continuing support from TRIUMF in: 1) muon beam production, 2) cryogenic liquid helium production, and 3) personnel. The new β-NMR capability has excellent potential to make high impact contributions to nanoscience, but only if the available beam time can be increased. This will be possible with the e-linac, second proton beam line, and second ISAC production target that is the centrepiece of the 2010–2015 Five-Year Plan.

6.2.5

TRIUMF Theory Group

The theory group plays an important role by contributing to the intellectual leadership of TRIUMF, by providing theoretical guidance and support to the TRIUMF experimental program, and as a theoretical resource for the broader Canadian subatomic physics community. There is currently an urgent demand for increased theoretical activity in nuclear physics, nuclear astrophysics and in particle phenomenology, especially to support the ISAC facility and for the upcoming experiments with ATLAS at the Large Hadron Collider (LHC). One of the priorities of this plan is to develop a theory program that fills this need and provides a centre for theoretical activity for the laboratory and the larger Canadian subatomic physics community.

The theory group connects TRIUMF to theoretical innovations in Canada and around the world, through active collaborations with scientists from 35 different institutions in 14 different countries in Asia, Europe and North America. Among several coordinated efforts with other national and international institutes, the theory group is a member of the Joint Institute for Nuclear Astrophysics (JINA) in the United States and an international collaborator in the SciDAC (Scientific Development through Advanced Computing) UNEDF effort to develop a Universal Nuclear Energy Density Functional.

Nuclear Physics

We have entered one of the most exciting eras in nuclear physics, in which substantial progress can be expected on many fundamental problems. This is due to advances on many fronts, including the development of effective field theory and the renormalization group in nuclear physics, advances in *ab initio* methods for nuclear structure, the effort to develop a universal density functional from microscopic interactions, and the application of large-scale computing resources. At the same time, the ISAC facility is discovering new phenomena and will provide critical new data. Unique opportunities to make progress on solving both existing and new problems in nuclear physics will arise during the 2010 to 2015 period, and TRIUMF has to be at the forefront of this theoretical and experimental synergy.

Strong interaction physics in laboratory nuclei and in the cosmos extends over extremes in density and temperature, and reaches to unexplored nucleonic compositions. In nuclear theory, there is a coherent worldwide effort based on the same nucleon-nucleon and many-nucleon interactions with techniques suitable for each range of atomic number, from light to heavy nuclei, and for astrophysics. For the first time a unified description is possible due to effective field theory and the application of renormalization group methods in nuclear physics. The TRIUMF theory group has played a key role in these developments. Using the renormalization group, we have shown that nuclear forces evolve to universal low-momentum interactions for all nuclei. For lower energies, an effective field theory without explicit pions is extremely successful in capturing universal physics dominated by large scattering lengths, with applications ranging from halo nuclei to low-density matter and reactions under astrophysical conditions.

Three-nucleon interactions are a frontier in the physics of nuclei. They play a central role for nuclear masses, for shell structure and isospin dependences, and for extrapolations to the extremes of astrophysics. For the 2010 to 2015 period, TRIUMF is in the unique position to study three-nucleon interactions beyond light nuclei for the first time. Three-nucleon contributions are amplified in many-nucleon systems. This means that we will be able to test predictions for key nuclei at ISAC and by confronting global trends in nuclear masses and structure with experiments.

Low-momentum interactions are advantageous for nuclei and rapid convergence has been demonstrated in exact diagonalizations for *p*-shell nuclei. Coupled-cluster theory combined with this rapid convergence pushes the limits of accurate calculations to medium-mass nuclei and sets new benchmarks for ^{16}O and ^{40}Ca. Coupled-cluster theory highlights the spin-offs of nuclear theory. It was developed in nuclear physics 50 years ago and has become the method of choice in quantum chemistry for up to 100 electrons. The first coupled-cluster results with three-nucleon forces indicate that phenomenological monopole shifts in the shell model may be due to three-nucleon contributions. This exciting new development links understanding the origin of the shell model and the location of the drip lines to three-nucleon interactions. To test these findings, nuclear structure experiments with neutron-rich and neutron-deficient nuclei towards the drip lines will be essential. In addition, effective field theory and renormalization group methods provide powerful tools for estimating theoretical uncertainties. One of the goals of the TRIUMF theory group is to apply these techniques to matrix elements needed in fundamental symmetry tests like those for isospin-symmetry-breaking corrections to superallowed nuclear decay, for double beta decay, and for parity violation studies with nuclei.

Perturbative approaches to nuclear matter are possible with low-momentum interactions and will provide key guidance for constructing a universal density functional for all nuclei based on microscopic interactions. First proof-of-principle calculations using density-matrix expansions and low-momentum interactions for pairing are extremely encouraging. The TRIUMF theory group and collaborators will use effective field theory and renormalization group interactions to identify new terms in the density functional, to quantify the theoretical errors in the extrapolation and to benchmark against *ab initio* methods. At ISAC, we will be able to provide key constraints and uniquely test the discovery of new trends, for example, possible isovector dependences in pairing due to contributions beyond BCS theory.

In nuclear astrophysics, the theory group has made significant contributions to superfluidity in neutron stars and to the equation of state of nuclear matter. The nuclear equation of state is key input to neutron star structure and for the physics of core-collapse. Our group's advances are based on the new developments in nuclear interactions and in many-body methods for dense matter, and on new systematic approaches for low densities near the supernova neutrinosphere. Our results for neutron superfluidity are used in all modern neutron star cooling simulations and provide constraints for the neutron star crust in low-mass X-ray binaries. In addition to advancing our understanding of the nature and evolution of neutron stars, TRIUMF theorists have begun work on the conditions for nucleosynthesis in neutrino-driven supernova outflow. With our plans for the future, the group will intensify the activity on nucleosynthesis and on nuclear reactions for astrophysics in the 2010 to 2015 period.

Particle Physics

The next few years will be a unique time in elementary particle physics. The LHC at CERN will be turning on this year. It will be the highest energy particle accelerator ever built and will almost certainly revolutionize our understanding of particle physics. It will, in effect, "rewrite the textbooks."

Our current understanding of elementary particles and their interactions is called the standard model. Completed in the early 1970s, it was based on experimental results from the previous decades. The ensuing 30 years have been a period of consolidation and refinement. Despite the successes of the standard model, it contains theoretical inconsistencies in the sector of the theory responsible for giving particles mass, technically known as electroweak symmetry breaking (EWSB). The purpose of the LHC is to understand the mechanism of EWSB and to search for physics beyond the standard model.

Canada has invested roughly C$100 million in this project. In addition, about 120 experimental physicists in Canada work on the LHC research program. Despite these major commitments, there is very limited theoretical support for the LHC program in Canada and yet much theoretical work remains to be done to understand the signatures of new physics, as they are unveiled at the LHC. If a Higgs boson or a Higgs-boson-like particle is discovered, much theoretical work will be required to determine if it is indeed the standard model Higgs boson or it simply corresponds to one of the extensions of the standard model. Independent of the Higgs boson, there will probably be other indications of physics beyond the standard model. With many possible extensions of the standard model, close interaction between theorists and experimentalists will be required to determine the implications of any results. TRIUMF is the natural place to develop this interaction because TRIUMF is currently building a sizable experimental group in conjunction with the ATLAS Tier-1 Data Centre to help analyze the ATLAS data.

In addition to the LHC, new results are expected on the properties of neutrinos from the T2K experiment, which has strong TRIUMF involvement, as well as from SNOLAB experiments, which could be crucial in determining if any new physics found at the LHC corresponds to dark matter.

A highlight of the group's theoretical work is the study of how neutrino properties tie into the new physics that may be discovered at the LHC. It is now generally accepted that the three active light neutrinos of the standard model have small masses. However, the origin of the masses is still not understood. The conventional view is that they result from the seesaw mechanism, which invokes the existence of two or more very massive, beyond 10^{12} GeV, right-handed standard-model singlet neutrinos. While the mechanism can be elegantly tied to grand unified theories, it remains very difficult to test directly. Recently, the group has taken the unconventional approach that the light neutrinos get masses from quantum effects without invoking the existence of very massive standard-model singlets. Without extending the gauge group of the standard model, we have extended the Higgs sector to include both a triplet and a singlet complex scalar field. This mechanism is also known as type-II seesaw. In addition, the group added to the usual construction by hypothesizing that the lepton number violating interactions reside only in the scalar potential while the Yukawa and gauge interactions all conserve lepton number. As a result, the active neutrinos acquire masses at the two-loop level and thus are naturally small.

We predict a normal hierarchy for neutrino masses. The additional scalars are all found to be in the TeV range in order for the theory to be predictive, which makes the model directly testable at the LHC. The most interesting signal will be due to doubly charged scalars that decay into the same sign lepton pairs of different flavors, such as $P^{++}{}_{1,2} \rightarrow \tau^{+}e^{+}$. In this model, the dominant amplitude that gives rise to nuclear neutrinoless double-beta decay will be due to virtual doubly charged scalar exchanges and not neutrino exchange. This result is due to the fact that neutrinoless double-beta decays measure the first element of the neutrino mass matrix, which in this model is not two-loop suppressed but also suppressed by the mass of the electron. Furthermore, this amplitude is also directly related to their production at the LHC and hence links high-energy and low-energy processes.

Plans for the Future

The TRIUMF theory group currently has four permanent members. Two new members are expected to join by 2010. In the 2010–2015 period, the group will be expanded and refocused to exploit synergies with the experimental program and the major new initiative. This enhancement will permit theoretical support for both the nuclear and particle physics areas with three to four people in each area.

The Theory Group Research Associate Program has served TRIUMF very well and was identified in the 2002 NRC External Review as a major success. NRC-funded research associates are hired as a resource for the whole laboratory. They have brought new expertise to TRIUMF to support areas of interest not currently covered by the permanent members. After their work at TRIUMF, many of our research associates have gone on to successful academic and industrial careers. There are currently five NRC-funded research associates and this program will continue in the upcoming five-year period.

The theory group provides an integral component of training future leaders in science and technology for Canada. The group offers an excellent training and research experience for undergraduate and graduate students, and a unique research environment for post-doctoral researchers. In the past two years, the theory group undergraduate positions have been the most popular within the TRIUMF summer undergraduate program.

As identified in the 2002 NRC External Review and the 2006 NSERC SAP Long-Range Plan, a vibrant Visitor and Workshop Program is an important service to the Canadian subatomic theory community. The group's Visitor Program supports scientists and students, some of whom come for a few days and others for one-year sabbaticals. These visitors not only add to the intellectual atmosphere at TRIUMF, they increase the profile of TRIUMF in the community. theory group visitors are provided with financial support and, for long-term visits, partial salaries, and living expenses.

Theory group workshops range from topical one-week workshops with 30 to 40 participants to smaller working group meetings of several weeks with 5 to 10 participants. Between 2010 and 2015, the group will expand its workshop program, to bring the expertise of the national and international subatomic theory community to TRIUMF, and to raise TRIUMF's profile. In addition, the workshops and meetings could be organized by university colleagues who would not have the infrastructure to host such meetings at their home institutions.

6.2.6

Detector Facilities

Introduction

TRIUMF contributes to the design, development, and construction of advanced detectors for diverse applications. The roots of this activity lie in the development of detectors for particle and nuclear physics, but the activities have expanded over time to support advanced detector development for molecular and materials sciences and nuclear medicine. TRIUMF has a long history of collaborating with researchers at Canadian universities in the design and construction of various state-of-the-art detector systems as Canadian contributions to experiments both at TRIUMF and at foreign laboratories. In addition to the TRIUMF detector group, the laboratory has expert designers, engineers, and technicians who are fully engaged in this enterprise.

TRIUMF's detector group now consists of the detector facility for construction and the recently subsumed Laboratory for Detector Development (LADD), which was created with Canada Foundation for Innovation (CFI) funding and which brought expertise and tools for the design and construction of the electronic signal processing systems that are vital for the acquisition of large volumes of data from modern detectors. The vision for the 2010–2015 period will place heavy demands on TRIUMF's detector infrastructure and, in doing so, will not only exploit new capabilities but also require further growth in specific areas. Prominent among these is the acquisition of expertise and design tools for application specific integrated circuits (ASICs), which are indispensable components of the complex high-density signal processing systems of modern detector systems.

Future Projects

Some of the anticipated projects during 2010–2015 that will utilize TRIUMF detector facilities include:

ATLAS Detector Upgrades

By 2015, parts of the present ATLAS detector will need to be replaced because of radiation damage as well as the anticipated ten-fold increase in particle fluxes from the planned upgrade of the Large Hadron Collider accelerator complex. Two ATLAS upgrade projects have been approved by NSERC for R&D: very high-rate, forward calorimeters and diamond-based pixel trackers. Both projects require contributions from TRIUMF infrastructure, including mechanical engineering, design, and technical support. If ATLAS electronics upgrade projects proceed in Canada, the detector group's new ASIC capability will be needed to develop a chip for the upgraded silicon tracker and also for the investigation of new radiation-hard electronic technology to be placed inside the liquid-argon cryostat of the hadronic end-cap calorimeter.

CMMS detectors

Over the years, researchers in molecular and materials sciences that utilize secondary beams at TRIUMF have been steady clients of the TRIUMF detector facility. Because the time from conception to measurement is typically much shorter in materials science than in particle and nuclear physics, these researchers count on prompt responses from the highly experienced experts in the scintillator shop to requests to construct new configurations of plastic scintillators, often of complex shapes. This reliance on the facility can be expected to continue indefinitely.

ILC Detector Development

TRIUMF scientists have been strongly involved in the development of a next-generation time projection chamber (TPC) that is a prime candidate for the large central tracker of the International Linear Collider (ILC) detector. The expertise of the detector group with multi-pixel photon counters can be expected to be applicable to the readout of a fine-grained hadron calorimeter that is being studied for ILC. In addition, TRIUMF's expertise in the use of micro-pattern gas detectors as the sensors of the ILC TPC led to their timely application in the TPCs now being constructed for the T2K experiment in Japan.

Medical Imaging

One of the new initiatives that attracted the CFI funding establishing LADD is the development of a liquid-xenon TPC for positron emission tomography (PET). In collaboration with the University of British Columbia, the TRIUMF detector group has designed and constructed a prototype for one segment of an eventual 12-segment microPET ring detector suitable for small animals. The group plans to construct the whole-ring detector, using external funding now being pursued.

In another collaboration, the group plans to work with R. Lecomte's group at l'Université de Sherbrooke to extend PET research to the investigation of other possible detector technologies, both conventional and advanced. A new material called cadmium zinc telluride (CZT) is a high-density semi-conductor with unsurpassed energy resolution at room temperature and the potential for much improved spatial resolution. The detector group intends to work in collaboration with Redlen Industries in Sydney, BC, which has developed methods to produce large crystal detectors. The group is also interested in investigating designs for internal PET probes using CZT by performing simulations and test measurements.

Thirdly, the group plans to study a method of enhancing the background suppression abilities of conventional PET detectors by improving the time resolution of the light detectors viewing the scintillators.

In addition to the activities at TRIUMF for detector research, development, and construction, a request to CFI for new infrastructure similar to LADD is being considered. This infrastructure would enhance the group's capabilities, particularly in the area of ASIC design and development.

Nuclear Physics

Ongoing work on various detectors for TRIUMF's ISAC program has led to a new collaboration with the GSI German national laboratory in Darmstadt. GSI is embarking on a major program of building new accelerators and facilities, many of them for nuclear physics or astrophysics. Several members of GSI management attended a recent workshop at TRIUMF and identified several areas of detector R&D where collaboration could be fruitful.

The first area of collaboration would be work on double-sided silicon-strip detectors. TRIUMF has little experience here and could benefit from work on the planned application of this technology to DESPEC at GSI. The second area of collaboration would be small TPCs containing the target gas with both cylindrical and Cartesian geometries. Here, TRIUMF's experience and expertise with cylindrical geometries in TACTIC (TRIUMF Annular Chamber for Tracking and Identification of Charged Particles) and with micro-pattern gas detectors are particularly relevant. A third area would be scintillator readout with multi-pixel photon counters, which could be applicable to the DESPEC neutron detector array at GSI. Finally, the two laboratories could collaborate on the possible application of a liquid xenon TPC to the EXL facility planned at GSI. These latter two areas are particularly synergistic with the medical imaging program described below.

SNOLAB Detectors

The detector group has proposed a signal-processing solution to the Dark Matter Experiment with Argon Pulse-shape discrimination (DEAP) collaboration, which is designing an experiment using a one-tonne liquid-argon scintillator detector to search for dark matter at the Sudbury Neutrino Observatory Laboratory (SNOLAB). As a member of the DEAP collaboration, TRIUMF would construct and implement this electronic system between 2010 and 2015.

The expertise of the detector group in mechanical design, signal processing, gas control and purification systems is expected to play an important role in

EXO (Enriched Xenon Observatory), another challenging SNOLAB experiment that needs significant R&D. The EXO detector is a high-pressure xenon time projection chamber dedicated to detecting neutrinoless double-beta decay. The construction of a large-scale prototype will begin around 2010.

SuperB

Canadian institutes are members of a new collaboration that plans to build a detector system at a future very high luminosity B-Factory in Italy. If this facility is funded soon, construction of this detector can be expected to require the participation of TRIUMF in the period 2010 to 2015.

Conclusion

TRIUMF detector facilities have been key to the success of many Canadian-led projects in particle physics, nuclear physics, molecular and materials science, and medical imaging, including experiments based both at TRIUMF and off-site. Both TRIUMF scientists and university faculty have led these projects, but the central infrastructure provided by TRIUMF enables this Canadian leadership. As technology advances between 2010 and 2015, so will the demands on the TRIUMF detector facilities. TRIUMF is prepared to meet these challenges and continue the progress of Canadian research.

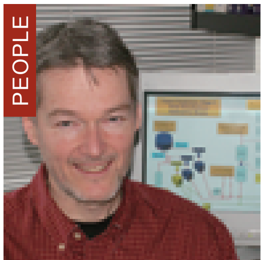
6.3

Accelerator Technology Development and Stewardship

The Role of TRIUMF Accelerators

TRIUMF accelerators are the heart of the Canadian accelerator-based experimental subatomic physics program, both because they enable on-site world-class research in nuclear physics and because TRIUMF's expertise allows Canada to make significant in-kind contributions to off-site international accelerator projects thus enabling participation in experiments at those facilities. In addition, the TRIUMF accelerator complex is the basis for high-impact Canadian research in materials science and PET-based nuclear medicine programs. Finally, we envision expansion of programs designed to utilize the accelerator infrastructure and expertise as a training ground for the next generation of accelerator scientists and engineers. A major aim of this expansion is to establish a strong graduate student program in accelerator physics in collaboration with member universities, from the University of British Columbia to the University of Toronto.

PEOPLE



ROBERT LAXDAL

TRIUMF Research Scientist

Robert Laxdal received his B.Sc. (Honours) and M.Sc. degrees in physics from the University of Saskatchewan in 1977 and 1980, respectively. His M.Sc. thesis, "Design of an Energy Compression System for the Saskatchewan Accelerator Laboratory," provided the design for a magnet chicane and RF cavity to reduce the energy spread in the electron beam from the SAL electron linear accelerator.

Mr. Laxdal joined the TRIUMF cyclotron group in 1980, contributing to, and eventually leading, the team developing the TRIUMF 500MeV cyclotron to be used as an injector to the proposed KAON Factory. In 1995, he joined the ISAC project and led a number of design and commissioning teams responsible for the installation of the ISAC-I accelerators and beam lines. In 2000, he began developing superconducting RF technical expertise at TRIUMF with the goal to build and install a heavy ion superconducting linac (SC-linac) as part of the ISAC-II project. The initial phase of the project was completed in 2006, with the commissioning of the medium-beta section of the ISAC-II linac with accelerating gradients significantly higher than those available at competing facilities.

Bob is now collaborating with a local company, PAVAC Industries Inc., in the fabrication of superconducting cavities, a first for Canadian industry. The cavities will be used in the next phase of the SC-linac installation to be completed by the end of 2009. He is currently head of the ISAC-II project, the Beam Delivery Group and the SCRF Group. ■

The TRIUMF cyclotron offers the highest power on-line separated isotope beam (ISOL) driver in the world giving the ISAC facility the world lead in the production of many exotic ion beams particularly on the neutron-deficient side. These beams offer a major advance in probing nuclear physics processes and uniquely place TRIUMF as a leader in experiments at the "precision frontier" to address some of the fundamental scientific questions of our time.

While TRIUMF does not support on-site subatomic physics research at the "energy frontier," its accelerator scientists contribute significantly to projects around the world, and thus provide a mechanism by which Canadian scientists participate in international experiments such as ATLAS at CERN, T2K at J-PARC, and possibly the International Linear Collider (ILC) and CERN Large Hadron Collider (LHC) upgrades.

TRIUMF accelerators also enable a research program in materials, bulk and surface effects in extreme conditions, as well as a world-renowned nuclear medicine program that utilizes medical isotopes combined with positron emission tomography detectors.

TRIUMF has a clear vision of how to enhance the base for Canadian accelerator science and technology human capital. We plan to strengthen our ties to the university community, primarily within BC, but extending as far as Ontario, and to set up an accelerator physics program with TRIUMF staff teaching courses and mentoring students towards advanced degrees. These education and mentorship opportunities will build up on the already successful Co-operative Education Program that involves tens of undergraduate students a year, who gain practical knowledge in the field of accelerator engineering at TRIUMF.

Future Scientific Goals

TRIUMF's scientific program for the next decade will focus on two main areas of study. The first is the study of neutron-rich nuclei, which will complement the current neutron-deficient program. This program will address fundamental questions in nuclear physics and nuclear astrophysics such as element abundances, supernova explosions, neutron density models, neutron star crusts, and three-nucleon interactions. The second area of study is fundamental symmetries, which will provide stringent probes into physics beyond the standard model. In addition, new initiatives in the materials sciences and nuclear medicine will include increasing the β-NMR running time, developing new radiotracers with actinides, and the expansion of cancer imaging and therapy.

Support of these challenging but promising goals requires higher proton-beam intensity, more rare-isotope beam (RIB) time, and new reach for both the neutrin-rich and neutron-deficient exotic ions.

Accelerator Projects in Support of Future Scientific Goals

To realize these scientific goals and continue to advance our knowledge, from the smallest to the largest scale, we are planning the following five accelerator projects, which are a combination of upgrades of existing infrastructure and new initiatives. These projects together represent an efficient plan to address all the accelerator infrastructure initiatives and extend beyond the next five-year funding cycle to sets goals and milestones for the decade from 2008 to 2018.

1. The 500 MeV H^- cyclotron will retain its key role in supporting a multifaceted science program based on primary proton beams. Deployment of the intensity upgrade will enhance the extracted beam current from 250 A to 300 A by 2015 and above 400 A in the future while preserving the present reliability level with machine uptime of above 90%. A significant component of this program is refurbishing or replacing old equipment, some of which has been in operation for 35 years and must be considered close to its lifespan. New beam extraction techniques and algorithms for beam intensity stabilization will be developed.

2. A major driver of the need for increased cyclotron beam current is a new primary proton beam line that will deliver protons to a new actinide target station (one more station will be added around 2017) in the ISAC complex. This line will have an advanced beam transport design in comparison to the existing ISAC beam line and will include a beam dump compatible with 200 A operation to facilitate cyclotron tuning and development.

3. To maintain its world leadership in ISOL techniques, TRIUMF continually invests in the development of new exotic beams by studying new target materials, inventing new target configurations, and employing new on-line ion sources. A new target station, in combination with high-intensity proton and electron driving beams, will enhance the RIB development capabilities. ISAC beam time will be efficiently shared between experiments and developments to the maximum benefit of the RIB users.

4. The ISAC complex of heavy-ion linear accelerators has demonstrated excellent reliability combined with the flexibility to accelerate different ion species over a wide range of energies. Expansion of the ISAC accelerator facilities will increase the mass reach of accelerated ions into the *terra incognita*, opening new frontiers for nuclear physics experiments. A major goal of the ISAC facility upgrade in the longer term is to provide, simultaneously, multiple exotic beams delivered to the three distinct experimental areas, where eight state-of-the-art unique apparatuses are available to produce unique science.

5. The electron linear accelerator (e-linac) and its photo-fission based actinide target station represent the major laboratory infrastructure initiative for the Five-Year Plan. It will provide an additional source of neutron-rich isotopes for nuclear physics, and of ^{8}Li for β-NMR studies in molecular and materials science. The accelerator will be based on the 1.3 GHz superconducting radio-freuqency (SRF) technology that incorporates the latest advancements in this field from the frontier ILC design. A major distinction of the e-linac is its continuous wave (cw) mode of operation. Our R&D efforts towards improvements of high-power machine components, such as RF input couplers, will benefit all future MW regime facilities such as injec-

tors for fourth-generation light sources or accelerator-driven subcritical (nuclear) reactors for power generation.

Establishing SRF as a Core Competency and Partnering with Industry

In addition to the projects outlined above, it is the vision of TRIUMF to elevate its already prominent superconducting RF (SRF) expertise into a true core competency in the service of future TRIUMF projects, Canadian and international accelerator initiatives, and promoting and directly contributing to the Canadian entrepreneurial advantage. The majority of the new and proposed accelerators worldwide are based on SRF technology. The tremendous progress made in the last decades has proven this technology to be reliable, cost-effective, and capable of delivering beams of the highest quality and precision.

TRIUMF's SRF team has already gained international recognition by developing and putting into operation a record-breaking, high-gradient, low beam velocity ($\beta = v/c \ll 1$), heavy ion superconducting linac. This team is now viewed as a capable partner for high frequency (1.3 GHz), $\beta \approx 1$ SC accelerator development. This status has recently allowed TRIUMF to establish collaborations with key players in the field, such as DESY and Fermilab, and to become a member of the Tesla Technology Collaboration. Further, based on TRIUMF's valued status in the field, the Indian Variable Energy Cyclotron Centre (VECC) is prepared to partner and directly contribute to our SRF development program.

Developing SRF into one of TRIUMF's core competencies has much broader implications. The need for Canada to stay at the forefront of subatomic research and to transfer technology knowledge to industry is best exemplified in the following excerpt from the Report of the NSERC 2006 Long-Range Planning Committee: "Canada's economy is undergoing significant change as it transitions from being resource-based to being knowledge-based. It is critical for Canada to have a strong and vibrant scientific community, to provide expertise and highly qualified people to Canadian industry. …. In particular, Canada must remain at the forefront of subatomic physics research" ["Perspectives on Subatomic Physics in Canada 2006–2016," Report of the NSERC Long-Range Planning Committee]. While building the ISAC-II superconducting (SC) linac, TRIUMF promoted and assisted a local BC-based engineering company, PAVAC Industries Inc. in developing technology for fabrication of bulk niobium superconducting cavities. This technology transfer directly responds to the NSERC Long-Range Planning Committee's vision and has great potential for the future international accelerator facilities. It will transform Canada from a purchaser of SRF technology to a nation with the capability to produce, process and sell niobium cavities and their attendant components. Presently, there are only a few vendors of SRF technology worldwide, and through our collaboration with PAVAC, Canadian industry will be able to join this elite group.

The TRIUMF SRF R&D program will expand beyond the needs of the e-linac to aim at the quest for higher accelerating gradients and higher operational quality factors via the use of single-crystal or few-crystal SC cavities. With these activities, we plan to contribute to the ILC design and to the development of the LHC and its upgraded injector, the superconducting proton linac (SPL). The Canadian university community has a very strong interest in both these high-energy physics frontier experimental facilities.

Superconducting electron linacs are proposed around the world as drivers for fourth-generation light sources; future reconfiguration of the e-linac as an ERL opens the door to such a possibility. A shortcut to high-energy X-rays is proposed via inverse Compton scattering (ICS) of optical photons off of electrons of hundreds of MeV. ICS has applications in molecular and materials science and medical imaging. E-linac could serve as a test-bed for the enabling technologies for an ICS source at the Canadian Light Source in Saskatoon.

Adding new SRF expertise in 1.3 GHz cavities design to the existing capabilities developed with ISAC-II SC linac construction, TRIUMF will become a unique centre for SRF science and accelerator physics.

TRIUMF's International Competitiveness

The TRIUMF Accelerator Division is uniquely positioned to support these future scientific opportunities. The accelerator division staff possesses all the required knowledge and expertise to both upgrade the facilities and operate them efficiently and, by doing so, satisfy this domain's science needs.

TRIUMF, despite its modest size (equivalent to a division at other accelerator laboratories such as CERN, Fermilab and KEK), holds a mix of accelerator expertise that could be matched in range at other laboratories only by pooling divisions. These areas of expertise, unique in Canada and rare in the world when viewed as a combined set, include:

- Physics of accelerated beams (cyclotrons, synchrotrons and linacs)
- Superconducting RF (SRF) cavities
- Low-level RF (LLRF)
- High power RF (HPRF)
- H^- high-intensity ion sources
- Heavy-ion particle sources
- High power targets and radiochemistry
- Nuclear engineering and remote handling techniques
- Beam diagnostics
- Cryogenics and vacuum
- Magnets design
- High power pulsed power supplies
- Experimental physics control systems

This expertise must be preserved and augmented in order to secure Canada's subatomic physics future as well as to produce a new spin-off for Canadian nuclear medicine.

TRIUMF's accelerator scientists and engineers are highly regarded and sought after worldwide as scientific collaborators, project reviewers, members of high-level committees, and international conference organizers. Just to name a few examples: three of the laboratory's staff are presently serving as members of US National Academy of Sciences committees; several serve on international review boards, for example in Israel, Germany, Japan, Switzerland, the UK, and the US; and two taught in the US Particle Accelerator School. Two major international accelerator conferences: LINAC-08 and PAC-09 with about 400 and 1,500 participants, respectively, will be hosted by TRIUMF.

In the early 1990s, while designing the KAON accelerator facility, TRIUMF developed a highly reputable expertise in synchrotron beam dynamics, which was not lost with termination of the KAON project. Moreover, it appeared to be in high demand in other accelerator laboratories and has been efficiently applied at CERN as a Canadian contribution to the LHC project. This expertise, together with other core competencies such as RF cavity and kicker magnet design, is being requested again by CERN. Our contribution to the future LHC accelerators upgrades will secure a strong Canadian position in the LHC experimental program.

Education and Training

The TRIUMF accelerator development and exploitation program will provide many opportunities to train highly qualified personnel and university students in the fields of cryogenic, vacuum and radio-frequency engineering; accelerator science (including particle beam dynamics); ion source physics and electromagnetic field modeling; radiochemistry, high power target and nuclear engineering; high power electronics; and many others.

Summary

TRIUMF's accelerator facilities will be used to address the fundamental scientific questions of our time. They will be used to explore ultimate structure and properties of matter from the smallest to the largest scales, will expand the materials and life sciences programs, will enable partnerships with industry to contribute to knowledge-based economic transformation of Canada, and will educate the next generation of accelerator scientists and engineers.

6.4

University-led Initiatives Based at TRIUMF

6.4.1

Introduction

As a joint venture of seven Canadian universities, TRIUMF provides centralized resources to a broad group of researchers and students. In this context, TRIUMF is predominantly a user facility. For example, ISAC has a large user community that works with a smaller complement of TRIUMF scientists and engineers to exploit the accelerators, beams, and detectors at TRIUMF. This model is even better defined in the Centre for Molecular and Materials Science where outside users bring their expertise and research questions and frequently equipment or major detector facilities. For the physical sciences, the funding for this equipment comes predominately from the Natural Sciences and Engineering Research Council of Canada (NSERC) or the Canada Foundation for Innovation (CFI) programs. Indeed, almost all the "end-user" experimental facilities, as opposed to the accelerators and beam lines, are funded through NSERC or CFI; only relatively small contributions have come through TRIUMF's NRC funding. TRIUMF's success relies as much upon this cooperation among the funding agencies as it does on the partnership of its member universities.

TRIUMF's major ISAC-I facilities, like DRAGON and TIGRESS, are led by university-based research collaborations. Each collaboration has developed its own governance and has successfully sought support from the Canadian research councils to design and build their experiments in consultation with TRIUMF. The resulting detector facility is then made available to the large TRIUMF user community. An analogy would be large astronomy teams that construct a telescope, which is then put into service for the larger scientific community.

At TRIUMF, the NSERC-funded experimental facilities, whose accounting is overseen by TRIUMF, represent a large financial investment that exceeded $100 million over the past few decades. To date, the CFI investments in some detector facilities, like DESCANT, have been smaller but are still significant. In these cases, the subsequent NSERC and CFI investments are highly leveraged.

This multi-agency funding model is still evolving. Traditionally, the NRC Contribution Agreement has funded the basic accelerator and beams infrastructure and the province has supported buildings with NSERC supporting individual teams of researchers developing custom experimental apparatus. The scale of awards from the CFI has made it possible, however, for the Canadian community to create large new facilities (such as the Canadian Light Source) as well as central additions to the TRIUMF facilities. While TRIUMF cannot apply directly for CFI funds, university scientists can and do use CFI funds to enhance the lab's facilities.

CFI investments at TRIUMF through the university research community fall into two categories. The first category supports enhancements to the TRIUMF facility itself that provide new research capabilities for the nation. This includes the upgrade to the M20 beam line and the ATLAS Tier-1 Data Centre. At the end of the CFI funding period, TRIUMF will operate these facilities as part of its core program through the NRC Contribution Agreement. The second category supports the development of detector facilities, in a manner similar to NSERC capital support. The prime example here is the DESCANT detector.

In the 2010–2015 Five-Year Plan for TRIUMF, the Canadian research community is putting forward CFI proposals in both categories. In the first category, two top priority proposals are central to TRIUMF and will provide unique new capabilities to Canada:

- The e-linac, a novel new accelerator that will open significant windows to ISAC physics, provide strong ties to the international accelerator community and direct ties to leading particle physics projects, involve strong collaboration with the Canadian university community and unique ties to developing Canadian industry;
- The nuclear-medicine network, which will link radioisotope production centres across Canada and provide direct benefits to Canadian health and society.

These proposals are highly leveraged by the present TRIUMF infrastructure and have been discussed in detail (see Sections 6-2-1-2-2 and 6-2-3 respectively).

In the second category, the three principal proposals are:

- Ultra-Cold Neutron Source (UCN);
- Gamma-Ray Infrastructure for Fundamental Investigations of Nuclei (GRIFFIN); and
- ISAC Charged Particle Spectroscopy Station (IRIS).

The UCN would be used for a variety of scientific experiments: quantum levels of neutrons in gravitational field, neutron lifetime measurements, and neutron electric dipole moment measurements. This is a large project with significant contributions from international partners and is headed by a group from the University of Winnipeg and the University of Manitoba.

GRIFFIN is a new, state-of-the-art, high-efficiency γ-ray spectrometer that will, during the 2010–2015 TRIUMF Five-Year Plan period, replace the current 8π spectrometer as the primary decay spectroscopy facility at ISAC-I. This project is being proposed by a group from the University of Guelph.

IRIS is designed to study charged particle spectroscopy at ISAC-II. It could be used as a stand-alone facility or in conjunction with the existing EMMA facility and is led by a group from Saint Mary's University.

These three CFI proposals, UCN, GRIFFIN, and IRIS, are discussed in this section. They are expected to be the principal projects being proposed to CFI by Canadian researchers inspired by TRIUMF capabilities over the 2010–2015 period.

6.4.2

Canadian Spallation Ultracold Neutron Source: UCN

Introduction

The construction of the world's highest density source of ultracold neutrons (UCN) at TRIUMF has been proposed to enable precision measurements of the fundamental interactions of the neutron to be conducted with significantly improved statistical and systematic uncertainties. This source would therefore make a major impact on studies of fundamental physics with UCN that would complement and enhance the ISAC program. The technical requirements of a UCN source can be worked out so that the program would run concurrently with ISAC and μSR. A window of opportunity exists to capitalize on the successes of Y. Masuda's group at KEK and at the Research Center for Nuclear Physics (RCNP) at Osaka University. Timeliness would be served by testing the UCN source components in Japan, and then installing at TRIUMF in 2013.

Operation of a UCN source in 2013 with a density exceeding 1×10^4 UCN/cm^3 would place TRIUMF at the forefront of UCN technology. We anticipate that the highest priority initiatives for a UCN source beginning in

2013 will be a neutron lifetime experiment and/or a test of micron-scale gravity using UCN. In the longer term, a search for a non-zero neutron electric dipole moment would be pursued with very high priority.

Significant support for the UCN source would be requested from the Canada Foundation for Innovation (CFI), with matching funds from Japanese sources, and from TRIUMF. Funding for specific physics experiments would be requested from a combination of the Natural Sciences and Engineering Research Council of Canada (NSERC), Japan, and other international sources.

Physics with Ultracold Neutrons

UCN are neutrons of such remarkably low energies that they are totally reflected from the surfaces of a variety of materials. Hence, they can be confined in material bottles for long periods. Typically, UCN have kinetic energies less than 300 neV. Correspondingly, they are strongly affected by various fields, such as the Earth's gravitational field, and by strong magnetic fields.

UCN sources are often characterized and compared by the limiting UCN density achieved (ρ_{UCN}). The UCN source proposed for TRIUMF would have $\rho_{UCN} = 5 \times 10^4$ UCN/cm^3, which is at least a factor of 100 greater than any UCN source ever operated. Currently, there is only one operating UCN source in the world, at Institut Laue-Langevin (ILL) in Grenoble, France. The source at ILL typically achieves 40 UCN/cm^3 at the exit of the source. Typically, 1 to 2 UCN/cm^3 is achieved in experiments, such as in the completed ILL n-EDM experiment.

With the advent of superthermal sources of UCN, a new generation of UCN sources is under development at various laboratories (see Table 1). It is important to note that all the sources in the table are future sources that have listed projected densities, except for the LANL UCN source. TRIUMF would eventually surpass the future highest density source, which is under development at the Munich FRM-II reactor. In addition, the pulsed nature of the proposed TRIUMF source would offer considerable advantages for reduction of background compared to a reactor source.

Location	Technology	Critical Energy E_c (neV)	Storage Time τ_s(s)	Density in Experiment ρ_{UCN} (UCN/cm^3)
TRIUMF	spallation He-II	210	150	$1 - 5 \times 10^4$
ILL Grenoble	CN beam He-II	250	150	1000
SNS ORNL	CN beam He-II	134	500	150
Munich	reactor SD_2	250		10^4
NCSU	reactor SD_2	335		1000
PSI	spallation SD_2	250	6	1000
LANL	spallation SD_2	250	1.6	145

Table 1: Future UCN sources worldwide. The Los Alamos National Lab (LANL) source is the only source listed that is currently in operation (on a testing basis). All other sources are proposed (future) sources, including a future He-II source at the ILL reactor for the CryoEDM project. These are the Spallation Neutron Source (SNS) at Oak Ridge National Lab (ORNL) for the n-EDM project there, the Munich FRM-II reactor (Forschungsneutronenquelle Heinz Maier-Leibnitz), the North Carolina State University nuclear reactor (NCSU), and the Paul Scherrer Institut (PSI) source in Switzerland. The TRIUMF source figures are quoted for 20 kW peak power delivered to the spallation source. The range indicated for the TRIUMF source results from use of differing cold moderator materials, as discussed in the text.

For the TRIUMF UCN source, the lower value of 1×10^4 UCN/cm^3 in Table 1 corresponds to the version of the source that we will pursue for first operation. By modifying the source to use a liquid deuterium cold moderator, a factor of 5 in UCN density can be achieved, or 5×10^4 UCN/cm^3. The heavy water ice moderator is preferred initially for its similarity to the existing Japanese UCN source (and hence the available expertise), for its simplicity in terms of implementation and safety, and for the implied savings in cost.

Given this breakthrough in UCN production, a variety of new UCN experiments can be envisioned that are only now possible with the new generation of sources. We have discussed a variety of physics experiments that could be done with such a source and have decided to focus on the following possible experiments:

- A precise measurement of the neutron lifetime;
- Characterization of the UCN quantum states in the Earth's gravitational field; and

- A search for a non-zero neutron electric dipole moment.

Each experiment has its own physics interest and time line, so that, in time, one could envision performing a series of UCN experiments at TRIUMF. We now briefly describe the physics motivation and timeline for each experiment.

Neutron Lifetime

Subsecond measurements of the neutron lifetime are of physics interest for two reasons: 1) the neutron lifetime is currently the dominant uncertainty for accurate predictions of Big Bang nucleosynthesis, and 2) the neutron lifetime can be used to extract the Cabbibo-Kobayashi-Maskawa (CKM) matrix element V_{ud} and hence to form unitarity tests of the CKM matrix. An experiment at TRIUMF would build on preliminary work done at LANL by Bowman *et al.* and would aim for a determination of the neutron lifetime at the 0.1 s level, a factor of 8 better than the most precise determination to date.

UCN Quantum States in Gravity

This experiment aims at the precise spectroscopy of neutrons confined in energy levels above a UCN mirror in the Earth's gravitational field. The experiment is an interesting application of quantum mechanics to micron-sized quantum states. The experimental result can be used to place limits on modifications to the short-range (10 μm) behaviour of gravity, for example, theories involving micron-scale extra dimensions. The result can also be used to constrain axion models. The experiment would be led by a Japanese group (S. Komamiya *et al.*) where detector development is proceeding.

Neutron Electric Dipole Moment (nEDM)

The nEDM is a T-violating observable, and a non-zero nEDM at the current level of precision would imply CP violation beyond the standard model. A next generation search for an EDM at TRIUMF would aim for a determination at the 10^{-28} e-cm level, which is two orders of magnitude beyond the current best limit and would tightly constrain new CP-violating phases in a number of theoretical models. An nEDM project is a longer-term goal for the UCN source at TRIUMF and would build on the mature efforts underway at ILL Grenoble, PSI, and SNS.

Timeline to First Experiments

The UCN source would be developed and optimized at RCNP Osaka until 2012. The source would then be installed in the M11/M13 area. Commissioning of the source and achievement of the world record UCN density at TRIUMF are envisioned for 2013. A first flagship physics experiment, either the lifetime or gravity experiment, would be conducted in 2013 and beyond. In 2015 and beyond, an nEDM measurement could be pursued.

The UCN Source Project and Resource Requirements

The UCN source requires delivery of a 500 MeV proton beam at 40 μA to a new tungsten spallation target in the Meson Hall at TRIUMF. A new beam line and a fast kicker system are required to deliver beam to the new spallation target, with a pulsed time structure that would utilize on average 7% of the high intensity beam delivered to the Meson Hall, leaving the beam otherwise unaffected when not being delivered for UCN production. The MeV-scale spallation neutrons would be cooled via thermal equilibrium with cryogenic moderators at 20 K. Cold neutrons would become ultracold by downscattering in a superfluid ^{4}He volume, producing phonons; the resultant UCN would diffuse out of the ^{4}He for delivery to experiments. Shielding, cooling, and remote handling would be required for the target. The UCN cryostat would require liquid helium operated in a closed loop with a liquifier.

Detailed cost and manpower estimates were conducted in preparation for the Five-Year Plan and for the CFI New Initiatives Fund (NIF) request selected to be put forward by the University of Winnipeg. The overall project cost is C$10 million. TRIUMF would supply some matching funds. Funding for the physics experiments will be pursued through subsequent requests to NSERC and to other international funding sources.

Grant-Eligible Investigators and Other Collaborators

The Canadian grant-eligible UCN collaborators include: J. Martin (U. Winnipeg, spokesperson), J. Birchall, M. Gericke, S. Page, W. van Oers (Manitoba), E. Korkmaz (UNBC), M. Hayden (SFU), and L. Buchmann and C. Davis (TRIUMF).

Martin, Davis, Gericke, Hayden, and Page have directly relevant experience in cold or ultracold neutron research. Upon approval of the project, this core group is expected to expand and draw substantial international collaboration, particularly from the US and Japan. Several world experts from the US have already joined the collaboration including: R. Golub (NCSU), a key researcher who invented superfluid ^{4}He UCN source technology; J.D. Bowman (ORNL), a leading scientist in past and future nEDM searches, and B. Filippone (Caltech), T. Ito (LANL), and B. Plaster (Kentucky). The Japanese collaboration consists of large number of collaborators from RCNP Osaka, KEK, Osaka U., and U. Tokyo. Y. Masuda from KEK is the leader of the UCN source R&D project, and has successfully developed the only spallation driven superfluid ^{4}He UCN source in the world

6.4.3

Gamma-Ray Infrastructure for Fundamental Investigations of Nuclei: GRIFFIN

Introduction

GRIFFIN (Gamma-Ray Infrastructure for Fundamental Investigations of Nuclei) is a new state-of-the-art high-efficiency γ-ray spectrometer. Between 2010 and 2015, the period of TRIUMF's new Five-Year Plan, GRIFFIN will replace the current 8π spectrometer as the primary decay spectroscopy facility at ISAC-I. GRIFFIN will provide more than a 20-fold increase in absolute γ-ray detection efficiency, representing a 400-fold efficiency increase for γ–γ coincidence experiments. This enormous gain in detection efficiency will enable detailed studies of the most exotic radioactive beams produced by ISAC and its future target and driver upgrades at TRIUMF. With GRIFFIN, nuclear decay and structural properties will be measured for isotopes produced with intensities below 0.1 ions/s, extending the reach of ISAC experiments to the extremes of neutron richness. It is the properties of these isotopes, many of which are completely unknown, that are the current focus of the worldwide nuclear structure community as they determine the pathways, time scales, and energy releases in the explosive astrophysical environments responsible for the synthesis of the heavy elements.

The GRIFFIN detectors will also be available for use in other ISAC applications in which high-efficiency and/or high-rate γ-ray detection is required. Examples include, but are not limited to, the search for new CP-violating fundamental interactions through precision electric dipole moment (EDM) searches with Rn isotopes at ISAC-I (S929), and high-efficiency decay spectroscopy at the focal plane of the EMMA recoil separator at ISAC-II. GRIFFIN will thus make major contributions to all of the nuclear structure, nuclear astrophysics, and fundamental symmetries programs at TRIUMF's ISAC facility.

"Full exploitation of the high-intensity radioactive beams for nuclear physics and nuclear astrophysics at ISAC and ISAC-II" was identified as one of the highest priority projects of the Canadian subatomic physics community for 2006–2016 in the recently completed NSERC Long-Range Plan. Through its dramatically increased γ-ray detection efficiency, GRIFFIN will enable the full exploitation of the rare-isotope beams produced not only by the current ISAC facility, but also by the second high-intensity proton beam line to ISAC, the actinide production targets, and the new electron linear accelerator proposed in this 2010–2015 TRIUMF Five-Year Plan.

Detailed Description of Apparatus

GRIFFIN will be composed of 16 unsegmented clover-type HPGe detectors. Similar to the TIGRESS γ-ray detectors, each of the GRIFFIN detectors will consist of 4 individual high-purity germanium (HPGe) crystals packed in a four-leaf clover geometry. The proposed geometry of GRIFFIN involves the construction of detectors with mechanical exterior dimensions identical to those of the TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer) detectors in order to capitalize on the extensive developments for the mechanical support and rapid reconfiguration of these detectors that have been carried out by the TRIUMF design office and engineering staff over the past several years.

Unlike the TIGRESS detectors, which have been optimized for use in experiments with accelerated radioactive beams at ISAC-II and thus have highly segmented electrical contacts to provide γ-ray position resolution to reduce Doppler broadening effects, the GRIFFIN detectors are intended for use in decay experiments with stopped radioactive beams. In such experiments, Doppler shifts and broadening are not a concern. The GRIFFIN detector electrical contacts need not be segmented, and the interior design of the detectors can be optimized for both efficiency and mechanical robustness to enable simple redeployment of the detectors in a variety of ISAC applications. With the current design, the full GRIFFIN array will provide an absolute detection efficiency greater than 21% for 1 MeV γ-rays. This represents more than a 20-fold increase in efficiency compared to the current 8π spectrometer at ISAC-I and, for a typical γ-γ coincidence experiment, more than a 400-fold increase in detection efficiency. It is this enormous gain in detection efficiency provided by GRIFFIN that will enable detailed spectroscopic studies of the most exotic radioactive beams produced by ISAC and its future target and driver upgrades.

In addition to the 16 HPGe clover detectors, GRIFFIN will also employ segmented bismuth-germanate (BGO) Compton suppression shields. These shields will provide both segment-specific vetoing of events in which γ-rays escape the HPGe volume, and the “active collimation” necessary to shield the HPGe detectors from background in experiments with low-intensity radioactive beams. As with TIGRESS, the GRIFFIN suppression shields will be mounted in a mechanical structure that enables rapid reconfiguration between a “maximum-efficiency” and an “optimal-suppression” configuration.

While the new GRIFFIN HPGe detectors, BGO suppression shields, and outer mechanical support structure will replace those of the current 8π spectrometer, all of the components of the 8π installation inside the beam line vacuum that have been developed over the past several years will be reused with GRIFFIN. These components include: the low-energy beam transport (LEBT) line itself, with its well-established optics and tuning; the in-vacuum tape transport system on which the radioactive beam is deposited at the centre of the array and then moved behind a lead shielding wall to remove long-lived daughter activities; the 20-element SCintillating Electron-Positron Tagging Array (SCEPTAR) plastic scintillator β-detector array inside the central vacuum chamber; and the 5-element Pentagonal Array for Conversion Electron Spectroscopy (PACES) liquid-nitrogen cooled Si(Li) detector array, also inside the central vacuum chamber. Further, 8 of the 10 BaF_2 γ-ray detectors of the Dipentagonal Array for Nuclear Timing Experiments (DANTE) will be reused with GRIFFIN to provide fast γ-ray timing information. GRIFFIN will thus continue to provide the full suite of detection capabilities for decay spectroscopy with radioactive beams that has been developed in association with the 8π spectrometer at ISAC-I, extended by the enormous increase in γ-ray detection efficiency provided by the state-of-the-art GRIFFIN HPGe clover detectors.

Resources Requested

The combination of advanced accelerator, target, and experimental facility developments at TRIUMF will enable the Canadian research community working at ISAC to maintain and enhance its international leadership in the production and use of rare-isotope radioactive beams. The community has thus rallied behind the GRIFFIN proposal, with current GRIFFIN collaboration representatives from TRIUMF and seven Canadian universities, including six Member and Associate Member universities of the TRIUMF joint venture. This collaboration is preparing the GRIFFIN funding proposal for submission to the Canada Foundation for Innovation (CFI) and the Ontario Ministry of Research and Innovation in 2008 as an application led by the University of Guelph. The total project cost is estimated at C$10.6 million over 4 years (2010–13), with the 20% matching contribution derived from vendor discounts and major in-kind contributions from TRIUMF (described below) to the design, installation, and support of GRIFFIN. GRIFFIN would become operational in 2013.

Partners

Guelph University, Laval University, McMaster University, l'Université de Montréal, Saint Mary's University, Simon Fraser University, and the University of Toronto.

TRIUMF's Role

TRIUMF will make major contributions to all of the design, installation, and support of GRIFFIN at ISAC-I. The mechanical mounting of GRIFFIN detectors will make extensive use of developments for TIGRESS carried out by the TRIUMF design office and verified by TRIUMF engineers. Additional contributions by the fesign office will be required for the installation of GRIFFIN at the current location of the 8π spectrometer in the ISAC-I hall. Machining of components for GRIFFIN will be carried out in parallel in the TRIUMF and Guelph machine shops, as well as by external contractors.

TRIUMF has provided a dedicated detector laboratory in the ISAC-II building for the testing and characterization of the TIGRESS γ-ray detectors, and this laboratory will also be used for the testing and maintenance of GRIFFIN detectors. TRIUMF staff designed, fabricated, and installed many components of the current 8π installation, including the dedicated low-energy beam-transport line to the 8π location, the central vacuum chamber, the SCEPTAR plastic scintillator β-detector array, the rails, stand and shielding wall for the in-vacuum tape transport system, electrical services, and an air conditioned electronics enclosure, all of which will be reused for GRIFFIN.

Three TRIUMF staff scientists (G.C. Ball, B. Davids, and G. Hackman) are currently members of the GRIFFIN collaboration. A dedicated TRIUMF technician will provide ongoing technical support for GRIFFIN, while a second technician will be required to coordinate the design, procurement, parts, and machining during the mechanical construction phase.

Members of the TRIUMF DAQ group (C. Pearson, P. Amaudruz) have been instrumental in the development and implementation of the custom waveform digitizer modules developed for the TIGRESS project. These modules will also be used for GRIFFIN, and members of the TRIUMF DAQ group will contribute to the implementation and ongoing support of the GRIFFIN data acquisition. Front-end readout, back-end workstations, and networks for GRIFFIN data acquisition will also be provided by TRIUMF.

6.4.4

ISAC Charged-Particle Spectroscopy Station: IRIS

Introduction

IRIS (ISAC Charged-Particle Spectroscopy Station) consists of a low-pressure ion chamber, a cryogenic, solid-hydrogen target, and a ΔE-E detector telescope consisting of silicon detectors and CsI. It will be used to study reaction dynamics of unstable nuclei and will extend ISAC-II's capabilities into a new area and exploit the neutron-rich beams the actinide target will make available.

Nuclei with extreme neutron-to-proton ratios offer a unique opportunity to probe the isospin dependences of nuclear interaction and properties that are inaccessible otherwise. These asymmetric nuclei also contribute to the synthesis of heavy elements. The unstable nuclei with large neutron excess are efficient means to gain insight into the properties of highly neutron-rich stellar environments such as neutron stars and supernovae. Studies of nuclear reactions provide a view to their internal structure and give the reaction rates governing nucleosynthesis.

Surprisingly, these asymmetric nuclei have features that are markedly different from the stable nuclei existing on Earth. The nuclear halo is the most exotic nuclear structure observed for very neutron-rich (or proton-rich) nuclei close to the edge of nuclear binding. The unknown exotic nature makes it crucial for experiments to unveil their structure and understand their interaction capabilities, including excitation mechanisms. Nucleon transfer reactions are the most sensitive traditional probes to understand the internal arrangement of nucleons inside a complex nucleus. These reactions are best performed at energies around 5*A* MeV. They are complementary to the knockout reactions employed at high energies and can therefore lead to a definitive understanding of nuclear structure.

Inelastic scattering of unstable nuclei offer the possibility of studying new modes of excitation that can occur due to exotic structures such as nuclear halo and skin. One such important mode is the soft dipole resonance mode where the excess neutrons can oscillate against the rest of the nucleus. These resonances are expected to occur at low excitation energies, and if they are located just above the neutron threshold, they can have significant impact on the fusion probability that leads to formation of heavy elements in our universe.

These reactions lead to the reaction residue being in its different excited states. One therefore needs to identify the residue in the different excited states. Due to the weak binding nature of these asymmetric nuclei, the unbound states in them have a strong impact on their structure and role in nucleosynthesis. The gamma detection has been used for observing bound excited states, *i.e.*, those below the neutron or proton threshold. The low yield of these nuclei often makes it difficult to rely solely on gamma spectroscopy because of limited gamma detection efficiency. Furthermore, it is impossible to observe the unbound states (located above the neutron threshold) by gamma detection. Reaction spectroscopy, through the precise detection of the light and heavy nuclei, *i.e.*, the charged particles, after the reactions is required to disentangle the nuclear levels and reaction channels. Internal arrangement in a nucleus and the nature of excitation can be studied from the angular distribution of the charged reaction residues. Charged-particle reaction spectroscopy is thus an important part of studying exotic nuclei and the IRIS CFI would, if funded, provide a charged-particle spectroscopy facility at ISAC-II.

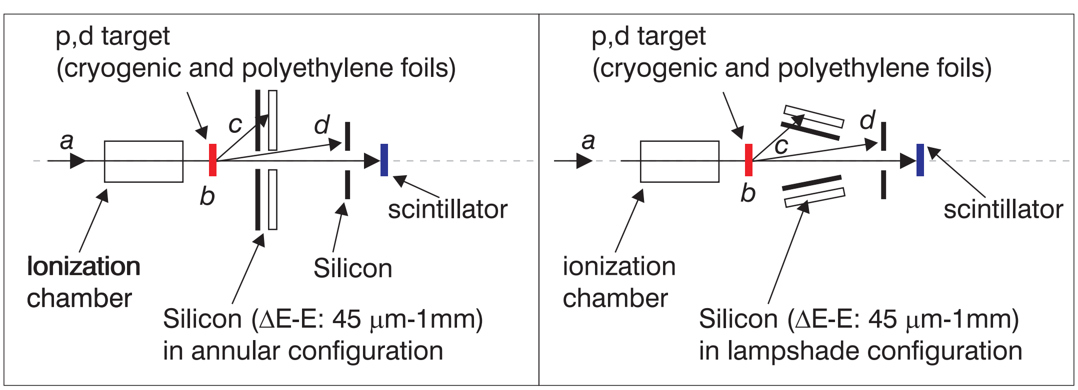


Figure 1: Layout of the proposed ISIS facility. Two different arrangements are shown for the silicon *E*-*E* detector telescope.

Detailed Description of Apparatus

The ISAC Charged-Particle Spectroscopy Station (IRIS) facility is being designed for nuclear reactions with $E \geq 3A$ MeV at ISAC-II (see Figure 1). Two-body reactions like $a+b \rightarrow c+d$ will be measured, where a = incident nucleus, b = light targets (*e.g., p, d), c* = light particle (*e.g., p,d,t,*^{3}He) and d = recoiling nucleus. The beam of unstable nuclei first passes through an ionization chamber. This low-pressure ionization chamber counts the beam and identifies the isobaric contaminants in the beam through an energy-loss measurement in this detector. This will be the first time beam species have been identified on an event-by-event basis at an ISOL facility. This event-by-event identification is very important because the production of heavy unstable nuclei is often accompanied by substantial amounts of contamination from other nuclei with the same mass (isobaric contaminants). The fabrication of novel cryogenic solid ^{1}H, ^{2}H targets is envisioned. This will increase the reaction yield by an order of magnitude (compared to polyethylene targets such as CH_2 or CD_2), thereby extending the experimental reach to more neutron-rich or proton-rich species. For nuclei that can be produced with fairly high intensity, thin foil targets will be used. The scattering angles and energies of particles c and d will be measured using a position sensitive ΔE-E detector telescope. The telescope will be made of silicon strip detectors that measure the scattering angle of the particles and the energy loss, while a CsI detector placed directly behind the silicon stops the particles measuring its energy. The telescope can be in the form of an annulus or a lampshade, to allow the unreacted beam to pass through. A scintillator placed at zero degrees downstream of the telescope detects the un-reacted nuclei.

The facility can be used either as a stand-alone system or at the target station of the recoil spectrometer EMMA (ElectroMagnetic Mass Analyser). Either the focal plane detectors of EMMA or an annular silicon strip detector can be used to detect the recoiling nucleus d. The significant features of this facility are therefore: (a) cryogenic targets that increase the reaction yield by one order of magnitude; (b) identification of the incoming nuclei; and (c) the use of a flexible detector telescope system capable of ΔE-E identification of different reaction channels.

Resources Required

The nuclear science community supports the IRIS project, with current collaboration representatives from TRIUMF, four Canadian universities (all members of the Joint Venture), and one in Japan. This collaboration is preparing the IRIS funding proposal for submission to the Canada Foundation for Innovation (CFI) led by Saint Mary's University. The total project cost is estimated at C$1.2 million with major contributions from TRIUMF in the form of detector group support for ionization chamber fabrication R&D, DAQ support, and design office and machine shop support.

Partners

McMaster University, Osaka University, Simon Fraser University, Saint Mary's University, and the University of Guelph.

6.5

Broader Impacts

TRIUMF is strongly committed to undertaking high-impact research and delivering value beyond its pure research program. TRIUMF's skill in this latter area has grown into a string of success stories (see Section 4.4). The chief objectives of the current Five-Year Plan have been selected not only because of the opportunities they afford for high-impact scientific excellence, but also because of their potential for economic impact, their contribution towards commercialization of research, and their ability to attract top talent to Canada as well as retain it.

These objectives are explicit to TRIUMF's forward-looking vision, and this section will highlight just a few of the broader impacts that will arise when they are met. Subsection 6.5.1 focuses on the nuclear medicine program and the production and use of radioactive isotopes in medicine. Subsection 6.5.2 focuses on molecular and materials sciences and identifies a number of opportunities for practical applications. Subsection 6.5.3 discusses the commercialization of the superconducting radio-frequency cavity technology developed with TRIUMF's help. Finally, Subsection 6.5.4 highlights TRIUMF role in preparing the next generation of leaders.

Leading the Nuclear-Medicine Revolution

Functional imaging is aimed at gaining an understanding of basic biological processes, in essence asking the question: "What is the basis for health and disease?" It is similar to the question nuclear physicists ask as they probe the nature of fundamental matter. Trying to find a better way to diagnose disease is a driving force behind nuclear medicine. We are beginning to understand how

MORGAN DEHNEL

President, D-Pace, Inc.

Morgan Dehnel undertook his Ph.D. work at TRIUMF in Applied Accelerator Physics under British Columbia Science Council G.R.E.A.T. Scholarship collaboration. He utilized a 1 MeV test Cyclotron to develop the injection system for the TR-13 cyclotron and to make ground-breaking injected beam and central region beam measurements in close proximity to a spiral inflector. In 1995 he and his wife established Dehnel Consulting Ltd. (DCL) in Nelson, BC, Canada, and immediately proceeded to develop the Beamline Simulator software with his brother, computer scientist, Kurt Dehnel. Through a combination of NRC-IRAP grants, First Year in Science and Technology grants, and SRED credits, DCL was able to release the software for global sales in 1998. DCL provided charged particle transport system and component engineering consultation into the radioisotope production industry, the ion implanter industry, and for national laboratories such as TRIUMF. In 2001 DCL licensed a number of TRIUMF technologies including a negative hydrogen ion source, radiation detector, emittance scanner, wire scanner etc.. In 2004, DCL became Dehnel – Particle Accelerator Components & Engineering, Inc. (D-Pace) a new company formed by Dehnel and his brothers. The new company name highlighted a change of direction from strict consulting to the production and sale of accelerator components. D-Pace has been able to commercialize successfully the ion source, target, and detector technologies and to sell these technologies on a global basis. TRIUMF & D-Pace received the NSERC Synergy Award in 2007. ■

living species function through genome research and better diagnostic tools. Functional imaging touches on many aspects of health sciences and is an extremely sensitive tool for probing at all levels of health and disease.

TRIUMF works closely with the University of British Columbia, (UBC), the BC Cancer Agency (BCCA), and the Pacific Parkinson's Research Centre (PPRC) on research that may revolutionize the understanding of mental disease, cancer imaging, and their therapies. This work will result in a substantial expansion of the current medical isotope and life sciences programs and will launch a new national program in molecular imaging focused on neurodegenerative diseases and cancer.

The emerging revolution in nuclear medicine will dramatically change the way we deal with disease. New tracer molecules with attached unstable rare isotopes, called radiotracers, allow doctors to select and image specific metabolic activity associated with the growth of disease. It will soon be possible to "see" the progressive death of a cancer tumour after radiation treatment or chemotherapy. The success of the treatment would become obvious. If the treatment is ineffective, the doctor could quickly change the approach. The number of lives saved, and the reduced costs of treatments, are expected to be enormous. It is anticipated that thousands of such tracers will eventually be developed and used in the detection and treatment of neurodegenerative diseases such as Parkinson's and Alzheimer's as well as all forms of cancer. Canada and BC are world leaders in producing medical isotopes and employing molecular imaging using positron emission tomography (PET). When combined with the advances in custom-designed tracer molecules, the ability to monitor microscopic disease progression during treatment will become possible and perhaps even routine.

Because medicine/biological studies do not require the type of infrastructure that is required for astrophysics or particle physics, it is extremely difficult to carve out a unique place in the world as, for example, ISAC or μSR can. The holdback in functional imaging is achieving a critical mass of specific specialties to advance the understanding of biological functioning. The strength of the TRIUMF life sciences program has been its ability to focus. TRIUMF has been fortunate to be able to focus and use PET as it should, as an analytical tool to probe fundamental questions.

The new nuclear medicine initiative proposed for TRIUMF will have profound implications for the future of Canada's role in the production and innovation of medical isotopes. While TRIUMF does not directly manufacture or distribute medical isotopes, its research activities and key industrial partnerships will enable breakthroughs innovations. The nuclear medicine laboratories located in the new TRUMF nuclear medicine building will allow researchers to work alongside technicians from MDS Nordion and clinicians from UBC and BCCA to develop new applications of medical isotopes.

The radioactive isotope itself is only useful when it is chemically attached to an existing molecule that has biological function or selectivity. Future "personalized medicine" will rely on accurately and precisely "labelling" numerous biologically active molecules with these medical isotopes. Once labelled, these tracers can be used in human health research or in the clinic to tag and identify cancer tumours, and other diseases in the body. As more and more countries around the world develop the capacity to make their own medical isotopes domestically, the Canadian share of the world market will dwindle. The type of research to be performed in this dedicated nuclear medicine suite of laboratories will add significant value to the medical isotope product and ensure Canada's dominance of the market. TRIUMF and UBC together are leading a national proposal to form a virtual network of nuclear medicine laboratories to shorten the "time-to-clinic" cycle of purchasing, installing, testing, and the using a cyclotron in hospitals. The nuclear medicine initiative at TRIUMF will underpin a national initiative that will allow hospitals to more quickly gain the expertise and flexibility of using on-site cyclotrons for medical imaging.

At present, the medical isotopes produced with cyclotrons like those at TRIUMF, MDS Nordion, and a half-dozen other cancer centres in Canada are distinct from those produced in nuclear reactors such as Chalk River but that may change. The TRIUMF proposal includes the construction and operation of a new type of accelerator that will allow very heavy isotopes to be produced in a beam rather than from the inside of a nuclear reactor. The accelerator will be sited in the underground tunnel that connects to the proposed new TRIUMF nuclear medicine building. These accelerator-produced isotopes can be harvested to provide a modest supply of medically relevant isotopes such as ^{211}At or even ^{99}Mo. TRIUMF's breakthrough research in this area is not currently capable of producing a commercially viable supply of these isotopes, but it will only be a matter of a few years of concentrated engineering effort to tune the system for scalable solutions. With alpha emitters, the best potential will be with ^{211}Rn, which is the precursor for ^{211}At, an alpha emitting nuclide that is being explored by many institutions. It is traditionally made by bombarding ^{209}Bi with alpha particles, but there are very few alpha producing cyclotrons.

It is difficult to speculate on the future growth of Canadian production capacity in terms of quantitative numbers. If MDS Nordion matches the growth that TRIUMF envisions in this area, and if Canadian health authorities adopt modern nuclear medicine imaging standards that are in play in the United States and Europe, one could see the TRIUMF-MDS Nordion contribution doubling from an annual level of patient doses from 2.5 million to 5.0 million.

Although it is not easy to compute the economic impact of selecting the "right" cancer therapy early in the treatment process, the impact on the lives of Canadians is dramatic. A 2007 clinical study in France reported that for the case of colorectal cancer, PET imaging saved more than US$5,000 on average per patient for successful management of the disease. Other studies report as much as US$32,000 of savings per patient. Integration of PET into the pre-surgical evaluation of patients with hepatic metastases also likely reduced overall costs and patients' morbidity. However, the main motivation for the new developments is not to save money on treating already curable diseases but to address incurable ones.

As a matter of course, TRIUMF will continue to operate its Applied Technology Group for applied-isotope production at MDS Nordion.

Molecular and Materials Science

Ultra-low-energy muon beams have the potential to revolutionize μSR, having recently demonstrated their applicability to investigations of surfaces, thin-films, and multi-layered compounds by addressing some longstanding issues in condensed matter physics. These structures are important for future technologies.

With a significant increase of ^{8}Li beam because of the e-linac, a -NMR user facility will become feasible and open a new avenue for condensed matter research in thin-film hetero-structures, with high potential impact. There is no comparable facility in the world, except the low-energy SR facility at the Paul Scherrer Institute (PSI) near Zurich. The ISAC beams are much more intense than the moderated low-energy muon beams and the facility is already much more capable of running many different types of measurements, although -NMR has far less beam time per year. The proposed plans will address this shortfall.

Similar types of probes of matter, μSR and β-NMR are implanted particles that sense the environment of the material they are implanted in and report this information through a special property of their beta decay. They are complementary in the implantation process. The low-energy ion beams are near-surface probes, and their implantation depth can be varied; they are depth controlled. In contrast, muons always go far into the bulk of the material, and there is no practical way at TRIUMF to control their implantation depth significantly. The -NMR probes have a range of radioactive lifetimes that are much longer than the muon lifetime, making them sensitive to phenomena that the muon is not. Conversely, the muon can be used in situations where the -NMR probes are not useful because their lifetimes are much longer than an intrinsic time scale for magnetic relaxation in the system.

The ISAC -NMR facility is unique. Other -NMR facilities exist, but none combine laser polarization separated from the sample, low beam energies, and electrostatic deceleration to vary implantation depth, high beam intensities, and high experimental magnetic fields.

Biological Applications

The extreme sensitivity of the μSR technique to dynamics and weak magnetism makes it a potential tool for obtaining microscopic information in biological systems. One application is the study of structural and functional properties of macromolecules. For example, the μSR method has been demonstrated to be sensitive to the electron transfer process in the important protein cytochrome c. Although used only sparingly thus far for studies of this nature, future exploitation of the μSR technique will likely include increased biological applications.

Destruction of Toxic Waste

Muonium studies in sub and supercritical water provide unique information on a simple hydrophobic solute (H atom) in water over a wide range of temperature and pressure. The knowledge gained from studies of muonium reaction kinetics under such extreme conditions is required for the development of supercritical water reactors for the destruction of toxic waste, and is relevant to the radiation chemistry that occurs in the cooling cycle of pressurized water nuclear reactors.

Electron Transport in Non-Metals

Many non-conducting materials become ionized in high electric fields, resulting in an excess of “free” electrons. The material then becomes conducting. This phenomenon, known as electrical breakdown is a serious problem for high-voltage equipment, such as power transformers, because the high voltage cannot be maintained as charge flows through the insulating material. The μSR technique has provided detailed knowledge about the transport mechanisms of radiolysis electrons in insulators by way of quantitative measurements of the mobility of charge carriers liberated in the muon's ionization track. An electric field (EF)-μSR technique has been applied to various rare gas (Ne, Ar, and Xe) solids ("cryocrystals") to study the effects of electric field on the formation of muonium arising from radiolysis electrons that have enough mobility to reach the stopped μ^+. These studies have direct consequences for the design of rare-gas-charged particle detectors. The EF-μSR method has also been extended to the investigation of muonium formation via transport of radiolysis electrons in more conventional insulators and semiconductors, such as sapphire, quartz, Si and GaAs.

Conducting Polymers

The μSR technique is well suited to probe local charge transport processes in conducting polymers. The pliability and unique electronic and optoelectronic properties of these polymers make them candidates for such uses as in plastic solar cells, solid-state lasers, and flexible light-emitting diodes. The increasing technological importance of these materials is driving a large effort in industry to improve their stability, lifetime, and efficiency. In the undoped state of a conducting polymer, such as polyphenylenevinylene, muon implantation leads to the formation of a highly mobile negative polaron through the reaction of muonium with the polymer chains. Measurements of the intra-chain and inter-chain polaron diffusion rates are of fundamental importance in the development of these synthetic conductors, contributing significantly to our understanding of the charge transport mechanisms.

Ion Mobility

The μSR technique may be used to study ion mobility in materials by monitoring changes in the relaxation of the muon spin by the nuclear magnetic moment of the ion. μSR has been used to determine the mobility of Li^+ ions in $Li_x[Mn_{1.96}Li_{0.04}]O_4$. Such Li-based compounds are promising for use as cathode materials in rechargeable batteries. The μSR measurements indicate that the onset temperature of Li^+ diffusion can be varied with changes in Li concentration and thus provide information relevant to optimizing battery performance.

Semiconductors

As a trace impurity, atomic hydrogen (H) can have a profound effect on the electronic properties of semiconductors. It can "passivate" the electrical activity of donors and acceptors in crystalline semiconductors, "hydrogenate" dangling bonds in amorphous semiconductors, and even display its own electrical activity, all of which are important in the process of semiconductor fabrication. For low hydrogen concentrations, microscopic details of how these processes occur are not accessible by standard magnetic resonance techniques. Isolated atomic hydrogen is nearly impossible to detect because of its high diffusivity and reactivity with other defects. Most of the experimental information on isolated hydrogen in technologically important semiconductors comes from μSR studies of muonium (Mu $\mu+e^-$) which can exist in three charge states (Mu^0, Mu^+ and Mu^-) corresponding to the three distinct charge states of isolated hydrogen (H^0, H^+ and H^-) in semiconductors. As an experimental model for isolated hydrogen, μSR studies of semiconductors are the primary source of detailed information on the site migrations and dynamics of the charge states as well as how muonium diffuses and interacts with charge carriers.

Molecular Magnets and Clusters

Molecular-based magnets are a relatively new class of synthetic materials, made up of nanometer-sized molecules containing a handful of interacting magnetic ions. A versatile feature of these systems is that chemists can modify the magnetic interactions within and between neighboring molecules in a controlled manner. Inorganic materials composed of well-defined clusters of magnetically active atoms are also of great current interest. There are numerous anticipated technological and biomedical applications of molecular magnets, such as components of quantum computing, photonic switches, catalysts, magnetic filtering of blood, and the enhancement of magnetic resonance imaging signals. A high priority in this new field is the determination of the local magnetic properties. As a unique local probe of magnetism, μSR is being used more and more to provide microscopic information on the static and dynamical magnetic properties of these systems. Future studies of molecular magnets with the μSR technique will contribute significantly to the development and optimization of their magnetic properties.

Colossal Magnetoresistance

Colossal magnetoresistance, whereby the electrical resistance of a material changes by orders of magnitude in the presence of an external magnetic field, occurs in certain manganese-oxide compounds. This property makes these materials appealing for future use in a wide range of electronic devices, such as read heads for hard disks, magnetic storage, and sensing devices. The μSR technique has provided important, new information on the spin dynamics in these systems that can be combined with the structural and transport information obtained by other experimental methods.

Superconducting Radio-Frequency Cavity Technology

The electron linac (e-linac) and its future photo-fission-based actinide target station represent a major laboratory infrastructure initiative for the 2010–2015 Five-Year Plan. It will provide an additional source of neutron-rich isotopes for nuclear physics and of ^8Li for β-NMR studies in molecular and materials science. The accelerator will be based on the 1.3 GHz superconducting radio frequency (SRF) technology that absorbs the latest advancements in the field from the frontier International Linear Collider (ILC) design. A major distinction of the e-linac is its continuous wave (CW) mode of operation. TRIUMF's R&D efforts toward improvement of high-power components for the machine, such as RF input couplers, will benefit all future megawatt-regime facilities, such as energy recovery linacs (ERLs) and next-generation synchrotron light sources.

SRF as a Core Competency and Partnering with Industry

The majority of all new and proposed accelerators are based on SRF technology. The tremendous progress made in the last decades has proven this technology to be reliable, cost-effective, and capable of delivering beams of the highest quality and precision. Developing SRF into a core competency of TRIUMF will train highly qualified people for Canadian industry. It will transform Canada from a purchaser of SRF technology to a nation with the capability to construct, process and sell niobium cavities and their attendant components. Presently, there are only a few SRF-technology vendors worldwide, but TRIUMF, through its collaboration with PAVAC, will be able to join this elite group. TRIUMF will be able contribute to the ILC design and to the development of the CERN Large Hadron Collider (LHC) and its upgraded injector, the superconducting proton linac (SPL). Both of these high-energy facilities have strong interest from the Canadian university community.

Around the world, superconducting electron linacs (SC-linacs) are being proposed as drivers for fourth-generation light sources; future reconfiguration of the e-linac as an ERL opens the door to such a possibility. A shortcut to high-energy X-rays is proposed via inverse Compton scattering (ICS) of optical photons off hundreds MeV electrons. ICS has applications in molecular and materials science and medical imaging. E-linac could serve as a testbed for the enabling technologies for an ICS source at the Canadian Light Source (CLS) in Saskatoon.

By adding new SRF expertise in 1.3 GHz cavities design to the existing capabilities developed with ISAC-II SC-linac construction, TRIUMF will become a unique centre for SRF science and accelerator physics. The world physics community will propose, based on discoveries at the LHC, whether a major new initiative called the International Linear Collider (ILC) will move to project approval around 2012, or whether the LHC accelerator and detectors will be upgraded to be more sensitive to new physics. Canadian scientists are leaders in the international design effort for the ILC. The ILC is an ambitious project, initiated by all three regions of the world, and Canadian scientists and industry are well positioned to contribute to the SRF-based linear accelerator and detectors.

Preparing the Next Generation of Leaders

TRIUMF's five-year vision promises a positive impact on Canada's science and technology workforce. Increasing the beam time in the ISAC program, as envisioned in the Plan, will not only increase the science output, it will also increase, commensurately, the opportunities to train students. The impact will be especially large in -NMR where the program is expected to become a true user facility with a correspondingly large increase in the number of students involved in the program. The e-linac and other accelerator project will position TRIUMF to work with the universities to establish the first graduate program in accelerator physics in Canada. This program will further enhance Canada's high tech capabilities in all areas that use particle accelerators, whether for synchrotron light sources used in materials science research or for cyclotrons located in hospitals for medical use.

A vigorous TRIUMF community will serve as an inspiration to young Canadians to pursue careers in science and technology. The TRIUMF outreach program will introduce people to science and technology, not as something other people do, but as something they can do. TRIUMF personnel will be role models to show that all Canadians, whether from Vancouver, BC, or Centre Musquodoboit, NS, can compete with the best in the world.

Selected elements of the TRIUMF Outreach Program envisioned for 2010–2015 include:

- Continued public tours, serving more than 1,000 visitors each year.
- Undergraduate student programs
    - National scholarships for undergraduate students for summer research programs at TRIUMF.
    - Co-operative education placements for students from all across Canada for three-month work terms in the laboratory.
- High-school student programs
    - Continued partnership with British Columbia Innovation Council for scholarships to high-school students for summer research experiences at TRIUMF.
    - Monthly high-school physics lectures during the academic year co-hosted with the University of British Columbia Department of Physics and Astronomy featuring modern science topics in everyday plain language.
    - Design and production of additional multimedia educational materials, including digitally animated movies on high-school physics topics.
- High-school teacher programs
    - Internship program for teachers to travel to and spend about a week working with researchers on an active experiment; candidates are competitively selected.
    - Fellowship programs providing support for one teacher per year to spend up to six months conducting research at TRIUMF and developing educational materials for their classroom.
    - Biannual professional-development day hosted at TRIUMF in cooperation with the British Columbia Association of Physics Teachers.
- Continuation of the TRIUMF Summer Institute.
- New programs engaging the local community.

Although formal impact assessments of science outreach and education activities are still a hotly debated topic in the professional assessment community, TRIUMF proposes to use a combination of journals, surveys, longitudinal studies, and independent evaluations to judge the impact of its activities. The TRIUMF Outreach Program anticipates rigorous interpretation of new “teaching and learning of science" methodologies, such as those outlined in the 2007 U.S. National Academies report *Taking Science to School.*

Conclusion

TRIUMF's Five-Year Plan offers significant opportunities for economic and social impact through the development of critical technologies, recruitment, and training of new talent in science and engineering, and the direct commercialization of its research into the marketplace.

6.6

Implementation Scenarios

6.6.1

Introduction

As a publicly funded enterprise, the TRIUMF Five-Year Plan seeks to follow the four investment principles recommended by the Government of Canada for science and technology to foster a national competitive advantage:[1]

- Promoting world-class excellence;
- Focusing on national priorities, particularly in areas of strength and opportunity;
- Encouraging partnerships; particularly with the private sector and international organizations; and
- Enhancing accountability.

Recognizing that public funding decisions are difficult, this section also presents several alternative scenarios for TRIUMF programs (from 2010–2015), computes the corresponding funding levels, and examines the tradeoffs. Efforts were made to balance the portfolio of activities for diversity and to guarantee smooth and reasonable profiles for both financial and human resources over the five-year period. Three primary scenarios for the laboratory program are developed and analyzed:

A. **Optimal return on investment.** Provide the maximal return on the current investments in the laboratory while also developing infrastructure to ensure Canada's long-term national and international leadership. Where possible, this scenario builds on the successes and strong suits

1 Government of Canada, *Mobilizing Science and Technology to Canada's Advantage*, 2007, p. 4-5.

that have long-term advantages in terms of global market share for Canada.

B. **Ensuring international leadership.** Sacrifice short-term research and development activities to devote all possible financial and human resources to securing globally competitive advantages in the future. While ensuring generally smooth resource profiles, this scenario does not fully exploit the present capital investments but rather focuses on maximally pursuing the emerging opportunities that will have the most strategic advantage for Canada. This scenario seeks a long-term "win" while accepting short-term "losses."

C. **Exploiting current facilities.** This implementation strategy seeks to minimize new capital outlays while maximizing return on existing investments. That is, it seeks to reap the benefits of past investments in TRIUMF without any preparations for the long-term future of the on-site accelerator-based program. The scenario includes modest maintenance of present facilities coupled with minor upgrades to deliver a streamlined laboratory that delivers maximum short-term benefit at the risk of long-term competitiveness. For instance, options to capitalize on emerging technologies will be kept at a minimum.

For completeness, a fourth scenario (D) of so-called "flat-flat" funding was examined with a five-year total budget identical to that of the 2005–2010 Plan: $222 million via the National Research Council (NRC) Contribution Agreement. This funding level corresponds to a real funding drop in NRC funding levels due to inflation. Note that the total federal government funding to TRIUMF for 2005–2010, including NRC and CFI, was about $247 million, so the $222 million scenario represents a deeper cut in federal spending than just the effect of inflation.

6.6.2

The Planning Process

To develop its Five-Year Plan (5YP), TRIUMF and its user community engaged in a comprehensive series of exercises to identify the best possible opportunities that were ripe for investment, that made sense for TRIUMF, and would deliver the best value to Canada. The guiding principle of this planning process was to capture the best possible options and then to examine them rigorously in terms of schedule, resource requirements, feasibility, broader impacts, and overall priority.

The first step in preparing the decadal vision was to identify the principal activities in the 2010–2015 period that would involve TRIUMF. As expected, given TRIUMF's unique capabilities and the strong community interest in the laboratory's capabilities, we identified significantly more demand on TRIUMF's resources than could be reasonably accommodated. Therefore, the 5YP planning process became not only about which science to pursue but also about where to allocate resources. Several of the larger-scale initiatives also faced additional targeted reviews to ensure maximal clarity about their scientific impact, resource requirements, and feasibility.

TRIUMF serves the nation of Canada, and thus the support and guidance of the broad community was essential for its future. To start the formal planning process, the TRIUMF Users Group, under the chairmanship of P. Garrett (University of Guelph), organized a public meeting in July 2006 to discuss future research opportunities involving TRIUMF's unique combination of skills, resources, and capabilities. More than a hundred Canadian scientists in the broader TRIUMF community attended the meeting. An important fraction of American and international researchers also participated. The outcome of the meeting was a series of summary talks and white papers that were discussed at a follow-up meeting in December 2006. Another follow-up meeting in August 2007 expanded an initial list of possible future activities at TRIUMF and examined the synergies, overlaps, and conflicts among them.[1]

To facilitate and guide the process going forward, the TRIUMF Director appointed a Five-Year Plan Steering Committee (5YPSC). The subsequent steps of the process are summarized below; Appendix D provides additional information about these steps of the process including committee membership, meeting agendas, and locations of review reports, all of which are publicly available.[2]

- **STEP ONE: Community consultation to develop a complete list of proposed future activities for TRIUMF in the timeframe 2010–2015.** Using materials prepared by the TRIUMF Users Group (TUG) at their Annual General Meetings, a preliminary list was prepared. With the gracious assistance of IPP, CINP, several divisions of CAP, and the TRIUMF Users Executive Committee (TUEC), this list was distributed broadly to the community for comment. Feedback was received through Monday, February 4, 2008.
- **STEP TWO: Preparation of short few-page descriptions of every proposed activity in close consultation with its proponents.** Along with a preliminary vision statement from the director, we prepared a proposed description of the role that TRIUMF plays in the Canadian university research program, and a discussion of TRIUMF's role as a gateway to international science and technology. These few-page descriptions were made public on March 1, 2008.
- **STEP THREE: Community review and prioritization.** The Policy and Planning Advisory Committee (PPAC) was formed by the TRIUMF Board of Management (BOM) in autumn 2007. Its inaugural task was to review this portfolio of materials and perform an initial assessment and prioritization. This process was completed at the March 14-15, 2008, meeting of PPAC. In addition to this global review by PPAC, key proposed elements of the Five-Year Plan were subjected to intense scrutiny by the following ad hoc committees.
    - Subatomic physics projects were reviewed by an international scientific committee (the Special Subatomic Physics Experiments Evaluation Committee) on March 25-26, 2008.
    - The TRIUMF nuclear physics program in halo nuclei was analyzed in an international context at a special workshop convened by Saint Mary's University on March 27-28, 2008.
    - Life sciences and nuclear medicine projects were reviewed by an international scientific committee (the Life Sciences Projects Evaluation Committee) on April 3-4, 2008.

1 See the TUG Web site and links to meetings therein at http://www.triumf.ca/tug/

2 See the TRIUMF Five-Year Plan Web site and references therein at http://admin.triumf.ca/facility/5yp/overview.php

    - The technical, resource, and schedule aspects of the major accelerator projects were reviewed by an international panel of experts, the Accelerator Advisory Committee, on April 3-4, 2008.

- **STEP FOUR: Comments from the TRIUMF community via the Kitchen Cabinet.** The director is advised on policy-implementation issues by an on-site committee of scientists and technical staff called the Kitchen Cabinet Advisory Committee. This committee was publicly tasked to provide a reality check on the PPAC findings and recommendations. The committee prepared a brief public report that was publicly released on Thursday, March 20, 2008.
- **STEP FIVE: Comments from the TRIUMF Users Executive Committee (TUEC).** As the originators of the process, TUEC was consulted to provide further comments on the series of reports. Their written report was released on April 8, 2008.
- **STEP SIX: Preparation of a complete draft of the TRIUMF five-year vision and review by ACOT.** Combining all these contributions, the 5YPSC prepared a complete draft of the five-year vision for TRIUMF, including a resource needs analysis. A working draft of the vision was presented and discussed at the TRIUMF BOM meeting on April 11, 2008. The evidence layer of the report was publicly presented to the Advisory Committee on TRIUMF (ACOT) in advance of its meeting on May 9-10, 2008. The draft report was publicly circulated and posted on-line for review and comment; the PPAC was invited to comment in writing.
- **STEP SEVEN: Writing of the full Five-Year Plan Report.** Incorporating the guidance of ACOT, the 5YPSC revised the written report and prepared a final draft, which articulated the decadal vision and the five-year budget request. This report will be submitted to the NRC International Peer Review Committee in late summer 2008.
- **STEP EIGHT: Presentation to and review of the TRIUMF Five-Year Plan Report by the NRC International Peer Review Committee in September 2008.** The International Peer Review Committee will meet on September 24-26, 2008, to evaluate the 5YP. The full 5YP Report, with any sensitive financial information redacted, will be publicly available.
- **STEP NINE: Presentation of the Five-Year Plan to the NRC Council in February 2009.** This step represents the formal transmission of the TRIUMF request to Industry Canada. In addition to the written package of materials transmitted to NRC Council, the TRIUMF Director and the Chair of the International Peer Review Committee will testify in person.

Each step in this process added focus to TRIUMF's five-year vision and added a more sophisticated understanding of resources and talents required. In other words, the "wish list" drawn up in step one was refined and tuned at each step in the process to arrive at the one in the final plan that emerged in step nine. Although different committees used different relative weighting schemes in their "wish list" deliberations, three consistent sets of criteria were used by all. These were:

- **Scientific merit:** potential for scientific impact and overall research excellence, including the overall technical feasibility and readiness for investment;
- **Broader impacts:** opportunities for training of students, attracting talent to Canada, transferring knowledge to industry, or contributing to the health and well-being of Canadians; and
- **Relevance to the TRIUMF Mission:** alignment with TRIUMF's mission statement in terms of its international presence and its role within the Canadian university system.

6.6.3

Building the Optimal Strategy for the TRIUMF Five-Year Plan

As a first step, all the 2010–2015 proposed projects were considered that were ranked with high priority by the review committees. Taken in full, these proposals would have required more than $370 million in federal funds and an increase in personnel too large to be obtained quickly and managed efficiently. While it was clear that a more manageable program would be needed to optimize the cost/benefit of the public investment in TRIUMF, it was also clear that reducing the program would require difficult choices. Faced with many proposals, each with a compelling potential for scientific impact, a program-planning framework was developed to analyze the resource requirements and map the high-priority activities into scenarios that addressed and resolved issues such as resource profiles, phasing and staging of projects, personnel skill sets, and international partnerships and agreements. Three distinct implementation strategies were studied in the framework, giving rise to the following scenarios.

	SCENARIO A *Optimal*	
	PEOPLE	**CAPITAL ($k)**
OPERATIONAL COSTS		
NET POWER COSTS		15,000
ADMINISTRATIVE SUPPORT		6,700
ISAC BEAM DEVELOPMENT		3,000
SITE INFRASTRUCTURE		8,000
SAFETY & LICENSING		2,300
ACCELERATOR DIVISION		10,000
ENGINEERING DIVISION		7,000
UNIVERSITY SCIENCE/EXPT SUPPORT		5,000
SCIENCE OPERATIONS-EXPT SUPPORT		10,000
LAB OPERATIONS TOTALS	250	67,000
NEW PROJECTS		
ATLAS TIER-1 CENTRE	10	9,300
FRONT END	5	3,500
TARGET STATION 1	9	8,000
SPECIALIZED ACTINIDE BEAM LINE	8	4,500
ACC REF & UPGR TO 300μA	12	4,000
HELIUM LIQUEFACTION	1	1,250
LIFE SCIENCES	8	5,400
E-LINAC	22	15,500
SNOLAB	3	100
INTL ACCELERATOR CONTRIBUTIONS	4	4,000
DETECTOR DEVELOPMENT/SUPPORT	5	200
NEW PROJECTS TOTALS	**87**	**55,750**
TOTAL PERSONNEL REQUIRED	**337**	
TOTAL MATERIALS BUDGET		**122,750**
NEW HIRES	20	
TOTAL SALARY BUDGET		**205,000**
TOTAL BUDGET ESTIMATE		**327,750**

Table 1: Five-year spending plan for TRIUMF from the federal government in the “Optimal” scenario.

Scenario A: Optimal Return on Investment

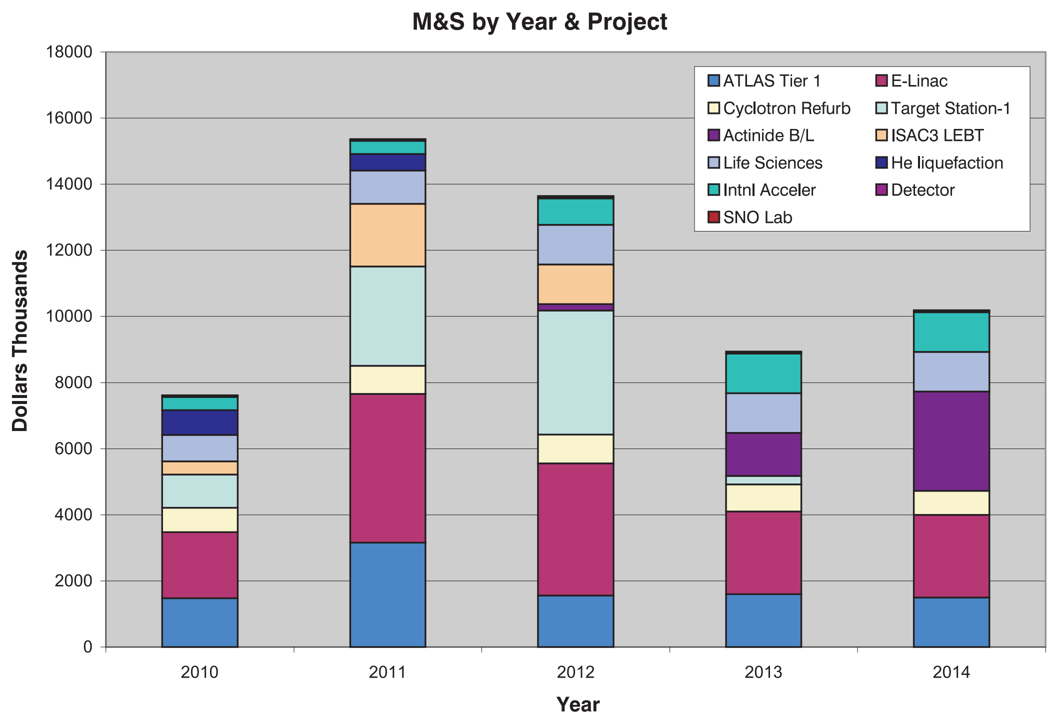
TRIUMF, with its university and user communities, seeks to provide the maximal return on the current investments in the laboratory while also developing infrastructure to ensure Canada's long-term national and international leadership. The spending plan for this scenario is presented in Table 1. Rather than attempt to pursue all the high-priority programs immediately, the major new projects were profiled in a way that would allow the lab to maintain a realistic staffing level. At the present time, TRIUMF's staff complement (excluding employees managing the TRIUMF guest house and working on a contract basis for MDS Nordion) is 317.

In this scenario, TRIUMF operations would be supported at a level where the lab is able to exploit fully the previous investments in ISAC, ATLAS at the Large Hadron Collider (LHC), T2K, molecular and materials science, and nuclear medicine. Industrial and international partnerships would be strongly exploited. The new ISAC program would proceed aggressively with the electron linear accelerator (e-linac) and new target station, which are fast-tracked to begin operations in 2013, and the specialized actinide beam line, which would be operational by 2015. These projects are closely linked both scientifically and technically and should proceed most efficiently together.

By re-profiling in the above manner, TRIUMF can maintain realistic staffing levels and move people from construction to operations as the new projects come on-line. Approximately ten new strategic hires above the current TRIUMF staffing levels, primarily in the accelerator division, would be required in this scenario in addition to shifting the ATLAS Tier-1 Data Centre personnel from CFI to NRC funding.

The benefits of this scenario would be:

- Complete the initial e-linac and new target station by 2013; the launch of a new prong in the ISAC program, including neutron-rich nuclear physics; more than doubling the running time of all ISAC experiments, and increasing β-NMR running from 4 to 16 weeks/year: all of which will cement TRIUMF's and Canada's role as leaders in the international accelerator network. The new ISAC-specialized actinide beam line would be operational by 2015 (options for advancing the schedule are being studied). The e-linac and new proton beam line, together with the new target station, are tightly linked and use overlapping space and common infrastructure, and therefore it is cost effective to proceed with them together. As the new projects come online, significantly more beam time will be available from the existing beam line for neutron deficient astrophysics studies.
- Contribute significantly to the design stage of the LHC superconducting proton linac (SPL) and the International Linear Collider (ILC) accelerator programs, including engagement of Canadian industrial partners, such as PAVAC Industries, Inc.
- Maximize the laboratory on-site accelerator operations at a high level, maximize physics output of ISAC, and capture the full advantage of this facility's present capabilities.



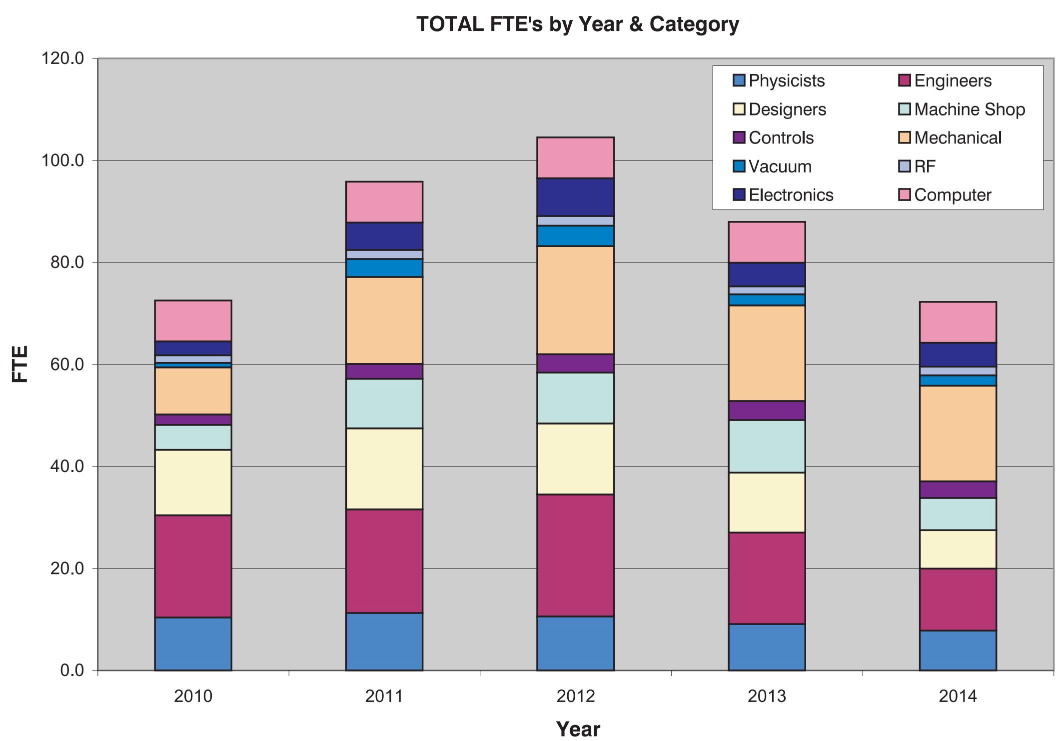


Figure 1: Spending (top) and personnel (bottom) profiles for the new projects in the “optimal return on investment” scenario.

- Exploit the current proton ISAC beam line, including low-power actinide target operations with the existing beam line as well as beam development for neutron deficient astrophysics measurement.
- Support and grow the ATLAS Tier-1 Data Centre, including strong intellectual contributions to the emerging computing grid application field.
- Establish a TRIUMF-based ATLAS national analysis centre.
- Enhance the TRIUMF theory group to exploit synergies with the experimental program and other theory institutes in Canada such as the Perimeter Institute.
- Consolidate nuclear medicine and on-site radioisotope production and enhance commercialization aspects.
- Initiate the new Osaka ultracold neutron program, starting physics late in the planning period.
- Upgrade the cyclotron, pacing it for increased intensities towards the end of the planning period when the new beam line is fully operational.
- Maximize scientific output from the newly constructed μSR beam lines and experimental stations for materials science.
- Continue support for university researcher-led efforts concentrated at TRIUMF.
- Maintain TRIUMF's contributions to particle detector research, development, and construction, with contributions to the SNOLAB project as the top priority in this area.

This program requires $328 million in total federal funding. The breakdown of materials, supplies, and personnel costs are shown for the new projects in Figure 1. The year-by-year breakdown of the total budget required to fulfill the program is shown in Table 1.

	2010	2011	2012	2013	2014	2010-2014
TOTAL SALARY BUDGET	35,000	39,000	42,000	43,500	45,500	**205,000**
TOTAL MATERIALS BUDGET	19,365	27,470	28,645	22,985	24,285	**122,750**
TOTAL BUDGET	**54,365**	**66,470**	**70,645**	**66,485**	**69,785**	**327,750**

Table 1: Breakdown of total spending across the five fiscal years of the plan in the "optimal return on investment" scenario.

6.6.4

Sub-optimal Strategies

While the optimal plan would return the maximum benefit to Canada for the public investment, public spending is constrained by many factors. The major items that were considered in building the sub-optimal scenarios are listed in Table 1. Sufficient information is provided to identify the relative cost savings and impacts of removing selected projects from the program.

Scenario B: Ensuring International Leadership

The first alternate implementation strategy relaxes the goal of near-term exploitation of the current investments and maintains the commitment to new initiatives that keep TRIUMF competitive at the end of the five years. Reducing on-site operations was considered by reducing the budget by about one third (primarily by running the cyclotron for fewer months per year) but retaining progress toward the next generation of ISAC, the ATLAS Tier-1 Data Centre and the physics analysis centre, nuclear medicine, and materials science programs. Compared to the optimal implementation budget, relative cost savings are achieved by reducing cyclotron and ISAC operations by three months per year (out of a usual nine), correspondingly reducing the laboratory's scientific productivity. It would be necessary to maintain roughly a constant total laboratory staffing level, which could be made possible by reducing accelerator applications. This program would require $304 million in total federal funding.

Some of the sacrifices in this scenario include:

- Reduce output of the local accelerator-based science program by reducing operations by one third. Researchers in ISAC-I, such as the nuclear astrophysicists, would be forced to "wait" even longer for access to TRIUMF's beams. Presently, one major experiment in nuclear astrophysics is run each year; this reduction in running time would eliminate TRIUMF's ability to assume world leadership in this exciting and internationally competitive field. For instance, the world's best nuclear astro-

<table>
<tr><th rowspan="3">Item</th><th rowspan="3">Benefits</th><th colspan="4">Five Year Resources</th></tr>
<tr><th colspan="2">People</th><th rowspan="2">Capital M C$</th><th rowspan="2">Total M C$</th></tr>
<tr><th>FTE</th><th>M C$</th></tr>
<tr><td rowspan="4">ISAC Next-Generation Facility, including e-linac, specialized actinide beam line and targets

The three main elements of the initiative have been broken out separately for ease of the reader.</td><td rowspan="4">Nuclear Physics: Fundamental symmetries, neutron-rich nuclear structure and astrophysics, long term international leadership in RIB physics
Materials Sciences: β-NMR program
Industrial Partnerships: Strong ties to developing expertise in Canadian industry, in particular PAVAC Industries Inc., in the emerging SRF program
University Partnerships: Large user base
International Partnerships: Ties to Europe, India, Japan. Retain international leadership in accelerator physics.</td><td>53</td><td>32</td><td>34</td><td>66</td></tr>
<tr><td colspan="3">e-linac</td><td>29</td></tr>
<tr><td colspan="3">Specialized actinide beam line</td><td>17</td></tr>
<tr><td colspan="3">Common infrastructure:
Target station and front end</td><td>20</td></tr>
<tr><td>ATLAS Tier-1 Data Centre and Physics Analysis Centre</td><td>Particle Physics: Leadership in LHC physics program
Industrial Partnerships: Enabling computing grid technology development and deployment in Canada
Universities Partnerships: Ties to 10 leading Canadian universities with more than 40 faculty and 60 graduate students
International Partnerships: Ties to CERN and leading international particle physics</td><td>10</td><td>6</td><td>9</td><td>15</td></tr>
<tr><td>Nuclear Medicine Initiative</td><td>Life Sciences: Understanding of mechanisms for Parkinson's, cancer, and other diseases. Direct benefit to health of Canadians
Industrial Partnerships: Collaborate with MDS Nordion, BC Cancer Agency, D-Pace, etc.
University Partnerships: Growing university partnerships in medical isotope production including non-traditional TRIUMF partners</td><td>8</td><td>5</td><td>5</td><td>10</td></tr>
<tr><td>International Accelerator Contributions</td><td>Particle Physics: Enable Canadian physics to participate in offsite accelerator-based experiments.
Industrial Partnerships: Enable Canadian access to industry contracts in a high-technology field
University Partnerships: Ties to leading Canadian universities
International Partnerships: Ties to leading international scientific laboratories</td><td>4</td><td>2.5</td><td>4</td><td>6.5</td></tr>
<tr><td>Experimental Support: Science Division and Universities</td><td>Physics programs: Support projects in key areas with pressing timescales enabling critical advances
University Partnerships: Enable university researchers to optimally exploit and leverage other resources</td><td>-</td><td>-</td><td>15</td><td>15</td></tr>
<tr><td>Cyclotron Operations (effect of reduction of 1/3 for five years)</td><td>Nuclear physics: Beams for ISAC
Materials Sciences: Novel μSR and β-NMR programs
Industrial Partnerships: Production of high-value medical isotopes MDS Nordion solid target facility, commercial irradiation and testing program.</td><td>25</td><td>15</td><td>3</td><td>18</td></tr>
</table>

Table 1: Major items considered in building different TRIUMF programs between 2010 and 2015. The "Cyclotron Operations" item corresponds to a reduction from 9 months to 6 months per year of operations. For simplicity, an estimated TRIUMF 2010–2015 salary average is used to convert all FTEs (labour) into dollars.

physics spectrometer DRAGON in this scenario would no longer be fully leveraged by the laboratory. The reduction in cyclotron operations would also decrease beam delivery to commercial ventures; for example, delivery of proton beams to the MDS Nordion Solid-Target Facility would be reduced by 30%, limiting worldwide availability of several novel high-value medical isotopes (e.g., strontium generator). Approximately $3 million in capital expenditures would be saved.

- Maintain a flat laboratory staffing level by shifting current operations positions into construction efforts for the new accelerator initiatives, and for the ATLAS Tier-1 Data Centre. This approach reduces costs by about $15 million.
- Reduce support that would enable university researcher-led projects at TRIUMF. Fewer university led initiatives would take place, but this reduction would save about $5 million.

Scenario C: Exploit Current Facilities

This implementation strategy seeks to minimize new capital outlays while maximizing return on existing investments. To do so, the scenario investigates the impact of abandoning all new on-site accelerator initiatives while running the current accelerator facilities to maximize the science output. The cyclotron itself would receive no significant upgrades and would undergo minor maintenance-related improvements. Canada would maintain a minimal program at TRIUMF including only the highest priority existing activities such as the ATLAS Tier-1 Data Centre, life sciences effort, and engagement in the international accelerator community. Strategic initiatives designed to move Canada to the forefront would be deferred.

The major sacrifices in this scenario include:

- No new on-site accelerator projects, reducing expenditures by $34 million. This scenario jeopardizes Canada's leading international position in advanced facilities for unstable beams because the major investments of other countries (CERN, Germany, France, US, and Japan) would surpass TRIUMF. Canadian investment in the next Five-Year Plan would be too late to compete.
- TRIUMF would not proceed with the e-linac, target station, and specialized actinide beam line in this scenario.
- Research and development of heavy isotopes would not be possible, eliminating opportunities for commercial and health exploitation of alpha-emitting isotopes for applications such as cancer therapy. Canada's global lead in the medical-isotope market would disappear.
- Stopping all new accelerator projects along with significant reductions in detector design and construction support will reduce spending by an additional $45 million over five years in the personnel budget compared to the optimal scenario TRIUMF staffing level.

	SCENARIO D *Flat-Flat*	
	PEOPLE	**CAPITAL ($k)**
OPERATIONAL COSTS		
NET POWER COSTS		15,000
ADMINISTRATIVE SUPPORT		5,500
ISAC BEAM DEVELOPMENT		3,500
SITE INFRASTRUCTURE		7,000
SAFETY & LICENSING		2,000
ACCELERATOR DIVISION		9,000
ENGINEERING DIVISION		6,000
UNIVERSITY SCIENCE/EXPT SUPPORT		
SCIENCE OPERATIONS-EXPT SUPPORT		9,000
LAB OPERATIONS TOTALS	190	57,000
NEW PROJECTS		
ATLAS TIER-1 CENTRE	10	9,300
FRONT END		
TARGET STATION 1		
SPECIALIZED ACTINIDE BEAM LINE		
ACC REF & UPGR TO 300μA	3	2,000
HELIUM LIQUEFACTION	1	
LIFE SCIENCES	5	3,500
E-LINAC		
SNOLAB	3	100
INTL ACCELERATOR CONTRIBUTIONS	4	200
DETECTOR DEVELOPMENT/SUPPORT	5	200
NEW PROJECTS TOTALS	**31**	**15,300**
TOTAL PERSONNEL REQUIRED	**221**	
TOTAL MATERIALS BUDGET		**72,300**
NEW HIRES		
TOTAL SALARY BUDGET		**150,000**
TOTAL BUDGET ESTIMATE		**222,300**

Table 2: Five-year spending plan for TRIUMF from the federal government in the “Flat-Flat” scenario.

- Staff reduction by 50 FTEs. The affected personnel would most likely be TRIUMF experts in accelerators, making it very difficult to imagine reviving a leading on-site accelerator program in the future.
- Finally, Canada's participation in international accelerator contributions would be scaled back to a bare minimum level, about $4 million.

In this scenario, there would be no e-linac, which would significantly reduce Canadian public/private partnerships between TRIUMF and companies such as PAVAC Industries, Inc., and Canadian CNC Machining, Ltd. The opportunities for breakthroughs in nuclear medicine and accelerator production of medical isotopes would be lost. Canada would maintain the industrial liaison with the international accelerator community as much as possible. International accelerator-technology partnerships with India, Japan, and the European Union would not be possible.

This scenario requires $245 million over five years in federal funding.

The total federal government investment in TRIUMF in 2005–2010, including NRC, CFI for the ATLAS Tier-1 Data centre and μSR beam line plus provincial government matching funds, was $247 million, effectively making this a constant funding level with no increase for inflation.

Scenario D: Constant Budget

The final scenario presented here selects an overall federal funding level for 2010–2015 equal to the NRC contribution agreement for 2005–2010 ($222 million) without inflationary corrections. This does not include the additional funding supporting the core TRIUMF program received from CFI and provincial matching, which brought the total Government of Canada investment to about $247 million. The budgets and personnel for this scenario are shown in Table 2. In this scenario, TRIUMF would be forced to remove all new on-site accelerator initiatives, reduce the nuclear medicine program, and remove all TRIUMF support of the university-research community. The overall staffing level of the laboratory would be reduced by nearly one hundred.

The major sacrifices in this scenario include:

- No new on-site accelerator projects, jeopardizing TRIUMF's leading international position in rare-isotope beam physics in the future, resulting in about $34 million reduction in capital investments.
- Remove all TRIUMF support for university research programs, including removing new ISAC detectors, costing about $6 million.
- Reduce the nuclear medicine program, reducing costs by about $2 million.
- Reduce the international accelerator program, saving about $4 million.
- Cut the laboratory staffing level by 100 FTEs, accounting for the reduced program, saving about $55 million over five years compared to the optimal scenario.
- Funding at this level would require a serious re-evaluation of the goals of the laboratory with the stakeholders and the Government of Canada.

As mentioned above, both of these final scenarios would substantially damage TRIUMF's contribution to the national interest: the reductions in personnel would target the accelerator and engineering physicists, technicians, and operations staff. These teams are elite among the industrialized world and would simply relocate to other countries with more promising and aggressive research programs. Their critical absence would slow and possibly stop TRIUMF's engine of innovation, the drive to develop breakthroughs in accelerator science and technology. AAPS, Inc., would suffer without proximal consulting access; partners like BC Cancer Agency, the Pacific Parkinson's Research Centre, D-Pace, and MDS Nordion would be unable to guarantee the future success of their business operations with the wealth of expertise available through TRIUMF.

6.6.5

Recap of Scenarios

To aid decision makers, several implementation strategies have been presented, including comments on the relative tradeoffs. To achieve an optimal return on Canada's investment in TRIUMF, approximately $328 million is required summed over years 2010–2015. It is clear that the choices made for this Five-Year Plan will have long-term strategic consequences not only for TRIUMF but also for Canada.

The relative tradeoffs among the four scenarios are summarized in Table 1. The four priority activities are all supported effectively and efficiently in the

Scenario	$M	Δ Staff	Super-ISAC	ATLAS	Nuclear Medicine	Cyclotron Operations
A: Optimal	328	20				
B: Ensure International Leadership	303	(5)				
C: Exploit Current Facilities	245	(53)				
D: Constant Budget	222	(96)				

Table 1: Diagram showing the relative tradeoffs among the key initiatives of the five-year vision. Green denotes a fully exploited program, yellow a partially supported program, and red denotes removing a program altogether.

optimal scenario. To achieve Scenario B, operations of the present facilities are truncated to free up personnel and financial resources needed to deliver on the full package of capital initiatives. The consequence, as noted above, is a substantial delay in providing the scientific community with the full dividends of the investments in TRIUMF and its ISAC facilities. Figure 1 captures the change in annual delivery of rare-isotope beams. By definition, Scenario B meets Scenario A at the end of the five-year planning period in terms of capability, but the TRIUMF community would have given up more than 8,000 hours of beam time. TRIUMF is on the verge of being the world's leading ISOL facility. The possibility of achieving world leadership in nuclear astrophysics (*i.e.*, utilizing existing investments in the DRAGON facility) and nuclear structure within the next five years would be forestalled. Key collaborations with international partners would not be possible, such as with CERN on high-power targets. TRIUMF's early access to lead the world in specialized actinide beam physics would be severely compromised.

Scenario C proposes to support the exploitation of current ISAC facilities operations. The result is a decrease in the number of staff, leaving TRIUMF in an internationally non-competitive position in 2015. The existing single ISAC beam line would be forced to service all projects, significantly slowing the science output of TRIUMF and reducing the user community. Finally, Scenario D

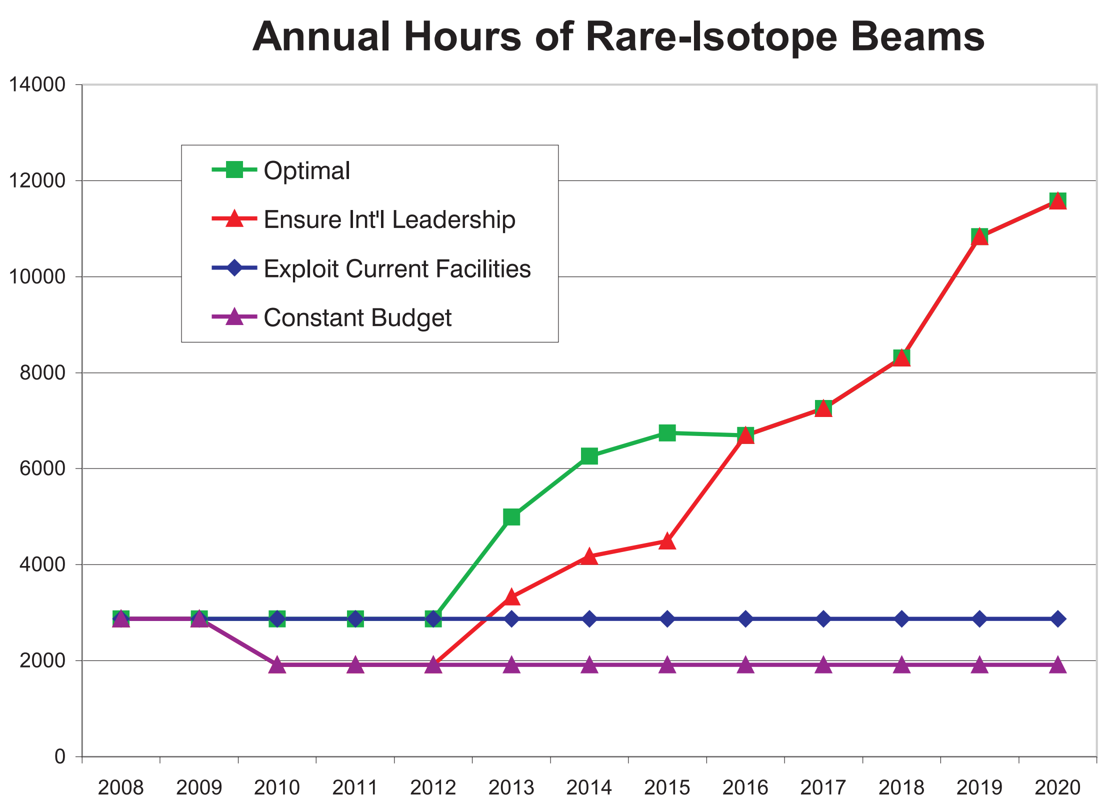


Figure 1: Chart showing year-by-year annual totals for delivery of rare-isotope beams to science experiments at TRIUMF for the four different scenarios. Continued operations are assumed in the 2015–2020 period.

indicates a major reduction in force and undermines the ability to undertake new initiatives.

Scenario C puts TRIUMF's long-term future at risk in two ways: because the reduction in force in key areas will likely be irreversible and because other nations will reposition themselves to attract scientific and technical talent away from Canada. Scenario D will retain limited international competitiveness through the ATLAS Tier-1 Data Centre, but Canada will not be able to guarantee credible future participation in other key global science projects.

6.6.6

Provincial Participation

The proposed transformation of TRIUMF relies upon the development of new infrastructure at the TRIUMF site for two new buildings to house initiatives in nuclear medicine and information technology and an underground complex for the new accelerator beams. These capital initiatives are physically and scientifically linked. Their construction will build and expand upon TRIUMF's growing collaborations with Canadian research institutions, international partners, and the existing highly sophisticated detector and accelerator infrastructure and expertise at TRIUMF. Historically, the Province of British Columbia has funded similar TRIUMF infrastructure.

TRIUMF is seeking provincial support for a key set of three civil-construction initiatives that will enable and drive its decadal vision:

- A specialized Health Sciences Building to support the expansion of TRIUMF's world-leading nuclear-medicine program and to bring TRIUMF together with its team of industrial and academic partners in a laboratory that meets Good Manufacturing Practices. The building will house a cyclotron underground and hot cells, microfluidics, and a small-animal barrier facility in the floors above.
- A purpose-built data laboratory building for the Canadian ATLAS Tier-1 Data Centre to accommodate its growth as the LHC project at CERN ramps up and the global scientific community relies more heavily upon Canada.

- An underground complex to transport the new accelerator beams in a safe and secure manner from their origin to the existing experimental halls.

Figure 1 shows a sketch of the two above ground buildings. The construction of these three elements can be phased, although full value of the TRIUMF Five-Year Plan will only be realized when all three are completed.

Primary support from the Province of British Columbia is being sought with the help of the University of British Columbia, Simon Fraser University, and the University of Victoria. Discussions have been positive. TRIUMF and its stakeholders are committed to reaching a mutually beneficial arrangement during FY2009. In the scenarios, provincial government support for these three key projects is assumed.

Figure 1: Sketch of the proposed buildings.

6.6.7

Conclusion

The TRIUMF Five-Year Plan lays out an ambitious vision for the future and calls for a transformation of the laboratory. It will position Canada to be a key member of the global science, technology, and innovation community. More importantly, however, a major investment by the Government of Canada in scientific research will excite the next generation of scientists, engineers, and citizens. It will send a signal that Canada is prepared to face head-on the challenges of energy, environment, human health, and sustainability that will define the next century.

Appendix A

Publications 2003–2008

Appendix A

Publications 2003–2008

Journal Publications

Particle, Nuclear and Atomic Physics – *2003*

W.M. Snow, W.S. Wilburn, J.D. Bowman, M.B. Leushcner, S.I. Penttila, V.R. Pomeroy, D.R. Rich, E.I. Sharapov and V.W. Yuan, *Progress toward a new measurement of the parity violating asymmetry in* $\vec{n}+p \rightarrow d+\gamma$, Nucl. Instrum. Methods **A515**, 563 (2003).

J. Wozniak, A. Adamczak, G.A. Beer, V.M. Bystritsky, M. Filipowicz, M.C. Fujiwara, T.M. Huber, O. Huot, R. Jacot-Guillarmod, P. Kammel, S.K. Kim, P.E. Knowles, A.R. Kunselman, G.M. Marshall, F. Mulhauser, A. Olin, C. Petitjean, T.A. Porcelli, L.A. Schaller, V.A. Stolupin and J. Zmeskal, *Scattering of* $p\mu$ *muonic atoms in solid hydrogen*, Phys. Rev. **A68**, 062502 (2003) [nucl-ex/0212005].

H. Iimura, M. Miyabe, M. Oba, T. Shibata, N. Shinohara, Y. Ishida, T. Horiguchi and H.A. Schuessler, *Nuclear moments and isotope shifts of* ^{135}*La,* ^{137}*La and* ^{138}*La by collinear laser spectroscopy*, Phys. Rev. **C68**, 054328 (2003).

A. Toyoda, K. Ishida, K. Shimomura, S.N. Nakamura, Y. Matsuda, W. Higemoto, T. Matsuzaki and K. Nagamine, *New insights in muon-catalyzed dd fusion by using ortho-para controlled solid deuterium*, Phys. Rev. Lett. **90**, 243401 (2003).

C.D. O'Leary, C.E. Svensson, S.G. Frauendorf, D.E. Appelbe, R.A.E. Austin, G.C. Ball, J.A. Cameron, R.M. Clark, M. Cromaz, P. Fallon, D.F. Hodgson, N.S. Kelsall, A.O. Macchiavelli, D. Sarantites, J.C. Waddington, R. Wadsworth, D. Ward, A. Afanasjev and I. Ragnarsson, *Evidence for isovector neutron-proton pairing from high-spin states in* ^{74}*Rb*, Phys. Rev. **C67**, R021301 (2003).

S. Gu and J.A. Behr, *Off-Raman resonance effects of hyperfine coherences*, Phys. Rev. **A68**, 015804 (2003).

A.R. Berdoz, J. Birchall, J.B. Bland, J.D. Bowman, J.R. Campbell, G.H. Coombes, C.A. Davis, A.A. Green, P.W. Green, A.A. Hamian, R. Helmer, S. Kadantsev, Y. Kuznetsov, L. Lee, C.D.P. Levy, R.E. Mischke, N.T. Okumusoglu, S.A. Page, W.D. Ramsay, S.D. Reitzner, T. Ries, G. Roy, A.M. Sekulovich, J. Soukup, G.M. Stinson, T. Stocki, V. Sum, N.A. Titov, W.T.H. van Oers, R.J. Woo, S. Zadorozny and A.N. Zelenski (E497 collaboration), *Parity violation in proton-proton scattering at 221 MeV*, Phys. Rev. **C68**, 034004 (2003) [TRI-PP-02-18, nucl-ex/0211020].

A.K. Opper, E. Korkmaz, D.A. Hutcheon, R. Abegg, C.A. Davis, R.W. Finlay, P.W. Green, L.G. Greeniaus, D.V. Jordan, J.A. Niskanen, G.V. O'Rielly, T. Porcelli, S.D. Reitzner, P.L. Walden and S. Yen, *Charge symmetry breaking in* $np \rightarrow d\pi^0$, Phys. Rev. Lett. **91**, 212302 (2003) [nucl-ex/0306027].

B.L. Zhuikov, M.V. Mebel, V.M. Kokhanyuk, A.S. Iljinov, A.Yu. Zyuzin and J.S. Vincent, *Production of high spin isomers in proton induced reactions at 100–500 MeV on* ^{181}*Ta*, Phys. Rev. **C68**, 054611 (2003).

M.B. Smith, P.M. Walker, G.C. Ball, J.J. Carroll, P.E. Garrett, G. Hackman, R. Propri, F. Sarazin and H.C. Scraggs, γ*-rays emitted in the decay of 31-yr* $^{178}Hf^{m2}$, Phys. Rev. **C68**, 031302 (2003).

A. Pouladdej, T.P. Gorringe, M.D. Hasinoff, A.J. Larabee, A.J. Noble, C.J. Virtue, D.H. Wright, G. Azuelos and B.C. Robertson, *Photon asymmetry measurement in radiative muon capture on* ^{40}*Ca*, Phys. Rev. **C68**, 034605 (2003).

A.R. Junghans, E.C. Mohrmann, K.A. Snover, T.D. Steiger, E.G. Adelberger, J.M. Casandjian, H.E. Swanson, L. Buchmann, S.H. Park, A. Zyuzin and A. Laird, *Precise measurement of the* $^{7}Be(p,\gamma)^{8}B$ *S-factor*, Phys. Rev. **C68**, 065803 (2003) [nucl-ex/0308003].

A. Piechaczek, E.F. Zganjar, G.C. Ball, B. Bricault, J. D'Auria, J.C. Hardy, D.F. Hodgson, V. Iacob, P. Klages, W.D. Kulp, J.R. Leslie, M. Lipoglavsek, J.A. Macdonald, H.-B. Mak, D.M. Moltz, G. Savard, J. von Schwarzenberg, C.E. Svensson, I.S. Towner and J.L. Wood, *High precision branching ratio measurements for the superallowed* β*-decay of* ^{74}*Rb: a prerequisite for exacting tests of the standard model*, Phys. Rev. **C67**, 051305 (2003).

G.J. Hofman, J. Breitschopf, K. Craig, H. Denz, E.F. Gibson, E.L. Mathie, R. Meier, M. Pavan, C. Riedel and R. Tacik, *Ana-*

lyzing powers for $\pi^- p$ elastic scattering at 279 MeV, Phys. Rev. **C68**, 018202 (2003).

J.-M. Poutissou, M. Craddock and J. Gillies, *TRIUMF: the home of Canadian subatomic physics*, CERN Courier **43N1**, 30 (2003).

M. Trinczek, A. Gorelov, D. Melconian, W.P. Alford, D. Asgeirsson, D. Ashery, J.A. Behr, P.G. Bricault, J.M. D'Auria, J. Deutsch, J. Dilling, M. Dombsky, P. Dubé, S. Eaton, J. Fingler, U. Giesen, S. Gu, O. Häusser, K.P. Jackson, B. Lee, J.H. Schmid, T.J. Stocki, T.B. Swanson and W. Wong, *Novel search for heavy ν mixing from the β^+ decay of ^{38m}K confined in an atom trap*, Phys. Rev. Lett. **90**, 012501 (2003).

S. Gu, J.A. Behr, M.N. Groves and D. Dhat, *Coherent population trapping states with cold atoms in a magnetic field*, Optics Communications **220**, 365 (2003).

W. Liu *et al.*, *Charge state studies of low energy heavy ions passing through hydrogen and helium gas*, Nucl. Instrum. Methods **A496**, 198 (2003).

S. Bishop, R.E. Azuma, L. Buchmann, A.A. Chen, M.L. Chatterjee, J.M. D'Auria, S. Engel, D. Gigliotti, U. Greife, M. Hernanz, D. Hunter, A. Hussein, D. Hutcheon, C. Jewett, J. Jose, J. King, S. Kubono, A.M. Laird, M. Lamey, R. Lewis, W. Liu, S. Michimasa, A. Olin, D. Ottewell, P.D. Parker, J.G. Rogers, F. Strieder and C. Wrede, *^{21}Na$(p,\gamma)^{22}$Mg reaction and oxygen-neon novae*, Phys. Rev. Lett. **90**, 162501 (2003), erratum *ibid.* 229902 (2003) [astro-ph/0303285].

G.F. Grinyer, J.C. Waddington, C.E. Svensson, R.A.E. Austin, G.C. Ball, G.S. Hackman, J.M. O'Meara, C. Osborne, F. Sarazin, H.C. Scraggs and H.D.H. Stover, *The half-life of ^{176}Lu*, Phys. Rev. **C67**, 14302 (2003).

B. Aubert *et al.* (BaBar collaboration), *Study of inclusive production of charmonium mesons in B decay*, Phys. Rev. **D67**, 032002 (2003) [SLAC-PUB-9327, BABAR-PUB-02-04, hep-ex/0207097].

B. Aubert *et al.* (BaBar collaboration), *A measurement of the $B^0 \to J/\psi\pi^+\pi^-$ branching fraction*, Phys. Rev. Lett. **90**, 091801 (2003) [SLAC-PUB-9261, BABAR-PUB-02-06, hep-ex/0209013].

B. Aubert *et al.* (BaBar collaboration), *Measurement of the branching fraction for inclusive semileptonic B meson decays*, Phys. Rev. **D67**, 031101 (2003) [SLAC-PUB-9306, BABAR-PUB-02-011, hep-ex/0208018].

B. Aubert *et al.* (BaBar collaboration), *Measurement of the CKM matrix element $|V_{ub}|$ with $B \to \rho e\nu$ decays*, Phys. Rev. Lett. **90**, 181801 (2003) [SLAC-PUB-9618, BABAR-PUB-02-015, hep-ex/0301001].

B. Aubert *et al.* (BaBar collaboration), *Measurement of $B^0 \to D^{(*)+}D^{*-}$ branching fractions and $B^0 \to D_s^{*+}D^{*-}$ polarization with a partial reconstruction technique*, Phys. Rev. **D67**, 092003 (2003) [SLAC-PUB-9644, BABAR-PUB-03-001, hep-ex/0302015].

B. Aubert *et al.* (BaBar collaboration), *Evidence for $B^+ \to J/\psi p\overline{\Lambda}$ and search for $B^0 \to J/\psi p\overline{p}$*, Phys. Rev. Lett. **90**, 231801 (2003) [SLAC-PUB-9690, BABAR-PUB-03-007, hep-ex/0303036].

K. Ackerstaff *et al.* (HERMES collaboration), *Nuclear effects on $R = \sigma_L/\sigma_T$ in deep-inelastic scattering*, Phys. Lett. **B475**, 386 (2002), erratum *ibid.* **B567**, 339 (2003) [DESY-99-150, hep-ex/9910071, DESY-02-092, hep-ex/0210067].

A. Airapetian *et al.* (HERMES collaboration), *Evidence for quark-hadron duality in the proton spin asymmetry A_1*, Phys. Rev. Lett. **90**, 092002 (2003) [DESY-02-137, hep-ex/0209018].

A. Airapetian *et al.* (HERMES collaboration), *The Q^2-dependence of nuclear transparency for exclusive ρ^0 production*, Phys. Rev. Lett. **90**, 052501 (2003) [DESY-02-152, hep-ex/0209072].

A. Airapetian *et al.* (HERMES collaboration), *The Q^2-dependence of the generalized Gerasimov-Drell-Hearn integral for the deuteron, proton and neutron*, Eur. Phys. J. **C26**, 527 (2003) [DESY-02-172, hep-ex/0210047].

A. Airapetian *et al.* (HERMES collaboration), *Measurement of single-spin azimuthal asymmetries in semi-inclusive electroproduction of pions and kaons on a longitudinally polarised deuterium target*, Phys. Lett. **B562**, 182 (2003) [DESY 02-226, hep-ex/0212039].

A. Airapetian *et al.* (HERMES collaboration), *Double-spin asymmetries in the cross section of diffractive ρ^0 and ϕ production at intermediate energies*, Eur. Phys. J. **C29**, 171 (2003) [DESY-02-230, hep-ex/0302012].

A. Airapetian *et al.* (HERMES collaboration), *Quark fragmentation to $\pi^\pm$, π^0, $K^\pm$, p and $\overline{p}$ in the nuclear environment*, Phys. Lett. **B577**, 37 (2003) [DESY-03-088, hep-ex/0307023].

V.V. Anisimovsky *et al.* (KEK-PS E246 collaboration), *First measurement of the T-violating muon polarization in the decay $K^+ \to \mu^+\nu\gamma$*, Phys. Lett. **B562**, 166 (2003) [hep-ex/0304027].

M.A. Aliev *et al.* (KEK-E470 collaboration), *Measurement of direct photon emission in $K^+ \to \pi^+\pi^0\gamma$ decay using stopped positive kaons*, Phys. Lett. **B554**, 7 (2003) [hep-ex/0212048].

G. Abbiendi *et al.* (OPAL collaboration), *Measurement of the mass of the W boson in e^+e^- collisions using the fully leptonic channel*, Eur. Phys. J. **C26**, 321 (2003) [CERN-EP-2002-022, hep-ex/0203026].

G. Abbiendi *et al.* (OPAL collaboration), *Decay mode independent searches for new scalar bosons with the OPAL detector at LEP*, Eur. Phys. J. **C27**, 311 (2003) [CERN-EP-2002-032, hep-ex/0206022].

G. Abbiendi *et al.* (OPAL collaboration), *Charged particle momentum spectra in* e^+e^- *annihilation at* $\sqrt{1/2}$ *= 192–209 GeV*, Eur. Phys. J. **C27**, 467 (2003) [CERN-EP-2002-057, hep-ex/0209048].

G. Abbiendi *et al.* (OPAL collaboration), *Search for a low mass* CP *odd Higgs boson in* e^+e^- *collisions with the OPAL detector at LEP-2*, Eur. Phys. J. **C27**, 483 (2003) [CERN-EP-2002-058, hep-ex/0209068].

G. Abbiendi *et al.* (OPAL collaboration), *Search for the standard model Higgs boson with the OPAL detector at LEP*, Eur. Phys. J. **C26**, 479 (2003) [CERN-EP-2002-059, hep-ex/0209078].

G. Abbiendi *et al.* (OPAL collaboration), *A measurement of the* $\tau^- \rightarrow \mu^-\overline{\nu}_\mu\nu_\tau$, Phys. Lett. **B551**, 35 (2003) [CERN-EP-2002-085, hep-ex/0211066].

G. Abbiendi *et al.* (OPAL collaboration), *Di-jet production in photon-photon collisions at* $\sqrt{s_{ee}}$ *from 189 to 209 GeV*, Eur. Phys. J. **C31**, 307 (2003) [CERN-EP-2002-093, hep-ex/0301013].

G. Abbiendi *et al.* (OPAL collaboration), *Bose-Einstein correlations of* π^0 *pairs from hadronic* Z^0 *decays*, Phys. Lett. **B559**, 131 (2003) [CERN-EP-2003-005, hep-ex/0302027].

G. Abbiendi *et al.* (OPAL collaboration), *Test of non-commutative QEC in the process* $e^+e^- \rightarrow \gamma\gamma$ *at LEP*, Phys. Lett. **B568**, 181 (2003) [CERN-EP-2003-010, hep-ex/0303035].

G. Abbiendi *et al.* (OPAL collaboration), *Search for stable and longlived massive charged particles in* e^+e^- *collisions at* $\sqrt{1/2}$ *= 130 GeV to 209 GeV*, Phys. Lett. **B572**, 8 (2003) [CERN-EP-2003-016, hep-ex/0305031].

G. Abbiendi *et al.* (OPAL collaboration), *Search for pair produced leptoquarks in* e^+e^- *interactions at* $\sqrt{1/2} \simeq$ *189 GeV to 209 GeV*, Eur. Phys. J. **C31**, 281 (2003) [CERN-EP-2003-021, hep-ex/0305053].

G. Abbiendi *et al.* (OPAL collaboration), *Measurement of isolated prompt photon production in photon photon collisions at* $\sqrt{s_{ee}}$ *= 183–209 GeV*, Eur. Phys. J. **C31**, 491 (2003) [CERN-EP-2003-023, hep-ex/0305075].

G. Abbiendi *et al.* (OPAL collaboration), *Measurement of heavy quark forward backward asymmetries and average* B *mixing using leptons in hadronic* Z *decays*, Phys. Lett. **B577**, 18 (2003) [CERN-EP-2003-039, hep-ex/0308051].

G. Abbiendi *et al.* (OPAL collaboration), *Search for the single production of doubly charged Higgs bosons and constraints on their couplings from Bhabha scattering*, Phys. Lett. **B577**, 93 (2003) [CERN-EP-2003-041, hep-ex/0308052].

G. Abbiendi *et al.* (OPAL collaboration), *Study of* Z *pair production and anomalous couplings in* e^+e^- *collisions at* $\sqrt{s}$ *between 190 GeV and 209 GeV*, Eur. Phys. J. **C32**, 303 (2003) [CERN-EP-2003-049, hep-ex/0310013].

G.M. Huber *et al.* (TAGX collaboration), *In-medium* ρ^0 *spectral function study via the* ^2H*,* ^3He*,* $^{12}C(\gamma,\pi^+\pi^-)$ *reaction*, Phys. Rev. **C68**, 065202 (2003) [nucl-ex/0310011].

Particle, Nuclear and Atomic Physics – *2004*

S. Asai, G. Azuelos, C. Buttar, V. Cavasinni, D. Costanzo, K. Cranmer, R. Harper, K. Jakobs, J. Kanzaki, M. Klute, R. Mazini, B. Mellado, W. Quayle, E. Richter-Was, T. Takemoto, I. Vivarelli and Sau Lan Wu, *Prospects for the search for a standard model Higgs boson in ATLAS using vector boson fusion*, Eur. Phys. J. **C32S2**, 19 (2004) [hep-ph/0402254].

P. Dubé and M. Trinczek, *Hyperfine structure splittings and absorption strengths of molecular iodine transitions near the trapping frequencies of francium*, J. Optical Society of America **B21**, 1113 (2004).

Z. Salman, E.P. Reynard, R.F. Kiefl, W.A. MacFarlane, J. Chakhalian, K.H. Chow, S. Daviel, S. Kreitzman, C.D.P. Levy and R. Poutissou, *Beta-detected nuclear quadrupole resonance with a low energy beam of* $^8Li^+$, Phys. Rev. **B70**, 104404 (2004).

U. Greife, S. Bishop, L. Buchmann, M.L. Chatterjee, A.A. Chen, J.M. D'Auria, S. Engel, D. Gigliotti, D. Hunter, D.A. Hutcheon, A. Hussein, C.C. Jewett, A.M. Laird, M. Lamey, W. Liu, A. Olin, D. Ottewell, J. Rogers and C. Wrede, *Energy loss around the stopping power maximum of Ne, Mg and Na ions in hydrogen gas*, Nucl. Instrum. Methods **B217**, 1 (2004).

M. Hunyadi, C. Bäumer, A.M. van den Berg, N. Blasi, M. Csatlós, L. Csige, B. Davids, U. Garg, J. Gulyás, M.N. Harakeh, M. de Huu, B.C. Junk, A. Krasznahorkay, S. Rakers, D. Sohler and H.J. Wörtche, *Particle decay of the isoscalar giant dipole resonance in* ^{208}Pb, Nucl. Phys. **A731**, 49 (2004).

J. Guillot, D. Beaumel, A.M. van den Berg, S. Brandenburg, B. Davids, S. Fortier, M. Fujiwara, S. Galés, M.N. Harakeh, M. Hunyadi, M. de Huu and H.J. Wörtche, *Investigation of IVGRs via the* $^{58}Ni(t,{}^3He)^{58}Co$ *reaction*, Nucl. Phys. **A731**, 106 (2004).

E.W. Grewe, C. Bäumer, A.M. van den Berg, N. Blasi, B. Davids, D. De Frenne, D. Frekers, P. Haefner, M.N. Harakeh, M. Huynyadi, E. Jacobs, B. Junk, A. Korff, A. Negret, P. von Neumann-Cosel, L. Popescu, S. Rakers and H.J. Wörtche, *Gamow-Teller transitions to* ^{32}P *studied through the* $^{32}S(d,{}^2He)$ *reaction at* E_d *= 170 MeV*, Phys. Rev. **C69**, 064325 (2004).

S. Rakers, C. Bäumer, A.M. van den Berg, B. Davids, D. Frekers, D. De Frenne, Y. Fujita, E.-W. Grewe, P. Haefner, M.N. Harakeh, M. Hunyadi, E. Jacobs, H. Johansson, B.C. Junk, A.

Korff, A. Negret, L. Popescu, H. Simon and H.J. Wörtche, *Nuclear matrix elements for the ^{48}Ca two-neutrino double-β decay from high-resolution charge-exchange reactions*, Phys. Rev. **C70**, 054302 (2004).

A. Korff, P. Haefner, C. Bäumer, A.M. van den Berg, N. Blasi, B. Davids, D. De Frenne, R. de Leo, D. Frekers, E.-W. Grewe, M.N. Harakeh, F. Hofmann, M. Hunyadi, E. Jacobs, B.C. Junk, A. Negret, P. von Neumann-Cosel, L. Popescu, S. Rakers, A. Richter and H.J. Wörtche, *Deuteron elastic and inelastic scattering at intermediate energies from nuclei in the mass range 6 $\leq A \leq$ 116*, Phys. Rev. **C70**, 067601 (2004).

G.S. Mitchell, C.S. Blessinger, J.D. Bowman, T.E. Chupp, K.P. Coulter, M. Gericke, G.L. Jones, M.B. Leuschner, H. Nann, S.A. Page, S.I. Penttila, T.B. Smith, W.M. Snow and W.S. Wilburn, *A measurement of parity-violating gamma-ray asymmetries in polarized cold neutron capture on ^{35}Cl, ^{113}Cd, and ^{139}La*, Nucl. Instrum. Methods **A521**, 468 (2004) [nucl-ex/0401009].

A. Bacchetta, U. D'Alesio, M. Diehl and C.A. Miller, *Single-spin asymmetries: the Trento conventions*, Phys. Rev. **D70**, 117504 (2004) [DESY-04-193, hep-ph/0410050].

F. Sarazin, J.S. Al-Khalili, G.C. Ball, G. Hackman. P.M. Walker, R.A.E. Austin, B. Eshpeter, P. Finlay, P.E. Garrett, G.F. Grinyer, K.A. Koopmans, W.D. Kulp, J.R. Leslie, D. Melconian, C.J. Osborne, M.A. Schumaker, H.C. Scraggs, J. Schwarzenberg, M.B. Smith, C.E. Svensson, J.C. Waddington and J.L. Wood, *Halo neutrons and the β decay of ^{11}Li*, Phys. Rev. **C70**, 031302 (2004) [TRI-PP-04-13].

S. Shimizu, K. Horie, M. Aliev, Y. Asano, T. Baker, P. Depommier, M. Hasinoff, Y. Igarashi, J. Imazato, A.P. Ivashkin, M.M. Khabibullin, A.N. Khotjantsev, Y.G. Kudenko, A. Levchenko, G.Y. Lim, J.A. Macdonald, O.V. Mineev, C. Rangacharyulu and S. Sawada, *Measurement of $K^+ \to \pi^0\pi^0 e^+\nu$ (K^{00}_{e4}) decay using stopped positive kaons*, Phys. Rev. **D70**, 037101 (2004) [hep-ex/0408098].

J.T.M. Goon, D.J. Hartley, L.L. Riedinger, M.P. Carpenter, F.G. Kondev, R.V.F. Janssens, K.H. Abu Saleem, I. Ahmad, H. Amro, J.A. Cizewski, C.N. Davids, M. Danchev, T.L. Khoo, A. Heinz, T. Lauritsen, W.C. Ma, G.L. Poli, J. Ressler, W. Reviol, D. Seweryniak, M.B. Smith, I. Wiedenhöver and J.-Y. Zhang, *Shape coexistence and band crossings in ^{174}Pt*, Phys. Rev. **C70**, 014309 (2004).

J.M. D'Auria, R.E. Azuma, S. Bishop, L. Buchmann, M.L. Chatterjee, A.A. Chen, S. Engel, D. Gigliotti, U. Greife, D. Hunter, A. Hussein, D. Hutcheon, C.C. Jewett, J. José, J.D. King, A.M. Laird, M. Lamey, R. Lewis, W. Liu, A. Olin, D. Ottewell, P. Parker, J. Rogers, C. Ruiz, M. Trinczek and C. Wrede, *The ^{21}Na(p,γ)^{22}Mg reaction from $E_{c.m.}$ = 200 to 1103 keV in novae and x-ray bursts*, Phys. Rev. **C69**, 065803 (2004).

R.J. Peterson, C.E. Allgower, V. Bekrenev, W.J. Bricoe, J.R. Comfort, K. Craig, D. Grosnick, D. Isenhower, N. Knecht, D. Koetke, A.A. Kulbardis, G. Lolos, V. Lopatin, D.M. Manley, R. Manweiller, A. Marušić, S. McDonald, B.M.K. Nefkens, J. Olmsted, Z. Papandreou, D.C. Peaslee, N. Phaisangittiskaul, J. Price, D.E. Prull, A.F. Ramirez, M. Sadler, A. Shafi, H. Spinka, T.D.S. Stanislaus, A. Starostin, H.M. Staudenmaier, I. Strakovsky and I. Supek, *y scaling in quasifree pion-single-charge exchange*, Phys. Rev. **C69**, 064612 (2004).

E. Friedman, M. Bauer, J. Breitschopf, H. Clement, H. Denz, E. Doroshkevich, A. Erhardt, G.J. Hofman, R. Meier, G.J. Wagner and G. Yaari, *The in-medium isovector πN amplitude from low energy pion scattering*, Phys. Rev. Lett. **93**, 122302 (2004) [nucl-ex/0404031].

P.A. Zolnierczuk, D.S. Armstrong, E. Christy, J.H.D. Clark, T.P. Gorringe, M.D. Hasinoff, M.A. Kovash, S. Tripathi and D.H. Wright, *Search for exotic baryons in double radiative capture on pionic hydrogen*, Phys. Lett. **B597**, 131 (2004) [nucl-ex/0403046].

C.D. O'Leary, R. Wadsworth, P. Fallon, C.E. Svensson, K. Ragnarsson, D.E. Appelbe, R.A.E. Austin, G.C. Ball, J.A. Cameron, M.P. Carpenter, R.M. Clark, M. Cromaz, M.A. Deleplanque, R.M. Diamond, D.F. Hodgson, R.V.F. Janssens, D.G. Jenkins, N.S. Kelsall, G.J. Lane, C.J. Lister, A.O. Macchiavelli, D. Sarantites, F.S. Stephens, D. Seweryniak, K. Vetter, J.C. Waddington and D. Ward, *High spin study of rotational structures in ^{72}Br*, Phys. Rev. **C69**, 034316 (2004).

N.S. Kelsall, C.E. Svensson, S.M. Fisher, D.E. Appelbe, R.A.E. Austin, D.P. Balamuth, G.C. Ball, J.A. Cameron, M.P. Carpenter, R.M. Clark, M. Cromaz, M.A. Deleplanque, R.M. Diamond, P. Fallon, D.F. Hodgson, R.V.F. Janssens, D.G. Jenkins, G.J. Lane, C.J. Lister, A.O. Macchiavelli, C.D. O'Leary, D.G. Sarantites, F.S. Stephens, D.C. Schmidt, D. Seweryniak, K. Vetter, J.C. Waddington, R. Wadsworth, D. Ward, A.N. Wilson, A.V. Afanasjev, S. Frauendorf and I. Ragnarsson, *High spin structure of N-Z nuclei around the A=72 region*, Eur. Phys. J. **A20**, 131 (2004).

R. Meier, M. Cröni, R. Bilger, B. van den Brandt, J. Breitschopf, H. Clement, J.R. Comfort, H. Denz, A. Erhardt, K. Föhl, E. Friedman, J. Gräter, P. Hautle, G.J. Hofman, J.A. Konter, S. Mango, J. Pätzold, M.M. Pavan, G.J. Wagner, G. von Wrochem, *Low energy analyzing powers in pion-proton elastic scattering*, Phys. Lett. **B588**, 155 (2004) [nucl-ex/0402018].

G.D. Morris, W.A. MacFarlane, K.H. Chow, Z. Salman, D.J. Arseneau, S. Daviel, A. Hatakeyama, S.R. Kreitzman, C.D.P. Levy, R. Poutissou, R.H. Heffner, J.E. Elenewski, L.H. Greene and R.F. Kiefl, *β-detected NMR of ^{8}Li implanted in a thin silver film*, Phys. Rev. Lett. **93**, 157601 (2004).

P. Camerini, E. Fragiacomo, N. Grion, S. Piano, R. Rui, J. Clark, L. Felawka, E.F. Gibson, G. Hofman, E.L. Mathie, R. Meier, G. Moloney, D. Ottewell, K. Raywood, M.E. Sevior, G.R. Smith and R. Tacik, *General properties of the pion production reaction in nuclear matter*, Nucl. Phys. **A735**, 89 (2004) [nucl-ex/0401018].

P.-N. Seo, J.D. Bowman, M. Gericke, J. Long, G.S. Mitchell, S.I. Penttila and W.S. Wilburn, *A measurement of the Flight Path 12 cold moderator brightness at LANSCE*, Nucl. Instrum. Methods **A517**, 285 (2004).

S. Adler *et al.* (BNL E787 collaboration), *Further search for the decay $K^+ \to \pi^+\nu\bar{\nu}$ in the momentum region $P <$ 195 MeV/c*, Phys. Rev. **D70**, 037102 (2004) [BNL-72163-2004-JA, hep-ex/0403034].

V.V. Anisimovsky *et al.* (BNL E949 collaboration), *Improved measurement of the $K^+ \to \nu\bar{\nu}$ branching ratio*, Phys. Rev. Lett. **93**, 031801 (2004) [TRI-PP-04-07, BNL-72164-2004-JA, KEK-PREPRINT-2004-2, FERMILAB-PUB-04-173-E, hep-ex/0403036].

K.A. Aniol *et al.* (HAPPEX collaboration), *Parity violating electroweak asymmetry in polarized $\vec{e}p$ scattering*, Phys. Rev. **C69**, 065501 (2004) [JLAB-PHY-04-4, nucl-ex/0402004].

A. Airapetian *et al.* (HERMES collaboration), *Flavor decomposition of the sea quark helicity distributions in the nucleon from semi-inclusive deep-inelastic scattering*, Phys. Rev. Lett. **92**, 012005 (2004) [DESY-03-067, hep-ex/0307064].

A. Airapetian *et al.* (HERMES collaboration), *Nuclear polarization of molecular hydrogen recombined on a non-metallic surface*, Eur. Phys. J. **D29**, 21 (2004) [DESY-03-168, physics/0408138].

A. Airapetian *et al.* (HERMES collaboration), *Evidence for a narrow $|S|$ = 1 baryon state at a mass of 1528 MeV in quasi-real photoproduction*, Phys. Lett. **B585**, 213 (2004) [DESY-03-213, HERMES-DC-56, hep-ex/0312044].

A. Airapetian *et al.* (HERMES collaboration), *Hard exclusive electroproduction of $\pi^+\pi^-$ pairs*, Phys. Lett. **B599**, 212 (2004) [DESY-04-097, hep-ex/0406052].

M. Abe *et al.* (KEK-E246 collaboration), *A new limit of T-violating transverse muon polarization in the $K^+ \to \pi^0\mu^+\nu$ decay*, Phys. Rev. Lett. **93**, 131601 (2004) [hep-ex/0408042].

G. Abbiendi *et al.* (OPAL collaboration), *Tests of models of color reconnection and a search for glueballs using gluon jets with a rapidity gap*, Eur. Phys. J. **C35**, 293 (2004) [CERN-EP-2003-031, hep-ex/0306021].

G. Abbiendi *et al.* (OPAL collaboration), *Search for R-parity violating decays of scalar fermions at LEP*, Eur. Phys. J. **C33**, 149 (2004) [CERN-EP-2003-036, hep-ex/0310054].

G. Abbiendi *et al.* (OPAL collaboration), *Search for anomalous production of dilepton events with missing transverse momentum in e^+e^- collisions at $\sqrt{s}$ = 183–209 GeV*, Eur. Phys. J. **C32**, 453 (2004) [CERN-EP-2003-040, hep-ex/0309014].

G. Abbiendi *et al.* (OPAL collaboration), *Measurement of charged current triple gauge boson couplings using W pairs at LEP*, Eur. Phys. J. **C33**, 463 (2004) [CERN-EP-2003-042, hep-ex/0308067].

G. Abbiendi *et al.* (OPAL collaboration), *A study of $W^+W^-\gamma$ events at LEP*, Phys. Lett. **B580**, 17 (2004) [CERN-EP-2003-043, hep-ex/0309013].

G. Abbiendi *et al.* (OPAL collaboration), *A study of charm production in beauty decays with the OPAL detector at LEP*, Eur. Phys. J. **C35**, 149 (2004) [CERN-EP-2003-050, hep-ex/0308050].

G. Abbiendi *et al.* (OPAL collaboration), *Tests of the standard model and constraints on new physics from measurements of fermion pair production at 189–209 GeV at LEP*, Eur. Phys. J. **C33**, 173 (2004) [CERN-EP-2003-053, hep-ex/0309053].

G. Abbiendi *et al.* (OPAL collaboration), *Experimental studies of unbiased gluon jets from e^+e^- annihilations using the jet boost algorithm*, Phys. Rev. **C69**, 032002 (2004) [CERN-EP-2003-067, hep-ex/0310048].

G. Abbiendi *et al.* (OPAL collaboration), *Flavor independent search for Higgs bosons decaying into hadronic final states in e^+e^- collisions at LEP*, Phys. Lett. **B597**, 11 (2004) [CERN-EP-2003-081, hep-ex/0312042].

G. Abbiendi *et al.* (OPAL collaboration), *Measurement of the partial widths of the Z into up and down type quarks*, Phys. Lett. **B586**, 167 (2004) [CERN-EP-2003-082, hep-ex/0312043].

G. Abbiendi *et al.* (OPAL collaboration), *W boson polarization at LEP2*, Phys. Lett. **B585**, 223 (2004) [CERN-EP-2003-088, hep-ex/0312047].

G. Abbiendi *et al.* (OPAL collaboration), *Search for chargino and neutralino production at $\sqrt{1/2}$ = 192–209 GeV at LEP*, Eur. Phys. J. **C35**, 1 (2004) [CERN-EP-2003-090, hep-ex/0401026].

G. Abbiendi *et al.* (OPAL collaboration), *Constraints on anomalous quartic gauge boson couplings from $\nu\bar{\nu}\gamma\gamma$ and $q\bar{q}\gamma\gamma$ events at LEP2*, Phys. Rev. **D70**, 032005 (2004) [CERN-PH-EP-2004-003, hep-ex/0402021].

G. Abbiendi *et al.* (OPAL collaboration), *Study of Bose-Einstein correlations in $e^+e^- \to W^+W^-$ events at LEP*, Eur. Phys. J. **C36**, 297 (2004) [CERN-PH-EP-2004-008, hep-ex/0403055].

G. Abbiendi *et al.* (OPAL collaboration), *Measurement of the strange spectral function in hadronic τ decays*, Eur. Phys. J. **C35**, 437 (2004) [CERN-PH-EP-2004-010, hep-ex/0406007].

G. Abbiendi *et al.* (OPAL collaboration), *Scaling violations of quark and gluon jet fragmentation functions in e^+e^- annihilations at $\sqrt{s}$ = 91.2 GeV and 183–209 GeV*, Eur. Phys. J. **C37**, 25 (2004) [CERN-PH-EP-2004-011, hep-ex/0404026].

G. Abbiendi *et al.* (OPAL collaboration), *Search for neutral Higgs boson in CP-conserving and CP-violating MSSM scenar-*

ios, Eur. Phys. J. **C37**, 49 (2004) [CERN-PH-EP-2004-020, hep-ex/0406057].

G. Abbiendi *et al.* (OPAL collaboration), *Determination of the LEP beam energy using radiative fermion-pair events*, Phys. Lett. **B604**, 31 (2004) [CERN-PH-EP-2004-042, hep-ex/0408130].

B. Aharmim *et al.* (SNO collaboration), *Electron antineutrino search at the Sudbury Neutrino Observatory*, Phys. Rev. **D70**, 093014 (2004) [hep-ex/0407029].

S.N. Ahmed *et al.* (SNO collaboration), *Measurement of the total active ^{8}B solar neutrino flux at the Sudbury Neutrino Observatory with enhanced neutral current sensitivity*, Phys. Rev. Lett. **92**, 181301 (2004) [nucl-ex/0309004].

S.N. Ahmed *et al.* (SNO collaboration), *Constraints on nucleon decay via 'invisible' modes from the Sudbury Neutrino Observatory*, Phys. Rev. Lett. **92**, 102004 (2004) [hep-ex/0310030].

R.A. Scalzo *et al.* (STACEE collaboration), *High-energy gamma-ray observations of W Comae with STACEE*, Astrophys. J. **607**, 778 (2004) [astro-ph/0403114].

Particle, Nuclear and Atomic Physics – *2005*

G. Azuelos, K. Benslama, D. Costanzo, G. Couture, J.E. Garcia, I. Hinchliffe, N. Kanaya, M. Lechowski, R. Mehdiyev, G. Polesello, E. Ros and D. Rousseau, *Exploring little Higgs models with ATLAS at the LHC*, Eur. Phys. J. **C39S2**, 13 (2005) [LBNL-54488, SN-ATLAS-2004-038, hep-ph/0402037].

Y.L. Ye, D.Y. Pang, D.X. Jiang, T. Zheng, Q.J. Wang, Z.H. Li, X.Q. Li, Y.C. Ge, C. Wu, G.L. Zhang, Q.Y. Hu, J. Wang, Z.Q. Chen, A. Ozawa, Y. Yamaguchi, R. Kanungo and I. Tanihata, *Quasielastic scattering of ^{6}He on ^{9}Be at 25 MeV/nucleon*, Phys. Rev. **C71**, 014604 (2005).

R. Kanungo, Z. Elekes, H. Baba, Zs. Dombrádi, Zs. Fülöp, J. Gibelin, A. Horváth, Y. Ichikawa, E. Ideguchi, N. Iwasa, H. Iwasaki, S. Kawai, Y. Kondo, T. Motobayashi, M. Notani, T. Ohnishi, A. Ozawa, H. Sakurai, S. Shimoura, E. Takeshita, S. Takeuchi, I. Tanihata, Y. Togano, C. Wu, Y. Yamaguchi, Y. Yanagisawa, A. Yoshida and K. Yoshida, *Excited states in neutron-rich boron isotopes*, Phys. Lett. **B608**, 206 (2005).

Z. Elekes, Zs. Dombrádi, R. Kanungo, H. Baba, Zs. Fülöp, J. Gibelin, A. Horváth, Y. Ichikawa, E. Ideguchi, N. Iwasa, H. Iwasaki, S. Kawai, Y. Kondo, T. Motobayashi, M. Notani, T. Ohnishi, A. Ozawa, H. Sakurai, S. Shimoura, E. Takeshita, S. Takeuchi, I. Tanihata, Y. Togano, C. Wu, Y. Yamaguchi, Y. Yanagisawa, A. Yoshida and K. Yoshida, *Low-lying excited states in $^{17,19}C$*, Phys. Lett. **B614**, 174 (2005).

R. Kanungo, Z. Elekes H. Baba, Zs. Dombrádi, Zs. Fülöp, J. Gibelin, A. Horváth, Y. Ichikawa, E. Ideguchi, N. Iwasa, H. Iwasaki, S. Kawai, Y. Kondo, T. Motobayashi, M. Notani, T. Ohnishi, A. Ozawa, H. Sakurai, S. Shimoura, E. Takeshita, S. Takeuchi, I. Tanihata, Y. Togano, C. Wu, Y. Yamaguchi, Y. Yanagisawa, A. Yoshida and K. Yoshida, *Search for an isomeric state in ^{19}C*, Nucl. Phys. **A757**, 315 (2005).

Zs. Dombrádi, Z. Elekes, R. Kanungo, H. Baba, Zs. Fülóp, J. Gibelin, A. Horváth, Y. Ichikawa, E. Ideguchi, N. Iwasa, H. Iwasaki, S. Kawai, Y. Kondo, T. Motobayashi, M. Notani, T. Ohnishi, A. Ozawa, H. Sakurai, S. Shimoura, E. Takeshita, S. Takeuchi, I. Tanihata, Y. Togano, C. Wu, Y. Yamaguchi, Y. Yanagisawa, A. Yoshida and K. Yoshida, *Decoupling of valence neutrons from the core in ^{17}B*, Phys. Lett. **B621**, 81 (2005).

H. Iwasaki, N. Aoi, S. Takeuchi, S. Ota, H. Sakurai, M. Tamaki, T.K. Onishi, E. Takeshita, H.G. Ong, N. Iwasa, H. Baba, Z. Elekes, T. Fukuchi, Y. Ichikawa, M. Ishihara, S. Kanno, R. Kanungo, S. Kawai, T. Kubo, K. Kurita, S. Michimasa, M. Niikura, A. Saito, Y. Satou, S. Shimoura, H. Suzuki, M.K. Suzuki, Y. Togano, Y. Yanagisawa and T. Motobayashi, *Intermediate-energy Coulomb excitation of neutron-rich Ge isotopes around N = 50*, Eur. Phys. J. **A25**, 415 (2005).

R. Kanungo, M. Chiba, B. Abu-Ibrahim, S. Adhikari, D. Fang, N. Iwasa, K. Kimura, K. Maeda, S. Nishimura, Y. Ogawa, T. Ohnishi, A. Ozawa, C. Samanta, T. Suda, T. Suzuki, Q. Wang, C. Wu, Y. Yamaguchi, K. Yamada, A. Yoshida, T. Zheng and I. Tanihata, *Observation of a two-proton halo in ^{17}Ne*, Eur. Phys. J. **A25**, 327 (2005).

R. Kanungo, M. Chiba, B. Abu-Ibrahim, S. Adhikari, D. Fang, N. Iwasa, K. Kimura, K. Maeda, S. Nishimura, Y. Ogawa, T. Ohnishi, A. Ozawa, C. Samanta, T. Suda, T. Suzuki, Q. Wang, C. Wu, Y. Yamaguchi, K. Yamada, A. Yoshida, T. Zheng and I. Tanihata, *A new view to the structure of ^{19}C*, Eur. Phys. J. **A25**, 261 (2005).

J.J. Valiente-Dubón, T. Steinhardt, C.E. Svensson, A.V. Afanasjev, I. Ragnarsson, C. Andreoiu, R.A.E. Austin, M.P. Carpenter, D. Dashdorj, G. de Angelis, F. Dönau, J. Eberth, E. Farnea, S.J. Freeman, A. Gadea, P.E. Garrett, A. Görgen, G.F. Grinyer, B. Hyland, D. Jenkins, F. Johnston-Theasby, P. Joshi, A. Jungclaus, K.P. Lieb, A.O. Macchiavelli, E.F. Moore, G. Mukherjee, D.R. Napoli, A.A. Phillips, C. Plettner, W. Reviol, D. Sarantites, H. Schnare, M.A. Schumaker, R. Schwengner, D. Seweryniak, M.B. Smith, I. Stefanescu, O. Thelen and R. Wadsworth, *Evidence for nontermination of rotational bands in ^{74}Kr*, Phys. Rev. Lett. **95**, 232501 (2005).

B. Davids and C.N. Davids, *EMMA: a recoil mass spectrometer for ISAC-II at TRIUMF*, Nucl. Instrum. Methods **A544**, 565 (2005).

A. Mills, J.A. Behr, L.A. Courneyea and M.R. Pearson, *Lifetime of the potassium $5P_{1/2}$ state*, Phys. Rev. **A72**, 024501 (2005).

S. Yamamoto, I. Kato *et al.*, *Design, construction, and initial performance of SciBar detector in K2K experiment*, IEEE Trans. Nucl. Sci. **52**, 2992 (2005).

W.S. Wilburn, J.D. Bowman, S.I. Penttila and M.T. Gericke, *A low-noise current-mode preamplifier for gamma asymmetry measurements*, Nucl. Instrum. Methods **A540**, 180 (2005).

Y. Hirayama, T. Shimoda, H. Izumi, A. Hatakeyama, K.P. Jackson, C.D.P. Levy, H. Miyatake, M. Yagi and H. Yano, *Structure of ^{11}Be studied in β-delayed decays from polarized ^{11}Li*, Phys. Lett. **B611**, 239 (2005).

S. Engel, D. Hutcheon, S. Bishop, L. Buchmann, J. Caggiano, M.L. Chatterjee, A.A. Chen, J. D'Auria, D. Gigliotti, U. Greife, D. Hunter, A. Hussein, C.C. Jewett, A.M. Laird, M. Lamey, W. Liu, A. Olin, D. Ottewell, J. Pearson, C. Ruiz, G. Ruprecht, M. Trinczek, C. Vockenhuber and C. Wrede, *Commissioning the DRAGON facility at ISAC*, Nucl. Instrum. Methods **A553**, 491 (2005).

G.F. Grinyer, C.E. Svensson, C. Andreoiu, A.N. Andreyev, R.A.E. Austin, G.C. Ball, R.S. Chakrawarthy, P. Finlay, P.E. Garrett, G. Hackman, J.C. Hardy, B. Hyland, V.E. Iacob, K.A. Koopmans, W.D. Kulp, J.R. Leslie, J.A. Macdonald, A.C. Morton, W.E. Ormand, C.J. Osborne, C.J. Pearson, A.A. Phillips, F. Sarazin, M.A. Schumaker, H.C. Scraggs, J. Schwarzenberg, M.B. Smith, J.J. Valiente-Dobón, J.C. Waddington, J.L. Wood and E.F. Zganjar, *High precision measurements of ^{26}Na β-decay*, Phys. Rev. **C71**, 044309 (2005).

S. Naguleswaran, R.S. Chakrawarthy, U. Garg, K.L. Lamkin, G. Smith, J.C. Walpe, A. Galindo-Uribarri, V.P. Janzen, D.C. Radford, R. Kaczarowski, D.B. Fossan, D.R. Lafosse, P. Vaska, Ch. Droste, T. Morek, S. Pilotte, J. DeGraaf, T. Drake and R. Wyss, *Magnetic and intruder bands in ^{113}In*, Phys. Rev. **C72**, 044304 (2005).

A.N. Andreyev, D. Ackermann, S. Antalic, I.G. Darby, S. Franchoo, F.P. Hessberger, S. Hofmann, M. Huyse, P. Kuusiniemi, B. Lommel, B. Kindler, R. Mann, G. Münzenberg, R.D. Page, S. Saro, B. Sulignano, B. Streicher, K. Van de Vel, P. Van Duppen and D.R. Wiseman, *Cross section systematics for the lightest Bi and Po nuclei produced in complete fusion reactions with heavy ions*, Phys. Rev. **C72**, 014612 (2005).

E. Friedman, M. Bauer, J. Breitschopf, H. Clement, H. Denz, E. Doroshkevich, A. Erhardt, G.J. Hofman, S. Kritchman, R. Meier, G.J. Wagner and G. Yaari, *Elastic scattering of low energy pions by nuclei and the in-medium isovector πN amplitude*, Phys. Rev. **C72**, 034609 (2005) [nucl-ex/0507008].

W.D. Kulp, J.L. Wood, P.E. Garrett, J.M. Allmond, D. Cline, A.B. Hayes, H. Hua, K.S. Krane, R.-M. Larimer, J. Loats, E.B. Norman, P. Schmelzenbach, C.J. Stapels, R. Teng and C.Y. Wu, *Identification of a pairing isomeric band in ^{152}Sm*, Phys. Rev. **C71**, 041303 (2005).

D.A. Bramel, J. Carson, C.E. Covault, P. Fortin, D.M. Gingrich, D.S. Hanna, A. Jarvis, J. Kildea, T. Lindner, R. Mukherjee, C. Mueller, R.A. Ong, K. Ragan, R.A. Scalzo, D.A. Williams and J. Zweerink, *Observations of the BL Lac object 3C 66A with STACEE*, Astrophys. J. **629**, 108 (2005) [astro-ph/0504515].

J.J. Valiente-Dobón, C.E. Svensson, C.D. O'Leary, I. Ragnarsson, C. Andreoiu, D.E. Appelbe, R.A.E. Austin, G.C. Ball, J.A. Cameron, M.P. Carpenter, R.M. Clark, M. Cromaz, D. Dashdorj, P. Fallon, P. Finlay, S.J. Freeman, P.E. Garrett, A. Gorgen, G.F. Grinyer, D.F. Hodgson, B. Hyland, D. Jenkins, F. Johnston-Theasby, P. Joshi, N.S. Kelsall, A.O. Macchiavelli, F. Moore, G. Mukherjee, A.A. Phillips, W. Reviol, D. Sarantites, M.A. Schumaker, D. Seweryniak, M.B. Smith, J.C. Waddington, R. Wadsworth, D. Ward and S.J. Williams, *High-spin rotational structures in ^{76}Kr*, Phys. Rev. **C71**, 034311 (2005) [DAPNIA-05-35].

C. Ruiz, T. Davinson, F. Sarazin, I. Roberts, A. Robinson, P.J. Woods, L. Buchmann, A.C. Shotter, P. Walden, N.M. Clarke, A.A. Chen, B.R. Fulton, D. Groombridge, J. Pearson and A.S. Murphy, *Multichannel R-matrix analysis of elastic and inelastic resonances in the ^{21}Na+p compound system*, Phys. Rev. **C71**, 025802 (2005).

S.D. Covrig, E.J. Beise, R. Carr, K.K. Gustafsson, L. Hannelius, M.-C. Herda, C.E. Jones, J. Liu, R.D. McKeown, R. Neveling, A.W. Rauf and G. Smith, *The cryogenic target for the $G\emptyset$ experiment at Jefferson Lab*, Nucl. Instrum. Methods **A551**, 218 (2005) [nucl-ex/0502019].

J.J. Ressler, C.W. Beausang, H. Ai, H. Amro, M. Babilon, J.A. Caggiano, R.F. Casten, G. Gurdal, A. Heinz, R.O. Hughes, E.A. McCutchan, D.A. Meyer, C. Plettner, J. Qian, M.J.S. Sciacchitano, N.J. Thomas, E. Williams and N.V. Zamfir, *Isomeric decay of ^{208}Ra*, Phys. Rev. **C71**, 014302 (2005).

D. Axen *et al.*, *Signal feedthroughs for the ATLAS barrel and endcap calorimeters*, Rev. Sci. Instrum. **76**, 063306 (2005).

D. Melconian, M. Trinczek, A. Gorelov, W.P. Alford, J.A. Behr, J.M. D'Auria, M. Dombsky, U. Giesen, K.P. Jackson, T.B. Swanson and W. Wong, *Release of ^{37}K from catcher foils*, Nucl. Instrum. Methods **A538**, 93 (2005).

G. Azuelos and G. Polesello, *Prospects for the detection of Kaluza-Klein excitations of gauge bosons in the ATLAS detector at the LHC*, Eur. Phys. J. **C39S2**, 1 (2005) [SN-ATLAS-2003-023].

M. Agnello, G. Beer, L. Benussi, M. Bertani, S. Bianco, E. Botta, T. Bressani, L. Busso, D. Calvo, P. Camerini, P. Cerello, B. Dalena, F. De Mori, A. D'Erasmo, D. Di Santo, F.L. Fabbri, D. Faso, A. Feliciello, A. Filippi, V. Filippini, R. Fini, E.M. Fiore, H. Fujioka, P. Gianotti, N. Grion, V. Lucherini, S. Marcello, T. Maruta, N. Mirfakhrai, O. Morra, T. Nagae, A. Olin, H. Outa, E. Pace, M. Pallotta, M. Palomba, A. Pantaleo, A. Panzarasa, V. Paticchio, S. Piano, F. Pompili, R. Rui, G. Simonetti, H. So, S. Tomassini, A. Toyoda, R. Wheadon and A. Zenoni, *Evidence for a kaon-bound state K^-pp produced in K^- absorption reactions at rest*, Phys. Rev. Lett. **94**, 212303 (2005).

M. Agnello, G. Beer, L. Benussi, M. Bertani, H.C. Bhang, S. Bianco, E. Botta, T. Bressani, M. Bregant, L. Busso, D. Calvo, P. Camerini, P. Cerello, B. Dalena, F. De Mori, A. D'Erasmo, D.

Di Santo, R. Dona, D. Elia, F.L. Fabbri, D. Faso, A. Feliciello, A. Filippi, V. Filippini, E.M. Fiore, H. Fujioka, P. Gianotti, N. Grion, V. Lucherini, S. Marcello, T. Maruta, N. Mirfakhrai, O. Morra, T. Nagae, A. Olin, H. Outa, E. Pace, M. Pallotta, M. Palomba, A. Pantaleo, A. Panzarasa, V. Paticchio, S. Piano, F. Pompili, R. Rui, G. Simonetti, H. So, S. Tomassini, A. Toyoda, R. Wheadon and A. Zenoni, *First results on $^{12}_{\Lambda}C$ production at DAΦNE*, Phys. Lett. **B622**, 35 (2005) [nucl-ex/0506028].

T. Warner, G. Ball, J.A. Behr, T.E. Chupp, P. Finlay, G. Hackman, M.E. Hayden, B. Hyland, K. Koopmans, S.R. Nuss-Warren, M.R. Pearson, A.A. Phillips, M.A. Schumaker, M.B. Smith, C.E. Svensson and E.R. Tardiff, *Diffusion of Xe in Zr, Ta, and Pt*, Nucl. Instrum. Methods **A538**, 135 (2005).

H.C. Scraggs, C.J. Pearson, G. Hackman, M.B. Smith, R.A.E. Austin, G.C. Ball, A.J. Boston, P. Bricault, R.S. Chakrawarthy, R. Churchman, N. Cowan, G. Cronkhite, E.S. Cunningham, T.E. Drake, P. Finlay, P.E. Garrett, G.F. Grinyer, B. Hyland, B. Jones, J.R. Leslie, J.-P. Martin, D. Morris, A.C. Morton, A.A. Phillips, F. Sarazin, M.A. Schumaker, C.E. Svensson, J.J. Valiente-Dobón, J.C. Waddington, L.M. Watters and L. Zimmerman, *TIGRESS highly-segmented high-purity germanium clover detector*, Nucl. Instrum. Methods **A543**, 431 (2005) [TRI-PP-04-23].

C.E. Svensson, G. Hackman, C.J. Pearson, M.A. Schumaker, H. Scraggs, M.B. Smith, C. Andreoiu, A. Andreyev, R.A. Austin, G.C. Ball, A.J. Boston, R.S. Chakrawarthy, R. Churchman, N. Cowan, T.E. Drake, P. Finlay, P.E. Garrett, G.F. Grinyer, B. Hyland, B. Jones, J.P. Martin, A.C. Morton, A.A. Phillips, R. Roy, F. Sarazin, N. Starinsky, J.J. Valiente-Dobón, J.C. Waddington and L.M. Watters, *Position sensitivity of the TIGRESS 32-fold segmented HPGE clover detector*, Nucl. Instrum. Methods **A540**, 348 (2005).

A. Gorelov, D. Melconian, W.P. Alford, D. Ashery, G. Ball, J.A. Behr, P.G. Bricault, J.M. D'Auria, J. Deutsch, J. Dilling, M. Dombsky, P. Dubé, J. Fingler, U. Giesen, F. Glück, S. Gu, O. Häusser, K.P. Jackson, B.K. Jennings, M.R. Pearson, T.J. Stocki, T.B. Swanson and M. Trinczek, *Scalar interaction limits from the $\beta - \nu$ correlation of trapped radioactive atoms*, Phys. Rev. Lett. **94**, 142501 (2005) [TRI-PP-04-27, nucl-ex/0412032].

M.T. Gericke, C. Blessinger, J.D. Bowman, R.C. Gillis, J. Hartfield, T. Ino, M. Leuschner, Y. Masuda, G.S. Mitchell, S. Muto, H. Nann, S.A. Page, S.I. Penttilä, W.D. Ramsay, P.-N. Seo, W.M. Snow, J. Tasson and W.S. Wilburn, *A current mode detector array for gamma-ray asymmetry measurements*, Nucl. Instrum. Methods **A540**, 328 (2005) [LA-UR-1055, nucl-ex/0411022].

A. Gaponenko, R. Bayes, Yu.I. Davydov, P. Depommier, J. Doornbos, W. Faszer, M.C. Fujiwara, C.A. Gagliardi, D.R. Gill, P. Green, P. Gumplinger, M.D. Hasinoff, R.S. Henderson, J. Hu, B. Jamieson, P. Kitching, D.D. Koetke, A.A. Krushinsky, Yu.Yu. Lachin, J.A. Macdonald, R.P. MacDonald, G.M. Marshall, E.L. Mathie, L.V. Miasoedov, R.E. Mischke, J.R. Musser, P.M. Nord, M. Nozar, K. Olchanski, A. Olin, R. Openshaw, T.A. Porcelli, J.-M. Poutissou, R. Poutissou, M.A. Quraan, N.L. Rodning, V. Selivanov, G. Sheffer, B. Shin, F. Sobratee, T.D.S. Stanislaus, R. Tacik, V.D. Torokhov, R.E. Tribble, M.A. Vasiliev and D.H. Wright, *Measurement of the muon decay parameter δ*, Phys. Rev. **D71**, 071101 (2005) [TRI-PP-04-22, hep-ex/0410045].

G. Azuelos, P.H. Beauchemin and C.P. Burgess, *Phenomenological constraints on extra dimensional scalars*, J. Phys. **G31**, 1 2005 [MCGILL-03-17, SN-ATLAS-2004-037, hep-ph/0401125].

N. Grion *et al.* (CHAOS collaboration), *The $\pi \to \pi\pi$ process in nuclei and the restoration of chiral symmetry*, Nucl. Phys. **A763**, 80 (2005) [nucl-ex/0508028].

A.V. Artamonov *et al.* (E949 collaboration), *Search for the decay $K^+ \to \pi^+\gamma\gamma$ in the π^+ momentum region $P > 213$ MeV/c*, Phys. Lett. **B623**, 192 (2005) [BNL-73917-2005-JA, FERMILAB-PUB-05-449-E, IHEP-2005-08, KEK-2005-8, TRI-PP-05-07, TUHEP-EX-05-001, hep-ex/0505069].

A.V. Artamonov *et al.* (E949 collaboration), *Upper limit on the branching ratio for the decay $\pi^0 \to \nu\bar{\nu}$*, Phys. Rev. **D72**, 091102 (2005) [BNL-73936-2005-JA, IHEP-2005-09, KEK-2005-11, TRI-PP-05-08, TUHEP-EX-05-002, hep-ex/0506028].

D.S. Armstrong *et al.* ($G\emptyset$ collaboration), *Strange quark contributions to parity-violating asymmetries in the forward $G\emptyset$ electron-proton scattering experiment*, Phys. Rev. Lett. **95**, 092001 (2005) [JLAB-PHY-05-315, nucl-ex/0506021].

A. Airapetian *et al.* (HERMES collaboration), *Quark helicity distributions in the nucleon for up, down, and strange quarks from semi-inclusive deep-inelastic scattering*, Phys. Rev. **D71**, 012003 (2005) [DESY-04-107, hep-ex/0407032].

A. Airapetian *et al.* (HERMES collaboration), *The HERMES polarized hydrogen and deuterium gas target in the HERA electron storage ring*, Nucl. Instrum. Methods **A540**, 68 (2005) [DESY-04-128, physics/0408137].

A. Airapetian *et al.* (HERMES collaboration), *Single-spin asymmetries in semi-inclusive deep-inelastic scattering on a transversely polarized hydrogen target*, Phys. Rev. Lett. **94**, 012002 (2005) [DESY-04-141, hep-ex/0408013].

A. Airapetian *et al.* (HERMES collaboration), *Search for an exotic S = –2, Q = –2 baryon resonance at a mass near 1862 MeV in quasi-real photoproduction*, Phys. Rev. **D71**, 032004 (2005) [DESY-04-239, hep-ex/0412027].

A. Airapetian *et al.* (HERMES collaboration), *Subleading-twist effects in single-spin asymmetries in semi-inclusive deep-inelastic scattering on a longitudinally polarized hydrogen target*, Phys. Lett. **B622**, 14 (2005) [DESY-05-072, hep-ex/0505042].

A. Airapetian *et al.* (HERMES collaboration), *First measurement of the tensor structure function b_1 of the deuteron*, Phys. Rev. Lett. **95**, 242001 (2005) [DESY-05-077, hep-ex/0506018].

E. Aliu *et al.* (K2K collaboration), *Evidence for muon neutrino oscillation in an accelerator-based experiment*, Phys. Rev. Lett. **94**, 081802 (2005) [hep-ex/0411038].

M. Hasegawa *et al.* (K2K collaboration), *Search for coherent charged pion production in neutrino-carbon interactions*, Phys. Rev. Lett. **95**, 252301 (2005) [DAPNIA-05-106, hep-ex/0506008].

G. Abbiendi *et al.* (OPAL collaboration), *Flavor independent h^0A^0 search and two Higgs doublet model interpretation of neutral Higgs boson searches at LEP*, Eur. Phys. J. **C40**, 317 (2005) [CERN-PH-EP-2004-039, hep-ex/0408097].

G. Abbiendi *et al.* (OPAL collaboration), *Search for radions at LEP2*, Phys. Lett. **B609**, 20 (2005) [CERN-PH-EP-2004-041, hep-ex/0410035].

G. Abbiendi *et al.* (OPAL collaboration), *Measurement of event shape distributions and moments in $e^+e^- \rightarrow$ hadrons at 91–209 GeV and a determination of α_s*, Eur. Phys. J. **C40**, 287 (2005) [CERN-EP-04-044, hep-ex/0503051].

G. Abbiendi *et al.* (OPAL collaboration), *Measurement of R_b in e^+e^- collisions at 182–209 GeV*, Phys. Lett. **B609**, 212 (2005) [CERN-PH-EP-2004-051, hep-ex/0410034].

B. Aharmim, R.L. Helmer *et al.* (SNO collaboration), *Electron energy spectra, fluxes, and day-night asymmetries of ^{8}B solar neutrinos from measurements with NaCl dissolved in the heavy-water detector at the Sudbury Neutrino Observatory*, Phys. Rev. **C72**, 055502 (2005) [nucl-ex/0502021].

B. Aharmim *et al.* (SNO collaboration), *A search for periodicities in the ^{8}B solar neutrino flux measured by the Sudbury Neutrino Observatory*, Phys. Rev. **D72**, 052010 (2005) [hep-ex/0507079].

J. Adams, F. Retiere *et al.* (STAR collaboration), *Incident energy dependence of p_t correlations at RHIC*, Phys. Rev. **C72**, 044902 (2005) [nucl-ex-0504031].

J. Adams, F. Retiere *et al.* (STAR collaboration), *Multi-stange baryon elliptic flow in Au + Au collisions at $\sqrt{S_{NN}}$ = 200 GeV*, Phys. Rev. Lett. **95**, 122301 (2005) [nucl-ex/0504022].

J. Adams, F. Retiere *et al.* (STAR collaboration), *Multiplicity and pseudorapidity distributions of photons in Au + Au collisions at $\sqrt{S_{NN}}$ = 62.4 GeV*, Phys. Rev. Lett. **95**, 062301 (2005) [nucl-ex/0502008].

J. Adams, F. Retiere *et al.* (STAR collaboration), *Distributions of charged hadrons associated with high transverse momentum particles in pp and Au + Au collisions at $\sqrt{S_{NN}}$ = 200 GeV*, Phys. Rev. Lett. **95**, 152301 (2005) [nucl-ex/0501016].

J. Adams, F. Retiere *et al.* (STAR collaboration), *Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR collaboration's critical assessment of the evidence from RHIC collisions*, Nucl. Phys. **A757**, 102 (2005).

J. Adams, F. Retiere *et al.* (STAR collaboration), *$K(892)$ resonance production in Au + Au and $p + p$ collisions at $\sqrt{S_{NN}}$ = 200 GeV*, Phys. Rev. **C71**, 064902 (2005).

J. Adams, F. Retiere *et al.* (STAR collaboration), *Pion interferometry in Au + Au collisions at $\sqrt{S_{NN}}$ = 200 GeV*, Phys. Rev. **C71**, 044906 (2005).

J. Adams, F. Retiere *et al.* (STAR collaboration), *Azimuthal anisotropy in Au + Au collisions at $\sqrt{S_{NN}}$ = 200 GeV*, Phys. Rev. **C72**, 014904 (2005).

J. Adams, F. Retiere *et al.* (STAR collaboration), *ϕ production in Au + Au and $p + p$ collisions at $\sqrt{S_{NN}}$ = 200 GeV*, Phys. Lett. **B612**, 181 (2005).

J.R. Musser, R. Bayes, Yu.I. Davydov, P. Depommier, J. Doornbos, W. Faszer, C.A. Gagliardi, A. Gaponenko, D.R. Gill, P. Green, P. Gumplinger, M.D. Hasinoff, R.S. Henderson, J. Hu, B. Jamieson, P. Kitching, D.D. Koetke, A.A. Krushinsky, Yu.Yu. Lachin, J.A. Macdonald, R.P. MacDonald, G.M. Marshall, E.L. Mathie, L.V. Miasoedov, R.E. Mischke, P.M. Nord, K. Olchanski, A. Olin, R. Openshaw, T.A. Porcelli, J.-M. Poutissou, R. Poutissou, M.A. Quraan, N.L. Rodning, V. Selivanov, G. Sheffer, B. Shin, F. Sobratee, T.D.S. Stanislaus, R. Tacik, V.D. Torokhov, R.E. Tribble, M.A. Vasiliev and D.H. Wright (TWIST collaboration), *Measurement of the Michel parameter ρ in muon decay*, Phys. Rev. Lett. **94**, 101805 (2005) [TRI-PP-04-21, hep-ex/0409063].

Particle, Nuclear and Atomic Physics – *2006*

S. Schael *et al.*, *Precision electroweak measurements on the Z resonance*, Phys. Rep. **47**, 257 (2006) [hep-ex/0509008].

W. Guo, D.Q. Fang, Y.G. Ma, C.W. Ma, K. Wang, T.Z. Yan, X.Z. Cai, W.Q. Shen, Z.Y. Sun, Z.Z. Ren, J.G. Chen, J.H. Chen, G.H. Liu, E.J. Ma, G.L. Ma, Y. Shi, Q.M. Su, W.D. Tian, H.W. Wang, C. Zhong, J.X. Zuo, M. Hosoi, T. Izumikawa, R. Kanungo, S. Nakajima, T. Ohnishi, T. Ohtsubo, A. Ozawa, T. Suda, K. Sugawara, T. Suzuki, A. Takisawa, K. Tanaka, T. Yamaguchi and I. Tanihata, *Measurements of reaction cross section and fragment momentum distribution for N = 10 proton-rich isotones*, Int. J. Mod. Phys. **E15,28**, 1523 (2006).

M. Mazzocco, C. Signorini, M. Romoli, A. De Francesco, M. Di Pietro, E. Vardaci, K. Yoshida, A. Yoshida, R. Bonetti, A. De Rosa, T. Glodariu, A. Guglielmetti, G. Inglima, M. La Commara, B. Martin, D. Pierroutsakou, M. Sandoli, F. Soramel, L. Stroe, R. Kanungo, N. Khai, T. Motobayashi, T. Nomura, T. Ishikawa, H. Ishiyama, S. Jeong, H. Miyatake, M.H. Tanaka, I. Sugai and Y. Watanabe, *Scattering of ^{11}Be halo nucleus from ^{209}Bi at the Coulomb barrier*, Eur. Phys. J. **A28**, 295 (2006).

J. Dilling, R. Baartman, P. Bricault, M. Brodeur, L. Blomeley, F. Buchinger, J. Crawford, J.R. Crespo López-Urrutia, P. Delheij, M. Froese, G.P. Gwinner, Z. Ke, J.K.P. Lee, R.B. Moore,

V. Ryjkov, G. Sikler, M. Smith, J. Ullrich, J. Vaz *et al.* (TITAN collaboration), *Mass measurements on highly charged radioactive ions, a new approach to high precision with TITAN*, Int. J. Mass Spect. **251**, 198 (2006).

B. Hyland, C.E. Svensson, G.C. Ball, J.R. Leslie, T. Achtzehn, D. Albers, C. Andreoiu, P. Bricault, R. Churchman, D. Cross, M. Dombsky, P. Finlay, P.E. Garrett, C. Geppert, G.F. Grinyer, G. Hackman, V. Hanemaayer, J. Lassen, J.P. Lavoie, D. Melconian, A.C. Morton, C.J. Pearson, M.R. Pearson, A.A. Phillips, M.A. Schumaker, I.S. Towner, J.J. Valiente-Dobón, K. Wendt and E.F. Zganjar, *Precision branching ratio measurement for the superallowed β^+ emitter ^{62}Ga and isospin-symmetry-breaking corrections in $A \geq 62$ nuclei*, Phys. Rev. Lett. **97**, 102501 (2006).

C. Matei, L. Buchmann, W.R. Hannes, D.A. Hutcheon, C. Ruiz, C.R. Brune, J. Caggiano, A.A. Chen, J. D'Auria, A. Laird, M. Lamey, Z.H. Li, W.P. Liu, A. Olin, D. Ottewell, J. Pearson, G. Ruprecht, M. Trinczek, C. Vockenhuber and C. Wrede, *Measurement of the cascade transition via the first excited state of ^{16}O in the ^{12}C$(\alpha,\gamma)^{16}$O reaction, and its S factor in stellar helium burning*, Phys. Rev. Lett. **97**, 242503 (2006) [TRI-PP-06-09].

R. Kanungo, T.K. Alexander, A.N. Andreyev, G.C. Ball, R.S. Chakrawarthy, M. Chicoine, R. Churchman, B. Davids, J.S. Forster, S. Gujrathi, G. Hackman, D. Howell, J.R. Leslie, A.C. Morton, S. Mythili, C.J. Pearson, J.J. Ressler, C. Ruiz, H. Savajols, M.A. Schumaker, I. Tanihata, P. Walden and S. Yen, *Lifetime of ^{19}Ne*(4.03 MeV)*, Phys. Rev. **C74**, 045803 (2006).

J.L. Fisker, J. Gorres, M. Wiescher and B. Davids, *The importance of ^{15}O(α,γ) ^{19}Ne to X-ray bursts and superbursts*, Astrophys. J. **650**, 332 (2006) [astro-ph/0410561].

R.E. Warner, F. Carstoiu, J.A. Brown, F.D. Becchetti, D.A. Roberts, B. Davids, A. Galonsky, R.M. Ronningen, M. Steiner, M. Horoi, J.J. Kolata, A. Nadasen, C. Samanta, J. Schwarzenberg and K. Subotic, *Reaction and proton-removal cross sections of ^{6}Li, ^{7}Be, ^{10}B, ^{9,10,11}C, ^{12}N, ^{13,15}O and ^{17}Ne on Si at 15 to 53 MeV/nucleon*, Phys. Rev. **C74**, 014605 (2006) [nucl-ex/0507025].

C. Ruiz, A. Parikh, J. José, L. Buchmann, J.A. Caggiano, A.A. Chen, J.A. Clark, H. Crawford, B. Davids, J.M. D'Auria, C. Davis, C. Deibel, L. Erikson, L. Fogarty, D. Frekers, U. Greife, A. Hussein, D.A. Hutcheon, M. Huyse, C. Jewett, A.M. Laird, R. Lewis, P. Mumby-Croft, A. Olin, D.F. Ottewell, C.V. Ouellet, P. Parker, J. Pearson, G. Ruprecht, M. Trinczek, C. Vockenhuber and C. Wrede, *Measurement of the $E_{\rm c.m.}$ = 184 keV resonance strength in the ^{26g}Al$(p,\gamma)^{27}$Si reaction*, Phys. Rev. Lett. **96**, 252501 (2006).

W. Loveland, A.M. Vinodkumar, R.S. Naik, P.H. Sprunger, B. Matteson, J. Neeway, M. Trinczek, M. Dombsky, P. Machule, D. Ottewell, D. Cross, K. Gagnon and W.J. Mills, *Subbarrier fusion of ^{9}Li with ^{70}Zn*, Phys. Rev. **C74**, 064609 (2006).

A.N. Andreyev, S. Antalic, M. Huyse, P. Van Duppen, D. Ackermann, L. Bianco, D.M. Cullen, I.G. Darby, S. Franchoo, S. Heinz, F.P. Hessberger, S. Hofmann, I. Kojouharov, B. Kindler, A.-P. Leppänen, B. Lommel, R. Mann, G. Münzenberg, J. Pakarinen, R.D. Page, J.J. Ressler, S. Saro, B. Streicher, B. Sulignano, J. Thomson and R. Wyss, *α decay of the new isotopes ^{193,194}Rn*, Phys. Rev. **C74**, 064303 (2006).

C. Vockenhuber, M. Bichler, W. Kutschera, A. Wallner, I. Dillmann and F. Kappeler, *Half-life of Hf183*, Phys. Rev. **C74**, 057303 (2006).

B. Jamieson, R. Bayes, Yu.I. Davydov, P. Depommier, J. Doornbos, W. Faszer, M.C. Fujiwara, C.A. Gagliardi, A. Gaponenko, D.R. Gill, P. Gumplinger, M.D. Hasinoff, R.S. Henderson, J. Hu, P. Kitching, D.D. Koetke, J.A. Macdonald, R.P. MacDonald, G.M. Marshall, E.L. Mathie, R.E. Mischke, J.R. Musser, M. Nozar, K. Olchanski, A. Olin, R. Openshaw, T.A. Porcelli, J.-M. Poutissou, R. Poutissou, M.A. Quraan, N.L. Rodning, V. Selivanov, G. Sheffer, B. Shin, T.D.S. Stanislaus, R. Tacik, V.D. Torokhov, R.E. Tribble and M.A. Vasiliev (TWIST collaboration), *Measurement of $P_\mu\xi$ in polarized muon decay*, Phys. Rev. **D74**, 072007 (2006) [TRI-PP-06-06; hep-ex/0605100].

A.A. Phillips, C. Andreoiu, G.C. Ball, D. Bandyopadhyay, J.A. Behr, T.E. Chupp, P. Finlay, P.E. Garrett, G.F. Grinyer, G. Hackman, M.E. Hayden, B. Hyland, S.R. Nuss-Warren, M.R. Pearson, M.A. Schumaker, M.B. Smith, C.E. Svensson, E.R. Tardiff, J.J. Valiente-Dobón and T. Warner, *Half-life of ^{120}Xe*, Phys. Rev. **C74**, 027302 (2006).

A. Ozawa, K. Matsuta, T. Nagatomo, M. Mihara, K. Yamada, T. Yamaguchi, T. Ohtsubo, S. Momota, T. Izumikawa, T. Sumikama, Y. Nakashima, H. Fujiwara, S. Kumashiro, R. Matsumiya, M. Ota, D. Shinojima, H. Tanaka, T. Yasuno, S. Nakajima, T. Suzuki, K. Yoshida, K. Muranaka, T. Maemura, A. Chiba, Y. Utsuno, M. Fukuda, K. Tanaka, I. Tanihata, Y. Nojiri, T. Minamisono, J.R. Alonso, G.F. Krebs and T.J.M. Symons, *Measurement of the spin and magnetic moment of ^{23}Al*, Phys. Rev. **C74**, 021301 (2006).

B. Hu, R. Woo *et al.*, *Polarization transfer in the ^{2}H$(\vec{e},e'\vec{p})n$ reaction up to Q^2 = 1.61 GeV/c^2*, Phys. Rev. **C73**, 064004 (2006) [JLAB-PHY-06-458].

T. Numao, Yu.I. Davydov, J.-M. Poutissou, T.C. Awes, V. Cianciolo, S. Berridge, W. Bugg, Yu. Efremenko, R. Gearhart and S. Ovchinnikov, *Search for free decay of negative pions in water and light materials*, Phys. Rev. **D73**, 092004 (2006) [TRI-PP-06-07, hep-ex/0605121].

M. Petrascu, A. Constantinescu, I. Cruceru, M. Giurgiu, A. Isbasescu, H. Petrascu, C. Bordeanu, S. Serban, V. Stoica, I. Tanihata, W.G. Lynch, M.A. Famiano, V.L. Lyuboshits, V.V. Lyuboshits and K. Ieki, *Target screening effect on the pre-emission of neutrons from ^{11}Li halo nuclei*, Phys. Rev. **C73**, 057601 (2006).

A.St.J. Murphy, M. Aliotta, T. Davinson, C. Ruiz, P.J. Woods, J.M. D'Auria, L. Buchmann, A.A. Chen, A.M. Laird, F. Sarazin, P. Walden, B.R. Fulton, J.E. Pearson and B.A. Brown, *Level structure of ^{21}Mg: nuclear and astrophysical implications*, Phys. Rev. **C73**, 034320 (2006).

A.N. Andreyev, S. Antalic, D. Ackermann, S. Franchoo, F.P. Hessberger, S. Hofmann, M. Huyse, I. Kojouharov, B. Kindler, P. Kuusiniemi, S.R. Lesher, B. Lommel, R. Mann, G. Münzenberg, K. Nishio, R.D. Page, J.J. Ressler, B. Streicher, S. Saro, B. Sulignano, P. Van Duppen, D. Wiseman and R. Wyss, *α-decay of the new isotope ^{187}Po: probing prolate structures beyond the neutron mid-shell at N = 104*, Phys. Rev. **C73**, 044324 (2006).

A.N. Andreyev, S. Antalic, D. Ackermann, S. Franchoo, F.P. Hessberger, S. Hofmann, M. Huyse, I. Kojouharov, B. Kindler, P. Kuusiniemi, S.R. Lesher, B. Lommel, R. Mann, G. Münzenberg, K. Nishio, R.D. Page, J.J. Ressler, B. Streicher, S. Saro, B. Sulignano, P. Van Duppen and D.R. Wiseman, *α-decay spectroscopy of the new isotope ^{192}At*, Phys. Rev. **C73**, 024317 (2006).

J.M. Sisterson and J. Vincent, *Cross section measurements for proton-induced reactions in Fe and Ni producing relatively short-lived radionuclides at E_p = 140–500 MeV*, Nucl. Instrum. Methods **B251**, 1 (2006).

D. Bryman, A.J. Buras, G. Isidori and L. Littenberg, *$K_L \to \pi^0\nu\overline{\nu}$ as a probe of new physics*, Int. J. Mod. Phys. **A21**, 487 (2006) [TRI-PP-05-09, hep-ph/0505171].

R. Sánchez, W. Nörtershäuser, G. Ewald, D. Albers, J. Behr, P. Bricault, B.A. Bushaw, A. Dax, J. Dilling, M. Dombsky, G.W.R. Drake, S. Götte, R. Kirchner, H.-J. Kluge, Th. Kühl, J. Lassen, C.D.P. Levy, M.R. Pearson, E.J. Prime, V. Ryjkov, A. Wojtaszek, Z.-C. Yan and C. Zimmermann, *Nuclear charge radii of ^{9,11}Li: the influence of halo neutrons*, Phys. Rev. Lett. **96**, 033002 (2006).

H. Denz, P. Amaudruz, J.T. Brack, J. Breitschopf, P. Camerini, J.L. Clark, H. Clement, L. Felawka, E. Fragiacomo, E.F. Gibson, N. Grion, G.J. Hofman, B. Jamieson, E.L. Mathie, R. Meier, G. Moloney, D. Ottewell, O. Patarakin, J.D. Patterson, M.M. Pavan, S. Piano, K. Raywood, R.A. Ristinen, R. Rui, M.E. Sevior, G.R. Smith, J. Stahov, R. Tacik, G.J. Wagner, F. von Wrochem and D.M. Yeomans, *$\pi^{\pm}p$ differential cross sections at low energies*, Phys. Lett. **B633**, 209 (2006) [JLAB-PHY-05-455, nucl-ex/0512006].

D. Attwood, P. Bell, S. Bull, T. McMahon, J. Wilson, R. Fernow, P. Gruber, A. Jamdagni, K. Long, E. McKigney, P. Savage, M. Curtis-Rouse, T.R. Edgecock, M. Ellis, J. Lidbury, W.J. Murray, P. Norton, K. Peach, K. Ishida, Y. Matsuda, K. Nagamine, S. Nakamura, G.M. Marshall, S. Benveniste, D. Cline, Y. Fukui, K. Lee, Y. Pischalnikov, S. Holmes and A. Bogacz, *The scattering of muons in low Z materials*, Nucl. Instrum. Methods **B251**, 41 (2006) [hep-ex/0512005].

R.S. Chakrawarthy, P.M. Walker, J.J. Ressler, E.F. Zganjar, G.C. Ball, M.B. Smith, A.N. Andreyev, S.F. Ashley, R.A.E. Austin, D. Bandyopadhyay, J.A. Becker, J.J. Carroll, D.S. Cross, D. Gohlke, J.J. Daoud, P.E. Garrett, G.F. Grinyer, G. Hackman, G.A. Jones, R. Kanungo, W.D. Kulp, Y. Litvinov, A.C. Morton, W.J. Mills, C.J. Pearson, R. Propri, C.E. Svensson, R. Wheeler and S.J. Williams, *$K^{\pi} = 0^+$ 2.29 s isomer in neutron-rich ^{174}Tm*, Phys. Rev. **C73**, 024306 (2006) [TRI-PP-05-30].

J.H.D. Clark, D.S. Armstrong, T.P. Gorringe, M.D. Hasinoff, P.M. King, T.J. Stocki, S. Tripathi, D.H. Wright and P.A. Zolnierczuk, *Ortho-para transition rate in μ-molecular hydrogen and the proton's induced pseudoscalar coupling g_p*, Phys. Rev. Lett. **96**, 073401 (2006) [nucl-ex/0509025].

G. Azuelos, K. Benslama and J. Ferland, *Prospects for the search for a doubly-charged Higgs in the left-right symmetric model with ATLAS*, J. Phys. **G32**, 73 (2006) [hep-ph/0503096].

S. Schael *et al.* (ALEPH, DELPHI, L3 and OPAL collaborations), *Search for neutral MSSM Higgs bosons at LEP*, Eur. Phys. J. **C47**, 547 (2006) [CERN-PH-EP-2006-001, hep-ex/0602042].

M. Agnello *et al.* (FINUDA collaboration), *A study of the proton spectra following the capture of K^- in ^{6}Li and ^{12}C with FINUDA*, Nucl. Phys. **A775**, 35 (2006) [nucl-ex/0606021].

A. Airapetian *et al.* (HERMES collaboration), *Double hadron leptoproduction in the nuclear medium*, Phys. Rev. Lett. **96**, 162301 (2006) [DESY-05-205, hep-ex/0510030].

A. Airapetian *et al.* (HERMES collaboration), *Longitudinal spin transfer to the Λ hyperon in semi-inclusive deep-inelastic scattering*, Phys. Rev. **D74**, 072004 (2006) [hep-ex/0607004].

M.H. Ahn *et al.* (K2K collaboration), *Measurement of neutrino oscillation by the K2K experiment*, Phys. Rev. **D74**, 072003 (2006) [hep-ex/0606032].

R. Gran *et al.* (K2K collaboration), *Measurement of the quasi-elastic axial vector mass in neutrino-oxygen interactions*, Phys. Rev. **D74**, 052002 (2006) [hep-ex/0603034].

S. Yamamoto *et al.* (K2K collaboration), *An improved search for $\nu_\mu \to \nu_e$ oscillation in a long-baseline accelerator experiment*, Phys. Rev. Lett. **96**, 181801 (2006) [hep-ex/0603004].

M. Abe, M. Aliev, V. Anisimovsky, M. Aoki, Y. Asano, T. Baker, M. Blecher, P. Depommier, M. Hasinoff, K. Horie, Y. Igarashi, J. Imazato, A.P. Ivashkin, M.M. Khabibullin, A.N. Khotjantsev, Yu.G. Kudenko, Y. Kuno, K.S. Lee, A. Levchenko, G.Y. Lim, J.A. Macdonald, O.V. Mineev, N. Okorokova, C. Rangacharyulu, S. Shimizu, Y.-H. Shin, Y.-M. Shin, K.S. Sim, N. Yershov and T. Yokoi (KEK-E246 collaboration), *Search for T-violating transverse muon polarization in the $K^+ \to \pi^0\mu^+\nu$ decay*, Phys. Rev. **D73**, 072005 (2006).

M.A. Aliev *et al.* (KEK-E470 collaboration), *New result of the measurement of the direct photon emission in $K^+ \to \pi^+\pi^0\gamma$ decay*, Eur. Phys. J. **C46**, 61 (2006) [hep-ex/0511060].

S. Shimizu *et al.* (KEK-E470 collaboration), *Measurement of $K^+ \to \pi^0\mu^+\nu\gamma$ decay using stopped kaons*, Phys. Lett. **B633**, 190 (2006) [hep-ex/0512068].

M.T. Gericke *et al.* (NPDGamma collaboration), *Upper bounds on parity violating gamma-ray asymmetries in compound nuclei from polarized cold neutron capture*, Phys. Rev. **C74**, 065503 (2006) [nucl-ex/0608006].

G. Abbiendi *et al.* (OPAL collaboration), *Measurement of the running of the QED coupling in small-angle Bhabha scattering at LEP*, Eur. Phys. J. **C45**, 1 (2006) [CERN-PH-EP-2005-014, hep-ex/0505072].

G. Abbiendi *et al.* (OPAL collaboration), *Determination of α_s using jet rates at LEP with the OPAL detector*, Eur. Phys. J. **C45**, 547 (2006) [CERN-PH-EP-2005-024, hep-ex/0507047].

G. Abbiendi *et al.* (OPAL collaboration), *Searches for gauge-mediated supersymmetry breaking topologies in e^+e^- collisions at LEP2*, Eur. Phys. J. **C46**, 307 (2006) [CERN-PH-EP-2005-025, hep-ex/0507048].

G. Abbiendi *et al.* (OPAL collaboration), *Colour reconnection in $e^+e^- \to W^+W^- \sqrt{s}$ = 189–209 GeV*, Eur. Phys. J. **C45**, 291 (2006) [CERN-PH-EP-2005-035, hep-ex/0508062].

G. Abbiendi *et al.* (OPAL collaboration), *Measurement of the mass and width of the W boson*, Eur. Phys. J. **C45**, 307 (2006) [OPAL-PR-410, CERN-PH-EP-2005-038, hep-ex/0508060].

G. Abbiendi *et al.* (OPAL collaboration), *Measurement of the strong coupling α_S from four-jet observables in e^+e^- annihilation*, Eur. Phys. J. **C47**, 295 (2006) [CERN-PH-EP-2005-057, hep-ex/0601048].

G. Abbiendi *et al.* (OPAL collaboration), *QCD coherence and correlations of particles with restricted momenta in hadronic Z decays*, Phys. Lett. **B638**, 30 (2006) [CERN-PH-EP-2006-003, hep-ex/0604003].

B. Aharmim *et al.* (SNO collaboration), *A search for neutrinos from the solar hep reaction and the diffuse supernova neutrino background with the Sudbury Neutrino Observatory*, Astrophys. J. **653**, 1545 (2006) [hep-ex/0607010].

J. Adams, F. Retiere *et al.* (STAR collaboration), *Multiplicity and pseudorapidity distributions of charged particles and photons at forward pseudorapidity in Au + Au collisions at $\sqrt{S_{NN}}$ = 62.4 GeV*, Phys. Rev. **C73**, 034906 (2006) [nucl-ex/0511026].

J. Adams, F. Retiere *et al.* (STAR collaboration), *Transverse-momentum p_t correlations on (η, ϕ) from mean-p_t fluctuations in Au + Au collisions at $\sqrt{S_{NN}}$ = 200 GeV*, J. Phys. **G32**, L37 (2006) [nucl-ex/0509030].

J.A. Behr, J.R.A. Pitcairn, D.G. Roberge, M.R. Pearson, C. Höhr, G. Gwinner, D. Ashery, B. Dej, A. Gaudin, K.P. Jackson and A. Gorelov, *Ion detection from beta and two-body decay experiments with laser-cooled atoms*, Hyp. Int. **173**, 41 (2006).

Particle, Nuclear and Atomic Physics – *2007*

G. Andresen, W. Bertsche, A. Boston, P.D. Bowe, C.L. Cesar, S. Chapman, M. Charlton, M. Chartier, A. Deutsch, J. Fajans, M.C. Fujiwara, R. Funakoshi, D.R. Gill, K. Gomberoff, J.S. Hangst, R.S. Hayano, R. Hydomako, M.J. Jenkins, L.V. Jorgensen, L. Kurchaninov, N. Madsen, P. Nolan, K. Olchanski, A. Olin, A. Povilus, F. Robicheaux, E. Sarid, D.M. Silveira, J.W. Storey, H.H. Telle, R.I. Thompson, D.P. van der Werf, J.S. Wurtele and Y. Yamazaki, *Antimatter plasmas in a multipole trap for antihydrogen*, Phys. Rev. Lett. **98**, 023402 (2007).

J.C. Armitage, A. Artamonov, L. Babukhadia, M. Dixit, T.M. Embry, V. Epshteyn, P. Estabrooks, P. Gravelle, J. Hamm, V. Khovansky, D.A. Koolbeck, P. Krieger, P. Loch, M. Losty, J. Mayer, R. Mazini, F.G. Oakham, M. O'Neill, R.S. Orr, J.P. Rutherfoord, M. Ryabinin, A. Savine, C.J. Seely, P. Shatalov, L.S. Shaver, M.A. Shupe, G. Stairs, D. Tompkins, W. Trischuk, K. Vincent and V. Zaitsev, *Electron signals in the forward calorimeter prototype for ATLAS*, JINST **2**, P11001 (2007).

J.E. Carson *et al.*, *The energy spectrum of the Blazar Markarian 421 above 130 GeV*, Astrophys. J. **662**, 199 (2007) [astro-ph/0612562].

R. Kanungo, *Shell closures in the N and Z = 40-60 region for neutron and proton-rich nuclei*, Phys. Lett. **B649**, 31 (2007).

Z. Ke, W. Shi, G. Gwinner, K. Sharma, S. Toews, J. Dilling, V.L. Ryjkov *et al.* (TITAN collaboration), *Electron capture branching ratios for the odd-odd intermediate nuclei in double-beta decay using the TITAN ion trap facility*, Can. J. Phys. **85**, 57 (2007).

S. Berridge, W. Bugg, Yu. Efremenko, R. Gearhart, S. Ovchinnikov, T.C. Awes, V. Cianciolo, Yu.I. Davydov, T. Numao and J.-M. Poutissou, *π^- nuclear capture ratio on hydrogen and oxygen in water*, Phys. Rev. **A75**, 034501 (2007) [TRI-PP-07-01].

C. Wrede, J.A. Caggiano, J.A. Clark, C. Deibel, A. Parikh and P.D. Parker, *New $^{30}P(p,\gamma)^{31}S$ resonances and oxygen-neon nova nucleosynthesis*, Phys. Rev. **C76**, 052802 (2007).

D.G. Jenkins, B.R. Fulton, P. Marley, S.P. Fox, R. Glover, R. Wadsworth, D.L. Watson, S. Courtin, F. Haas, D. Lebhertz, C. Beck, P. Papka, M. Rousseau, A. Sanchez, D.A. Hutcheon, C. Davis, D. Ottewell, M.M. Pavan, J. Pearson, C. Ruiz, G. Ruprecht, J. Slater, M. Trinczek, J. D'Auria, C.J. Lister, P. Chowdhury, C. Andreoiu, J.J. Valiente-Dobón and S. Moon, *Decay strength distributions in $^{12}C(^{12}C, \gamma)$ radiative capture*, Phys. Rev. **C76**, 044310 (2007).

G.A. Jones, P.H. Regan, P.M. Walker, Zs. Podolyák, P.D. Stevenson, M.P. Carpenter, J.J. Carroll, R.S. Chakrawarthy, P. Chowdhury, A.B. Garnsworthy, R.V.F. Janssens, T.L. Khoo, F.G. Kondev, G.J. Lane, Z. Liu, D. Seweryniak, N.J. Thompson, S. Zhu and S.J. Williams, *Identification of a high-spin isomer in* ^{99}*Mo*, Phys. Rev. **C76**, 047303 (2007).

C. Vockenhuber, C.O. Ouellet, L.-S. The, L. Buchmann, J. Caggiano, A.A. Chen, H. Crawford, J.M. D'Auria, B. Davids, L. Fogarty, D. Frekers, A. Hussein, D.A. Hutcheon, W. Kutschera, A.M. Laird, R. Lewis, E. O'Connor, D. Ottewell, M. Paul, M.M. Pavan, J. Pearson, C. Ruiz, G. Ruprecht, M. Trinczek, B. Wales and A. Wallner, *Measurement of the* $^{40}Ca(\alpha,\gamma)^{44}Ti$ *reaction relevant for supernova nucleosynthesis*, Phys. Rev. **C76**, 035801 (2007).

D.Q. Fang, W. Guo, C.W. Ma, K. Wang, T.Z. Yan, Y.G. Ma, X.Z. Cai, W.Q. Shen, Z.Z. Ren, Z.Y. Sun, J.G. Chen, W.D. Tian, C. Zhong, M. Hosoi, T. Izumikawa, R. Kanungo, S. Nakajima, T. Ohnishi, T. Ohtsubo, A. Ozawa, T. Suda, K. Sugawara, T. Suzuki, A. Takisawa, K. Tanaka, T. Yamaguchi and I. Tanihata, *Examining the exotic structure of the proton-rich nucleus* ^{23}*Al*, Phys. Rev. **C76**, 031601 (2007) [arXiv:0709.1081].

G.F. Grinyer, M.B. Smith, C. Andreoiu, A.N. Andreyev, G.C. Ball, P. Bricault, R.S. Chakrawarthy, J.J. Daoud, P. Finlay, P.E. Garrett, G. Hackman, B. Hyland, J.R. Leslie, A.C. Morton, C.J. Pearson, A.A. Phillips, M.A. Schumaker, C.E. Svensson, J.J. Valiente-Dobón, S.J. Williams and E.F. Zganjar, *Half-life of the superallowed* β^+ *emitter* ^{18}*Ne*, Phys. Rev. **C76**, 025503 (2007).

K. Andgren, E. Ganioglu, B. Cederwall, R. Wyss, S. Bhattacharyya, J.R. Brown, G. de Angelis, G. de France, Zs. Dombrádi, J. Gál, B. Hadinia, A. Johnson, F. Johnston-Theasby, A. Jungclaus, A. Khaplanov, J. Kownacki, K. Lagergren, G. La Rana, J. Molnár, R. Moro, B.S. Nara Singh, J. Nyberg, M. Sandzelius, J.-N. Scheurer, G. Sletten, D. Sohler, J. Timár, M. Trotta, J.J. Valiente-Dobón, E. Vardaci, R. Wadsworth and S. Williams, *Low-spin collective behavior in the transitional nuclei* ^{86,88}*Mo*, Phys. Rev. **C76**, 014307 (2007).

B. Clasie, X. Qian, J. Arrington, R. Asaturyan, F. Benmokhtar, W. Boeglin, P. Bosted, A. Bruell, M.E. Christy, E. Chudakov, W. Cosyn, M.M. Dalton, A. Daniel, D. Day, D. Dutta, L. El Fassi, R. Ent, H.C. Fenker, J. Ferrer, N. Fomin, H. Gao, K. Garrow, D. Gaskell, C. Gray, T. Horn, G.M. Huber, M.K. Jones, N. Kalantarians, C.E. Keppel, K. Kramer, A. Larson, Y. Li, Y. Liang, A.F. Lung, S. Malace, P. Markowitz, A. Matsumura, D.G. Meekins, T. Mertens, G.A. Miller, T. Miyoshi, H. Mkrtchyan, R. Monson, T. Navasardyan, G. Niculescu, I. Niculescu, Y. Okayasu, A.K. Opper, C. Perdrisat, V. Punjabi, A.W. Rauf, V.M. Rodriquez, D. Rohe, J. Ryckebusch, J. Seely, E. Segbefia, G.R. Smith, M. Strikman, M. Sumihama, V. Tadevosyan, L. Tang, V. Tvaskis, A. Villano, W.F. Vulcan, F.R. Wesselmann, S.A. Wood, L. Yuan and X.C. Zheng, *Measurement of nuclear transparency for the* $A(e,e'\pi^+)$ *reaction*, Phys. Rev. Lett. **99**, 242502 (2007) [JLAB-PHY-07-678, arXiv:0707.1481].

W.J. Mills, J.J. Ressler, R.A.E. Austin, R.S. Chakrawarthy, D.S. Cross, A. Heinz, E.A. McCutchan and M.D. Strange, *Search for the low-lying* $(\pi 1g\frac{9}{2})^4 6_2^+$ *state in* ^{94}*Ru*, Phys. Rev. **C75**, 047302 (2007).

C. Andreoiu, C.E. Svensson, A.V. Afanasjev, R.A.E. Austin, M.P. Carpenter, D. Dashdorj, P. Finlay, S.J. Freeman, P.E. Garrett, J. Greene, G.F. Grinyer, A. Görgen, B. Hyland, D. Jenkins, F. Johnston-Theasby, P. Joshi, A.O. Machiavelli, F. Moore, G. Mukherjee, A.A. Phillips, W. Reviol, D.G. Sarantites, M.A. Schumaker, D. Seweryniak, M.B. Smith, J.J. Valiente-Dobón and R. Wadsworth, *High-spin lifetime measurements in the* $N = Z$ *nucleus* ^{72}*Kr*, Phys. Rev. **C75**, 041301(R)(E) (2007).

P.J. Davies, A.V. Afanasjev, R. Wadsworth, C. Andreoiu, R.A.E. Austin, M.P. Carpenter, D. Dashdorj, S.J. Freeman, P.E. Garrett, A. Görgen, J. Greene, D.G. Jenkins, F.L. Johnston-Theasby, P. Joshi, A.O. Macchiavelli, F. Moore, G. Mukherjee, W. Reviol, D. Sarantites, D. Seweryniak, M.B. Smith, C.E. Svensson, J.J. Valiente-Dobon and D. Ward, *Identification of the* $g\frac{9}{2}$ *proton and neutron band crossing in the* $N = Z$ *nucleus* ^{76}*Sr*, Phys. Rev. **C75**, 011302 (2007).

C.M. Mattoon, F. Sarazin, G. Hackman, E.S. Cunningham, R.A.E. Austin, G.C. Ball, R.S. Chakrawarthy, P. Finlay, P.E. Garrett, G.F. Grinyer, B. Hyland, K.A. Koopmans, J.R. Leslie, A.A. Phillips, M.A. Schumaker, H.C. Scraggs, J. Schwarzenberg, M.B. Smith, C.E. Svensson, J.C. Waddington, P.M. Walker, B. Washbrook and E. Zganjar, β*-decay of* ^{32}*Na*, Phys. Rev. **C75**, 017302 (2007).

C. Vockenhuber, L. Dillmann, M. Heil, F. Käppler, N. Winckler, W. Kutschera, A. Wallner, M. Bichler, S. Dababneh, S. Bisterzo and R. Gallino, *Stellar* (n,γ) *cross sections of* ^{174}*Hf and radioactive* ^{182}*Hf*, Phys. Rev. **C75**, 015804 (2007).

J. Zylberberg, D. Hutcheon, L. Buchmann, J. Caggiano, W.R. Hannes, A. Hussein, E. O'Connor, D. Ottewell, J. Pearson, C. Ruiz, G. Ruprecht, M. Trinczek and C. Vockenhuber, *Charge-state distributions after radiative capture of helium nuclei by a carbon beam*, Nucl. Instrum. Methods **B254**, 17 (2007).

L. Buchmann, J. D'Auria, M. Dombsky, U. Giesen, K.P. Jackson, P. McNeely and J. Powell, β*-delayed* α*-emission of* ^{18}*N: broad* $J^\pi = 1^-$ *states in the* ^{14}*C +* α *system*, Phys. Rev. **C75**, 012804 (2007).

E.J. Prime, J.A. Behr and M.R. Pearson, *Loading of a far off-resonance dipole force trap for stable* ^{39}*K*, Can. J. Phys. **85**, 1 (2007).

D. Melconian, J.A. Behr, D. Ashery, O. Aviv, P.G. Bricault, M. Dombsky, S. Fostner, A. Gorelov, S. Gu, K.P. Jackson, M.R. Pearson and I. Vollrath, *Measurement of the neutrino asymmetry in the* β *decay of laser-cooled, polarized* ^{37}*K*, Phys. Lett. **B649**, 370 (2007) [TRI-PP-06-13].

E.R. Tardiff, J.A. Behr, T.E. Chupp, K. Gulyuz, R.S. Lefferts, W. Lorenzon, S.R. Nuss-Warren, M.R. Pearson, N. Pietralla, G.

Rainovski, J.F. Sell and G.D. Sprouse, *Polarization and relaxation of radon*, Nucl. Instrum. Methods **A579**, 472 (2007) [nucl-ex/0612006].

L. Guo *et al.* (CLAS collaboration), *Cascade production in the reactions $\gamma p \to K^+K^+(X)$ and $\gamma p \to K^+K^+\pi^-(X)$*, Phys. Rev. **C76**, 025208 (2007) [nucl-ex/0702027].

V.M. Abazov *et al.* (D0 collaboration), *Evidence for production of single top quarks and first direct measurement of $| V_t b |$*, Phys. Rev. Lett. **98**, 181902 (2007) [hep-ex/0612052, FERMILAB-PUB-06-475-E].

B. Hu *et al.* (E89-028 collaboration), *Polarization transfer in the $d(\vec{e}, e'\vec{p})n$ reaction up to Q^2 = 1.61 GeV/c^2*, Phys. Rev. **C73**, 064004 (2007) [JLAB-PHY-06-458, nucl-ex/0601025].

M. Agnello *et al.* (FINUDA collaboration), *Correlated Λd pairs from the $K^-_{\rm stop}A \to \Lambda d\, A'$ reaction*, Phys. Lett. **B654**, 80 (2007) [arXiv:0708.3614].

M. Agnello *et al.* (FINUDA collaboration), *Experimental study of the (K^+, K^0) interactions on ^{7}Li close to threshold*, Phys. Lett. **B649**, 25 (2007).

D.S. Armstrong *et al.* ($G\emptyset$ collaboration), *Transverse beam spin asymmetries in forward-angle elastic electron-proton scattering*, Phys. Rev. Lett. **99**, 092301 (2007) [WM-07-04, JLAB-PHY-07-651, arXiv:0705.1525].

A. Airapetian *et al.* (HERMES collaboration), *Precise determination of the spin structure function g_1*, Phys. Rev. **D75**, 012007 (2007) [DESY-06-142, hep-ex/0609039].

A. Airapetian *et al.* (HERMES collaboration), *Beam-spin asymmetries in the azimuthal distribution of pion electroproduction*, Phys. Lett. **B648**, 164 (2007) [DESY-06-227, hep-ex/0612059].

A. Airapetian *et al.* (HERMES collaboration), *Transverse polarization of λ and $\overline{\lambda}$ hyperons in quasireal photoproduction*, Phys. Rev. **D76**, 092008 (2007) [arXiv:0704.3133].

A. Airapetian *et al.* (HERMES collaboration), *Hadronization in semi-inclusive deep-inelastic scattering on nuclei*, Nucl. Phys. **B780**, 1 (2007) [arXiv:0704.3270].

D.B. Chitwood *et al.* (MuLan collaboration), *Improved measurement of the positive-muon lifetime and determination of the Fermi constant*, Phys. Rev. Lett **99**, 032001 (2007) [arXiv:0704.1981].

G. Abbiendi *et al.* (OPAL collaboration), *Measurement of the $e^+e^- \to W^+W^-$ cross section and W decay branching fractions at LEP*, Eur. Phys. J. **C52**, 767 (2007) [arXiv:0708.1311].

G. Abbiendi *et al.* (OPAL collaboration), *Bose-Einstein study of position-momentum correlations of charged pions in hadronic Z^0 decays*, Eur. Phys. J. **C52**, 787 (2007) [arXiv:0708.1122].

G. Abbiendi *et al.* (OPAL collaboration), *Inclusive production of charged hadrons in photon-photon collisions*, Phys. Lett. **B651**, 92 (2007) [CERN-PH-EP-2006-038, hep-ex/0612045].

B. Aharmim *et al.* (SNO collaboration), *Measurement of the ν_e and total ^8B solar neutrino fluxes with the Sudbury neutrino observatory phase I data set*, Phys. Rev. **C75**, 045502 (2007) [nucl-ex/0610020].

J. Adams, F. Retiere *et al.* (STAR collaboration), *Strangelet search at RHIC*, Phys. Rev. **C76**, 011901 (2007) [nucl-ex/0511047].

Particle, Nuclear and Atomic Physics – *2008*

L.V. Jorgensen, G. Andresen, W. Bertsche, A. Boston, P.D. Bowe, C.L. Cesar, S. Chapman, M. Charlton, J. Fajans, M.C. Fujiwara, R. Funakoshi, D.R. Gill, J.S. Hangst, R.S. Hayano, R. Hydomako, M.J. Jenkins, L. Kurchaninov, N. Madsen, P. Nolan, K. Olchanski, A. Olin, R.D. Page, A. Povilus, F. Robicheaux, E. Sarid, D.M. Silveira, J.W. Storey, R.I. Thompson, D.P. van der Werf, J.S. Wurtele and Y. Yamazaki, *Towards trapped antihydrogen*, Nucl. Instrum. Methods **B266**, 357 (2008).

G.B. Andresen, W. Bertsche, A. Boston, P.D. Bowe, C.L. Cesar, S. Chapman, M. Charlton, M. Chartier, A. Deutsch, J. Fajans, M.C. Fujiwara, R. Funakoshi, D.R. Gill, K. Gomberoff, J.S. Hangst, R.S. Hayano, R. Hydomako, M.J. Jenkins, L.V. Jorgensen, L. Kurchaninov, N. Madsen, P. Nolan, K. Olchanski, A. Olin, A. Povilus, F. Robicheaux, E. Sarid, D.M. Silveira, J.W. Storey, R.I. Thompson, D.P. van der Werf, J.S. Wurtele and Y. Yamazaki, *Production of antihydrogen at reduced magnetic field for anti-atom trapping*, J. Phys. **B41**, 011001 (2008).

G.B. Andresen, W. Bertsche, P.D. Bowe, C.C. Bray, E. Butler, C.L. Cesar, S. Chapman, M. Charlton, J. Fajans, M.C. Fujiwara, R. Funakoshi, D.R. Gill, J.S. Hangst, W.N. Hardy, R.S. Hayano, M.E. Hayden, A.J. Humphries, R. Hydomako, M.J. Jenkins, L.V. Jorgensen, L. Kurchaninov, R. Lambo, N. Madsen, P. Nolan, K. Olchanski, A. Olin, R.D. Page, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, S. Seif El Nasr, D.M. Silveira, J.W. Storey, R.I. Thompson, D.P. van der Werf, J.S. Wurtele and Y. Yamazaki, *A novel antiproton radial diagnostic based on octupole induced ballistic loss*, Phys. Plasmas **15**, 032107 (2008).

G.B. Andresen, W. Bertsche, P.D. Bowe, C.C. Bray, E. Butler, C.L. Cesar, S. Chapman, M. Charlton, J. Fajans, M.C. Fujiwara, R. Funakoshi, D.R. Gill, J.S. Hangst, W.N. Hardy, R.S. Hayano, M.E. Hayden, R. Hydomako, M.J. Jenkins, L.V. Jorgensen, L. Kurchaninov, R. Lambo, N. Madsen, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, S. Seif El Nasr, D.M. Silveira, J.W. Storey, R.I. Thompson, D.P. van der Werf, J.S. Wurtele and Y. Yamazaki, *Compression of antiproton clouds for antihydrogen trapping*, Phys. Rev. Lett. **100**, 203401 (2008).

L. Buchmann, P. Amaudruz, J.M. D'Auria, D.A. Hutcheon, C. Matei, J. Pearson, C. Ruiz, G. Ruprecht, M. Trinczek, C. Vockenhuber and P. Walden, *Nuclear astrophysics at TRIUMF*, Nucl. Phys. **A805**, 462c (2008).

C. Vockenhuber, M. Bichler, A. Wallner, W. Kutschera, I. Dillmann and F. Käppeler, *Measurement of the thermal neutron capture cross section and the resonance integral of radioactive* ^{182}*Hf*, Phys. Rev. **C77**, 044608 (2008).

C. Vockenhuber, C.O. Ouellet, L.-S. The, L. Buchmann, J. Caggiano, A.A. Chen, J.M. D'Auria, B. Davids, L. Fogarty, D. Frekers, A. Hussein, D.A. Hutcheon, W. Kutschera, D. Ottewell, M. Paul, M.M. Pavan, J. Pearson, C. Ruiz, G. Ruprecht, M. Trinczek and A. Wallner, $^{40}Ca(\alpha,\gamma)^{44}Ti$ *and the production of* ^{44}Ti *in supernovae*, J. Phys. **G35**, 014034, 2008.

G. Ruprecht, C. Vockenhuber, C. Ruiz, L. Buchmann, J. Pearson, D. Ottewell, K. Czerski and A. Huke, *On the possible influence of electron screening on the lifetime of radioactive nuclei*, J. Phys. **G35**, 014017 (2008).

I. Tanihata, M. Alcorta, D. Bandyopadhyay, R. Bieri, L. Buchmann, B. Davids, N. Galinski, D. Howell, W. Mills, R. Openshaw, E. Padilla-Rodal, G. Ruprecht, G. Sheffer, A.C. Shotter, S. Mythili, M. Trinczek, P. Walden, H. Savajols, T. Roger, M. Caamano, W. Mittig, P. Roussel-Chomaz, R. Kanungo, A. Gallant, M. Notani, G. Savard and I.J. Thompson, *Measurement of two-neutron transfer reaction* 1*H(*^{11}*Li,*^{9}*Li)3H at3A MeV*, Phys. Rev. Lett. **100**, 192502 (2008).

M. Mukherjee, D. Beck, K. Blaum, G. Bollen, P. Delahaye, J. Dilling, S. George, C. Guénaut, F. Herfurth, A. Herlert, A. Kellerbauer, H.-J. Kluge, U. Köster, D. Lunney, S. Schwarz, L. Schweikhard and C. Yazidjian, *Mass measurements and evaluation around A = 22*, Eur. Phys. J. **A35**, 31 (2008).

G.F. Grinyer, P. Finlay, C.E. Svensson, G.C. Ball, J.R. Leslie, R.A.E. Austin, D. Bandyopadhyay, A. Chaffey, R.S. Chakrawarthy, P.E. Garrett, G. Hackman, B. Hyland, R. Kanungo, K.G. Leach, C.M. Mattoon, A.C. Morton, C.J. Pearson, A.A. Phillips, J.J. Ressler, F. Sarazin, H. Savajols, M.A. Schumaker and J. Wong, *High-precision half-life determination for the superallowed* β^+ *emitter* ^{62}Ga, Phys. Rev. **C77**, 015501 (2008).

J.J. Valiente Dobón, C.E. Svensson, A.V. Afanasjev, I. Ragnarsson, C. Andreoiu, D.E. Appelbe, R.A.E. Austin, G.C. Ball, J.A. Cameron, M.P. Carpenter, R.M. Clark, M. Cromaz, D. Dashdorj, P. Fallon, S.J. Freeman, P.E. Garrett, A. Görgen, G.F. Grinyer, D.F. Hodgson, B. Hyland, D. Jenkins, F. Johnston Theasby, P. Joshi and N.S. Kelsall, *Low spin lifetime measurements in* ^{74}Kr, Phys. Rev. **C77**, 024312 (2008).

K.G. Leach, C.E. Svensson, G.C. Ball, J.R. Leslie, R.A.E. Austin, D. Bandyopadhyay, C. Barton, E. Bassiachvilli, S. Ettenauer, P. Finlay, P.E. Garrett, G.F. Grinyer, G. Hackman, D. Melconian, A.C. Morton, S. Mythili, O. Newman, C.J. Pearson, M.R. Pearson, A.A. Phillips, H. Savajols, M.A. Schumaker and J. Wong, *Internal* γ *decay and the superallowed branching ratio for the* β^+ *emitter* ^{38m}K, Phys. Rev. Lett. **100**, 192504 (2008).

S. Mythili, B. Davids, T.K. Alexander, G.C. Ball, M. Chicoine, R.S. Chakrawarthy, R. Churchman, J.S. Forster, S. Gujrathi, G. Hackman, D. Howell, R. Kanungo, J.R. Leslie, E. Padilla, C.J. Pearson, C. Ruiz, G. Ruprecht, M.A. Schumaker, I. Tanihata, C. Vockenhuber, P. Walden and S. Yen, *Lifetimes of states in* ^{19}*Ne above the* ^{15}*O +* α *breakup threshold*, Phys. Rev. **C77**, 035803 (2008) [arXiv:0711.0777].

R. Kanungo, A.N. Andreyev, L. Buchmann, B. Davids, G. Hackman, D. Howell, P. Khalili, B. Mills, E. Padilla Rodal, Steven C. Pieper, J. Pearson, C. Ruiz, G. Ruprecht, A. Shotter, I. Tanihata, C. Vockenhuber, P. Walden and R.B. Wiringa, *Spectroscopic factors for the* ^{9}*Li ground state and* $N = 6$ *shell closure*, Phys. Lett. **B660**, 26 (2008).

I. Tanihata, M. Alcorta, D. Bandyopadhyay, R. Bieri, L. Buchmann, B. Davids, N. Galinski, D. Howell, W. Mills, S. Mythili, R. Openshaw, E. Padilla-Rodal, G. Ruprecht, G. Sheffer, A. C. Shotter, M. Trinczek, P. Walden, H. Savajols, T. Roger, M. Caamano, W. Mittig, P. Roussel-Chomaz, R. Kanungo, A. Gallant, M. Notani, G. Savard and I. J. Thompson, *Measurement of the two-halo neutron transfer reaction* $^{1}H(^{11!}Li,{}^{9}Li)^{3}H$ *at 3A MeV*, Phys. Rev. Lett. **100**, 192502 (2008).

V.V. Anisimovsky *et al.* (E949 collaboration), *Measurement of the* $K^+ \rightarrow \pi^+\nu\overline{\nu}$ *branching ratio*, Phys. Rev. **D77**, 052003 (2008) [BNL-79257-2007-JA, KEK-2007-34, TRI-PP-07-18, TUHEP-EX-07-002, arXiv:0709.1000].

A. Airapetian *et al.* (HERMES collaboration), *Cross sections for hard exclusive electroproduction of* π^+ *mesons on a hydrogen target*, Phys. Lett. **B659**, 486 (2008) [DESY-07-098, arXiv:0707.0222].

G. Abbiendi *et al.* (OPAL collaboration), *Inclusive jet production in photon-photon collisions at* $\sqrt{s_{ee}}$ *from 189 to 209 GeV*, Phys. Lett. **B658**, 185 (2008) [CERN-PH-EP-2007-016, arXiv:0706.4382].

Particle, Nuclear and Atomic Physics – *submitted*

A.St.J. Murphy, A.M. Laird, C. Angulo, L. Buchmann, T. Davinson, P. Descouvemont, S.P. Fox, J. José, R. Lewis, C. Ruiz, K. Vaughan and P. Walden, *The* $^{18}F(p,\alpha)^{15}O$ *reaction and* ^{18}*F production in novae* (submitted for publication).

R. Raabe, M. Huyse, I. Mukha, J. Ponsaers, P. Van Duppen, A. Andreyev, L. Buchmann, P. Capel, R. Kanungo, T. Kirchner, A.C. Morton, J. Pearson, P.G. Ruprecht, P. Walden, M.J.G. Borge, O. Tengblad, H. Fynbo, K. Riisager, C. Mattoon, F. Sarazin, J.J. Ressler and C. Ruiz, *Deuteron emission in the* β*-decay of* ^{11}*Li: decay of the halo* (submitted for publication).

M. Vetterli *et al.* (D0 collaboration), *Evidence for production of single top quarks at D0* (Phys. Rev. D, in press).

M. Vetterli *et al.* (ATLAS collaboration), *The ATLAS experiment at the CERN Large Hadron Collider* (J. Instrum., in press).

M. Raidal *et al.*, *Flavour physics of leptons and dipole moments* [arXiv:0801.1826].

V.L. Ryjkov, M. Brodeur, T. Brunner, M. Smith, R. Ringle, P. Delheij, F. Ames, P. Bricault, M. Dombsky and J. Dilling, *Direct mass measurement of the four-neutron halo nuclide* ^{8}He (Phys. Rev. Lett., in press).

P. Finlay, G.F. Grinyer, C.E. Svensson, I.S. Towner, G.C. Ball, J.R. Leslie, R.A.E. Austin, D. Bandyopadhyay, A. Chaffey, R.S. Chakrawarthy, P.E. Garrett, G. Hackman, B. Hyland, R. Kanungo, K.G. Leach, C.M. Mattoon, A.C. Morton, C.J. Pearson, A.A. Phillips, J.J. Ressler, F. Sarazin, H. Savajols, M.A. Schumaker and J. Wong, *High-precision branching ratio measurement for the superallowed* β^+ *emitter* ^{62}Ga (submitted to Phys. Rev. C).

E.R. Tardiff, J.A. Behr, T.E. Chupp, K. Gulyuz, R.S. Lefferts, W. Lorenzon, S.R. Nuss-Warren, M.R. Pearson, N. Pietralla, G. Rainovski, J.F. Sell and G.D. Sprouse, *Polarization and relaxation rates of radon* (accepted by Phys. Rev. C Rapid Communications).

P.-N. Seo, L. Barron-Palos, J.D. Bowman, T.E. Chupp, C. Crawford, M. Dabaghyan, M. Dawkins, S.J. Freedman, T. Gentile, M.T. Gericke, R.C. Gillis, G.L. Greene, F.W. Hersman, G.L. Jones, M. Kandes, S. Lamoreaux, B. Lauss, M.B. Leuschner, R. Mahurin, M. Mason, J. Mei, G.S. Mitchell, H. Nann, S.A. Page, S.I. Penttila, W.D. Ramsay, A. Salas Bacci, S. Santra, M. Sharma, T.B. Smith, W.M. Snow, W.S. Wilburn and H. Zhu, *High-efficiency resonant rf spin rotator with broad phase space acceptance for pulsed polarized cold neutron beams* [arXiv:0710.2871].

W.D. Kulp, J.L. Wood, P.E. Garrett, C.Y. Wu, D. Cline, J.M. Allmond, D. Bandyopadhyay, D. Dashdorj, S.N. Choudry, A.B. Hayes, H. Hua, M.G. Mynk, M.T. McEllistrem, C.J. McKay, J.N. Orce, R. Teng and S.W. Yates, *Search for intrinsic collective excitations in* ^{152}Sm (Phys. Rev. C, in press) [arXiv:0805.1912].

B. Davids, *Comment on* $^{15}O(\alpha,\gamma)^{19}Ne$ *breakout reaction and impact on X-ray bursts* (submitted to Phys. Rev. Lett.) [arXiv:0804.1977].

T. Horn, X. Qian, J. Arrington, R. Asaturyan, F. Benmokthar, W. Boeglin, P. Bosted, A. Bruell, M.E. Christy, E. Chudakov, B. Clasie, M.M. Dalton, A. Daniel, D. Day, D. Dutta, L. El Fassi, R. Ent, H.C. Fenker, J. Ferrer, N. Fomin, H. Gao, K. Garrow, D. Gaskell, C. Gray, G.M. Huber, M.K. Jones, N. Kalantarians, C.E. Keppel, K. Kramer, Y. Li, Y. Liang, A.F. Lung, S. Malace, P. Markowitz, A. Matsumura, D.G. Meekins, T. Mertens, T. Miyoshi, H. Mkrtchyan, R. Monson, T. Navasardyan, G. Niculescu, I. Niculescu, Y. Okayasu, A.K. Opper, C. Perdrisat, V. Punjabi, A.W. Rauf, V. Rodriguez, D. Rohe, J. Seely, E. Segbefia, G.R. Smith, M. Sumihama, V. Tadevosyan, L. Tang, V. Tvaskis, A. Villano, W.F. Vulcan, F.R. Wesselmann, S.A. Wood, L. Yuan and X.C. Zheng, *Scaling study of the pion electroproduction cross sections and the pion form factor* [JLAB-PHY-07-679, arXiv:0707.1794].

D. Axen and A. Astbury, *Comparison of GEANT4 simulation of atmospheric cosmic rays with measured terrestrial muon and neutron spectra* [TRI-PP-06-14].

L.J.S. Halloran, J.A. Behr, S. Fostner and E. Paradis, *Specific mass shift of potassium* $5P_{1/2}$ *state* (submitted to Can. J. Phys.).

G. Abbiendi *et al.* (OPAL collaboration), *Search for Dirac magnetic monopoles in* e^+e^- *collisions with the OPAL detector at LEP2* (submitted to Phys. Lett. B) [CERN-PH-EP-2007-019, arXiv:0707.0404].

Instrumentation / Accelerator Physics / Computing Sciences – *2003*

D. Hutcheon *et al.*, *The DRAGON facility for nuclear astrophysics at TRIUMF-ISAC: design, construction and operation*, Nucl. Instrum. Methods **A498**, 190 (2003).

C. Johnstone and S. Koscielniak, *FFAGs for rapid acceleration*, Nucl. Instrum. Methods **A503**, 445 (2003).

P. Gumplinger, F. Jones, S. Agostinelli *et al.* (GEANT4 collaboration), *GEANT4 – a simulation toolkit*, Nucl. Instrum. Methods **A506**, 250 (2003).

M. Abe *et al.* (KEK-PS E246 collaboration), *Apparatus for a search for* T*-violating muon polarization in stopped-kaon decays*, Nucl. Instrum. Methods **A507**, 60 (2003) [INR-1094-2003, KEK-PREPRINT-2002-130, TRI-PP-03-01, hep-ex/0302001].

N.J. Buchanan and D.M. Gingrich, *Proton radiation effects in XC4036XLA field programmable gate arrays*, IEEE Trans. Nucl. Sci. **NS-50**, 263 (2003).

P. Paillet, J.R. Schwank, M.R. Shaneyfelt, V. Ferlet-Cavrois, R.L. Jones, O. Flament and E.W. Blackmore, *Total dose hardness assurance testing using laboratory radiation sources*, IEEE Trans. Nucl. Sci. **50**, 2310 (2003).

Instrumentation / Accelerator Physics / Computing Sciences – *2004*

S.R. Nuss-Warren, E.R. Tardiff, T. Warner, G. Ball, J.A. Behr, T.E. Chupp, K.P. Coulter, G. Hackman, M.E. Hayden, M.R. Pearson, A.A. Phillips, M.B. Smith and C.E. Svensson, *On-line collection and transfer of radioactive noble gas isotopes*, Nucl. Instrum. Methods **533**, 275 (2004).

M. Craddock, *The rebirth of the FFAG*, CERN Courier **44**(6), 23 (2004).

S. Koscielniak and C. Johnstone, *Mechanisms for non-linear acceleration in FFAGs with fixed rf*, Nucl. Instrum. Methods **A523**, 25 (2004).

M.S. Dixit, J. Dubeau, J.-P. Martin and K. Sachs, *Position sensing from charge dispersion in micro-pattern gas detectors with a resistive anode*, Nucl. Instrum. Methods **A518**, 721 (2004) [physics/0307152].

Ch. Rauth, Ch. Geppert, R. Horn, J. Lassen, P.G. Bricault and K. Wendt, *First laser ions at an off-line mass separator of the ISAC facility at TRIUMF*, Nucl. Instrum. Methods **B215**, 268 (2004).

Ch. Geppert, P. Bricault, R. Horn, J. Lassen, Ch. Rauth and K. Wendt, *Resonance ionization laser ion source – off-line tests at TRIUMF*, Nucl. Phys. **A746**, 631c (2004).

J. Baggio, V. Ferlet-Cavrois and O. Flament, *Comparison of SER test methods for commercial SRAMs*, IEEE Trans. Nucl. Sci. **51** (2004).

J.R. Schwank, P.E. Dodd, M.R. Shaneyfelt, J.A.. Felix, G.L. Hash, V. Ferlet-Cavrois, P. Paillet, J. Baggio, P. Tangyunyong and E. Blackmore, *Issues for single-event proton testing of SRAMs*, IEEE Trans. Nucl. Sci. **51**, 3692 (2004).

C. Cojocaru *et al.* (ATLAS Liquid Argon EMEC/HEC collaboration), *Hadronic calibration of the ATLAS liquid argon end-cap calorimeter in the pseudorapidity region 1.6 < $|\eta|$ < 1.8 in beam tests*, Nucl. Instrum. Methods **A531**, 481 (2004) [MPP-2004-81, physics/0407009].

D. Binosi and L. Theussl, *JaxoDraw: A graphical user interface for drawing Feynman diagrams*, Comput. Phys. Commun. **161**, 76 (2004) [FTUV-03-0902, hep-ph/0309015].

Instrumentation / Accelerator Physics / Computing Sciences – *2005*

M.J. Barnes, E.W. Blackmore, G.D. Wait, J. Lemire-Elmore, B. Rablah, G. Leyh, M. Nguyen and C. Pappas, *Analysis of high power IGBT short-circuit failures*, IEEE Trans. Plasma Sci. **33**, 1252 (2005).

D. Karlen, P. Poffenberger and G. Rosenbaum, *TPC performance in magnetic fields with GEM and PAD readout*, Nucl. Instrum. Methods **A555**, 80 (2005) [physics/0509051].

Yu.I. Davydov, R. Openshaw, V. Selivanov and G. Sheffer, *Gas gain on single wire chambers filled with pure isobutane at low pressure*, Nucl. Instrum. Methods **A545**, 194 (2005) [physics/0410004].

R.S. Henderson, Yu.I. Davydov, W. Faszer, D.D. Koetke, L.V. Miasoedov, R. Openshaw, M.A. Quraan, J. Schaapman, V. Selivanov, G. Sheffer, T.D.S. Stanislaus and V. Torokhov, *Precision planar drift chambers and cradle for the TWIST muon decay spectrometer*, Nucl. Instrum. Methods **A548**, 306 (2005) [TRI-PP-04-20, hep-ex/0409066].

R.K. Carnegie, M.S. Dixit, J. Dubeau, D. Karlen, J.P. Martin, H. Mes and K. Sachs, *Resolution studies of cosmic ray tracks in a TPC with GEM readout*, Nucl. Instrum. Methods **A538**, 372 (2005) [physics/0402054].

Instrumentation / Accelerator Physics / Computing Sciences – *2006*

G. Gwinner, E. Gomez, L.A. Orozco, A.P. Galvan, D. Sheng, Y. Zhao, G.D. Sprouse, J.A. Behr, K.P. Jackson, M.R. Pearson, S. Aubin and V.V. Flambaum, *Fundamental symmetries studies with cold trapped francium atoms at ISAC*, Hyp. Int. **172**, 45 (2006).

M. Trinczek, S. Lapi, B. Guo, F. Ames, K.R. Buckley, J.M. D'Auria, K. Jayamanna, W.P. Liu, C. Ruiz and T.J. Ruth, *Production of intense radioactive beams at ISAC using low-energy protons*, Can. J. Phys. **84**, 325 (2006).

Yu.I. Davydov and R. Openshaw, *Study of a self quenching streamer mode in the pure gases of DME and isobutane*, Nucl. Instrum. Methods **A557**, 561 (2006) [physics/0506172].

L. Ahrens, A. Artamonov, G. Atoian, K. Brown, C. Cantley, N. Cartiglia, I.A. Christidi, J.W. Glenn, A. Hatzikoutelis, D.E. Jaffe, S. Koscielniak, D.M. Lazarus, J. Mabanta, M. Marx, P. Pile, G. Redlinger, C. Scarlett and M. Sivertz, *Interbunch extinction measurement at the BNL AGS for the KOPIO experiment*, Nucl. Instrum. Methods **A560**, 256 (2006).

J. Hu, G. Sheffer, Yu.I. Davydeov, D.R. Gill, P. Gumplinger, R.S. Henderson, B. Jamieson, C. Lindsay, G.M. Marshall, K. Olchanski, A. Olin, R. Openshaw and V. Selivanov, *Time expansion chamber for characterization of TWIST low energy muon beams*, Nucl. Instrum. Methods **A566**, 563 (2006) [TRI-PP-06-04; physics/0604107].

M.S. Dixit and A. Rankin, *Simulating the charge dispersion phenomena in micro pattern gas detectors with a resistive anode*, Nucl. Instrum. Methods **A566**, 281 (2006) [physics/0605121].

A. Facco, F. Scarpa, D. Zenere, R. Losito and V. Zviagintsev, *Low- and intermediate-beta, 352 MHz superconducting half-wave resonators for high power hadron acceleration*, Phys. Rev. ST Accel. Beams **9**, 110101 (2006).

K. Fransham, R. Hasanen and D. Karlen, *A new technique for independent control of high voltage surfaces in a multi-GEM stack*, JINST **1**, T11001 (2006).

W. Bertsche, A. Boston, P.D. Bowe, C.L. Cesar, S. Chapman, M. Charlton, M. Chartier, A. Deutsch, J. Fajans, M.C. Fujiwara, R. Funakoshi, K. Gomberoff, J.S. Hangst, R.S. Hayano, M.J.

Jenkins, L.V. Jorgensen, P. Ko, N. Madsen, P. Nolan, R.D. Page, L.G.C. Posada, A. Povilus, E. Sarid, D.M. Silveira, D.P. van der Werf, Y. Yamazaki, B. Parker, J. Escallier and A. Ghosh, *A magnetic trap for antihydrogen confinement*, Nucl. Instrum. Methods **A566**, 746 (2006).

Y.S. Hwang, G. Cojocaru, D. Yuan, M. McDonald, K. Jayamanna, G.H. Kim and G. Dutto, *Characterization of TRIUMF dc H^- ion sources for enhanced brightness*, Rev. Sci. Instrum. **77**, 03A509 (2006).

J. Allison *et al.*, *Geant4 developments and applications*, IEEE Trans. Nucl. Sci. **53**, 270 (2006).

I. Sekachev, *Status of the cyclotron vacuum system at TRIUMF*, Vacuum **80**, 390 (2006).

Instrumentation / Accelerator Physics / Computing Sciences – *2007*

A. Agarwal *et al.*, *GridX1: a Canadian computational grid*, Future Gen. Comput. Syst. **23**, 680 (2007).

M. Dombsky, T. Achtzehn, P. Bricault, G. Hackman, V. Hanemaayer, J. Lassen, J.P. Lavoie, A.C. Morton, M.R. Pearson, E.J. Prime and M.B. Smith, *Development of a high intensity ^{26g}Al beam from SiC targets for accelerated beam experiments at ISAC*, Nucl. Instrum. Methods **B264**, 117 (2007).

M. Dombsky, T. Achtzehn, P. Bricault, G. Hackman, V. Hanemaayer, J. Lassen, J.P. Lavoie, A.C. Morton, M.R. Pearson, E.J. Prime and M.B. Smith, *Release of Al from SiC targets used for radioactive ion beam production*, Nucl. Instrum. Methods **B264**, 125 (2007).

C.D.P. Levy, T.E. Cocolios, J.A. Behr, K. Jayamanna, K. Minamisono and M.R. Pearson, *Feasibility study of in-beam polarization of fluorine*, Nucl. Instrum. Methods **A580**, 1571 (2007).

M.A. Schumaker, G. Hackman, C.J. Pearson, C.E. Svensson, C. Andreoiu, A. Andreyev, R.A.E. Austin, G.C. Ball, D. Bandyopadhyay, A.J. Boston, R.S. Chakrawarthy, R. Churchman, T.E. Drake, P. Finlay, P.E. Garrett, G.F. Grinyer, B. Hyland, B. Jones, R. Maharaj, A.C. Morton, A.A. Phillips, F. Sarazin, H.C. Scraggs, M.B. Smith, J.J. Valiente-Dobón, J.C. Waddington and L.M. Watters, *Measured and simulated performance of Compton-suppressed TIGRESS HPGe clover detectors*, Nucl. Instrum. Methods **A570**, 437 (2007).

T. Lindner, D.S. Hanna, J. Kildea, J. Ball, D.A. Bramel, J. Carson, C.E. Covault, D. Driscoll, P. Fortin, D.M. Gingrich, A. Jarvis, C. Mueller, R. Mukherjee, R.A. Ong, K. Ragan, R.A. Scalzo, D.A. Williams and J. Zweerink, *Very high energy observations of the BL Lac objects 3C 66A and OJ287*, Astropart. Phys. **28**, 338 (2007) [arXiv:0707.2815].

D.M. Gingrich *et al.* (ATLAS Hadronic End-cap Calorimeter group), *Construction, assembly and testing of the ATLAS hadronic end-cap calorimeter*, JINST **2**, P05005 (2007) [ATL-LARG-PUB-2007-009].

K. Boudjemline, M.S. Dixit, J.-P. Martin and K. Sachs, *Spatial resolution of a GEM readout TPC using the charge dispersion signal*, Nucl. Instrum. Methods **A574**, 22 (2007) [CARLETON-PHYS-061020, physics/0610232].

M.K. Craddock, *An introduction to FFAG accelerators and storage rings*, ICFA Beam Dyn. Newslett. **43**, 19 (2007) [TRI-PP-07-21].

S.R. Koscielniak, *Novel longitudinal dynamics of non-scaling FFAGs*, ICFA Beam Dyn. Newslett. **43**, 38 (2007) [TRI-PP-07-22].

C. Johnstone and S. Koscielniak, *A new non-scaling FFAG for medical applications*, ICFA Beam Dyn. Newslett. **43**, 125 (2007).

Instrumentation / Accelerator Physics / Computing Sciences – *2008*

K. Jayamanna and C. Vockenhuber, *A hybrid surface arc discharge ion source to produce ultra pure Ca^{2+} beams for $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction studies at ISAC/TRIUMF*, Rev. Sci. Instrum. **79**, 02c712 (2008).

Instrumentation / Accelerator Physics / Computing Sciences – *submitted*

D.C. Arogancia, A.M. Bacala, K. Boudjemline, D.R. Burke, P. Colas, M. Dixit, K. Fujii, H. Fujishima, A. Giganon, I. Giomataris, H.C. Gooc, M. Habu, T. Higashi, Y. Kato, M. Kobayashi, H. Kuroiwa, V. Lepeltier, T. Matsuda, S. Matsushita, K. Nakamura, O. Nitoh, R.L. Reserva, Ph. Rosier, K. Sachs, R. Settles, A. Sugiyama, T. Takahashi, T. Watanabe, A. Yamaguchi, H. Yamaoka and Th. Zerguerras, *Study in a beam test of the resolution of a Micromegas TPC with standard readout pads* (submitted to Nucl. Instrum. Methods A) [dapnia-07-35, KEK 2007-2, LAL-07-29, MPP-2007-41, MSU-IIT 2007-001, arXiv:0705.2210].

C.J. Oram, *The as-built parameters of the hadronic end cap* [CERN-ATL-COM-LARG-2006-007].

Molecular and Materials Science – *2003*

A. Fukaya, Y. Fudamoto, I.M. Gat, T. Ito, M.I. Larkin, A.T. Savici, Y.J. Uemura, P.P. Kyriakou, G.M. Luke, M.T. Rovers, K.M. Kojima, A. Keren, M. Hanawa and Z. Hiroi, *Muon spin relaxation and susceptibility studies of pure and doped spin 1/2*

Kagome-like system $(Cu_xZn_{1-x})_3V_2O_7(OH)_2$-$2(H_2O)$, Phys. Rev. Lett. **91**, 207603 (2003).

D.R. Harshman, J.D. Dow, W.J. Kossler, D.R. Noakes, C.E. Stronach, A.J. Greer, E. Koster, Z.F. Ren and D.Z. Wang, *Muon spin rotation study of $GdSr_2Cu_2RuO_8$: implications*, Philosophical Magazine **B83**, 2055 (2003).

J. Sugiyama, J.H. Brewer, E.J. Ansaldo, H. Itahara, K. Dohmae, Y. Seno, C. Xia and T. Tani, *Hidden magnetic transitions in thermoelectric layered cobaltite, $[Ca_2CoO_3]_{0.62}[CoO_2]$*, Phys. Rev. **B68**, 134423 (2003).

J. Sugiyama, J.H. Brewer, E.J. Ansaldo, H. Itahara, K. Dohmae, C. Xia, Y. Seno, B. Hitti and T. Tani, *A common behavior of thermoelectric layered cobaltites: incommensurate spin density wave states in $[Ca_2Co_{4/3}Cu_{2/3}O_4]_{0.62}[CoO_2]$ and $[Ca_2CoO_3]_{0.62}[CoO_2]$*, J. Phys.: Condensed Matter **15**, 8619 (2003).

P.J.C. King, R.L. Lichti and I. Yonenaga, *Hydrogen behaviour in bulk $Si_{1-x}Ge_x$ alloys as modelled by muonium*, Physica **B340-342**, 835 (2003).

J.E. Sonier, K.F. Poon, G.M. Luke, P. Kyriakou, R.I. Miller, R. Liang, C.R. Wiebe, P. Fournier and R.L. Greene, *Superconductivity and field-induced magnetism in $Pr_{2-x}Ce_xCuO_4$ single crystals*, Phys. Rev. Lett. **91**, 147002 (2003).

W. Higemoto, K. Satoh, A. Koda, K. Nishiyama, K. Shimomura, R. Kadono, A. Hanaoka, S. Koiwai, Y. Uwatoko and N. Mori, *μSR study of magnetism of $CeRh_2Si_2$ under a high pressure*, Physica **B329-333**, 601 (2003).

Y. Aoki, A. Tsuchiya, T. Kanayama, S.R. Saha, H. Sugawara, H. Sato, W. Higemoto, A. Koda, K. Ohishi, K. Nishiyama and R. Kadono, *Time-reversal symmetry-breaking superconductivity in heavy-fermion $PrOs_4Sb_{12}$ detected by muon-spin relaxation*, Phys. Rev. Lett. **91**, 067003 (2003).

R. Kadono, K. Ohishi, A. Koda, W. Higemoto, K.M. Kojima, S. Kuroshima, M. Fujita and K. Yamada, *Magnetic ground state of $Pr_{0.89}LaCe_{0.11}CuO_{4+\alpha-\delta}$ with varied oxygen depletion probed by muon spin relaxation*, J. Phys. Soc. Jpn. **72**, 2955 (2003).

K. Ohishi, K. Kakuta, J. Akimitsu, A. Koda, W. Higemoto, R. Kadono, J.E. Sonier, A.N. Price, R.I. Miller, R.F. Kiefl, M. Nohara, H. Suzuki and H. Takagi, *Excess quasiparticles outside the vortex cores in $Y(Ni_{1-x}Pt_x)_2B_2C$*, Physica **C388-389**, 197 (2003).

R. Kadono, W. Higemoto, A. Koda, M.I. Larkin, G.M. Luke, A.T. Savici, Y.J. Uemura, K.M. Kojima, T. Okamoto, T. Kakeshita, S. Uchida, T. Ito and K. Oka, *Large vortex core at low magnetic induction in $La_{2-x}Sr_xCuO_4$ probed by muon spin rotation*, Physica **C388-389**, 631 (2003).

J. Sugiyama, J.H. Brewer, E.J. Ansaldo, H. Itahara, S. Hirano and T. Tani, *μ^+SR studies on thermoelectric oxides*, Physica **B329-333**, 902 (2003).

J. Sugiyama, H. Itahora, J.H. Brewer, E.J. Ansaldo, T. Motohashi, M. Karppinen and H. Yamauchi, *Static magnetic order $Na_{0.75}CoO_2$ detected by muon spin rotation and relaxation*, Phys. Rev. **B67**, 214420 (2003).

J. van Lierop, H.S. Isaacs, D.H. Ryan, A. Beath and E. McCalla, *Muon spin relaxation study of exchange biased Co/CoO*, Phys. Rev. **B67**, 134430 (2003).

Y.J. Uemura, *Superfluid density of high-T_c cuprate systems: implication on condensation mechanisms, heterogeneity and phase diagram*, Solid State Comm. **126**, 23 (2003).

R.I. Miller and R.F. Kiefl, *Magnetism in the cuprates induced by an external magnetic field*, Solid State Comm. **126**, 77 (2003).

I.M. Gat-Malureanu, A. Fukaya, M.I. Larkin, A.J. Millis, P.L. Russo, A.T. Savici, Y.J. Uemura, P.P. Kyriakou, G.M. Luke, C.R. Wiebe, Y.V. Sushko, R.H. Heffner, D.E. MacLaughlin, D. Andreica and G.M. Kalvius, *Field dependence of muon spin relaxation rate in MnSi*, Phys. Rev. Lett. **90**, 157201 (2003).

J.A. Chakhalian, R.F. Kiefl, R.I. Miller, J.H. Brewer, S.R. Dunsiger, G.D. Morris, W.A. MacFarlane, J.E. Sonier, S. Eggert, I. Affleck, A. Keren and M. Verdaguer, *Local magnetic susceptibility of the positive muon in the quasi 1D S = 1/2 antiferromagnet dichlorobis (pyridine) copper (II)*, Phys. Rev. Lett. **91**, 027202 (2003).

D.R. Harshman, W.J. Kossler, A.J. Greer, D.R. Noakes, C.E. Stronach, E. Koster, M.K. Wu, F.Z. Chien, J.P. Franck, I. Isaac and J.D. Dow, *Spin-glass behavior, spin-fluctuations and superconductivity in $Sr_2Y(Ru_{1-u}Cu_u)O_6$*, Phys. Rev. **B67**, 054509 (2003).

J. Sugiyama, C. Xia and T. Tani, *Anisotropic magnetic properties of $Ca_3Co_4O_9$; the evidence of a spin density wave transition at 27 K*, Phys. Rev. **B67**, 104410 (2003).

V.G. Storchak, D.G. Eshchenko, R.L. Lichti and J.H. Brewer, *Weakly bound muonium state in GaP: validity of the effective mass approximation*, Phys. Rev. **B67**, 121201 (2003).

I. McKenzie, J.-C. Brodovitch, P.W. Percival, T. Ramnial and J.A.C. Clyburne, *The reactions of imidazol-2-ylidenes with the hydrogen atom: a theoretical study and experimental confirmation with muonium*, J. Am. Chem. Soc. **125**, 11565 (2003).

K. Ghandi, B. Addison-Jones, J.-C. Brodovitch, B. McCollum, I. McKenzie and P.W. Percival, *Enolization of acetone in superheated water detected via radical formation*, J. Am. Chem. Soc. **125**, 9594 (2003).

K. Ghandi and P.W. Percival, *Prediction of rate constants for reactions of the hydroxyl radical in water at high temperatures and pressures*, J. Phys. Chem. **A107**, 3005 (2003).

J.-C. Brodovitch, B. Addison-Jones, K. Ghandi, I. McKenzie, P.W. Percival and J. Schüth, *Free radicals formed by H(Mu) addition to fluoranthene*, Can. J. Chem. **81**, 1 (2003).

D.C. Walker, S. Karolczak, H.A. Gillis and G.B. Porter, *Hot model of muonium formation in liquids*, Can. J. Chem. **81**, 199 (2003).

D.C. Walker, S. Karolczak, G.B. Porter and H. A. Gillis, *No "delayed" muonium-formation in organic liquids*, J. Chem. Phys. **118**, 3233 (2003).

S. Karolczak, H.A. Gillis, G.B. Porter and D.C. Walker, *Solvent-dependent rate constants of muonium atom reactions*, Can. J. Chem. **81**, 175 (2003).

K. Ohishi, T. Muranaka, J. Akimitsu, A. Koda, W. Higemoto and R. Kadono, *Quasiparticle excitations outside the vortex cores in* MgB_2 *probed by muon spin rotation*, J. Phys. Soc. Jpn. **72**, 29 (2003).

D.H. Ryan, A.D. Beath, E. McCalla, J. van Lierop and J.M. Cadogan, *Transverse spin freezing in* $a-(Fe_{1-x}Mn_x)_{78}Si_8B_{14}$*: a site-frustrated metallic glass*, Phys. Rev. **B67**, 104404 (2003).

K. Ishida, D.E. MacLaughlin, Ben-Li Young, K. Okamoto, Y. Kawasaki, Y. Kitaoka, G.J. Nieuwenhuys, R.H. Heffner, O.O. Bernal, W. Higemoto, A. Koda, R. Kadono, O. Trovarelli, C. Geibel and F. Steglich, *Low-temperature magnetic order and spin dynamics in* $YbRh_2Si_2$, Phys. Rev. **B68**, 184401 (2003).

J.E. Sonier, K.F. Poon, G.M. Luke, P. Kyriakou, R.I. Miller, P. Fournier and R.L. Greene, *Paramagnetic vortex state in* $Pr_{2-x}Ce_xCuO_4$ *single crystals*, Physica **B329-333**, 685 (2003).

Molecular and Materials Science – *2004*

R.L. Lichti, *Diffusion of a light hydrogen isotope in the III-V nitrides* in Defects and Diffusion in Ceramics, ed. D.J. Fisher (Trans. Tech. Pub., 2004), p.69.

S.G. Ri, H. Watanabe, M. Ogura, D. Takeuchi, M. Hasegawa, H. Okushi, K. Shimomura and K. Nishiyama, *Muon spin relaxation in CVD polycrystalline diamond film*, Diamond Rel. Mat. **13**, 709 (2004).

J.J. Senkevich, A. Mallikarjunan, C.J. Wiegand, T.M. Lu, H.N. Bani-Salameh and R.L. Lichti, *Correlation between bond cleavage in parylene N and the degradation of its dielectric properties*, Electrochem. Solid State Lett. **7**, G56 (2004).

J. Chakhalian, R.F. Kiefl, J. Brewer, S.R Dunsiger, G. Morris, S. Eggert, I. Affleck and I. Yamada, *Impurity effects in quasi-one-dimensional* $S = \frac{1}{2}$ *antiferromagnetic chain* $KCuF_3$ *studied by muon spin rotation*, J. Magn. Mag. Mat. **272-76**, 979 (2004).

H. Manaka, I. Yamada and W. Higemoto, *Muon spin relaxation study of the Haldane state formed in ferromagnetic-antiferromagnetic alternating Heisenberg chains* $(CH_3)_2CHNH_3CuCl_3$, J. Magn. Mag. Mat.**272-76**, 863 (2004).

I. Watanabe, T. Adachi, S. Yairi, Y. Koike and K. Nagamine, *Precise muon-spin-relaxation measurements on the Cu-spin dynamics in* $La_{2-x}Sr_xCuO_4$, J. Magn. Mag. Mat. **272**, E1061 (2004).

K. Ghandi, M.D. Bridges, D.J. Arseneau and D.G. Fleming, *Muonium formation as a probe of radiation chemistry in sub- and supercritical carbon dioxide*, J. Phys. Chem. **A108**, 11613 (2004).

R.H. Heffner, D.E. MacLaughlin, G.J. Nieuwenhuys and J.E. Sonier, *The origin of multiple spin-relaxation channels below the metal-insulator transition in ferromagnetic colossal magnetoresistance (CMR) manganites*, J. Phys. Cond. Mat. **16**, S4541 (2004).

R.H. Heffner and K. Nagamine, *Preface – special issue on* μ*SR, muon spin rotation, relaxation or resonance*, J. Phys. Cond. Mat. **16**, No. 40 (2004).

R.L. Lichti, Y.G. Celebi, S.P. Cottrell, S.F.J. Cox and E.A. Davis, *Diffusion and trapping of Mu in the III-V nitrides*, J. Phys. Cond. Mat. **16**, S4721 (2004).

R.L. Lichti, Y.G. Celebi, S.F.J. Cox and E.A. Davis, *Location of the hydrogen donor in InN: evidence from muonium results*, J. Phys. Cond. Mat. **16**, 325 (2004).

J.S. Lord, S.F.J. Cox, M. Charlton, D.P. Van der Werf, R.L. Lichti and A. Amato, *The muon spin response to intermittent hyperfine interaction: modelling the high-temperature electrical activity of hydrogen in silicon*, J. Phys. Cond. Mat. **16**, S4739 (2004).

R. Kadono, K. Ohishi, A. Koda, W. Higemoto, K.M. Kojima, M. Fujita, S. Kuroshima and K. Yamada, *Strong correlation between field-induced magnetism and superconductivity in* $Pr_{0.89}LaCe_{0.11}CuO_4$, J. Phys. Soc. Japan **73**, 2944 (2004).

S. Kuroiwa, H. Takagiwa, M. Yamazawa, J. Akimitsu, K. Ohishi, A. Koda, W. Higemoto and R. Kadono, *Unconventional behavior of field-induced quasiparticle excitation in* $Ca(Al_{0.5}Si_{0.5})_2$, J. Phys. Soc. Japan **73**, 2631 (2004).

T. Adachi, S. Yairi, Y. Koike, I. Watanabe and K. Nagamine, *Muon-spin-relaxation and magnetic-susceptibility studies of the effects of the magnetic impurity Ni on the Cu-spin dynamics and superconductivity in* $La_{2-x}Sr_xCu_{1-y}Ni_yO_4$ *with* x*=0.13*, Phys. Rev. **B70**, 060504 (2004).

T. Adachi, S. Yairi, K. Takahashi, Y. Koike, I. Watanabe and K. Nagamine, *Muon spin relaxation and magnetic susceptibility studies of the effects of nonmagnetic impurities on the Cu spin dynamics and superconductivity in* $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ *around* x*=0.115*, Phys. Rev. **B69**, 184507 (2004).

D. Baabe, M Hillberg, F.J. Litterst, P. Adelmann and H.H. Klauss, *Schottky anomaly in Nd_2CuO_4 observed by muon spin relaxation*, Phys. Rev. **B69**, 134512 (2004).

D. Cao, I.K. Jeong, R.H. Heffner, T. Darling, J.K. Lee, F. Bridges, J.S. Park and K.S. Hong, *Local structure study of the off-center displacement of Ti and Zr across the morphotropic phase boundary of $PbZr_{1-x}Ti_xO_3$ (x=0.40,0.47,0.49,0.55)*, Phys. Rev. **B70**, 224102 (2004).

K.H. Chow, L.S. Vlasenko, P. Johannesen, C. Bozdog, G.D. Watkins, A. Usui, H. Sunakawa, C. Sasaoka and M. Mizuta, *Intrinsic defects in GaN. I. Ga sublattice defects observed by optical detection of electron paramagnetic resonance*, Phys. Rev. **B69**, 045207 (2004).

A.V. Dooglav, A.V. Egorov, I.R. Mukhamedshin, A.V. Savinkov, H. Alloul, J. Bobroff, W.A. MacFarlane, P. Mendels, G. Collin, N. Blanchard, P.G. Picard, P.J.C. King and J. Lord, *Antiferromagnetic properties of a water-vapor-inserted $YBa_2Cu_3O_{6.5}$ compound studied by NMR, NQR, and μSR*, Phys. Rev. **B70**, 054506 (2004).

T. Ito, Y. Fudamoto, A. Fukaya, I.M. Gat-Malureanu, M.I. Larkin, P.L. Russo, A. Savici, Y.J. Uemura, K. Groves, R. Breslow, K. Hotehama, S. Yamanaka, P. Kyriakou, M. Rovers, G.M. Luke and K.M. Kojima, *Two-dimensional nature of superconductivity in the intercalated layered systems Li_xHfNCl and Li_xZrNCl: muon spin relaxation and magnetization measurements*, Phys. Rev. **B69**, 134522 (2004).

G.D. Morris, R.H. Heffner, N.O. Moreno, P.G. Pagliuso, J.L. Sarrao, S.R. Dunsiger, G.J. Nieuwenhuys, D.E. MacLaughlin and O.O. Bernal, *Random spin freezing in Ce_2MIn_8 (M=Co,Rh,Ir) heavy-fermion materials*, Phys. Rev. **B69**, 214415 (2004).

C.R. Wiebe, G.M. Luke, Z. Yamani, A.A. Menovsky and W.J.L. Buyers, *Search for hidden orbital currents and observation of an activated ring of magnetic scattering in the heavy fermion superconductor URu_2Si_2*, Phys. Rev. **B69**, 132418 (2004).

B.L. Young, D.E. MacLaughlin, M.S. Rose, K. Ishida, O.O. Bernal, H.G. Lukefahr, K. Heuser and G.R. Stewart, *^{29}Si nuclear spin-lattice relaxation in $CePtSi_{1-x}Ge_x$ near a magnetic instability*, Phys. Rev. **B70**, 174430 (2004).

B.L. Young, D.E. MacLaughlin, M.S. Rose, K. Ishida, O.O. Bernal, H.G. Lukefahr, K. Heuser, G.R. Stewart, N.P. Butch, P.C. Ho and M.B. Maple, *Disorder effects near a magnetic instability in $CePtSi_{1-x}Ge_x$ (x=0,0.1)*, Phys. Rev. **B70**, 024401 (2004).

I.K. Jeong, T.W. Darling, M.J. Graf, T. Proffen, R.H. Heffner, Y. Lee, T. Vogt and J.D. Jorgensen, *Role of the lattice in the $\gamma \rightarrow \alpha$ phase transition of Ce: a high-pressure neutron and X-ray diffraction study*, Phys. Rev. Lett. **92**, 105702 (2004).

A. Keren, J.S. Gardner, G. Ehlers, A. Fukaya, E. Segal and Y.J. Uemura, *Dynamic properties of a diluted pyrochlore cooperative paramagnet $(Tb_pY_{1-p})_2Ti_2O_7$*, Phys. Rev. Lett. **92**, 107204 (2004).

G.D. Morris, W.A. MacFarlane, K.H. Chow, Z. Salman, D.J. Arseneau, S. Davie A. Hatakeyama, S.R. Kreitzman, C.D.P. Levy, R. Poutissou, R.H. Heffner, J.E. Elenewski, L.H. Greene and R.F. Kiefl, *Depth-controlled β-NMR of ^{8}Li in a thin silver film*, Phys. Rev. Lett. **93**, 157601 (2004).

K. Shimomura, R. Kadono, K. Ohishi, M. Mizuta, M. Saito, K.H. Chow, B. Hitti and R.L. Lichti, *Muonium as a shallow center in GaN*, Phys. Rev. Lett. **92**, 135505 (2004).

C.R. Wiebe, J.S. Gardner, S.J. Kim, G.M. Luke, A.S. Wills, B.D. Gaulin, J.E. Greedan, I. Swainson, Y. Qiu and C.Y. Jones, *Magnetic ordering in the spin-ice candidate $Ho_2Ru_2O_7$*, Phys. Rev. Lett. **93**, 076403 (2004).

X.G. Zheng, T. Mori, K. Nishiyama, W. Higemoto and C.N. Xu, *Dramatic suppression of antiferromagnetic coupling in nanoparticle CuO*, Solid St. Comm. **132**, 493 (2004).

K.M. Kojima, J. Yamanobe, H. Eisaki, S. Uchida, Y. Fudamoto, I.M. Gat, M.I. Larkin, A. Savici, Y.J. Uemura, P.P. Kyriakou, M.T. Rovers and G.M. Luke, *Site-dilution in quasi one-dimensional antiferromagnet $Sr_2(Cu_{1-x}Pd_x)O_3$: reduction of Néel temperature and spatial distribution of ordered moment sizes*, Phys. Rev. **B70**, 094402 (2004).

R.L. Lichti, W.A. Nussbaum and K.H. Chow, *Hyperfine spectroscopy of muonium in 4H and 6H silicon carbide*, Phys. Rev. **B70**, 165204-1 (2004).

V.G. Storchak, D.G. Eshchenko and J.H. Brewer, *Formation and dynamics of muonium centres in semiconductors – a new approach*, J. Phys. Condens. Matter **16**, 4761 (2004).

J.E. Sonier, K.F. Poon, G.M. Luke, P. Kyriakou, R.I. Miller, R. Liang, C.R. Wiebe, P. Fournier and R.L. Greene, *Field-induced antiferromagnetic order in $Pr_{2-x}Ce_xCuO_4$*, Physica **C408-10**, 783 (2004).

W. Higemoto, K. Ohishi, A. Koda, S.R. Saha, R. Kadono, K. Ishida, K. Takada, H. Sakurai, E. Takayama-Muromachi and T. Sasaki, *Possible unconventional superconductivity in $Na_xCoO_2 \cdot yH_2O$ probed by muon spin rotation and relaxation*, Phys. Rev. **B70**, 134508 (2004).

R. Kadono, W. Higemoto, A. Koda, M.I. Larkin, G.M. Luke, A.T. Savici, Y.J. Uemura, K.M. Kojima, T. Okamoto, T. Kakeshita, S. Uchida, T. Ito, K. Oka, M. Takigawa, M. Ichioka and K. Machida, *Expansion of vortex cores by strong electronic correlation in $La_{2-x}Sr_xCuO_4$ at low magnetic induction*, Phys. Rev. **B69**, 104523 (2004).

R. Kadono, K. Ohishi, A. Koda, W. Higemoto, K.M. Kojima, S. Kuroshima, M. Fujita and K. Yamada, *Strong corre-*

lation between field-induced magnetism and superconductivity in $Pr_{0.89}LaCe_{0.11}CuO_4$, J. Phys. Soc. Jpn. **73**, 2944 (2004).

S. Kuroiwa, H. Takagiwa, M. Yamazawa, J. Akimitsu, K. Ohishi, A. Koda, W. Higemoto and R. Kadono, *Unconventional behavior of field-induced quasiparticle excitation in Ca($Al_{0.5}Si_{0.5})_2$*, J. Phys. Soc. Jpn. **73**, 2631 (2004).

A. Koda, R. Kadono, W. Higemoto, K. Ohishi, H. Ueda, C. Urano, S. Kondo, M. Nohara and H. Takagi, *Spin fluctuation in LiV_2O_4 studied by muon spin relaxation*, Phys. Rev. **B69**, 012402 (2004).

S. Hirano, J. Sugiyama, T. Noritake and T. Tani, *Chemical pressure effect on magnetic properties in electron-doped Perovskite manganites $(Gd_{0.08}Ca_ySr_{0.92-y})MnO_3$ $(0 \leq y < 1)$: percolation transition of ferromagnetic clusters*, Phys. Rev. **B70**, 094419 (2004).

J. Sugiyama, J.H. Brewer, E.J. Ansaldo, B. Hitti, M. Mikami, Y. Mori and T. Sasaki, *Electron correlation in the two-dimensional triangle lattice of Na_xCoO_2*, Phys. Rev. **B69**, 214423 (2004).

D.E. MacLaughlin, R.H. Heffner, O.O. Bernal, K. Ishida, J.E. Sonier, G.J. Nieuwenhuys, M.B. Maple and G.R. Stewart, *Disorder, inhomogeneity and spin dynamics in f-electron non-Fermi liquid systems*, J. Phys. Condens. Matter **16**, S4479 (2004).

J.E. Sonier, *Investigations of the core structure of magnetic vortices in type-II superconductors using muon spin rotation*, J. Phys. Condens. Matter **16**, S4499 (2004).

J.E. Sonier, F.D. Callaghan, R.I. Miller, E. Boaknin, L. Taillefer, R.F. Kiefl, J.H. Brewer, K.F. Poon and J.D. Brewer, *Shrinking magnetic vortices in V_3Si due to delocalized quasiparticle core states: confirmation of the microscopic theory for interacting vortices*, Phys. Rev. Lett. **93**, 017002 (2004).

D.R. Harshman, W.J. Kossler, X. Wan, A.T. Fiory, A.J. Greer, D.R. Noakes, C.E. Stronach, E. Koster and J.D. Dow, *Nodeless pairing state in single-crystal $YBa_2Cu_3O_7$*, Phys. Rev. **B69**, 174505 (2004).

J. Sugiyama, J.H. Brewer, E.J. Ansaldo, H. Itahara, T. Tani, M. Mikami, Y. Mori, T. Sasaki, S. Hébert and A. Maignan, *Dome-shaped magnetic phase diagram of thermoelectric layered cobaltites*, Phys. Rev. Lett. **92**, 017602 (2004).

Molecular and Materials Science – *2005*

C.R. Wiebe, P.L. Russo, A.T. Savici, Y.J. Uemura, G.J. MacDougall, G.M. Luke, S. Kuchta and J.E. Greedan, *2D Kagomé ordering in the 3D frustrated spinel $Li_2Mn_2O_4$*, J. Phys. Cond. Mat. **17**, 6469 (2005).

O.O. Bernal, M.E. Moroz, D.E. MacLaughlin, H.G. Lukefahr, J.A. Mydosh and T.J. Gortenmulder, *Hidden and magnetic order in powdered URu_2Si_2 found by NMR at ambient pressure*, Physica **B359**, 994 (2005).

S.R. Saha, W. Higemoto, A. Koda, K. Ohishi, R. Kadono, Y. Aoki, H. Sugawara and H. Sato, *μSR study on filled skutterudite $PrRuP_{12}$*, Physica **B359**, 850 (2005).

J.E. Sonier, D.A. Bonn, J.H. Brewer, W.N. Hardy, R.F. Kiefl and R.X. Liang, *Comment on "Nodeless pairing state in single-crystal $YBa_2Cu_3O_7$"*, Phys. Rev. **B72**, 146501 (2005).

D. Cao, R.H. Heffner, F. Bridges, I.K. Jeong, E.D. Bauer, W.M. Yuhasz and M.B. Maple, *Local distortion induced metal-to-insulator phase transition in $PrRu_4P_{12}$*, Phys. Rev. Lett. **94**, 036403 (2005).

I.K. Jeong, T.W. Darling, J.K. Lee, T. Proffen, R.H. Heffner, J.S. Park, K.S. Hong, W. Dmowski and T. Egami, *Direct observation of the formation of polar nanoregions in $Pb(Mg_{1/3}Nb_{2/3})O_3$ using neutron pair distribution function analysis*, Phys. Rev. Lett. **94**, 147602 (2005).

B.E. Schultz, K.H. Chow, B. Hitti, R.F. Kiefl, R.L. Lichti and S.F.J. Cox, *Local structure of isolated positively charged muonium as an analog for the hydrogen ion in p-type GaAs*, Phys. Rev. Lett. **95**, 086404 (2005).

V.G. Storchak, D.G. Eshchenko, J.H. Brewer, B. Hitti, R.L. Lichti and B.A. Aronzon, *Magnetic freezeout of electrons into muonium atoms in GaAs*, Phys. Rev. **B71**, 113202 (2005).

B.E. Schultz, K.H. Chow, B. Hitti, Z. Salman, S.R. Kreitzman, R.F. Kiefl and R.L. Lichti, *Nature of charged muonium in GaAs with an electric field*, Phys. Rev. **B72**, 332001 (2005).

B.E. Schultz, K.H. Chow, B. Hitti, R.F. Kiefl, R.L. Lichti and S.F.J. Cox, *Local structure of isolated positively charged muonium in p-type GaAs*, Phys. Rev. Lett. **95**, 086404 (2005).

A.T. Savici, A. Fukaya, I.M. Gat-Malureanu, T. Ito, P.L. Russo, Y.J. Uemura, C.R. Wiebe, P.P. Kyriakou, G.J. MacDougall, M.T. Rovers, G.M. Luke, K.M. Kojima, M. Goto, S. Uchida, R. Kadono, K. Yamada, S. Tajima, T. Masui, H. Eisaki, N. Kaneko, M. Greven and G.D. Gu, *Muon spin relaxation studies of magnetic-field-induced effects in high-T_c superconductors*, Phys. Rev. Lett. **95**, 157001 (2005).

R. Kadono, K. Ohishi, A. Koda, S.R. Saha, W. Higemoto, M. Fujita and K. Yamada, *Field-induced uniform antiferromagnetic order associated with superconductivity in $Pr_{1-x}LaCe_xCuO_{4-\delta}$*, J. Phys. Soc. Jpn. **74**, 2806 (2005).

A. Koda, R. Kadono, K. Ohishi, S.R. Saha, W. Higemoto, Y. Matsushita and Y. Ueda, *Staggered magnetism in LiV_2O_4 at low temperatures probed by means of the muon Knight shift*, J. Phys. Cond. Mat. **17**, L257 (2005).

Y. Aoki, W. Higemoto, S. Sanada, K. Ohishi, S.R. Saha, A. Koda, K. Nishiyama, R. Kadono, H. Sugawara and H. Sato, *μSR* *studies on $LaOs_4Sb_{12}$ in comparison with the time-reversal-symmetry-broken superconductor $PrOs_4Sb_{12}$*, Physica **B359-361C**, 895 (2005).

H. Takagiwa, S. Kuroiwa, M. Yamazawa, J. Akimitsu, K. Ohishi, A. Koda, W. Higemoto and R. Kadono, *Correlation between superconducting carrier density and transition temperature in NbB_{2+x}*, J. Phys. Soc. Jpn. **74**, 1386 (2005).

A. Koda, W. Higemoto, K. Ohishi, S.R. Saha, R. Kadono, S. Yonezawa, Y. Muraoka and Z. Hiroi, *Possible anisotropic order parameter in the pyrochlore superconductor KOs_2O_6 probed by muon spin rotation*, J. Phys. Soc. Jpn. **74**, 1678 (2005).

R.C. Vilao, H.V. Alberto, J. Piroto Duarte, J.M. Gil, A. Weidinger, N. Ayres de Campos, R.L. Lichti, K.H. Chow and S.F.J. Cox, *Muonium spectroscopy in ZnSe: metastability and conversion*, Phys. Rev. **B72**, 235203 (2005).

K. Ohishi, I. Yamada, A. Koda, W. Higemoto, S.R. Saha, R. Kadono, K.M. Kojima, M. Azuma and M. Takano, *Magnetic phase diagram of hole-doped $Ca_{2-x}Na_xCuO_2Cl_2$ cuprate superconductor*, J. Phys. Soc. Japan **74**, 2408 (2005).

P.J.C. King, R.L. Lichti, S.P. Cottrell, I. Yonenaga and B. Hitti, *Characterization of hydrogen-like states in bulk $Si_{1-x}Ge_x$ alloys through muonium observations*, J. Phys. Cond. Mat. **17**, 4567 (2005).

C. Johnson, S.P. Cottrell, K. Ghandi and D.G. Fleming, *Muonium and muon molecular ions in inert gases studied by RFμSR*, J. Phys. **B38**, 119 (2005).

K. Ghandi, F.E. Zahariev and Y.A. Wang, *Theoretical studies of alkyl radicals in zeolites*, J. Phys. Chem. **A109**, 7242 (2005).

P.W. Percival, J.-C. Brodovitch, K. Ghandi, B. McCollum and I. McKenzie, *Organic free radicals in superheated water studied by muon spin spectroscopy*, J. Am. Chem. Soc. **127**, 13714 (2005).

J. Sugiyama, D. Andreica, H. Itahara and T. Tani, *The effect of pressure on the spin density wave transition in the layered cobaltites $[Ca_2CoO_3]_{0.62}[CoO_2]$ and $[Ca_2Co_{4/3}Cu_{2/3}O_4]_{0.62}[CoO_2]$*, Solid State Commun. **135**, 263 (2005).

F.D. Callaghan, M. Laulajainen, C.V. Kaiser and J.E. Sonier, *Field dependence of the vortex core size in a multiband superconductor*, Phys. Rev. Lett. **95**, 197001 (2005).

X.G. Zheng, H. Kubozono, K. Nishiyama, W. Higemoto, T. Kawae, A. Koda and C.N. Xu, *Coexistence of long-range order and spin fluctuation in geometrically frustrated clinoatacamite $Cu_2Cl(OH)_3$*, Phys. Rev. Lett. **95**, 057201 (2005).

J.H. Brewer, A.M. Froese, B.A. Fryer and K. Ghandi, *Relativistic shifts of bound negative muon precession frequencies*, Phys. Rev. A Brief Rept. **72**, 022504 (2005).

X.G. Zheng, C.N. Xu, K. Nishikubo, K. Nishiyama, W. Higemoto, W.J. Moon, E. Tanaka and E.S. Otabe, *Finite-size effect on Néel temperature in antiferromagnetic nanoparticles*, Phys. Rev. **B72**, 14464-2005 (2005).

X.G. Zheng, T. Mori, K. Nishiyama, W. Higemoto, H. Yamada, K. Nishikubo and C.N. Xu, *Antiferromagnetic transitions in polymorphous minerals of natural cuprates atacamite and botallackite $Cu_2Cl(OH)_3$*, Phys. Rev. **B71**, 174404 (2005).

J. Sugiyama, H. Nozaki, J.H. Brewer, E.J. Ansaldo, G.D. Morris and C. Delmas, *Frustrated magnetism in the two-dimensional triangular lattice of Li_xCoO_2*, Phys. Rev. **B72**, 144424-1 (2005).

J. Sugiyama, H. Nozaki, J.H. Brewer, E.J. Ansaldo, T. Takami, H. Ikuta and U. Mizutani, *Appearance of a two-dimensional antiferromagnetic order in quasi-one-dimensional cobalt oxides*, Phys. Rev. **B72**, 064418 (2005).

J.H. Brewer, K. Ghandi, A.M. Froese and B.A. Fryer, *Negative muon spin precession measurement of the hyperfine states of muonic sodium*, Phys. Rev. **C71**, 058501 (2005).

C. Xia, J. Sugiyama, H. Itahara and T. Tani, *Platelet crystals of thermoelectric layered cobaltites; pure and Sr-doped $[Ca_2CoO_3]_{0.62}[CoO_2]$*, J. Crystal Growth **276**, 519 (2005).

D.R. Noakes, R. Wäppling, G.M. Kalvius, M.F. White Jr. and C.E. Stronach, *Singlet ground-state fluctuations in praseodymium observed by muon spin relaxation in PrP and $PrP_{0.9}$*, J. Phys. Condens. Matter **17**, 119 (2005).

R.F. Kiefl, K.H. Chow, W.A. MacFarlane, C.D.P. Levy and Z. Salman, *Application of low energy spin polarized radioactive ion beams in condensed matter research*, Nucl. Phys. News **15**, 1 (2005).

Molecular and Materials Science – *2006*

J.J. Pan, D.J. Arseneau, M. Senba, D.M. Garner, D.G. Fleming, T. Xie and J.M. Bowman, *Termolecular kinetics for the Mu+CO+M recombination reaction: a unique test of quantum rate theory*, J. Chem. Phys. **125**, 014307 (2006).

G.D. Gu, M. Hucker, Y.J. Kim, J.M. Tranquada, H. Dabkowska, G.M. Luke, T. Timusk, B.D. Gaulin, Q. Li and A.R. Moodenbaugh, *Crystal growth and superconductivity of $(La_{1-x}Ca_x)_2CaCu_2O_{6+\delta}$*, J. Phys. Chem. Solids **67**, 431 (2006).

A. Fukaya, I. Watanabe, K. Yamada and K. Nagamine, *Spin dynamics in copper metaborate CuB_2O_4 studied by muon spin relaxation*, J. Phys. Soc. Japan **75**, 113705 (2006).

W. Higemoto, Y. Haga, T.D. Matsuda, Y. Onuki, K. Ohishi, T.U. Ito, A. Koda, S.R. Saha and R. Kadono, *Possible unconventional*

superconductivity and magnetism in $CePt_3Si$ probed by muon spin rotation and relaxation, J. Phys. Soc. Japan **75**, 124713 (2006).

K. Ohishi, W. Higemoto, A. Koda, S.R. Saha, R. Kadono, K. Inoue, H. Imai and H. Higashikawa, *Possible magnetic chirality in optically chiral magnet $[Cr(CN)_6][Mn(S)\text{-}pnH(H_2O)](H_2O)$ probed by muon spin rotation and relaxation*, J. Phys. Soc. Japan **75**, 063705 (2006).

S. Takeshita, J. Arai, T. Goko, K. Nishiyama and K. Nagamine, *Muon spin relaxation study of partially disordered state in triangular-lattice antiferromagnet: $Ca_3Co_2O_6$*, J. Phys. Soc. Japan **75**, 034712 (2006).

H.N. Bani-Salameh, Y.G. Celebi, S.F.J. Cox and R.L. Lichti, *Anisotropic muonium centers in aluminum nitride*, Physica **B374**, 372 (2006).

K. Shimomura, R. Kadono, K. Nishiyama, I. Watanabe, T. Suzuki, F. Pratt, K. Ohishi, M. Mizuta, M. Saito, K.H. Chow, B. Hitti, R.L. Lichti, H. Miyadera, Y. Ikedoa, H. Tanaka and K. Nagamine, *Isolated hydrogen center in wide gap semiconductors studied by μSR*, Physica **B376**, 444 (2006).

M. Senba, D.J. Arseneau, J.J. Pan and D.G. Fleming, *Slowing-down times and stopping powers for $\sim$2-MeV μ^+ in low-pressure gases*, Phys. Rev. **A4**, 042708 (2006).

H.N. Bani-Salameh, R.L. Lichti, Y.G. Celebi and S.F.J. Cox, *Diffusion and conversion dynamics for neutral muonium in aluminum nitride*, Phys. Rev. **B74**, 245203 (2006).

C.A. Bridges, T. Hansen, A.S. Wills, G.M. Luke and J.E. Greedan, *Frustrated magnetism and the effects of titanium substitution in the mixed-valence oxide $BaV_{10-x}Ti_xO_{15}$*, Phys. Rev. **B74**, 024426 (2006).

Y.G. Celebi, R.L. Lichti, B.E. Coss and S.F.J. Cox, *Dynamics of positively charged muonium centers in indium nitride*, Phys. Rev. **B74**, 245219 (2006).

S.R. Dunsiger, R.F. Kiefl, J.A. Chakhalian, J.E. Greedan, W.A. MacFarlane, R.I. Miller, G.D. Morris, A.N. Price, N.P. Raju and J.E. Sonier, *Magnetic field dependence of muon spin relaxation in geometrically frustrated $Gd_2Ti_2O_7$*, Phys. Rev. **B73**, 172418 (2006).

R. Kadono, K.H. Satoh, A. Koda, T. Nagata, H. Kawano-Furukawa, J. Suzuki, M. Matsuda, K. Ohishi, W. Higemoto, S. Kuroiwa, H. Takagiwa and J. Akimitsu, *Magnetic field-induced quasiparticle excitation in Nb_3Sn: evidence for anisotropic s-wave pairing*, Phys. Rev. **B74**, 024513 (2006).

R.I. Miller, R.F. Kiefl, J.H. Brewer, F.D. Callaghan, J.E. Sonier, R. Liang, D.A. Bonn and W. Hardy, *Coexistence of magnetism and superconductivity in ultraclean underdoped $YBa_2Cu_3O_{6.37}$*, Phys. Rev. **B73**, 144509 (2006).

A.S. Sefat, J.E. Greedan, G.M. Luke, M. Niewczas, J.D. Garrett, H. Dabkowska and A. Dabkowski, *Anderson-Mott transition induced by hole doping in $Nd_{1-x}TiO_3$*, Phys. Rev. **B74**, 104419 (2006).

J.E. Sonier, M.F. Hundley and J.D. Thompson, *Effect of delocalized vortex core states on the specific heat of Nb*, Phys. Rev. **B73**, 132504 (2006).

I. Watanabe, N. Oki, T. Adachi, H. Mikuni, Y. Koike, F.L. Pratt and K. Nagamine, *Muon spin relaxation study of the anomalous magnetic behavior in excess-oxygen-doped $La_{1.8}Nd_{0.2}CuO_{4+\delta}$ $(0.020 \leq \delta \leq 0.101)$*, Phys. Rev. **B73**, 134506 (2006).

X.G. Zheng, T. Kawae, H. Yamada, K. Nishiyama and C.N. Xu, *Coexisting ferromagnetic order and disorder in a uniform system of hydroxyhalide $Co_2(OH)_3Cl$*, Phys. Rev. Lett. **97**, 247204 (2006).

S. Kuroiwa, H. Takagiwa, M. Yamazawa, J. Akimitsu, A. Koda, R. Kadono, K. Ohishi, W. Higemoto and I. Watanabe, *Possible weak magnetism in MB_6 (M:Ca, Ba) probed by muon spin relaxation and muon level-crossing resonance*, Sci. Tech. Ad. Mat. **7**, 12 (2006).

J. Lefebvre, F. Callaghan, M.J. Katz, J.E. Sonier and D.B. Leznoff, *A new basic motif in cyanometallate coordination polymers: structure and magnetic behaviour of $M(\mu\text{-}OH_2)_2[Au(CN)_2]_2$ (M = Cu, Ni)*, Chemistry – A European Journal **26**, 6719 (2006).

J. Sugiyama, Y. Ikedo, Y. Ikedo, K. Mukai, J.H. Brewer, E.J. Ansaldo, K.H. Chow, H. Yoshida and Z. Hiroi, *Incommensurate magnetic order in Ag_2NiO_2 studied with muon-spin-rotation and relaxation spectroscopy*, Phys. Rev. **B73**, 224437 (2006).

J. Sugiyama, H. Nozaki, Y. Ikedo, K. Mukai, D. Andreica, A. Amato, J.H. Brewer, E.J. Ansaldo, G.D. Morris, T. Takami and H. Ikuta, *Evidence of two-dimensionality in quasi-one-dimensional cobalt oxides*, Phys. Rev. Lett. **96**, 197206 (2006).

H. Imao, N. Kawamura, K. Ishida, T. Matsuzaki, Y. Matsuda, A. Toyoda and K. Nagamine, *Dependence of muon-catalyzed $d-d$ fusion on the ortho-para ratio in solid and liquid deuterium*, Phys. Lett. **B632**, 192 (2006).

M. Laulajainen, F.D. Callaghan, C.V. Kaiser and J.E. Sonier, *Muon spin rotation measurements of the vortex state in vanadium: A comparative analysis using iterative and analytical solutions of the Ginzburg-Landau equations*, Phys. Rev. **B74**, 054511 (2006).

Z. Salman, R.F. Kiefl, K.H. Chow, M.D. Hossain, T.A. Keeler, S.R. Kreitzman, C.D.P. Levy, R.I. Miller, T.J. Parolin, M.R. Pearson, H. Saadaoui, J.D. Schultz, M. Smadella, D. Wang and W.A. MacFarlane, *Near-surface phase transition of $SrTiO_3$ studied with zero-field β-detected nuclear spin relaxation and resonance*, Phys. Rev. Lett. **96**, 147601-1 (2006).

R.H. Heffner, G.D. Morris, M.J. Fluss, B. Chung, S. McCall, D.E. MacLaughlin, L. Shu, K. Ohishi, E.D. Bauer, J.L. Sarrao, W. Higemoto and T.U. Ito, *Limits for ordered magnetism in Pu metal from muon spin rotation spectroscopy*, Phys. Rev. **B73**, 094453 (2006).

J. Sugiyama, J.H. Brewer, E.J. Ansaldo, J.A. Chakhalian, H. Nozaki, H. Hazama, Y. Ono and T. Kajitani, *Spin state transition in Ca-doped $Na_{0.7}CoO_2$ with the nominal Co valence below 3.16*, Solid State Commun. **137**, 36 (2006).

V.G. Storchak, D.G. Eshchenko, J.H. Brewer, S.P. Cottrell and R.L. Lichti, *Muonium in InSb: shallow acceptor versus deep trap or recombination center*, Physica **B73**, 081203 (2006).

K.H. Chow, B. Hitti and J. Lord, *Demonstration of the effect of uniaxial stress on the electronic structure of bond-centered muonium in Si*, Phys. Rev. **B73**, 113202 (2006).

Z. Salman, T.J. Parolin, K.H. Chow, T.A. Keeler, R.I. Miller, D. Wang and W.A. MacFarlane, *Muon spin relaxation study of the magnetism in unilluminated Prussian blue analogue photomagnets*, Phys. Rev. **B73**, 174427 (2006).

J. Sugiyama, H. Nozaki, Y. Ikedo, K. Mukai, J.H. Brewer, E.J. Ansaldo, G.D. Morris, D. Andreica, A. Amato, T. Fujii and A. Asamitsu, *Static magnetic order in metallic $K_{0.49}CoO_2$*, Phys. Rev. Lett. **96**, 037206 (2006).

Molecular and Materials Science – *2007*

R.H. Heffner, K. Ohishi, M.J. Fluss, G.D. Morris, D.E. MacLaughlin, L. Shu, B.W. Chung, S.K. McCall, E.D. Bauer, J.L. Sarrao, T.U. Ito and W. Higemoto, *The search for magnetic order in δ-Pu metal using muon spin relaxation*, J. Alloys Cmpds. **444**, 80 (2007).

R.H. Heffner, D.E. MacLaughlin, J.E. Sonier, M.F. Hundley and J.D. Thompson, *Two-fluid model of heavy fermion formation and μSR Knight shift measurements in UBe_{13}*, J. Magn. Mag. Mat. **310**, E6 (2007).

K. Ishida, W. Higemoto, K. Ohishi, A. Koda, K.H. Satoh, R. Kadono, M. Fujita and K. Yamada, *Magnetic correlations and superconductivity in $La_{1.93}Sr_{0.07}CuO_4$ revealed by μSR*, J. Magn. Mag. Mat. **310**, 526 (2007).

K. Ohishi, R.H. Heffner, G.D. Morris, M.J. Fluss, E.D. Bauer, L.A. Morales, J.L. Sarrao, D.E. MacLaughlin, L. Shu, T.U. Ito and W. Higemoto, *Magnetic penetration depth and self-induced irradiation effects in superconducting $PuCoGa_5$ probed by muon spin rotation*, J. Magn. Mag. Mat. **310**, 566 (2007).

K.H. Satoh, A. Koda, R. Kadono, H. Sakurai, K. Takada, T. Sasaki and E. Takayama-Muromachi, *Ferromagnetic correlation in the deuterated cobalt-oxyhydrate superconductor $Na_xCoO_2{\cdot}yD_2O$ probed by μSR*, J. Magn. Mag. Mat. **310**, E138 (2007).

L. Shu, W. Higemoto, Y. Aoki, N.A. Frederick, W.M. Yuhasz, R.H. Heffner, K. Ohishi, K. Ishida, R. Kadono, A. Koda, D. Kikuchi, H. Sato, H. Sugawara, T.U. Ito, S. Sanada, Y. Tunashima, Y. Yonezawa, M.B. Maple and D.E. MacLaughlin, *Time reversal symmetry breaking in superconducting $(Pr,La)Os_4Sb_{12}$ and $Pr(Os,Ru)_4Sb_{12}$*, J. Magn. Mag. Mat. **310**, 551 (2007).

X.G. Zheng, M. Hagihala and T. Toriyi, *Co-existence of long-range order and spin fluctuation in a new geometric frustration series $M_2(OH)_3Cl$*, J. Magn. Mag. Mat. **310**, 1288 (2007).

L. McKenzie, J.C. Brodovitch, K.Ghandi, B.M. McCollum and P.W. Percival, *Hyperfine coupling in methyl radical isotopomers*, J. Phys. Chem. **A111**, 10625 (2007).

S. Kuroiwa, K.H. Satoh, A. Koda, R. Kadono, K. Ohishi, W. Higemoto and J. Akimitsu, *μSR measurements on the vortex lattice of CaAlSi: anisotropic response in magnetic penetration depth*, J. Phys. Chem. Solids **68**, 2124 (2007).

K. Kawashima, H. Okabe, K. Suzuki, S. Kuroiwa, J. Akimitsu, K. Sato, A. Koda and R. Kadono, *Antiferromagnetic ordering in Cu_2OC_{l2} studied by the muon spin rotation/relaxation technique*, J. Phys. Cond. Mat. **19**, 145275 (2007).

Y. Aoki, T. Tayama, T. Sakakibara, K. Kuwahara, K. Iwasa, M. Kohgi, W. Higemoto, D.E. MacLaughlin, H. Sugawara and H. Sato, *The unconventional superconductivity of skutterudite $PrOS_4Sb_{12}$: time-reversal symmetry breaking and adjacent field-induced quadrupole ordering*, J. Phys. Soc. Japan **76**, 051006 (2007).

A. Koda, R. Kadono, K. Ohishi, S.R. Saha, W. Higemoto, S. Yonezawa, Y. Muraoka and Z. Hiroi, *Anomalous magnetic phase in an undistorted pyrochlore oxide $Cd_2Os_2O_7$ induced by geometrical frustration*, J. Phys. Soc. Japan **76**, 063703 (2007).

H. Manaka, I. Yamada and W. Higemoto, *Muon spin relaxation study of crossover from S=1/2 to S=1 of composite Haldane spin chains in IPA-$CuCl_3$*, J. Phys. Soc. Japan **76**, 014704 (2007).

C.R. Wiebe, J.A. Janik, G.J. MacDougall, G.M. Luke, J.D. Garrett, H.D. Zhou, Y.J. Jo, L. Balicas, Y. Qiu, J.R.D. Copley, Z Yamani and W.J.L. Buyers, *Gapped itinerant spin excitations account for missing entropy in the hidden-order state of URu_2Si_2*, Nature Phys. **3**, 96 (2007).

R.C. Vilao, J.M. Gil, A. Weidinger, H.V. Alberto, J.P. Duarte, N.A. de Campos, R.L. Lichti, K.H. Chow and S.F.J. Cox, *Information on hydrogen states in II-VI semiconductor compounds from a study of their muonium analogues*, Nucl. Instrum. Methods **A580**, 438 (2007).

H.N. Bani-Salameh, A.G. Meyer, B.R. Carroll, R.L. Lichti, Y.G. Celebi, K.H. Chow, P.J.C. King and S.F.J. Cox, *Charge-state* *transitions of muonium in 6H silicon carbide*, Physica **B401**, 631 (2007).

T. Dunlop, A.I. Mansour, Z. Salman, K.H. Chow, I. Fan, J. Jung, R.F. Kiefl, S.R. Kreitman, C.D.P. Levy, W.A. MacFarlane, G.D. Morris and T.J. Parolin, *^{8}Li in GaAs studied with β-NMR*, Physica **B401**, 254 (2007).

I. Fan, K.H. Chow, B. Hitti, R. Scheuermann, A.I. Mansour, R.L. Lichti, W.A. MacFarlane, J. Jung and B.E. Schultz, *Dynamics of diamagnetic muonium: Precession signature in Ge and optical excitation*, Physica **B401**, 624 (2007).

I. Fan, K.H. Chow, R. Scheuermann, B. Hitti, W.A. MacFarlane, B.E. Schultz, A.I. Mansour, J. Jung and R.L. Lichti, *Influence of optical excitation on the precession signature of charged muonium*, Physica **B401**, 635 (2007).

P.J.C. King, R.L. Lichti, B.R. Carroll, Y.G. Celebi, K.H. Chow and I. Yonenaga, *Muonium defect states and ionization energies in SiGe alloys*, Physica **B401**, 617 (2007).

R.L. Lichti, J.E. Vernon, B.R. Carroll, Y.G. Celebi, P.J.C. King and S.F.J. Cox, *Diffusion and trapping of positively charged muonium in InAs*, Physica **B401**, 627 (2007).

A.I. Mansour, G.D. Morris, Z. Salman, K.H. Chow, T. Dunlop, J. Jung, I. Fan, W.A. MacFarlane, R.F. Kiefl, T.J. Paroline, H. Saadaoui, D. Wang, M.D. Hossain, Q. Song, M. Smadella, O. Mosendz, B. Kardasz and B. Heinrich, *Development of the ^{8}Li cross-relaxation technique: applications in semiconductors and other condensed matter systems*, Physica **B401**, 662 (2007).

A.I. Mansour, Z. Salman, I. Fan, P.J.C. King, B. Hitti, S.P. Cottrell, J. Jung and K.H. Chow, *Stability and diffusivity of positively charged muonium in Si*, Physica **B401**, 621 (2007).

K. Tokiwa, S. Mikusu, W. Higemoto, K. Nishiyama, A. Iyo, Y. Tanaka, H. Kotegawa, H. Mukuda, Y. Kitaoka and T. Watanabe, *Muon spin rotation study of magnetism in multilayer $HgBa_2Ca_4Cu_5O_y$ superconductor*, Physica **C460**, 892 (2007).

A.A. Aczel, G.J. MacDougall, J.A. Rodriguez, G.M. Luke, P.L. Russo, A.T. Savici, Y.J. Uemura, H.A. Dabkowska, C.R. Wiebe, J.A. Janik and H. Kageyama, *Impurity-induced singlet breaking in $SrCu_2(BO_3)_2$*, Phys. Rev. **B76**, 214427 (2007).

R. Kadono, S. Kuroiwa, J. Akimitsu, A. Koda, K. Ohishi, W. Higemoto and S. Otani, *Microscopic properties of vortex states in YB_6 probed by muon spin rotation*, Phys. Rev. **B76**, 094501 (2007).

R.L. Lichti, H.N. Bani-Salameh, B.R. Carroll, K.H. Chow, B. Hitti and S.R. Kreitzman, *Donor and acceptor energies for muonium in GaAs*, Phys. Rev. **B76**, 045221 (2007).

K. Ohishi, R.H. Heffner, G.D. Morris, E.D. Bauer, M.J. Graf, J.X. Zhu, L.A. Morales, J.L. Sarrao, M.J. Fluss, D.E. MacLaughlin, L. Shu, W. Higemoto and T.U. Ito, *Muon spin rotation measurements of the superfluid density in fresh and aged superconducting $PuCoGa_5$*, Phys. Rev. **B76**, 064504 (2007).

L. Shu, D.E. MacLaughlin, Y. Aoki, Y. Tunashima, Y. Yonezawa, S. Sanada, D. Kikuchi, H. Sato, R.H. Heffner, W. Higemoto, K. Ohishi, T.U. Ito, O.O. Bernal, A.D. Hillier, R. Kadono, A. Koda, K. Ishida, H. Sugawara, N.A. Frederick, W.M. Yuhasz, T.A. Sayles, T. Yanagisawa and M.B. Maple, *Muon spin relaxation and hyperfine-enhanced ^{141}Pr nuclear spin dynamics in $Pr(Os,Ru)_4Sb_{12}$ and $(Pr,La)Os_4Sb_{12}$*, Phys. Rev. **B76**, 014527 (2007).

J.E. Sonier, F.D. Callaghan, Y. Ando, R.F. Kiefl, J.H. Brewer, C.V. Kaiser, V. Pacradouni, S.A. Sabok-Sayr, X.F. Sun, S. Komiya, W.N. Hardy, D.A. Bonn and R. Liang, *Spin-glass state of individual magnetic vortices in $YBa_2Cu_3O_y$ and $La_{2-x}Sr_xCuO_4$ below the metal-to-insulator crossover*, Phys. Rev. **B76**, 064522 (2007).

J.E. Sonier, S.A. Sabok-Sayr, F.D. Callaghan, C.V. Kaiser, V. Pacradouni, J.H. Brewer, S.L. Stubbs, W.N. Hardy, D.A. Bonn, R. Liang and W.A. Atkinson, *Hole-doping dependence of the magnetic penetration depth and vortex core size in $YBa_2Cu_3O_y$: evidence for stripe correlations near 1/8 hole doping*, Phys. Rev. **B76**, 134518 (2007).

J. Sugiyama, Y. Ikedo, P.L. Russo, H. Nozaki, K. Mukai, D. Andreica, A. Amato, M. Blangero and C. Delmas, *Magnetic nature of K_xCoO_2 near the antiferromagnetic phase with x=0.5: positive muon spin rotation and relaxation*, Phys. Rev. **B76**, 104412 (2007).

Z. Salman, D. Wang, K.H. Chow, M.D. Hossain, S.R. Kreitzman, T.A. Keeler, C.D.P. Levy, W.A. MacFarlane, R.I. Miller, G.D. Morris, T.J. Parolin, H. Saadaoui, M. Smadella and R.F. Kiefl, *Magnetic-field effects on the size of vortices below the surface of $NbSe_2$ detected using low energy β-NMR*, Phys. Rev. Lett. **98**, 167001 (2007).

P.L. Russo, C.R. Wiebe, Y.J. Uemura, A.T. Savici, G.J. MacDougall, J. Rodriguez, G.M. Luke, N. Kaneko, H. Eisaki, M. Greven, O.P. Vajk, S. Ono, Y. Ando, K. Fujita, K.M. Kojima and S. Uchida, *Muon spin relaxation study of superconducting $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (Bi2201)*, Phys. Rev. **B75**, 054511 (2007).

W. Higemoto, S.R. Saha, A. Koda, K. Ohishi, R. Kadono, Y. Aoki, H. Sugawara and H. Sato, *Spin-triplet superconductivity in $PrOs_4Sb_{12}$ probed by muon Knight shift*, Phys. Rev. **B75**, 020510(R) (2007).

Z. Salman, A.I. Mansour, K.H. Chow, M. Beaudoin, I. Fan, J. Jung, T.A. Keeler, R.F. Kiefl, C.D.P. Levy, R.C. Ma, G.D. Morris, T.J. Parolin, D. Wang and W.A. MacFarlane, *β-NMR of isolated ^{8}Li implanted into a thin copper film*, Phys. Rev. **B75**, 73405 (2007).

Y. Ikedo, J. Sugiyama, H. Nozaki, H. Itahara, J.H. Brewer, E.J. Ansaldo, G.D. Morris, D. Andreica and A. Amato, *Spatial in-*

homogeneity of magnetic moments in the cobalt oxide spinel Co_3O_4, Phys. Rev. **B75**, 054424 (2007).

Y.J. Uemura, T. Goko, I.M. Gat-Malureanu, J.P. Carlo, P.L. Russo, A.T. Savici, A. Aczel, G.J. MacDougall, J.A. Rodriguez, G.M. Luke, S.R. Dunsiger, A. McCollam, J. Arai, Ch. Pfleiderer, P. Böni, K. Yoshimura, E. Baggio-Saitovitch, M.B. Fontes, J. Larrea, Y.V. Sushko and J. Sereni, *Phase separation and suppression of critical dynamics at quantum phase transitions of MnSi and $(Sr_{1-x}Ca_x)RuO_3$*, Nature Physics **3**, 29 (2007).

M.D. Bridges, D.J. Arseneau, D.G. Fleming and K. Ghandi, *Hyperfine interactions and molecular motion of the Mu-ethyl radical in faujasites: NaY, HY, and USY*, J. Phys. Chem. **C111**, 9779 (2007).

K. Ghandi, I.P. Clark, J.S. Lord and S.P. Cottrell, *Laser-muon spin spectroscopy in liquids – a technique to study the excited state chemistry of transients*, Phys. Chem. Chem. Phys. **9** 353 (2007).

T.J. Parolin, Z. Salman, J. Chakhalian, Q. Song, K.H. Chow, M.D. Hossain, T.A. Keeler, R.F. Kiefl, S.R. Kreitzman, C.D.P. Levy, R.I. Miller, G.D. Morris, M.R. Pearson, H. Saadaoui, D. Wang and W.A. MacFarlane, *β-NMR of isolated lithium in nearly ferromagnetic palladium*, Phys. Rev. Lett. **98**, 047601 (2007) [TRI-PP-07-12].

Z. Salman, K.H. Chow, R.I. Miller, A. Morello, T.J. Parolin, M.D. Hossain, T.A. Keeler, C.D.P. Levy, W.A. MacFarlane, G.D. Morris, H. Saadaoui, D. Wang, R. Sessoli, G.G. Condorelli and R.F. Kiefl, *Local magnetic properties of a monolayer of Mn_{12} single molecule magnets*, Nano Lett. **7**, 1551 (2007).

K. Ohishi, R.H. Heffner, T.U. Ito, W. Higemoto, G.D. Morris, N. Hur, E.D. Bauer, J.L. Sarrao, J.D. Thompson, D.E. MacLaughlin and L. Shu, *μSR study of the effects of Ce dilution on the development of the heavy fermion state in $(Ce,La)_2IrIn_8$*, J. Phys. Chem. Solids **68**, 2068 (2007).

Z. Salman, D. Wang, K.H. Chow, M.D. Hossain, S.R. Kreitzman, T.A. Keeler, C.D.P. Levy, W.A. MacFarlane, R.I. Miller, G.D. Morris, T.J. Parolin, H. Saadaoui, M. Smadella and R.F. Kiefl, *Giant vortices below the surface of $NbSe_2$ detected using low energy β-NMR*, Phys. Rev. Lett. **98**, 167001 (2007) [arXiv:cond-mat/0703174v1].

T.U. Ito, W. Higemoto, K. Ohishi, T. Fujimoto, R.H. Heffner, N. Nishida, K. Satoh, H. Sugawara, Y. Aoki, D. Kikuchi and H. Sato, *Evolution of local magnetic state in $SmRu_4P_{12}$ probed by muon spin relaxation*, J. Phys. Soc. Jpn. **76**, 053707 (2007).

K. Mukai, Y. Ikedo, H. Nozaki, J. Sugiyama, P.L. Russo, K. Nishiyama, D. Andreica, A. Amato, J.H. Brewer, E.J. Ansaldo, K.H. Chow, K. Ariyoshi and T. Ohzuku, *Magnetic phase diagram in layered cobalt dioxide Li_xCoO_2*, Phys. Rev. Lett. **99**, 087601 (2007).

J. Sugiyama, K. Mukai, Y. Ikedo, P.L. Russo, T. Suzuki, I. Watanabe, J.H. Brewer, E.J. Ansaldo, K.H. Chow, K. Ariyoshi and T. Ohzuku, *Microscopic magnetic and structural nature of spinel $Li[Li_xMn_{2-x}]O_4$*, Phys. Rev. **B75**, 174424 (2007).

H. Nozaki, M. Janoschek, B. Roessli, J. Sugiyama, L. Keller, J.H. Brewer, E.J. Ansaldo, G.D. Morris, T. Takami and H. Ikuta, *Neutron diffraction and μSR study on the antiferromagnet $BaCoO_3$*, Phys. Rev. **B76**, 014402 (2007).

H. Nozaki, M. Janoschek, B. Roessli, J. Sugiyama, L. Keller, J.H. Brewer, E.J. Ansaldo, G.D. Morris, T. Takami and H. Ikuta, *Antiferromagnetic spin structure in $BaCoO_3$ below 15 K determined by neutron and μ^+SR*, J. Phys. Chem. Solids **68**, 2162 (2007).

W.A. MacFarlane, K.H. Chow, A.V. Tkachuk, A. Mar, P.L. Russo, M. Smadella, Q. Song, M. Xu, B. Hitti and D.J. Arseneau, *Local magnetic properties of $Ho_{12}Co_5Bi$ studied by μSR*, J. Phys. Chem. **C111**, 5526 (2007).

J.E. Sonier, *Muon spin rotation studies of electronic excitations and magnetism in the vortex cores of superconductors*, Rep. Prog. Phys. **70**, 1717 (2007).

T.U. Ito, W. Higemoto, K. Ohishi, R.H. Heffner, N. Nishida, K. Satoh, H. Sugawara, Y. Aoki, D. Kikuchi and H. Sato, *Magnetic properties of $SmRu_4P_{12}$ probed by μSR*, J. Phys. Chem. Solids **68**, 2072 (2007).

Molecular and Materials Science – *2008*

M. Xu, M.D. Hossain, H. Saadaoui, T.J Parolin, K.H. Chow, T.A. Keeler, R.F. Kiefl, G.D. Morris, Z. Salman, Q. Song, D. Wang and W.A. MacFarlane, *Proximal magnetometry in thin films using β-NMR*, J. Mag. Res. **191**, 47 (2008).

O.O. Bernal, D.E. MacLaughlin, L. Shu, D.J. Burnette and G.R. Stewart. *Transverse-field μSR and magnetic disorder in UCu_4Ni*, Physica **B403**, 1216 (2008).

T.U. Ito, W. Higemoto, K. Ohishi, R.H. Heffner, N. Nishida, K. Satoh, H. Sugawara, Y. Aoki, D. Kikuchi and H. Sato, *Muon Knight shift measurements in possible octupole ordering system $SmRu_4P_{12}$*, Physica **B403**, 1647 (2008).

D.E. MacLaughlin, L. Shu, R.H. Heffner, J.E. Sonier, F.D. Callaghan, G.D. Morris, O.O. Bernal, W.M. Yuhasz, N.A. Frederick and M.B. Maple, *Multiband superconductivity and penetration depth in $PrOs_4Sb_{12}$*, Physica **B403**, 1132 (2008).

K. Ohishi, R.H. Heffner, T.U. Ito, W. Higemoto, G.D. Morris, E.D. Bauer, M.J. Graf, J.X. Zhu, L.A. Morales, J.L. Sarrao, M.J. Fluss, D.E. MacLaughlin and L. Shu, *Influence of self-irradiation on the magnitude of the superfluid density in $PuCoGa_5$ probed by muon spin rotation*, Physica **B403**, 1013 (2008).

T.A. Keeler, Z. Salman, K.H. Chow, B. Heinrich, M.D. Hossain, B. Kardasz, R.F. Kiefl, S.R. Kreitzman, C. Levy, W.A. MacFarlane, O. Mosendz, T.J. Parolin, M. Pearson and D. Wang, *Hyperfine fields in an Ag/Fe multilayer film investigated with* ^8Li *β-detected NMR*, Phys. Rev. **B77**, 144429 (2008).

Risdiana, T. Adachi, N. Oki, S. Yairi, Y. Tanabe, K. Omori, Y. Koike, T. Suzuki, I. Watanabe, A. Koda and W. Higemoto, *Cu spin dynamics in the overdoped regime of* $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ *probed by muon spin relaxation*, Phys. Rev. **B77**, 054516 (2008).

J. Sugiyama, H. Nozaki, Y. Ikedo, P.L. Russo, K. Mukai, D. Andreica, A. Amato, T. Takami and H. Ikuta, *Muon-spin rotation and relaxation study on the quasi-one-dimensional compounds* Ca_3CoRhO_6, $Sr_4CoRh_2O_9$, *and* $Sr_5CoRh_3O_{12}$, Phys. Rev. **B77**, 092409 (2008).

H. Takeya, K. Ishida, K. Kitagawa, Y. Ihara, K. Onuma, Y. Maeno, Y. Nambu, S. Nakatsuji, D.E. MacLaughlin, A. Koda and R. Kadono, *Spin dynamics and spin freezing behavior in the two-dimensional antiferromagnet* $NiGa_2S_4$ *revealed by Ga-NMR, NQR and μSR measurements*, Phys. Rev. **B77**, 054429 (2008).

R. Kadono, K. Shimomura, K.H. Satoh, S. Takeshita, A. Koda, K. Nishiyama, E. Akiba, R.M. Ayabe, M. Kuba and C.M. Jensen, *Hydrogen bonding in sodium alanate: a muon spin rotation study*, Phys. Rev. Lett. **100**, 026401 (2008).

S. Kuroiwa, Y. Saura, J. Akimitsu, M. Hiraishi, M. Miyazaki, K.H. Satoh, S.. Takeshita and R. Kadono, *Multigap superconductivity in sesquicarbides* La_2C_3 *and* Y_2C_3, Phys. Rev. Lett. **100**, 097002 (2008).

I. Fan, K.H. Chow, B. Hitti, R. Scheuermann, W.A. MacFarlane, A.I. Mansour, B.E. Schultz, M. Egilmez, J. Jung and R.L. Lichti, *Optically induced dynamics of muonium centers in Si studied via their precession signatures*, Phys. Rev. **B77**, 035203 (2008).

W.A. Atkinson and J.E. Sonier, *Role of CuO chains in vortex core structure in* $YBa_2Cu_3O_{7-\delta}$, Phys. Rev. **B77**, 024514 (2008).

Molecular and Materials Science – *submitted*

T.J. Parolin, Z. Salman, K.H. Chow, Q. Song, J. Valiani, H. Saadaoui, A. O'Halloran, M.D. Hossain, T.A. Keeler, R.F. Kiefl, S.R. Kreitzman, C.D.P. Levy, R.I. Miller, G.D. Morris, M.R. Pearson, M. Smadella, D. Wang, M. Xu and W.A. MacFarlane, *High resolution β-NMR study of* $^8Li^+$ *implanted in gold* (submitted to Phys. Rev. B).

T.A. Keeler, Z. Salman, K.H. Chow, B. Heinrich, M.D. Hossain, B. Kardasz, R.F. Kiefl, S.R. Kreitzman, W.A. MacFarlane, O. Mosendz, T.J. Parolin and D. Wang, *Induced hyperfine magentism in a Ag/Fe magnetic multilayer studied with low energy beta-NMR* (submitted to Phys. Rev. Lett.).

K. Mukai, J. Sugiyama, Y. Ikedo, H. Nozaki, J.H. Brewer, E.J. Ansaldo, G.D. Morris, K. Ariyoshi and T. Ohzuku, *Microscopic magnetism in lithium insertion materials of* $LiNi_{1-x}Co_xO_2$ *(x = 0, 1/4, 1/2, 3/4, and 1)* (submitted to J. Power Sources).

K. Mukai, J. Sugiyama, Y. Ikedo, H. Nozaki, K. Shimomura, A. Nishiyama, K. Ariyoshi and T. Ohzuku, *Lithium diffusion and magnetism in* Li_xCoO_2 *by a muon spin rotation/relaxation (μ^+SR) technique* (submitted to J. Power Sources).

J. Sugiyama, Y. Ikedo, J.H. Brewer, K. Mukai, E.J. Ansaldo, G.D. Morris, T. Fujii and A. Asamitsu, *Spin reorientation in* $Na_{0.5}CoO_2$ *confirmed by muon-spin spectroscopy* (submitted to Phys. Rev. Lett.).

J.E. Sonier, F.D. Callaghan, Y. Ando, R.F. Kiefl, J.H. Brewer, C.V. Kaiser, V. Pacradouni, S.A. Sabok-Sayr, X.F. Sun, S. Komiya, W.N. Hardy, D.A. Bonn and R. Liang, *Avoided quantum criticality in* $YBa_2Cu_3O_y$ *and* $La_{2-x}Sr_xCuO_4$ (submitted to Phys. Rev. Lett.) [cond-mat/0610051].

Life Sciences – *2003*

C.-S. Yu, J. Eisenbarth, A. Runz, K. Weber, S. Zeisler and F. Oberdorfer, *Syntheses of 5-(2-radiohaloethyl)- and 5-(2-radiohalovinyl)-2'-deoxyuridines. Novel types of radiotracer for monitoring cancer gene therapy with PET*, J. Lab. Comp. Radiopharm. **46**, 421 (2003).

R.A. Pavan, W.Z. Gelbart and S.K. Zeisler, *Thermal modelling of high current solid targets*, J. Radioanal. Nucl. Chem. **257**, 203 (2003).

S. Zeisler, R.A. Pavan, J. Orzechowski, R. Langlois, S. Rodrigue and J.E. van Lier, *Production of ^{64}Cu on the Sherbrooke TR-PET cyclotron*, J. Radioanal. Nucl. Chem. **257**, 175 (2003).

P.L. McGeer, C. Schwab, A. Parent and D.J. Doudet, *Presence of reactive microglia in monkey substantia nigra years after MPTP administration*, Ann. Neurol. **54**, 599 (2003).

D.J. Doudet and J.E. Holden, *Sequential vs. non-sequential measurement of density and affinity of dopamine D_2 receptors with [^{11}C]raclopride: 1: effect of methamphetamine*, J. Cereb. Blood Flow Metab. **23**, 1489 (2003).

D.J. Doudet, S. Jivan and J.E. Holden, *In vivo measurement of receptor density and affinity: comparison of the routine sequential method with a non sequential method in studies of dopamine D2 receptors with [^{11}C]raclopride*, J. Cereb. Blood Flow Metab. **23**, 280 (2003).

V. Sossi, J.E. Holden, R. de la Fuente-Fernandez, T.J. Ruth and A.J. Stoessl, *The effect of dopamine loss and the metabolite 3-O-methyl-[^{18}F]fluorodopa on the relationship between the*

^{18}*F-fluorodopa tissue input uptake rate constant Kocc and the* ^{18}*F-fluorodopa plasma input uptake rate constant Ki*, J. Cereb. Blood Flow and Metab. **23**, 301 (2003).

V. Sossi, *Positron emission tomography (PET) advances in neurological applications*, Nucl. Instrum. Methods **A510**, 107 (2003).

C.W. Olanow, C.G. Goetz, J.H. Kordower, A.J. Stoessl, V. Sossi, M.F. Brin, K.M. Shannon, G.M. Nauert, D.P. Perl, J. Godbold and T.B. Freeman, *A double-blind controlled trial of bilateral fetal nigral transplantation in Parkinson's disease*, Ann. Neurol. **54**, 403 (2003).

A. Kumar, S. Mann, V. Sossi, T.J. Ruth, A.J. Stoessl, M. Schulzer and C.S. Lee, *[*^{11}*C]DTBZ-PET correlates of levodopa responses in asymmetric Parkinson's disease*, Brain, **126**, 2648 (2003).

A. Kumar, S.N. Silim, M. Okamoto, M.Y. Siddiqi and A.D.M. Glass, *Differential expression of three members of the AMT1 gene family encoding putative high-affinity* NH_4^+ *transporters in roots of Oryza sativa sub species indica*, Plant Cell & Environ. **26**, 907 (2003).

H.J. Kronzucker, M.Y. Siddiqi, A.D.M. Glass and D.T. Britto, *Root ammonium transport efficiency as a determinant in forest colonization patterns: a hypothesis*, Physiol. Plant **117**, 164 (2003).

P. Nazoa, J.J. Vidmar, T.J. Tranbarger, K. Mouline, I. Damiani, P. Tillard, D. Zhuo, A.D.M. Glass and B. Touraine, *Regulation of the nitrate transporter gene AtNRT2.1 in Arabidopsis thaliana: responses to nitrate, amino acids and developmental stage*, Plant Mol. Biol. **52**, 689 (2003).

A.D.M. Glass, *Physiological constraints on nitrogen uptake efficiency*, Critical Reviews in Plant Sciences **22**, 453 (2003).

M. Okamoto, J.J. Vidmar and A.D.M. Glass *Regulation of NRT1 and NRT2 gene families of Arabidopsis thaliana: responses to nitrate provision*, Plant Cell Physiol. **44**, 304 (2003).

A. Studenov, S. Jivan, K.R. Buckley and M.J. Adam, *Efficient in-loop synthesis of high specific radioactivity [*^{11}*C]Carfentanil*, J. Lab. Cmpds. Radiopharm. **46**, 837 (2003).

T.E. Barnhart, A.K. Converse, K.A. Dabbs, R.J. Nickles, K. Buckley, S. Jivan, T.J. Ruth and A.D. Roberts, *Water-cooled grid support system for high power irradiation with thin target windows*, Appl. Radiat. Isotopes **58**, 21 (2003).

A.J. Stoessl and R. de la Fuente-Fernandez, *Dopamine receptors in Parkinson's disease: imaging studies*, Advances in Neurol. **91**, 65 (2003).

R. de la Fuente-Fernandez, A.S. Lim, V. Sossi, M.J. Adam, T.J. Ruth, D.B. Calne, A.J. Stoessl and C.S. Lee, *Age and severity of nigrostriatal damage at onset of Parkinson's disease*, Synapse **47**, 152 (2003).

H. Dougan, J.I. Weitz, A.R. Stafford, K.D. Gillespie, P. Klement, J.B. Hobbs and D.M. Lyster, *Evaluation of DNA aptamers directed to thrombin as potential imaging agents*, Nucl. Med. and Biol. **30**, 61 (2003).

A.J. Stoessl, *Agonizing over dopaminergic replacement therapy – lessons from animal models of Parkinson's disease*, Exp. Neurol. **183**, 1 (2003).

A.L. Whone, R.L. Watts, A.J. Stoessl *et al.*, *Slower progression of Parkinson's disease with ropinirole versus levodopa: the REAL-PET study*, Ann. Neurol. **54**, 93 (2003).

R. de la Fuente-Fernandez, S. Furtado, M. Guttman, Y. Furukawa, C.S. Lee, D.B. Calne, T.J. Ruth, S.J. Kish and A.J. Stoessl, *VMAT2 binding is elevated in dopa-responsive dystonia: visualizing empty vesicles by PET*, Synapse **49**, 20 (2003).

Life Sciences – *2004*

J.E. Holden and D.J. Doudet, *PET receptor assay with multiple ligand concentrations: an equilibrium approach*, Methods in Enzymology: Imaging **385**, 169 (2004).

S.R. Bayly, C.L. Fisher, T. Storr, M.J. Adam and C. Orvig, *Carbohydrate conjugates for molecular imaging and radiotherapy:* ^{99m}*Tc(I) and* ^{186}*Re(I) tricarbonyl complexes of N-(2′-hydroxybenzyl)-2-amino-2-deoxy-D-glucose*, Bioconjugate Chemistry **15**, 923 (2004).

K.R. Buckley, S. Jivan and T.J. Ruth, *Improved yields for the in situ production of [*^{11}*C]*CH_4 *using a niobium target chamber*, Nucl. Med. Biology **31**, 825 (2004).

A.R. Studenov, S. Jivan, M.J. Adam, T.J. Ruth and K.R. Buckley, *Studies of the mechanism of the in-loop synthesis of pharmaceuticals*, Appl. Radiat. Isot. **61**, 1195 (2004).

A. Rahmim, M. Lenox, A.J. Reader, C. Michel, Z. Burbar, T.J. Ruth and V. Sossi, *Statistical list-mode image reconstruction for the high resolution research tomograph*, Phys. Med. Biol. **49**, 4239 (2004).

A. Rahmim, P. Bloomfield, S. Houle, M. Lenox, C. Michel, K.R. Buckley, T.J. Ruth and V. Sossi, *Motion correction in histogram-mode and list-mode EM reconstruction: beyond the event-driven approach*, IEEE Trans. Nucl. Sci. **51**, 2588 (2004).

H. Zaidi and V. Sossi, *Point-counterpoint: correction for image degrading factors is essential for accurate quantification of brain function using PET*, Med. Phys. **31**, 423 (2004).

R. de la Fuente-Fernández, V. Sossi, Z. Huang, S. Furtado, J.-Q. Lu, D.B. Calne, T.J. Ruth and A.J. Stoessl, *Levodopa-induced changes in synaptic dopamine levels increase with progression of Parkinson's disease: implications for Dyskinesias*, Brain **127**, 2747 (2004).

C.S. Lee, M. Schulzer, R. de la Fuente-Fernández, E. Mak, L. Kurtamoto, V. Sossi, T.J. Ruth, D.B. Calne and A.J. Stoessl, *Lack of regional selectivity during the progression in Parkinson's disease: implications for pathogenesis*, Ann. Neurol. **61**, 1920 (2004).

V. Sossi, R. de la Fuente-Fernández, J.E. Holden, M. Schulzer, T.J. Ruth and A.J. Stoessl, *Changes of dopamine turnover in the progression of Parkinson's disease as measured by positron emission tomography: their relation to disease-compensatory mechanisms*, J. Cereb. Blood Flow Metab. **24**, 869 (2004).

D.J. Doudet and J.E. Holden, *[^{11}C]raclopride PET studies of dopamine release by amphetamine: dependence on presynaptic integrity*, Biol. Psychiat. **54**, 1193 (2004).

D.T. Britto, T.J. Ruth, S. Lapi and H.J. Kronzucker, *Cellular and whole-plant chloride dynamics in barley: insights into chloride-nitrogen interactions and salinity responses*, Planta **218**, 615 (2004).

S.E. Unkles, R. Wang, Y. Wang, A.D.M. Glass, N. Crawford and J.R. Kinghorn, *Nitrate reductase is required for nitrate uptake into fungal but not plant cells*, J. Biol. Chem. **279**, 28182 (2004).

Life Sciences – *2005*

M.J. Adam and D.S. Wilbur, *Radiohalogens for imaging and therapy*, RSC Chem. Soc. Rev. **34**, 153 (2005).

T. Storr, Y. Sugai, C.A. Barta, Y. Mikata, M.J. Adam, S. Yano and C. Orvig, *Carbohydrate appended 2,2′-dipicolylamine metal complexes as potential imaging agents*, Inorg. Chem. **44**, 2698 (2005).

T. Storr, C. Fisher, Y. Mikata, S. Yano, M.J. Adam and C. Orvig, *A glucosamine-dipicolylamine conjugate of Tc-99m(I) and Re-186(I) for use in imaging and therapy*, Dalton Transactions 654-655 (2005).

T. Storr, M. Obata, C.L. Fisher, S.R. Bayly, D.E. Green, I. Brudzinska, Y. Mikata, B.O. Patrick, M.J. Adam, S. Yano and C. Orvig, *Novel carbohydrate-appended metal complexes for potential use in molecular imaging*, Chem. Eur. J. **11**, 195 (2005).

D.E. Green, C.L Ferreira, R.V. Stick, B.O. Patrick, M.J. Adam and C. Orvig, *Carbohydrate-bearing 3-hydroxy-4-pyridinonato complexes of gallium(III) and indium(III)*, Bioconjugate Chem. **16**, 1597 (2005).

S.E. Unkles, D.A. Rouch, Y. Wang, M.Y. Siddiqi, M. Okamoto, R.M. Stephenson, J.R. Kinghorn and A.D.M. Glass, *Determination of the essentiality of the eight cysteine residues of the NrtA protein for high-affinity nitrate transport and the generation of a functional cysteine-less transporter*, Biochem. **44**, 5471 (2005).

E.M. Strome, C.M. Clark, A.P. Zis and D.J. Doudet, *Electroconvulsive shock decreases binding to 5-HT2 receptors in nonhuman primates: an in-vivo PET study with [18f]setoperone1*, Biol. Psych. **57**, 1004 (2005).

S. Furtado, V. Sossi, R.A. Hauser, A. Samii, C.B. Murphy, T.B. Freeman and A.J. Stoessl, *Longitudinal study by PET after fetal tissue transplants in Huntington's disease*, Ann. Neurology **58**, 331 (2005).

A. Rahmim, J.C. Cheng, S. Blinder, M-L. Camborde and V. Sossi, *Statistical dynamic image reconstruction in state-of-the-art high resolution PET*, Phys. Med. Biol. **50**, 4887 (2005).

V. Sossi and T.J. Ruth, *Small animal PET imaging: in-vivo biochemistry*, J. Neural Trans. **112**, 319 (2005).

R. Ting, M.J. Adam, T.J. Ruth and D.M. Perrin, *Arylfluoroborates and alkylfluorosilicates as potential PET imaging agents: high yielding aqueous biomolecular ^{18}F-labelling*, J. Am. Chem. Soc. **127**, 13094 (2005).

V. Sossi, G. Tropini, D.J. Doudet, M-L. Camborde, A. Rahmim and T.J. Ruth, *The influence of measurement uncertainties on the evaluation of the distribution volume ratio and binding potential in rat studies on a microPET® R4: a phantom study*, Phys. Med. Biol. **50**, 2859 (2005).

A.R. Studenov, M.J. Adam, J.S. Wilson and T.J. Ruth, *New radiolabelling chemistry: synthesis of phosphorus-[^{18}F]fluorine compounds*, J. Label. Comp. Radiopharm. **48**, 497 (2005).

R. Mungur, A.D.M. Glass, D.B. Goodenow and D.A. Lightfoot, *Metabolite fingerprinting in transgenic Nicotiana tabacum altered by the Escherichia coli glutamate dehydrogenase*, J. Biomed. Biotech. **2005:2**, 198 (2005).

V. Sossi, K.R. Buckley, P. Piccioni, A. Rahmim, M-L. Camborde, S. Lapi, E. Strome and T.J. Ruth, *Printed sources for positron emission tomography (PET)*, IEEE Trans. Nucl. Sci. **52**, 114 (2005).

E.M. Strome, S. Jivan and D.J. Doudet, *Quantitative in-vitro phosphor imaging using [3H] and [18F] radioligands: the effects of chronic desipramine treatment on serotonin 5-HT2 receptors*, J. Neurosci. Methods **141**, 143 (2005).

Life Sciences – *2006*

M. Okamoto, A. Kumar, Y. Wang, W. Li, M.Y. Siddiqi, N.M. Crawford and A.D.M. Glass, *High-affinity nitrate transport in roots of Arabidopsis thaliana depends on expression of the NAR2-like gene AtNRT3.1.*, Plant Physiol. **140**, 1036 (2006).

A. Kumar, B.N. Kaiser, M.Y. Siddiqi, *et al.*, *Functional characterisation of OsAMT1.1 overexpression lines of rice, Oryza sativa*, Functional Plant Biology **33**, 339 (2006).

S.J. Kim, D.J. Doudet, A.R. Studenov, T.J. Ruth, S.S. Gambhir and C.H.S. McIntosh, *Quantitative micro positron emission to-*

mography (PET) for the in vivo determination of pancreatic islet graft survival, Nature Medicine **12**, 1423 (2006).

E.W.K. Young, D.M. Martinez, J.A. Olson, T. Ruth, V. Sossi, K. Buckley and S. Jivan, *Sedimentation of papermaking fibres*, Am. Inst. Chem. Eng. J. **52**, 8 (2006).

M.H. Holzscheiter, N. Bassler, N. Agazaryan, G. Beyer, E. Blackmore, J.J. DeMarco, M. Doser, R.E. Durand, O. Hartley, K.S. Iwamoto, H.V. Knudsen, R. Landua, C. Maggiore, W.H. McBride, S.P. Moller, J. Petersen, L.D. Skarsgard, J.B. Smathers, T.D. Solberg, U.I. Uggerhoj, S. Vranjes, H.R. Withers, M. Wong and B.G. Wouters, *The biological effectiveness of antiproton irradiation*, Radiotherapy and Oncology **81**, 233 (2006).

S.J. Kim, D.J. Doudet, A.R. Studenov, T.J. Ruth, S.S. Gambhir and C.H.S. McIntosh, *Seeing is believing – in vivo functional real-time imaging of transplanted islets using positron emission tomography (PET)*, Nature Protocols 10.1038 (2006).

Life Sciences – *2007*

J.T. Wong, P.T.W. Kim, A.L-F. Mui, S.T. Chung, V. Sossi, D. Doudet, D. Green, T. Ruth, R. Parsons, C.B. Verchere and C.J. Ong, *PTEN haploinsufficiency promotes insulin hypersensitivity*, Diabetes, **50**, 395 (2007).

N. Cauchon, R. Langlois, J.A. Rousseau, G. Tessier, J. Cadorette, R. Lecomte, D.J. Hunting, R.A. Pavan, S.K. Zeisler and J.E. van Lier, *PET imaging of apoptosis with ^{64}Cu-labelled streptavidin following pretargeting of phosphatidylserine with biotinylated annexin-V*, Eur. J. Nucl. Med. **34**, 247 (2007).

J.-C. Cheng, A. Rahmim, S. Blinder, M.-L. Camborde, K. Raywood and V. Sossi, *A scatter corrected list-mode reconstruction and a practical scatter/random approximation technique leading to a dual (histogram/list-mode) reconstruction scheme for dynamic PET imaging*, Phys. Med. Biology **52**, 2089 (2007).

V. Sossi, J.E. Holden, G.S. Topping, M.L. Camborde, R. Kornelsen, S. McCormick, J. Greene, A.R. Studenov, T.J. Ruth and D.J. Doudet, *In vivo measurement of density and affinity of the monoamine vesicular transporter in a unilateral 6-hydroxydopamine rat model of PD*, J. Cereb. Blood Flow Metab. **27**, 1407 (2007).

S. Heath, K. Buckley, D.M. Martinez, S. Lapi, J.A. Olson and T.J. Ruth, *Some observations of the flow of a semi-dilute fibre suspension through a sudden expansion using positron emission tomography*, Amer. Inst. Chem. Eng. **53**, 1 (2007).

E. Vandervoort, M.-L. Camborde, S. Jan and V. Sossi, *Monte Carlo modeling of singles-mode transmission data for small animal PET scanners*, Phys. in Med. and Biol. **52**, 3169 (2007).

W. Li, Y. Wang, M.Y. Siddiqi, S.E. Unkles, J.R. Kinghorn and A.D.M. Glass, *Evidence for post-translational regulation of NRTA, the Aspergillus nidulans high-affinity nitrate transporter*, New Phytologist **175**, 699 (2007).

W. Li, Y. Wang, M. Okamoto, N.M. Crawford, M.Y. Siddiqi and A.D.M. Glass, *Dissection of the* AtNRT2.1:AtNRT2.2 *inducible high-affinity nitrate transporter gene cluster*, Plant Physiol. **143**, 425 (2007).

S. Lapi, J. Wilson, S. McQuarrie, J. Publicover, M. Schueller, D. Schyler, J.J. Ressler and T.J. Ruth, *Measurement of production cross-sections of $^{181-186}$Re isotopes from proton bombardment of natural tungsten*, Appl. Rad. Isotopes **65**, 345 (2007).

Life Sciences – *submitted*

A. Astbury, *Fatal congenital malformations appear to have the same geographical distribution as cancer mortality* (submitted to Int. J. Rad. Biol.) [TRI-PP-07-24].

Y. Wang, W. Li, M.Y. Siddiqi, S.E. Unkles, J.R. Kinghorn and A.D.M. Glass, *Nitrite uptake by NRTA, NRTB and NITA, high-affinity transporters of Aspergillus nidulans* (submitted to Plant Physiology).

A. Astbury, *Cancer mortality rates and the flux of cosmic ray neutrons appear to share some common features* [TRI-PP-06-02].

A. Astbury, *Breast cancer mortality reveals the same geographical distribution within Australia, Brazil, France, and USA* [TRI-PP-06-12].

Theoretical Program – *2003*

B. Davids and S. Typel, *Electromagnetic dissociation of ^{8}B and the astrophysical S factor for ^{7}Be$(p,\gamma)^8$B*, Phys. Rev. **C68**, 045802 (2003).

S. Nakamura, T. Sato, S. Ando, T.-S. Park, F. Myhrer, V. Gudkov and K. Kubodera, *Neutrino-deuteron reactions at solar neutrino energies*, Nucl. Phys. **A721**, 549c (2003).

R.H. Cyburt, B.D. Fields and K.A. Olive, *Primordial nucleosynthesis in light of WMAP*, Phys. Lett. **B567**, 227 (2003) [astro-ph/0302431].

R.H. Cyburt, J. Ellis, B.D. Fields and K.A. Olive, *Updated nucleosynthesis constraints on unstable relic particles*, Phys. Rev. **D67**, 103521 (2003) [astro-ph/0203240].

A. Amghar, B. Desplanques and L. Theussl, *Comparison of form factors calculated with different expressions for the boost transformation*, Nucl. Phys. **A714**, 213 (2003) [nucl-th/0202046].

A. Amghar, B. Desplanques and L. Theussl, *The form factor of the pion in 'point-form' of relativistic dynamics revisited*, Phys. Lett. **B574**, 201 (2003) [hep-ph/0301235].

C. Barbieri and W.H. Dickhoff, *Extension of the random phase approximation including the self-consistent coupling to two phonon contributions*, Phys. Rev. **C68**, 014311 (2003) [nucl-th/0212025].

M.A. Doncheski and S. Godfrey, *Resolved photon contributions to Higgs boson production in gamma-gamma collisions*, Phys. Rev. **D67**, 073021 (2003) [TRI-PP-03-02, hep-ph/0105070].

C.P. Liu, C.H. Hyun and B. Desplanques, *Deuteron anapole moment with heavy mesons*, Phys. Rev. **C68**, 045501 (2003) [nucl-th/0306020].

F.E. Close and S. Godfrey, *Charmonium hybrid production in exclusive B meson decays*, Phys. Lett. **B574**, 210 (2003) [ADP-03-120-T558, TRI-PP-03-04, OUTP-03-13-P, hep-ph/0305285].

M.A. Doncheski, S. Godfrey and S. Zhu, *Measurement of* $\tan\beta$ *in associated $tH^{\pm}$ production in $\gamma\gamma$ collisions*, Phys. Rev. **D68**, 053001 (2003) [TRI-PP-03-05, ADP-02-121-T559, hep-ph/0306126].

J. Al-Khalili, C. Barbieri, J. Escher, B.K. Jennings and J.-M. Sparenberg, *Many body approach to proton emission and the role of spectroscopic factors*, Phys. Rev. **C68**, 024314 (2003) [TRI-PP-03-06, nucl-th/0304055].

C.Q. Geng and C.C. Liu, *Study of $B_s \to (\eta,\ \eta',\ \phi)\ell\bar{\ell}$ decays*, J. Phys. **G29**, 1103 (2003) [hep-ph/0303246].

C.-H. Chen, C.Q. Geng and I.L. Ho, *Forward backward asymmetry in $K^+ \to \pi^+\ell^+\ell^-$*, Phys. Rev. **D67**, 074029 (2003) [hep-ph/0302207].

W.F. Chang and J.N. Ng, *Neutrino masses in 5-D orbifold SU(5) unification models without right handed singlets*, JHEP **0310**, 36 (2003) [hep-ph/0308187].

C.V. Chang, W.F. Chang and J.N. Ng, *Neutrino masses in a 5-D SU(3)(W) TeV unification model*, Phys. Lett. **B558**, 92 (2003) [hep-ph/0301271].

R. Allahverdi, B. Dutta and A. Mazumdar, *Sleptogenesis*, Phys. Rev. **D67**, 123515 (2003) [TRI-PP-03-03, hep-ph/0301184].

M. deMontigny, F.C. Khanna and A.E. Santana, *Lorentz-like covariant equations for non-relativistic fluids*, J. Phys. **A36**, 2009 (2003).

L.M. Abreu, M. de Montigny, F.C. Khanna and A.E. Santana, *Galilei-covariant path-integral quantization of non-relativistic complex scalar fields*, Ann. Phys. **308**, 244 (2003).

U.T. Yakhshiev, A.W. Thomas and F.C. Khanna, *Meson nucleon vertex form-factors at finite temperature using a soft pion form-factor*, Phys. Rev. **C68**, 048201 (2003) [nucl-th/0304020].

M. de Montigny, F.C. Khanna and A.E. Santana, *Gauge symmetry in Fokker-Planck dynamics*, Physica **A323**, 327 (2003) [hep-ph/0301197].

S. Sengupta, F.C. Khanna and S.P. Kim, *Nonequilibrium evolution of correlation functions: a canonical approach*, Phys. Rev. **D68**, 105014 (2003) [hep-ph/0301071].

M. de Montigny, F.C. Khanna and A.E. Santana, *Nonrelativistic wave equations with gauge fields*, Int. J. Theor. Phys. **42**, 649 (2003).

D.U. Matrasulov, F.C. Khanna and H. Yusupov, *Spectra of heavy-light mesons*, J. Phys. **G29**, 475 (2003).

K. Tsushima and F.C. Khanna, *Λ_c^+ and Λ_b hypernuclei*, Phys. Rev. **C67**, 015211 (2003) [nucl-th/0207077].

C.P. Liu, G. Prézeau and M.J. Ramsey-Musolf, *Hadronic parity violation and inelastic electron deuteron scattering*, Phys. Rev. **C67**, 035501 (2003) [nucl-th/0212041].

A.K. Dutt-Mazumder, *Omega meson propagation in dense nuclear matter and collective excitations*, Nucl. Phys. **A713**, 119 (2003) [nucl-th/0207070].

S. Ando, Y.H. Song, T.S. Park, H.W. Fearing and K. Kubodera, *Solar neutrino reactions on deuteron in effective field theory*, Phys. Lett. **B555**, 49 (2003) [USC-NT-02-2, SNUTP-02-014, TRI-PP-02-07, nucl-th/0206001].

R. Lewis, W. Wilcox and R.M. Woloshyn, *The nucleon's strange electromagnetic and scalar matrix elements*, Phys. Rev. **D67**, 013003 (2003) [BU-HEPP-02-10, TRI-PP-02-15, hep-ph/0210064].

G. Rupak and X. Kong, *Quartet S-wave $p-d$ scattering in EFT*, Nucl. Phys. **A717**, 73 (2003) [TRI-PP-01-13, nucl-th/0108059].

Theoretical Program – *2004*

D. Baye and J.-M. Sparenberg, *Inverse scattering with supersymmetric quantum mechanics (Topical Review)*, J. Phys. **A37**, 10223 (2004).

P.C. de Holanda, W. Liao and A.Yu. Smirnov, *Toward precision measurements in solar neutrinos*, Nucl. Phys. **B702**, 307 (2004) [hep-ph/0404042].

P. Capel, G. Goldstein and D. Baye, *Time-dependent analysis of the breakup of ^{11}Be on ^{12}C at 67 MeV/nucleon*, Phys. Rev. **C70**, 064605 (2004).

K. Tsushima and F.C. Khanna, *Λ_c^+, Σ_c, Ξ_c and Λ_b hypernuclei in the meson-quark coupling model*, J. Phys. **G30**, 1765 (2004) [Alberta THy 07-03].

J. Ho, F.C. Khanna and B.C. Choi, *Dynamical invariant method and radiation-spin interaction to calculate magnetisation damping*, Phys. Rev. **B70**, 172402 (2004).

E.S. Santos, M. Montigny, F.C. Khanna and A.E. Santana, *Gauge covariant Lagrangian models*, J. Phys. **A37**, 9771 (2004).

G. Gour, F.C. Khanna, A. Mann and M. Revzen, *Optimisation of Bell's inequality violation for continuous variable systems*, Phys. Lett. **A324**, 415 (2004).

J. Ho, F.C. Khanna and B.C. Choi, *Radiation-spin interaction, Gilbert damping and spin torque*, Phys. Rev. Lett. **92**, 097601 (2004).

M.D. Oliviera, M.C.B. Fernandes, F.C. Khanna, A. Santana and J.D.M. Vianna, *Symplectic quantum mechanics*, Ann. Phys. **312**, 492 (2004).

G. Gour, F.C. Khanna and M. Revzen, *Self adjoint extensions of phase and time operators*, Phys. Rev. **A69**, 014101 (2004).

M. Kobayashi, F.C. Khanna, M. Revzen, A. Mann and A. Santana, *Maximal Bell's inequality violation for non-maximal entanglement*, Phys. Lett. **A323**, 190 (2004).

W.-F. Chang and J.N. Ng, *Phenomenology of a 5-D orbifold SU(3)(W) unification model*, Phys. Rev. **D69**, 056005 (2004) [hep-ph/0312199].

T. Gorringe and H.W. Fearing, *Induced pseudoscalar coupling of the proton weak interaction*, Rev. Mod. Phys. **76**, 31 (2004) [TRI-PP-02-08, nucl-th/0206039].

B. Desplanques and L. Theussl, *Form factors in the 'point form' of relativistic quantum mechanics: single and two-particle currents*, Eur. Phys. J. **A21**, 93 (2004) [LPSC-03-15, hep-ph/0307028].

L. Theussl, S. Noguera and V. Vento, *Generalized parton distributions of the pion in a Bethe-Salpeter approach*, Eur. Phys. J. **A20**, 483 (2004) [nucl-th/0211036].

G. Huey, R.H. Cyburt and B.D. Wandelt, *Precision primordial ^{4}He measurement from the CMB*, Phys. Rev. **D69**, 103503 (2004) [astro-ph/0307080].

R.H. Cyburt, B.D. Fields and K.A. Olive, *Solar neutrino constraints on the BBN production of Li*, Phys. Rev. **D69**, 123519 (2004) [astro-ph/0312629].

C.Q. Geng, I.-L. Ho and T.H. Wu, *Axial-vector form factors for $K_{l2\gamma}$ and $\pi_{l2\gamma}$ at $\mathcal{O}(p^6)$ in chiral perturbation theory*, Nucl. Phys. **B684**, 281 (2004) [hep-ph/0306165].

B. Davids and S. Typel, *Reply to comment on electromagnetic dissociation of ^{8}B and the astrophysical S factor for ^{7}Be$(p,\gamma)^8$B*, Phys. Rev. **C70**, 039802 (2004).

C. Barbieri and L. Lapikas, *Effects of rescattering in $(ee'p)$ reactions within a semiclassical model*, Phys. Rev. **C70**, 054612 (2004) [TRI-PP-04-15, nucl-th/0409032].

R. Allahverdi, R. Brandenberger and A. Mazumdar, *Enhanced reheating via Bose condensates*, Phys. Rev. **D70**, 083535 (2004) [TRI-PP-04-12, hep-ph/0407230].

P.H. Beauchemin, G. Azuelos and C.P. Burgess, *Dimensionless coupling of bulk scalars at the LHC*, J. Phys. **G30**, N17 (2004) [MCGILL-04-12, ATL-COM-PHYS-2004-031, hep-ph/0407196].

B.K. Jennings and K. Maltman, *Z* resonances: phenomenology and models*, Phys. Rev. **D69**, 094020 (2004) [YU-PP-I-E-03-KM-3, hep-ph/0308286].

C.B. Das, S. Das Gupta and B.K. Jennings, *Grand canonical model predictions for nuclear fragmentation*, Phys. Rev. **C70**, 044611 (2004) [nucl-th/0406073].

R.H. Cyburt, B. Davids and B.K. Jennings, *Determination of $S_{17}(0)$ from published data*, Phys. Rev. **C70**, 045801 (2004) [nucl-th/0406011].

Y. Fujiwara, K. Miyagawa, M. Kohno, Y. Suzuki, D. Baye and J.-M. Sparenberg, *Faddeev calculations of 3 α and $\alpha\alpha\Lambda$ systems using $\alpha\alpha$ resonating-group method kernel*, Phys. Rev. **C70**, 024002 (2004) [nucl-th/0404071].

Y. Fujiwara, M. Kohno, K. Miyagawa, Y. Suzuki and J.-M. Sparenberg, *Faddeev calculation of $^{\;6}_{\Lambda\Lambda}$He using SU_6 quark-model baryon-baryon interactions*, Phys. Rev. **C70**, 037001 (2004) [nucl-th/0405056].

R. Allahverdi, *Scenarios of modulated perturbations*, Phys. Rev. **D70**, 043507 (2004) [TRI-PP-04-06, astro-ph/0403351].

J.-M. Sparenberg, *Clarification of the relationship between bound and scattering states in quantum mechanics: application to ^{12}C + α*, Phys. Rev. **C69**, 034601 (2004).

C.P. Liu, C.H. Hyun and B. Desplanques, *Parity nonconservation in the photodisintegration of the deuteron at low-energy*, Phys. Rev. **C69**, 065502 (2004) [nucl-th/0403009].

S. Ando, H.W. Fearing, V. Gudkov, K. Kubodera, F. Myhrer, S. Nakamura and T. Sato, *Neutron beta decay in effective field theory*, Phys. Lett. **B595**, 250 (2004) [TRI-PP-04-05, USC-NT-04-04, nucl-th/0402100].

C. Barbieri, C. Giusti, G.D. Pacati and W.H. Dickhoff, *Effects of nuclear correlations on the ^{16}O$(e,e'pN)$ reactions to discrete final states*, Phys. Rev. **C70**, 014606 (2004) [TRI-PP-04-04, nucl-th/0402081].

W.H. Dickhoff and C. Barbieri, *Self-consistent Green's function method for nuclei and nuclear matter*, Prog. Part. Nucl. Phys. **52**, 377 (2004) [TRI-PP-03-40, nucl-th/0402034].

F. Okiharu and R.M. Woloshyn, *An alternate smearing method for Wilson loops in lattice QCD*, Eur. Phys. J. **C35**, 537 (2004) [hep-lat/0402009].

R. Allahverdi and M. Drees, *Leptogenesis from a sneutrino condensate revisited*, Phys. Rev. **D69**, 103522 (2004) [TRI-PP-04-01, hep-ph/0401054].

R. Allahverdi and M. Drees, *Leptogenesis as the source of gravitino dark matter and density perturbations*, Phys. Rev. **D70**, 123522 (2004) [TRI-PP-04-14, hep-ph/0408289].

R.H. Cyburt, *Primordial nucleosynthesis for the new cosmology: determining uncertainties and examining concordance*, Phys. Rev. **D70**, 023505 (2004) [astro-ph/0401091].

D.H. Wilkinson, *Super-allowed Fermi beta-decay: a further visit*, Nucl. Instrum. Methods **A526**, 386 (2004) [TRI-PP-03-41].

R. Allahverdi, C. Bird, S.G. Nibbelink and M. Pospelov, *Cosmological bounds on large extra dimensions from nonthermal production of Kaluza-Klein modes*, Phys. Rev. **D69**, 045004 (2004) [TRI-PP-03-07, UVIC-TH-05-03, hep-ph/0305010].

N. Knecht, Z. Papandreou, G.J. Lolos, K. Benslama, G.M. Huber, S. Li, V. Bekrenev, W.J. Briscoe, D. Grosnick, D. Isenhower, D.D. Koetke, N.G. Kozlenko, S. Kruglov, D.M. Manley, R. Manweiler, S. McDonald, J. Olmsted, A. Shafi and T.D.S. Stanislaus, *Relative branching ratio of the $\eta \rightarrow \pi^0\gamma\gamma$ decay channel*, Phys. Lett. **B589**, 14 (2004).

Theoretical Program – *2005*

C.H. Hyun, S.J. Lee, J. Haidenbauer and S.W. Hong, *Parity-nonconserving observables in thermal neutron capture on a proton*, Eur. Phys. J. **A24**, 129 (2005).

C.Y. Ryu, C.H. Hyun, J.Y. Lee and S.W. Hong, *Effective mass and decay of Θ^+ in nuclear matter in the quark-meson coupling models*, Phys. Rev. **C72**, 045206 (2005).

W.Y. So, S.W. Hong, B.T. Kim and T. Udagawa, *Extended optical model analyses of elastic scattering, direct reaction, and fusion cross sections for the ^{9}Be + ^{208}Pb system at near-Coulomb-barrier energies*, Phys. Rev. **C72**, 064602 (2005).

S.X. Nakamura, *Consideration of nuclear forces from the viewpoint of the renormalization group – relation of nuclear forces between phenomenological approach and nuclear effective field theory*, Prog. Theor. Phys. **114**, 77 (2005).

S.X. Nakamura, *Explanation of more effective effective field theory*, Prog. Theor. Phys. **114**, 713 (2005).

J.G. Cramer, G.A. Miller, J.M.S. Wu and J.H.S. Yoon, *Quantum opacity, the RHIC HBT puzzle, and the chiral phase transition*, Phys. Rev. Lett. **94**, 102302 (2005) [NT-WU-04-026, nucl-th/0411031].

S.R. Sharpe and J.M.S. Wu, *Twisted mass chiral perturbation theory at next-to-leading order*, Phys. Rev. **D71**, 074501 (2005) [UW-PT-04-20, SHEP-0438, hep-lat/0411021].

A. Walker-Loud and J.M.S. Wu, *Nucleon and delta masses in twisted mass chiral perturbation theory*, Phys. Rev. **D72**, 014506 (2005) [UW-PT-05-07, UW-NT-05-01, hep-lat/0504001].

W.-F. Chang and J.N. Ng, *An effective operators analysis of leptonic CP violation: bridging high and low energy processes*, J. High Energy Phys. **10**, 091 (2005) [hep-ph/0508076].

P. Capel and D. Baye, *Coupling-in-the-continuum effects in Coulomb dissociation of halo nuclei*, Phys. Rev. **C71**, 044609 (2005).

D. Baye, P. Capel and G. Goldstein, *Collisions of halo nuclei within a dynamical eikonal approximation*, Phys. Rev. Lett. **95**, 082502 (2005).

B.K. Jennings, *Projection operator formalisms and the nuclear shell model*, Europhys. Lett. **72**, 211 (2005) [TRI-PP-05-05, nucl-th/0504042].

B.K. Jennings, *The shell model, the renormalization group and the two-body interaction*, Europhys. Lett. **72**, 216 (2005) [TRI-PP-05-06, nucl-th/0504070].

C.S. Lam, *Neutrino 2-3 symmetry and inverted hierarchy*, Phys. Rev. **D71**, 093001 (2005) [hep-ph/0503159].

A.M. Abdel-Rehim, R. Lewis and R.M. Woloshyn, *Spectrum of quenched twisted mass lattice QCD at maximal twist*, Phys. Rev. **D71**, 094505 (2005) [hep-lat/0503007].

A.M. Abdel-Rehim, R. Lewis and R.M. Woloshyn, *Twisted mass lattice QCD and hadron phenomenology*, Int. J. Mod. Phys. **A20**, 6159 (2005).

C.Y. Ryu, C.H. Hyun, S.W. Hong and B.K. Jennings, *Hadron masses in medium and neutron star properties*, Eur. Phys. J. **A24**, 149 (2005) [nucl-th/0503004].

W.-F. Chang and J.N. Ng, *Lepton flavor violation in extra dimension models*, Phys. Rev. **D71**, 053003 (2005) [hep-ph/0501161].

D. Wilkinson, *Super-allowed Fermi beta-decay*, Nucl. Instrum. Methods **A543**, 497 (2005) [TRI-PP-04-17].

D. Wilkinson, *Super-allowed Fermi beta-decay: Unitarity of the CKM matrix*, Nucl. Instrum. Methods **A555**, 457 (2005) [TRI-PP-05-28].

C. Barbieri and B.K. Jennings, *Nucleon-nucleus optical potential in the particle-hole approach*, Phys. Rev. **C72**, 014613 (2005) [TRI-PP-04-26, nucl-th-0501072].

K.Y. Wong and R.M. Woloshyn, *Systematics of staggered fermion spectral properties and topology*, Phys. Rev. **D71**, 094508 (2005) [hep-lat/0412001].

H. Queiroz, J.C. da Silva, F.C. Khanna, J.M.C. Malbouisson, M. Revzen and A.E. Santana, *Thermofield dynamics and Casimir effect for fermions*, Ann. Phys. **317**, 220 (2005) [hep-th/0411228].

E.S. Santos, M. de Montigny and F.C. Khanna, *Canonical quantization of Galilean covariant field theories*, Ann. Phys. **320**, 21 (2005).

A.P.C. Malbouisson, J.M.C. Malbouisson, A.E. Santana and F.C. Khanna, *Critical behaviour of the compactified Ginzburg-Landau model*, Mod. Phys. Lett. **20**, 965 (2005).

C. Barbieri, D. Rohe, I. Sick and L. Lapikas, *Effect of kinematics on final state interactions in (e, e', p) reactions*, Phys. Lett. **B608**, 47 (2005) [TRI-PP-04-19, nucl-th/0411066].

W.-F. Chang and J.N. Ng, *Charged lepton electric dipole moments from TeV scale right-handed neutrinos*, New J. Phys. **7**, 65 (2005) [hep-ph/0411201].

R. Allahverdi, A. Jokinen and A. Mazumdar, *Gravitino production from reheating in split supersymmetry*, Phys. Rev. **D71**, 043505 (2005) [TRI-PP-04-25, NORDITA-2004-80, hep-ph/0410169].

R.H. Cyburt, B.D. Fields, K.A. Olive and E. Skillmann, *New BBN limits on physics beyond the standard model from ^4He*, Astropart. Phys. **23**, 313 (2005) [UMN-TH-2316-04, FTPI-MINN-04-28, astro-ph/0408033].

S. Ando and C.H. Hyun, *Effective field theory on the deuteron with dibaryon field*, Phys. Rev. **C72**, 014008 (2005) [TRI-PP-04-10, nucl-th/0407103].

D.U. Matrasulov, F.C. Khanna, U.R. Salomov and A.E. Santana, *Quantum chaos in the Yang-Mills-Higgs system at finite temperature*, Eur. Phys. J. **C42**, 183 (2005) [hep-ph/0306162].

E.S. Santos, M. de Montigny and F.C. Khanna, *Canonical quantization of Galilean covariant field theories*, Ann. Phys. **320**, 21 (2005).

F.C. Khanna, A.P.C. Malbouisson, J.M.C. Malbouisson, H. Queiroz, T.M. Rocha-Filho, A.E. Santana and J.C. da Silva, *Spatial confinement and thermal deconsignment in the 3d Gross-Neveu model*, Phys. Lett. **B624**, 316 (2005).

Theoretical Program – *2006*

A. Czarnecki, *Particle physics: a finer constant*, Nature **442**, 516 (2006) [TRI-PP-06-10].

E.M.C. Abreu, S.A. Diniz, C. Pinheiro and F.C. Khanna, *Electromagnetic waves, gravitational coupling and duality analysis*, Mod. Phys. Lett. **A21**, 151 (2006).

M. Revzen, F.C. Khanna, A. Mann and J. Zak, *Factorisation and physical representations*, J. Phys.: Math. Theor. **A39**, 5151 (2006).

H.G. Miller, F.C. Khanna, R. Teshima and A. Plastino, *Generalised thermostatics and Bose-Einstein condensate*, Phys. Lett. **A359**, 357 (2006).

D.M. Gingrich, *Black hole cross-section at the Large Hadron Collider*, Int. J. Mod. Phys. **A21**, 6653 (2006) [hep-ph/0609055].

C.-H. Chen and C.-Q. Geng, *Charged Higgs on $B^- \to \tau\overline{\nu}_\tau$ and $\overline{B} \to P(V)\ell\overline{\nu}_\ell$*, JHEP **0610**, 53 (2006) [hep-ph/0608166].

P.T. Reuter, *The complex gap in color superconductivity*, Phys. Rev. **D74**, 105008 (2006) [nucl-th/0608020].

W.-F. Chang, J.N. Ng and J.M.S. Wu, *A very narrow shadow extra Z-boson at colliders*, Phys. Rev. **D74**, 095005 (2006) [hep-ph/0608068].

S.X. Nakamura and S. Ando, *Renormalization group analysis of nuclear current operators*, Phys. Rev. **C74**, 034004 (2006) [TRI-PP-06-08, nucl-th/0606026].

D.U. Matrasulov, F.C. Khanna, Kh.T. Butanov and Kh.Yu. Rakhimov, *Spectra of quarkonia at finite temperature*, Mod. Phys. Lett. **A21**, 1383 (2006) [hep-ph/0606027].

W. Liao, *WZW action in odd dimensional gauge theories*, Phys. Rev. **D74**, 065010 (2006) [hep-th/0605016].

C. Barbieri, *Single particle spectra based on modern effective interactions*, Phys. Lett. **B643**, 268 (2006) [nucl-th/0604005].

S. Ando, J.-W. Chen and C.-W. Kao, *Leading chiral corrections to the nucleon generalized parton distributions*, Phys. Rev. **D74**, 094013 (2006) [hep-ph/0602200].

G. Goldstein, D. Baye and P. Capel, *Dynamical eikonal approximation in breakup reactions of ^{11}Be*, Phys. Rev. **C73**, 024602 (2006).

A.M. Abdel-Rehim, R. Lewis, R.M. Woloshyn and J.M.S. Wu, *Strange quarks in quenched twisted mass lattice QCD*, Phys. Rev. **D74**, 014507 (2006) [hep-lat/0601036].

T. Bhattacharya, R. Gupta, W. Lee, S.R. Sharpe and J.M.S. Wu, *Improved bilinears in lattice QCD with non-degenerate quarks*, Phys. Rev. **D73**, 034504 (2006) [LA-UR-05-8131, hep-lat/0511014].

K.Y. Wong, H.D. Trottier and R.M. Woloshyn, *Perturbative Wilson loops from unquenched Monte Carlo simulations at weak couplings*, Phys. Rev. **D73**, 094512 (2006) [hep-lat/0512012].

G. Goldstein, D. Baye and P. Capel, *Dynamical eikonal approximation in breakup reactions of* ^{11}Be, Phys. Rev. **C73**, 024602 (2006).

P. Capel and F.M. Nunes, *Influence of the projectile description on breakup calculations*, Phys. Rev. **C73**, 014615 (2006) [nucl-th/0601046].

Q. Mason, H.D. Trottier, R. Horgan, C.T.H. Davies and G.P. Lepage, *High-precision determination of the light-quark masses from realistic lattice QCD*, Phys. Rev. **D73**, 114501 (2006) [hep-ph/0511160].

S. Ando and K. Kubodera, *Neutron-neutron fusion*, Phys. Lett. **B633**, 253 (2006) [USC-NT-05-06, TRI-PP-05-25, nucl-th/0507048].

S. Ando, R.H. Cyburt, S.W. Hong and C.H. Hyun, *Radiative neutron capture on a proton at BBN energies*, Phys. Rev. **C74**, 025809 (2006) [TRI-PP-05-29, nucl-th/0511074].

H.X. He and F.C. Khanna, *Transverse Ward-Takahashi relation for the fermion-boson vertex at one-loop order*, J. Mod. Phys. **A21**, 2541 (2006).

R. Allahverdi and A. Mazumdar, *Supersymmetric thermalization and quasi-thermal universe: consequences for gravitinos and leptogenesis*, J. Cosmology Astro. Phys. **10**, 8 (2006) [TRI-PP-06-01, NORDITA-2005-82, hep-ph/0512227].

Theoretical Program – *2007*

R.H. Cyburt, J. Ellis, B.D. Fields, K.A. Olive and V.C. Spanos, *Bound-state effects on light-element abundances in gravitino dark matter scenarios*, J. Cosmology Astro. Phys. **11**, 14 (2007) [CERN-PH-TH-2006-168, UMN-TH-2516-06, FTPI-MINN-06-29, astro-ph/0608562].

P.T. Reuter, *A massive high density effective theory*, Phys. Rev. **D76**, 125022 (2007) [arXiv:0706.0277].

C.-H. Chen, C.-Q. Geng and S.-H. Nam, *Comment on "New physics contributions to the lifetime difference in* $D^0-\overline{D}^0$ *mixing"*, Phys. Rev. Lett. **99**, 019101 (2007) [arXiv:0707.0812].

C.-S. Chen, C.-Q. Geng, J.N. Ng and J.M.S. Wu, *Testing radiative neutrino mass generation at the LHC*, JHEP **0708**, 022 (2007) [arXiv:0706.1964].

D.M. Gingrich, *Missing energy in black hole production and decay at the Large Hadron Collider*, JHEP **0711**, 064 (2007) [arXiv:0706.0623].

C.-Q. Geng, S.H. Ho and J.N. Ng, *Neutrino number asymmetry and cosmological birefringence*, JCAP **0709**, 010 (2007) [arXiv:0706.0080].

Zh. Hao, G.M. von Hippel, R.R. Horgan, Q.J. Mason and H.D. Trottier (HPQCD collaboration), *Unquenching effects on the coefficients of the Lüscher-Weisz action*, Phys. Rev. **D76**, 034507 (2007) [arXiv:0705.4660].

G. Hagen, D.J. Dean, M. Hjorth-Jenson, T. Papenbrock and A. Schwenk, *Benchmark calculations for* ^3H, ^4He, ^{16}O *and* ^{40}Ca *with ab-initio coupled-cluster theory*, Phys. Rev. **C76**, 044305 (2007) [arXiv:0707.1516].

G. Hagen, T. Papenbrock, D.J. Dean, A. Schwenk, A. Nogga, M. Wloch and P. Piecuch, *Coupled-cluster theory for three-body Hamiltonians*, Phys. Rev. **C76**, 034302 (2007) [arXiv:0704.2854].

C.-H. Chen and C.-Q. Geng, *Unparticle physics on direct CP violation*, Phys. Rev. **D76**, 115003 (2007) [arXiv:0705.0689].

C.-H. Chen and C.-Q. Geng, *Unparticle phase effects*, Phys. Rev. **D76**, 036007 (2007) [arXiv:0706.0850].

C.-H. Chen, C.-Q. Geng and T.-C. Yuan, $D-\overline{D}$ *mixing and rare* D *decays in the littlest Higgs model with non-unitarity matrix*, Phys. Lett. **B655**, 50 (2007) [arXiv:0704.0601].

C.-H. Chen, C.-Q. Geng and T.-C. Yuan, $K^+ \to \pi^+\nu\overline{\nu}$ *and* $D^+ \to \pi^+\nu\overline{\nu}$ *decays*, Phys. Rev. **D75**, 077301 (2007) [hep-ph/0703196].

C.-H. Chen, C.-Q. Geng, C.-C. Lih and C.-C. Liu, *Study of* $B \to K_0^*(1430)l\overline{l}$ *decays*, Phys. Rev. **D75**, 074010 (2007) [hep-ph/0703106].

G.A. Miller and A. Schwenk, *Resonant relativistic corrections and the* A_y *problem*, Phys. Rev. **C76**, 024001 (2007) [TRI-PP-06-26, NT-UW-07-04, nucl-th/0703018].

C.Q. Geng, Y.K. Hsiao and J.N. Ng, *Study of* $B \to p\overline{p}K^*$ *and* $B \to p\overline{p}\rho$, Phys. Rev. **D75**, 094013 (2007) [hep-ph/0702249].

W.-F. Chang, J.N. Ng and J.M.S. Wu, *Shadow Higgs from a scale-invariant hidden* $U(1)_s$, Phys. Rev. **D75**, 115016 (2007) [hep-ph/0701254].

C.-H. Chen and C.-Q. Geng, *Expectations on* $B \to (K_0^*(1430), K_2^*(1430))\phi$ *decays*, Phys. Rev. **D75**, 054010 (2007) [hep-ph/0701023].

A.G. Akeroyd, C.-H. Chen and C.-Q. Geng, $B \to \eta^{(\prime)}$ $(l^-\overline{\nu}_l, l^+l^-, K, K^*)$ *decays in the quark-flavor mixing scheme*, Phys. Rev. **D75**, 054003 (2007) [TRI-PP-07-11, hep-ph/0701012].

M. Kobayashi, M. de Montigny and F.C. Khanna, *Galilean covariant theories for Bargmann-Wigner fields with arbitrary spin*, J. Phys. **A40**, 1117 (2007).

E. O'Connor, D. Gazit, C.J. Horowitz, A. Schwenk and N. Barnea, *Neutrino breakup of A = 3 nuclei in supernovae*, Phys. Rev. **C75**, 055803 (2007) [TRI-PP-06-25, nucl-th/0702044].

W.Y. So, T. Udagawa, K.S. Kim, S.W. Hong and B.T. Kim, *Extended optical model analyses of elastic scattering and fusion cross sections for ^{6}Li + ^{208}Pb system at near-Coulomb-barrier energies by using folding potential*, Phys. Rev. **C75**, 024610 (2007) [nucl-th/0612057].

C.-H. Chen and C.-Q. Geng, *Implications of the hyperCP data on B and τ decays*, Phys. Lett. **B645**, 189 (2007) [hep-ph/0612142].

D.M. Gingrich, *Effect of charged partons on black hole production at the Large Hadron Collider*, JHEP **0702**, 98 (2007) [hep-ph/0612105].

K. Hebeler, A. Schwenk and B. Friman, *Dependence of the S(0)-1 superfluid pairing gap on nuclear interactions*, Phys. Lett. **B648**, 176 (2007) [TRI-PP-06-21, nucl-th/0611024].

C.-S. Chen, C.Q. Geng and J.N. Ng, *Unconventional neutrino mass generation, neutrinoless double beta decays, and collider phenomenology*, Phys. Rev. **D75**, 053004 (2007) [hep-ph/0610118].

R.G.G. Amorim, M.C.B. Fernandes, F.C. Khanna, A.E. Santana and J.D.M. Vianna, *Noncommutative geometry and symplectic field theory*, Phys. Lett. **A361**, 464 (2007) [hep-th/0611081].

F.M. Saradzhev, F.C. Khanna, S.P. Kim and M. de Montigny, *A general form of magnetization damping*, Phys. Rev. **B75**, 024406 (2007) [cond-mat/0609431].

S.K. Bogner, R.J. Furnstahl, S. Ramanan and A. Schwenk, *Low-momentum interactions with smooth cutoffs*, Nucl. Phys. **A784**, 79 (2007) [TRI-PP-06-20, nucl-th/0609003].

S.K. Bogner, R.J. Furnstahl, R.J. Perry and A. Schwenk, *Are low-energy nuclear observables sensitive to high-energy phase shifts?*, Phys. Lett. **B649**, 488 (2007) [TRI-PP-06-24, nucl-th/0701013].

C.Q. Geng, Y.K. Hsiao and J.N. Ng, *Direct CP violation in $B^{\pm} \to p\bar{p}K^{(*)\pm}$*, Phys. Rev. Lett. **98**, 011801 (2007) [hep-ph/0608328].

C.-H. Chen and C.-Q. Geng, *η' productions in semileptonic B decays*, Phys. Lett. **B645**, 197 (2007) [TRI-PP-07-19, hep-ph/0608246].

S.-I. Ando and H.W. Fearing, *Ordinary muon capture on a proton in manifestly Lorentz invariant baryon chiral perturbation theory*, Phys. Rev. **D75**, 014025 (2007) [TRI-PP-06-11, hep-ph/0608195].

W. Liao, *Anomaly inflow mechanism using Wilson line*, Phys. Rev. **D75**, 065007 (2007) [TRI-PP-07-13, hep-th/0605134].

P. Capel and F.M. Nunes, *Peripherality of breakup reactions*, Phys. Rev. **C75**, 054609 (2007) [nucl-th/0605081].

D.J. Dean, G. Hagen, M. Hjorth-Jensen, T. Papenbrock and A. Schwenk, *Comment on "Ab initio study of ^{40}Ca with an importance-truncated no-core shell model"*, Phys. Rev. Lett. **99**, 092501 (2007) [arXiv:0709.0449].

S.J. Ferrell, A. Cingöz, A. Lapierre, A.-T. Nguyen, N. Leefer, D. Budker, V.V. Flambaum, S.K. Lamoreaux and J.R. Torgerson, *Investigation of the gravitational potential dependence of the fine-structure constant using atomic dysprosium*, Phys. Rev. **A76**, 062104 (2007) [arXiv:0708.0569].

D.H. Wilkinson, *Super-allowed Fermi beta-decay; the neutron lifetime; G/G*, Nucl. Instrum. Methods **A574**, 1 (2007) [TRI-PP-06-18].

J.D. Holt, N. Pietralla, J.W. Holt, T.T.S. Kuo and G. Rainovski, *Microscopic restoration of proton-neutron mixed symmetry in weakly collective nuclei*, Phys. Rev. **C76**, 034325 (2007) [nucl-th/0612070].

Theoretical Program – *2008*

J.W. Holt, G.E. Brown, T.T.S. Kuo, J.D. Holt and R. Machleidt, *Shell model description of the ^{14}C dating β decay with Brown-Rho-scaled NN interactions*, Phys. Rev. Lett. **100**, 062501 (2008) [arXiv:0710.0310].

R. Foot, A. Kobakhidze, K.L. McDonald and R.R. Volkas, *A solution to the hierarchy problem from an almost decoupled hidden sector within a classically scale invariant theory*, Phys. Rev. **D77**, 035006 (2008) [arXiv:0709.2750].

S.K. Bogner, R.J. Furnstahl, P. Maris, R.J. Perry, A. Schwenk and J.P. Vary, *Convergence in the no-core shell model with low-momentum two-nucleon interactions*, Nucl. Phys. **A801**, 21 (2008) [arXiv:0708.3754].

M. Rozali, H.-H. Shieh, M. Van Raamsdonk and J. Wu, *Cold nuclear matter in holographic QCD*, JHEP **0801**, 053 (2008) [arXiv:0708.1322].

D.M. Gingrich and K. Martell, *Microcanonical treatment of black hole decay at the Large Hadron Collider*, J. Phys. **35**, 035001 (2008) [arXiv:0708.0647].

B. Davids, A. Gruzinov and B.K. Jennings, *Comment on "Influence of protons on the capture of electrons by ^{7}Be in the Sun"*, Phys. Rev. **C77**, 019801 (2008) [arXiv:0705.4669].

M. Kobayashi, M. de Montigny and F.C. Khanna, *An eight-dimensional realization of the Clifford algebra in the five-dimensional Galilean covariant spacetime*, J. Phys. **A41**, 125402 (2008) [arXiv:0710:5556].

A.A. Usmani and F.C. Khanna, *Behaviour of the ΛN and ΛNN potential strengths in the ${}^5_\Lambda He$ hypernucleus*, J. Phys. **G35**, 025105 (2008) [nucl-th/0612004].

Theoretical Program – *submitted*

J. Braun and B. Klein, *Scaling functions for the O(4)-model in d=3 dimensions* [arXiv:0712.3574].

L. Tolos, B. Friman and A. Schwenk, *Neutron matter at finite temperature* [arXive:0711.3613].

S.X. Nakamura and A. Gardestig, *Consistency between renormalization group running of chiral operator and counting rule – case of chiral pion production operator for $NN \to d\pi$* (submitted to Phys. Rev. C) [TRI-PP-07-04].

M. Kobayashi, M. de Montigny and F.C. Khanna, *CPT theorem in a (5+1) Galilean space-time* [arXiv:0710:5557].

B.K. Jennings, B.R. Barrett and B.G. Giraud, *Bounds to binding energies from the concavity of thermodynamical functions* [arXiv:0708.3031].

B.R. Barrett, B.G. Giraud, B.K. Jennings and N.P. Toberg, *Bounds to binding energies from concavity* [arXiv:0707.4096].

B.G. Giraud, B.K. Jennings and B.R. Barrett, *Existence of a density functional for an intrinsic state* [arXiv:0707.3099].

J. Braun, H. Gies and J.M. Pawlowski, *Quark confinement from color confinement* [HD-THEP-07-22, arXiv:0708.2413].

M. de Montigny, F.C. Khanna and F.M. Saradzhev, *Path-integral quantization of Galilean Fermi fields* (submitted to Ann. Phys.) [arXiv:0706.4106].

Conference Publications

Particle, Nuclear and Atomic Physics – *2003*

Y. Itow, T. Kajita, K. Kaneyuki, M. Shiozawa, Y. Totsuka, Y. Hayato, T. Ishida, T. Ishii, T. Kobayashi, T. Maruyama, K. Nakamura, Y. Obayashi, Y. Oyama, M. Sakuda, M. Yoshida, S. Aoki, T. Hara, A. Suzuki, A. Ichikawa, T. Nakaya, K. Nishikawa, T. Hasegawa, K. Ishihara, A. Suzuki and A. Konaka, *The JHF-Kamioka neutrino project*, Proc. **3$^{\rm rd}$ Workshop on Neutrino Oscillations and Their Origin (NOON 2001), Kashiwa, Japan, December 5–8, 2001**, eds. Y. Suzuki *et al.* (World Scientific, Singapore, 2003) p.239 [KEK-REPORT-2001-4, ICRR-REPORT-477-2001-7, TRI-PP-01-05, hep-ex/0106019].

J.M. D'Auria, J. Thomson and M. Comyn, eds., Proc. **14$^{\rm th}$ Int. Conf. on Electromagnetic Isotope Separators and Techniques Related to Their Applications (EMIS-14), Victoria, BC, May 6–10, 2002** (Nucl. Instrum. Methods **B204**, 2003).

A. Shotter, *Advances at ISOL facilities, ibid.* 17 [TRI-PP-02-23].

S. Engel *et al.* (DRAGON collaboration), *Commissioning and operation of DRAGON, ibid.* 154 [TRI-PP-02-21].

M. Dombsky, P. Bricault, P. Schmor and M. Lane, *ISAC target operation with high proton currents, ibid.* 191 [TRI-PP-02-31].

P. Bricault, M. Dombsky, A. Dowling and M. Lane, *High power target developments at ISAC, ibid.* 319 [TRI-PP-02-27].

R. Baartman, *Low energy beam transport design optimization for RIBs, ibid.* 392 [TRI-PP-02-24].

R.E. Laxdal, *Acceleration of radioactive ions, ibid.* 400 [TRI-PP-02-25].

S. Engel, L. Buchmann, A. Chen, J.M. D'Auria, D.A. Hutcheon, C.S. Galovich, D. Gigliotti, U. Greife, D. Hunter, A. Hussein, C.C. Jewett, W. Liu, A. Olin, D. Ottewell and J. Rogers, *Testing the ISAC radioactive ion accelerator beam specifications using the H($^{15}N,\alpha\gamma$)^{12}C reaction, ibid.* 416.

S. Lapi, T.J. Ruth, A. Zyuzin and J.M. D'Auria, *Development of an intense ^{15}O radioactive ion beam using low energy protons, ibid.* 444 [TRI-PP-02-32].

J. Dilling, P. Bricault, M. Smith, H.-J. Kluge *et al.* (TITAN collaboration), *The proposed TITAN facility at ISAC for very precise mass measurements on highly charged short-lived isotopes, ibid.* 492 [TRI-PP-02-30].

J.A. Behr, *Neutral atom traps of radioactives, ibid.* 526 [TRI-PP-02-22].

D. Melconian, D. Ashery, G. Ball, J.A. Behr, P. Bricault, B.A. Brown, M. Dombsky, K.P. Jackson, S. Fostner, A. Gorelov, M.N. Groves, S. Gu, M.R. Pearson, I.S. Towner, M. Trinczek and I. Vollrath, *Measuring isospin mixing in ^{36}Ar using a polarized, neutral atom trap, ibid.* 540 [TRI-PP-02-28].

A.A. Chen *et al.* (DRAGON collaboration), *Results from the development of ionization detection systems for the DRAGON facility, ibid.* 614 [TRI-PP-02-20].

C. Wrede, A. Hussein, J.G. Rogers and J. D'Auria, *A double sided silicon strip detector as a DRAGON end detector, ibid.* 619.

C.E. Svensson, R.A.E. Austin, G.C. Ball, P. Finlay, P.E. Garrett, G.F. Grinyer, G.S. Hackman, C.J. Osborne, F. Sarazin, H.C. Scraggs, M.B. Smith and J.C. Waddington, *Radioactive beam experiments with large gamma-ray detector arrays, ibid.* 660.

D. Gigliotti, J.G. Rogers and A.H. Hussein, *Calibration and simulation of a gamma array for DRAGON at ISAC, ibid.* 671 [TRI-PP-02-19].

R.F. Kiefl, W.A. MacFarlane, P. Amaudruz, D. Arseneau, R. Baartman, T.R. Beal, A. Hatakeyama, B. Hitti, S.R. Kreitzman, C.D.P. Levy, R. Miller, M. Olivo, R. Poutissou, G.D. Morris, S.R. Dunsiger, R. Heffner, K.H. Chow, Y. Hirayama, H. Izumi, C. Bommas, E. Dumont and L.H. Greene, *Low energy spin polarized radioactive beams as a probe of thin films and interfaces, ibid.* 682 [TRI-PP-02-29].

C.D.P. Levy, A. Hatakeyama, Y. Hirayama, R.F. Kiefl, R. Baartman, J.A. Behr, H. Izumi, D. Melconian, G.D. Morris, R. Nussbaumer, M. Olivo, M. Pearson, R. Poutissou and G.W. Wight, *Polarized radioactive beam at ISAC, ibid.* 689 [TRI-PP-02-33].

G.-J. Beyer and T.J. Ruth, *The role of electromagnetic separators in the production of radiotracers for bio-medical research and nuclear medical application, ibid.* 694 [TRI-PP-02-26].

A.B. McDonald *et al.* (SNO collaboration), *Direct evidence for neutrino flavor transformation from neutral-current interactions in SNO*, Proc. **24$^{\rm th}$ Annual Montreal-Rochester-Syracuse-Toronto Conf. on Theoretical Physics (MRST 2002), Waterloo, ON, May 15–17, 2002**, eds. V. Elias *et al.* (AIP Conf. Proc. **646**, Melville, NY, 2003) p.43.

J.-M. Poutissou and K. Yoshimura, *Non-neutrino physics working group summary*, Proc. **4$^{\rm th}$ NuFact'02 Workshop (Neutrino Factories based on Muon Storage Rings), London, UK, July 1–6, 2002** (J. Phys. **G29**, 2003) p.2005.

S.H. Park, A.R. Junghans, E.C. Mohrmann, K.A. Snover, T.D. Steiger, E.G. Adelberger, J.M. Cajandian, H.E. Swanson, L.

Buchmann, A. Zyuzin and A. Laird, *A new measurement of* ^{7}*Be*$(p,\gamma)^8$*B cross section and its astrophysical meaning*, Proc. **7th Int. Symp. on Nuclei in the Cosmos (NIC7), Fuji-Yoshida, Japan, July 8–12, 2002**, eds. S. Kubono *et al.* (Nucl. Phys. **A718**, 2003) p.113.

R.E. Azuma, S. Bishop, L. Buchmann, M.L. Chatterjee, A.A. Chen, J.M. D'Auria, T. Davinson, S. Engel, B.R. Fulton, D. Gigliotti, U. Greife, D. Groombridge, D. Hunter, A. Hussein, D. Hutcheon, C. Jewett, J.D. King, N. Khan, S. Kubono, A.M. Laird, M. Lamey, R. Lewis, L. Ling, W. Liu, S. Michimasa, A.S. Murphy, A. Olin, D. Ottewell, P. Parker, J. Pearson, I. Roberts, A. Robinson, J.G. Rogers, G. Roy, C. Ruiz, F. Sarazin, A.C. Shotter, H. Sprenger, F. Strieder, P. Walden, P.J. Woods and C. Wrede, *Results of* $^{21}Na + p$ *experiments at ISAC, ibid.* 119.

J.C. Blackmon, D.W. Bardayan, W. Bradfield-Smith, R. Brummit, A.E. Champagne, A.A. Chen, T. Davinson, L. Dessieux, M.W. Guidry, K.I. Hahn, G.M. Hale, W.R. Hix, R.L. Kozub, Z. Ma, P.D. Parker, G. Rajbaidya, R.C. Runkle, C.M. Rowland, A.C. Shotter, M.S. Smith, L.A. Van Wormer, D.W. Visser and P.J. Woods, *The* $^{14}O(\alpha,p)^{17}F$ *reaction rate, ibid.* 127.

S. Bishop, R. Azuma, L. Buchmann, A.A. Chen, M.L. Chatterjee, J.M. D'Auria, S. Engel, D. Gigliotti, U. Greife, D. Hunter, A. Hussein, D. Hutcheon, C. Jewett, J. King, S. Kubono, M. Lamey, R. Lewis, W. Liu, S. Michimasa, A. Olin, D. Ottewell, P.D. Parker, J. Rogers and C. Wrede, *Nuclear astrophysics studies at DRAGON: the* ^{21}*Na*$(p,\gamma)^{22}$*Mg reaction and oxygen-neon novae, ibid.* 263.

D.A. Hutcheon, S. Bishop, L. Buchmann, M.L. Chatterjee, A.A. Chen, J.M. D'Auria, S. Engel, D. Gigliotti, U. Greife, D. Hunter, A. Hussein, C. Jewett, N. Khan, A. Lamey, W. Liu, A. Olin, D. Ottewell, J.G. Rogers, G. Roy, H. Sprenger and C. Wrede, *The DRAGON facility for nuclear astrophysics at TRIUMF-ISAC, ibid.* 515.

F. Sarazin, L. Buchmann *et al.* (TUDA collaboration), *(*$^3He,p$*) as an alternative to resonant elastic scattering, ibid.* 556.

S. Michimasa, S. Kubono, S.H. Park, T. Teranishi, Y. Yanagisawa, N. Imai, Zs. Fülöp, X. Liu, T. Minemura, C.C. Yun, J.M. D'Auria and K.P. Jackson, *Study on the* ^{21}*Na*$(p,\gamma)^{22}$*Mg stellar reaction by the* (p,t) *reaction, ibid.* 581.

B. Aubert *et al.* (BaBar collaboration), *A study of the rare decays* $B^0 \to D_s^{(*)+}\pi^-$ *and* $B^0 \to D_s^{(*)-}K^+$, Proc. **31st Int. Conf. on High Energy Physics (ICHEP 2002), Amsterdam, July 24–31, 2002**, eds. S. Bentvelsen *et al.* (Nucl. Phys. Proc. Suppl. **117**, 2003) [SLAC-PUB-9302, BABAR-CONF-02-034, hep-ex/0207053].

B. Aubert *et al.* (BaBar collaboration), *A study of time dependent* CP *asymmetry in* $B^0 \to J/\psi\pi^0$ *decays, ibid.* [SLAC-PUB-9298, BABAR-CONF-02-015, hep-ex/0207058].

B. Aubert *et al.* (BaBar collaboration), *A search for the decay* $B^0 \to \pi^0\pi^0$*, ibid.* [SLAC-PUB-9310, BABAR-CONF-02-32, hep-ex/0207063].

B. Aubert *et al.* (BaBar collaboration), *Measurements of branching fractions and direct* CP *asymmetries in* $\pi^+\pi^0$, $K^+\pi^0$ *and* $K^0\pi^0$ B *decays, ibid.* [SLAC-PUB-9304, BABAR-CONF-02-13, hep-ex/0207065].

B. Aubert *et al.* (BaBar collaboration), *Measurement of the branching fraction for* $B^\pm \to \chi_{c0}K^\pm$*, ibid.* [SLAC-PUB-9316, BABAR-CONF-02-22, hep-ex/0207066].

B. Aubert *et al.* (BaBar collaboration), *Search for* CP *violation in* $B^0\overline{B}^0$ *decays to* $\pi^+\pi^-\pi^0$ *and* $K^\pm\pi^m p\pi^0$ *in regions dominated by the* $\rho^\pm$ *resonance, ibid.* [SLAC-PUB-9303, BABAR-CONF-02-033, hep-ex/0207068].

B. Aubert *et al.* (BaBar collaboration), *A search for* $B^+ \to K^+\nu\overline{\nu}$*, ibid.* [SLAC-PUB-9309, BABAR-CONF-02-027, hep-ex/0207069].

B. Aubert *et al.* (BaBar collaboration), *Measurement of sin2*β *in* $B^0 \to \phi K_s^0$*, ibid.* [SLAC-PUB-9297, BABAR-CONF-02-016, hep-ex/0207070].

B. Aubert *et al.* (BaBar collaboration), *Simultaneous measurement of the* B^0 *meson lifetime and mixing frequency with* $B^0 \to D^{*-}\ell^+\nu_\ell$ *decays, ibid.* [SLAC-PUB-9307, BABAR-CONF-02-21, hep-ex/0207071].

B. Aubert *et al.* (BaBar collaboration), *Measurement of time dependent* CP *asymmetries and the* CP *odd fraction in the decay* $B^0 \to D^{*+}D^{*-}$*, ibid.* [SLAC-PUB-9299, BABAR-CONF-02-14, hep-ex/0207072].

B. Aubert *et al.* (BaBar collaboration), *Search for the exclusive radiative decays* $B \to \rho\gamma$ *and* $B^0 \to \omega\gamma$*, ibid.* [SLAC-PUB-9319, BABAR-CONF-02-024, hep-ex/0207073].

B. Aubert *et al.* (BaBar collaboration), $b \to s\gamma$ *using a sum of exclusive modes, ibid.* [SLAC-PUB-9308, BABAR-CONF-02-25, hep-ex/0207074].

B. Aubert *et al.* (BaBar collaboration), *Determination of the branching fraction for inclusive decays* $B \to X_s\gamma$*, ibid.* [SLAC-PUB-9301, BABAR-CONF-02-026, hep-ex/0207076].

B. Aubert *et al.* (BaBar collaboration), *Measurement of* $B^0 \to D_s^{(*)+}D^{*-}$ *branching fractions and polarization in the decay* $B^0 \to D_s^{*+}D^{*-}$ *with a partial reconstruction technique, ibid.* [SLAC-PUB-9321, BABAR-CONF-02-20, hep-ex/0207079].

B. Aubert *et al.* (BaBar collaboration), *Measurement of the CKM matrix element* $|V_{ub}|$ *with charmless exclusive semileptonic* B *meson decays at BABAR, ibid.* [SLAC-PUB-9305, BABAR-CONF-02-030, hep-ex/0207080].

B. Aubert *et al.* (BaBar collaboration), *Measurement of the inclusive electron spectrum in charmless semileptonic* B *decays* *near the kinematic endpoint, ibid.* [SLAC-PUB-9282, BABAR-CONF-02-012, hep-ex/0207081].

B. Aubert *et al.* (BaBar collaboration), *Evidence for the flavor changing neutral current decays $B \to K\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$, ibid.* [SLAC-PUB-9323, BABAR-CONF-02-023, hep-ex/0207082].

B. Aubert *et al.* (BaBar collaboration), *Search for decays of B^0 mesons into pairs of leptons, ibid.* [SLAC-PUB-9313, BABAR-CONF-02-028, hep-ex/0207083].

B. Aubert *et al.* (BaBar collaboration), *Measurement of the first hadronic spectral moment from semileptonic B decays, ibid.* [SLAC-PUB-9314, BABAR-CONF-02-029, hep-ex/0207084].

B. Aubert *et al.* (BaBar collaboration), *Measurement of the $B^0 \to D^{*-}a_1^+$ branching fraction with partially reconstructed D^*, ibid.* [SLAC-PUB-9315, BABAR-CONF-02-010, hep-ex/0207085].

B. Aubert *et al.* (BaBar collaboration), *Measurement of the branching fractions for the exclusive decays of B^0 and B^+ to $\overline{D}^{(*)}D^{(*)}K$, ibid.* [SLAC-PUB-9322, BABAR-CONF-02-19, hep-ex/0207086].

B. Aubert *et al.* (BaBar collaboration), *Measurement of the branching ratios and CP asymmetries in $B^- \to D^0_{(CP)}K^-$ decays, ibid.* [SLAC-PUB-9311, BABAR-CONF-02-18, hep-ex/0207087].

B. Aubert *et al.* (BaBar collaboration), *Dalitz plot analysis of D^0 hadronic decays $D^0 \to K^0K^-\pi^+$, $D^0 \to \overline{K}^0K^+\pi^-$ and $D^0 \to \overline{K}^0K^+K^-$, ibid.* [SLAC-PUB-9320, BABAR-CONF-02-031, hep-ex/0207089].

B. Aubert *et al.* (BaBar collaboration), *Measurement of branching fractions of color suppressed decays of the $\overline{B}^0$ meson to $D^0\pi^0$, $D^0\eta$, and $D^0\omega$, ibid.* [SLAC-PUB-9324, BABAR-CONF-02-17, hep-ex/0207092].

R. Carnegie, M. Dixit, H. Mes, A. Rankin, K. Sachs, D. Karlen and J.-P. Martin, *GEM TPC R&D in Canada*, Proc. **Int. Workshop on Physics and Experiments with Future Electron-Positron Linear Colliders (LCWS2002), Jeju Island, Korea, August 27, 2002** (Korean Phys. Soc., 2003) p.444.

S.I. Penttila, J.D. Bowman, R.D. Carlini, T. Case, T.E. Chupp, K.P. Coulter, S.J. Freedman, T.R. Gentile, M. Gericke, G.L. Greene, B. Hersmann, S. Ishimoto, G.L. Jones, M.B. Leuschner, Y. Masuda, G.S. Mitchell, K. Morimoto, H. Nann, S.A. Page, W.D. Ramsay, E.I. Sharapov, T.B. Smith, W.M. Snow, W.S. Wilburn and V.W. Yuan, *A measurement of the parity-violating gamma-ray asymmetry in neutron-proton capture*, Proc. **11$^{\mathbf{th}}$ Int. Symp. Capture Gamma-Ray Spectroscopy and Related Topics, Prague, Czech Republic, September 2–6, 2002**, eds. J. Kvasil, P. Cejnar and M. Krticka (World Scientific, Singapore, 2003) p.604.

C.A. Miller, *Semi-inclusive deep inelastic scattering*, Proc. **15$^{\mathbf{th}}$ Int. Spin Physics Symp. (SPIN 2002), Long Island, NY, September 9–14, 2002**, eds. Y.I. Makdisi *et al.* (AIP Conf. Proc. **675**, 2003) p.23 [DESY-HERMES-02-56].

W.D. Ramsay, *Parity violation in pp and np experiments, ibid.* 196 [TRI-PP-02-16, nucl-ex/0210008].

P.P.J. Delheij, W.T.H. van Oers, A.N. Zelenski *et al.*, *Spin at U-70: an experiment to measure the analyzing power A_N in very-high-p_t^2 pp elastic scattering at 70 GeV, ibid.* 538.

M. Abe, M. Aliev, V. Anisimovsky, M. Aoki, Y. Asano, T. Baker, M. Blecher, P. Depommier, M. Hasinoff, K. Horie, Y. Igarashi, J. Imazato, A. Ivashkin, M. Khabibullin, A. Khotjantsev, Yu. Kudenko, Y. Kuno, K.S. Lee, A. Levchenko, Y.-M. Shin, N. Yershov and T. Yokoi, *Further search for T violation in the decay $K^+ \to \pi^0\mu^+\nu$*, Proc. **16$^{\mathbf{th}}$ Int. Conf. on Particles and Nuclei (PANIC 02), Osaka, Japan, September 30 – October 4, 2002** (Nucl. Phys. **A721**, 2003) p.445 [hep-ex/0211049].

J.-M. Poutissou *et al.* (TWIST collaboration), *The TWIST experiment (TRIUMF weak interaction symmetry test), ibid.* 465.

Y. Masuda, J.D. Bowman, R.D. Carlini, T. Case, T.E. Chupp, K.P. Coulter, S.J. Freedman, T.R. Gentile, M. Gericke, G.L. Greene, F.W. Hersmann, T. Ino, S. Ishimoto, G.L. Jones, M.B. Leuschner, G.S. Mitchell, K. Morimoto, S. Muto, H. Nann, S.A. Page, S.I. Penttila, W.D. Ramsay, E.I. Sharapov, T.B. Smith, W.M. Snow, S.W. Wilburn and Y.W. Yuan, *Parity-violating gamma-ray asymmetry in the neutron-proton capture, ibid.* 485.

T. Numao, T. Awes, S. Berridge, W. Bugg, V. Cianciolo, Y. Davydov, Y. Efremenko, R. Gearhart, Y. Kamyshkov, S. Ovchinnikov, J.-M. Poutissou and G. Young, *π^- absorption in water and light material, ibid.* 491.

R. Meier *et al.* (CHAOS and LEPS collaborations), *Pion-proton scattering at TRIUMF and PSI, ibid.*, 649.

A. Olin, S. Bishop, L. Buchmann, M.L. Chatterjee, A. Chen, J.M. D'Auria, S. Engel, D. Gigliott, U. Griefe, D. Hunter, A. Hussein, D. Hutcheon, C. Jewett, J. King, S. Kubono, M. Lamey, A.M. Laird, R. Lewis, W. Liu, S. Michimasa, D. Ottewell, P. Parker, J. Rogers, F. Strieder and C. Wrede, *Nuclear astrophysics at ISAC with DRAGON: initial studies, ibid.* 1019.

A. Shotter, *Nuclear astrophysics with radioactive beams: a TRIUMF perspective*, Proc. **17$^{\mathbf{th}}$ Int. Nuclear Physics Divisional Conf. of the European Physical Society (NPDC-17), Budapest, Hungary, September 30–October 4, 2002** (Nucl. Phys. **A719**, 2003) p.240.

A. Shotter, *ISAC at TRIUMF: status and future*, Proc. **3$^{\mathbf{rd}}$ Int. Conf. on Fission and Properties of Neutron-Rich Nuclei, Sanibel Island, FL, November 3–9, 2002**, eds. J.H. Hamilton *et al.* (World Scientific, Singapore, 2003).

H.A. Schuessler, F. Buchinger and H. Iimura, *Laser spectroscopy of short lived rare earth isotopes*, Proc. **17$^{\mathbf{th}}$ Int. Conf. on the Application of Accelerators in Research and Industry**

(CAARI), Denton, TX, November 12–16, 2002, eds. J.L. Duggan and I.L. Morgan (AIP Conf. Proc. **680**, Melville, NY, 2003) p.223.

A.A. Chen *et al.*, *Measurement of the* $^{21}Na(p,\gamma)^{22}Mg$ *reaction with the DRAGON facility at TRIUMF-ISAC, ibid.* 237.

J. Dilling *et al.* (TITAN collaboration), *The proposed TITAN facility at TRIUMF: a next generation Penning trap mass spectrometer for highly charged ions, ibid.*

C.A. Miller, *Nucleon spin physics: experimental status*, Proc. **APS Meeting, Philadelphia, PA, April 5–8, 2003**, (Bull. Am. Phys. Soc. **48**, H2.004, 2003).

Particle, Nuclear and Atomic Physics – *2004*

C. Maggiore, N. Agazaryan, N. Bassler, E. Blackmore, G. Beyer, J.J. DeMarco, M. Doser, C.R. Gruhn, M.H. Holzscheiter, T. Ichioka, K.S. Iwamoto, H.V. Knudsen, R. Landua, W.H. McBride, S.P. Meller, J. Petersen, J.B. Smathers, L.D. Skarsgard, T.D. Solberg, U.I. Uggerhoj, H.R. Withers and B.G. Wouters, *Biological effectiveness of antiproton annihilation*, Proc. **7th Int. Conf. on Low-Energy Antiproton Physics (LEAP 03), Yokohama, Japan, March 3–7, 2003** (Nucl. Instrum. Methods **B214**, 2004). p.181.

R.K. Carnegie, M.S. Dixit, H. Mes, E. Neuheimer, A. Rankin, K. Sachs and J.-P. Martin, *First tracking experience for MPGD TPC readout with charge dispersion on a resistive anode*, Proc. **Int. Conf. on Linear Colliders (LCWS2004), Paris, France, April 19–23, 2003** (Paris, 2004) p.705.

D.S. Armstrong, T.D. Averett, J. Birchall, J.D. Bowman, R.D. Carlini, S. Chattopadhyay, C.A. Davis, J. Doornbos, J.A. Dunne, R. Ent, J. Erler, W.R. Falk, J.M. Finn, T.A. Forest, D.J. Gaskell, K.H. Grimm, C. Hagner, F.W. Hersman, M. Holtrop, K. Johnston, R.T. Jones, K. Joo, C. Keppel, E. Korkmaz, S. Kowalski, L. Lee, A. Lung, D. Mack, S. Majewski, G.S. Mitchell, H. Mkrtchyan, N. Morgan, A.K. Opper, S.A. Page, S.I. Penttila, M. Pitt, M. Poelker, T. Porcelli, W.D. Ramsay, M.J. Ramsey-Musolf, J. Roche, N. Simicevic, G.R. Smith, R. Suleiman, S. Taylor, W.T.H. van Oers, S.B. Wells, W.S. Wilburn, S.A. Wood and C. Zorn (Qweak collaboration), *Qweak: a precision measurement of the proton's weak charge*, Proc. **8th Conf. on the Intersections of Particle and Nuclear Physics (CIPANP 2003), New York, NY, May 19–24, 2003**, ed. Z. Parsa (AIP Conf. Proc. **698**, New York, 2004) p.172 [LA-UR-03-6031, hep-ex/0308049].

C.A. Gagliardi, *TWIST: measuring the space-time structure of muon decay, ibid.* 234.

P. Kitching *et al.* (TWIST collaboration), *A precision measurement of* μ^+ *decay*, Proc. **5th Int. Workshop on Neutrino Factories and Superbeams (NuFact03), New York, NY, June 5–11, 2003** (AIP **721**, 2004) p.301.

W.D. Ramsay, *Selected parity violation experiments*, Proc. **Advanced Study Inst. on Symmetries and Spin (SPIN-PRAHA-2003), Prague, Czech Republic, July 12–19, 2003** (Czech. J. Phys. **54**, 2004), p.B207 [TRI-PP-04-02, nucl-ex/0401028].

M. Dombsky, P. Bricault and V. Hanemaayer, *Increasing beam currents at the TRIUMF-ISAC facility; techniques and experiences*, Proc. **6th Int. Conf. on Radioactive Nuclear Beams (RNB6), Argonne, IL, September 22–26, 2003** (Nucl. Phys. **A746**, 2004) p.32 [TRI-PP-03-35].

Y. Hirayama, T. Shimoda, H. Izumi, H. Yano, M. Yagi, A. Hatakeyama, C.D.P. Levy, K.P. Jackson and H. Miyatake, *Structure of* ^{11}*Be studied in* β*-delayed neutron and* γ*-decay from polarized* ^{11}*Li, ibid.* 71.

C.D.P. Levy, R. Baartman, J.A. Behr, R.F. Kiefl, M. Pearson, R. Poutissou, A. Hatakeyama and Y. Hirayama, *The collinear laser beam line at ISAC, ibid.* 206 [TRI-PP-03-36].

D. Hutcheon *et al.* (DRAGON collaboration), *Study of* $^{21}Na(p,\gamma)^{22}Mg$ *using the DRAGON separator, ibid.* 359 [TRI-PP-03-37].

K. Minamisono, K. Matsuta, T. Minamisono, C.D.P. Levy, T. Nagatomo, M. Ogura, T. Sumikama, J.A. Behr and K.P. Jackson, *Quadrupole moments of* ^{20,21}*Na, ibid.* 501.

M.B. Smith, P.M. Walker, R.S. Chakrawarthy, R.A.E. Austin, G.C. Ball, J.J. Carroll, E. Cunningham, P. Finlay, P.E. Garrett, G.F. Grinyer, G. Hackman, B. Hyland, K. Koopmans, W.D. Kulp, J.R. Leslie, A.A. Phillips, R. Propri, P.H. Regan, F. Sarazin, M.A. Schumaker, H.C. Scraggs, T. Shizuma, C.E. Svensson, J. von Schwarzenberg, J.C. Waddington, D. Ward, J.L. Wood, B. Washbrook and E.F. Zganjar, *Studies of high-K isomers at TRIUMF-ISAC, ibid.* 617.

K. Minamisono, K. Matsuta, T. Minamisono, C.D.P. Levy, T. Nagatomo, M. Ogura, T. Sumikama, J.A. Behr, K.P. Jackson, H. Fujiwara, M. Mihara and M. Fukuda, *Alignment correlation term in the* β*-ray angular distribution from spin aligned* ^{20}*Na, ibid.* 673.

J. Lu *et al.* (HERMES collaboration), *Exclusive deeply inelastic electroproduction at HERMES*, Proc. **3rd Int. Symp. on the Gerasimov-Drell-Hearn Sum Rule and its Extensions (GDH 2004), Norfolk, VA, June 2–5, 2004** (Norfolk, 2004) p.216.

T. Numao, P. Amaudruz, D.A. Bryman, R. Henderson, N. Khan, C. Lim, J.A. MacDonald and H. Tam, *Development of multi-hole extruded scintallator*, Proc. **KEK-RCNP Int. School and Mini-workshop for Scintillating Crystals and their Applications in Particle and Nuclear Physics, Tsukuba, Japan, November 17–18, 2003** (KEK, Tsukuba, 2004) p.179.

M. Agnello *et al.* (FINUDA collaboration), *First results of FINUDA on hypernuclear spectroscopy*, Proc. **Workshop on Physics at Meson Factories (DAΦNE 2004), Frascati, Italy, June 7–11, 2004** (Frascati 2004, DAPHNE 2004) p.189.

M. Agnello *et al.* (FINUDA collaboration), *First observations of hypernuclear non mesonic weak decays with FINUDA, ibid.* 195.

M. Agnello *et al.* (FINUDA collaboration), *Search for neutron rich hypernuclei in FINUDA: preliminary results, ibid.* 201.

M. Agnello *et al.* (FINUDA collaboration), *Examining sigma-bound states with FINUDA, ibid.* 209.

M. Agnello *et al.* (FINUDA collaboration), *Search for deeply-bound kaonic nuclei at FINUDA, ibid.* 225.

D.R. Gill (TWIST collaboration) *TWIST: TRIUMF weak interaction symmetry test, ibid.* 427.

G. Abbiendi *et al.* (OPAL collaboration), *Multi-photon events with large missing energy in e^+e^- collisions at $\sqrt{s}$ = 192-209 GeV*, Proc. **2nd High-Energy Physics Conf. in Madagascar, Antananarivo, Madagascar, September 27–October 3, 2004** (eConf C0409272:012; Phys. Lett. **B602**, 2004), p.167 [CERN-PH-EP-2004-035, hep-ex/0412011].

Particle, Nuclear and Atomic Physics – *2005*

A. Konaka, *The JHFNU experiment and the systematic uncertainties*, Proc. **8th Int. Workshop on Topics in Astroparticle and Underground Physics (TAUP 2003), Seattle, WA, September 5–9, 2003**, eds. F. Avignone and W. Haxton (Nucl. Phys. **B138**, 2005) p.415.

H.S. Matis, F. Bieser, Y. Chen, R. Gareus, S. Kleinfelder, M. Oldenburg, F. Retiere, H.G. Ritter, H.H. Wieman, S.E. Wurzel and E. Yamamoto, *Using an active pixel sensor in a vertex detector*, Proc. **12th Int. Conf on Vertex Detectors (VERTEX 2003), Lake Windermere, UK, September 14–19, 2003**, ed. S.J. Watts (Nucl. Instrum. Methods **A549**, 2005) p.130.

M. Agnello, G. Beer, L. Benussi, M. Bertani, S. Bianco, E. Botta, T. Bressani, L. Busso, D. Calvo, P. Camerini, P. Cerello, B. Dalena, F. De Mori, A. D'Erasmo, D. Di Santo, F.L. Fabbri, D. Faso, A. Feliciello, A. Filippi, V. Filippini, E.M. Fiore, H. Fujioka, P. Gianotti, N. Grion, A. Krasnoperov, V. Lucherini, S. Marcello, T. Maruta, N. Mirfakhrai, O. Morra, A. Olin, E. Pace, M. Pallotta, M. Palomba, A. Pantaleo, A. Panzarasa, V. Paticchio, S. Piano, F. Pompili, R. Rui, G. Simonetti, H. So, S. Tomassini, R. Wheadon and A. Zenoni, *First results from the FINUDA experiment at DAΦNE*, Proc. **VIII Int. Conf. on Hypernuclear and Strange Particle Physics, Newport News, VA, October 14–18, 2003** (Nucl. Phys. **A754**, 2005) p.399 [LNF-03/23].

A. Astbury, B.A. Campbell, F.C. Khanna and M.G. Vincter, eds., Proc. **Lake Louise Winter Institute: Fundamental Interactions (LLWI04), Lake Louise, AB, February 15–21, 2004** (World Scientific, Hackensack, NJ, 2005).

B. Jamieson *et al.* (TWIST collaboration), *Status of the TWIST measurement of $P_\mu\xi$, ibid.* p.195.

R. MacDonald *et al.* (TWIST collaboration), *Precision measurement of the muon decay spectrum, ibid.* 225.

P.N. Seo, J.D. Bowman, M. Gericke, R.C. Gillis, G.L. Greene, M.B. Leuschner, J. Long, R. Mahurin, G.S. Mitchell, S.I. Penttila, G. Peralta, E.I. Sharapov and W.S. Wilburn, *A new pulsed cold neutron beam for fundamental nuclear physics at LANSCE*, Proc. **Int. Conf. on Precision Measurements with Slow Neutrons, Gaithersburg, MD, April 5–7, 2004** (J. Res. Nat. Inst. Stand. Technol. **110**, 2005) p.145.

S.A. Page, J.D. Bowman, R.D. Carlini, T. Case, T.E. Chupp, K.P. Coulter, M. Dabaghyan, D. Desai, S.J. Freedman, T.R. Gentile, M.T. Gericke, R.C. Gillis, G.L. Greene, F.W. Hersman, T. Ino, S. Ishimoto, G.L. Jones, B. Lauss, M.B. Leuschner, B. Losowski, R. Mahurin, Y. Masuda, G.S. Mitchell, H. Nann, S.I. Penttila, W.D. Ramsay, S. Santra, P.-N. Seo, I.I. Sharapov, T.B. Smith, W.M. Snow, W.S. Wilburn, V. Yuan and H. Zhu, *Measurement of parity violation in np capture: the NPDGamma experiment, ibid.* 195.

M.T. Gericke, J.D. Bowman, R.D. Carlini, T.E. Chupp, K.P. Coulter, M. Dabaghyan, D. Desai, S.J. Freedman, T.R. Gentile, R.C. Gillis, G.L. Greene, F.W. Hersman, T. Ino, S. Ishimoto, G.L. Jones, B. Lauss, M.B. Leuschner, B. Losowski, R. Mahurin, Y. Masuda, G.S. Mitchell, S. Muto, H. Nann, S.A. Page, S.I. Penttila, W.D. Ramsay, S. Santra, P.-N. Seo, E.I. Sharapov, T.B. Smith, W.M. Snow, W.S. Wilburn, V. Yuan and H. Zhu, *Commissioning of the NPDGamma detector array: counting statistics in current mode operation and parity violation in the capture of cold neutrons on B_4C and ^{27}Al, ibid.* 215.

M. Bertani, M. Agnello, G. Beer, L. Benussi, S. Bianco, E. Botta, T. Bressani, L. Busso, D. Calvo, P. Camerini, P. Cerello, B. Dalena, F. De Mori, A. D'Erasmo, D. Di Santo, F.L. Fabbri, D. Faso, A. Feliciello, A. Filippi, V. Filippini, E.M. Fiore, H. Fujioka, P. Gianotti, N. Grion, A. Krasnoperov, V. Lucherini, S. Marcello, T. Maruta, N. Mirfakhrai, O. Morra, A. Olin, E. Pace, M. Pallotta, M. Palomba, A. Pantaleo, A. Panzarasa, V. Paticchio, S. Piano, F. Pompili, R. Rui, G. Simonetti, H. So, S. Tomassini, R. Wheadon and A. Zenoni, *First hypernuclear results from the FINUDA experiment at DAΦNE*, Proc. **8th Int. Workshop on Meson Production, Properties and Interaction (MESON04), Kraków, Poland, June 4–8, 2004**, eds. S. Kistryn *et al.* (Int. J. Mod. Phys. **A20**, 2005) p.310.

D.S. Armstrong, T.D. Averett, J. Birchall, J.D. Bowman, R.D. Carlini, S. Chattopadhyay, C.A. Davis, J. Doornbos, J.A. Dunne, R. Ent, J. Erler, W.R. Falk, J.M. Finn, T.A. Forest, D.J. Gaskell, K.H. Grimm, C. Hagner, F.W. Hersman, M. Holtrop, K. Johnston, R.T. Jones, K. Joo, C. Keppel, E. Korkmaz, S. Kowalski, L. Lee, A. Lung, D. Mack, S. Majewski, G.S. Mitchell, H. Mkrtchyan, N. Morgan, A.K. Opper, S.A. Page, S.I. Penttila, M. Pitt, M. Poelker, T. Porcelli, W.D. Ramsay, M.J. Ramsey-Musolf, J. Riche, N. Simicevic, G.R. Smith, R. Suleiman, S.

Taylor, W.T.H. van Oers, S.B. Wells, W.S. Wilburn, S.A. Wood and C. Zorn, *Q^p_{weak}, a precision measurement of the proton's weak charge*, Proc. **Int. Workshop on Parity Violation and Hadronic Structure (PAVI 2004), Grenoble, France, June 8–11, 2004**, eds. S. Kox *et al.* (Eur. Phys. J. **A24**, 2005) p.155 [LA-UR-03-6031, JLAB-PHY-03-321].

D. Armstrong, T. Averett, J. Birchall, T. Botto, J.D. Bowman, A. Bruell, R. Carlini, S. Chattopadhyay, C. Davis, J. Doornbos, K. Dow, J. Dunne, R. Ent, J. Erler, W. Falk, M. Farkhondeh, J.M. Finn, T. Forest, W. Franklin, D. Gaskell, K. Grimm, F.W. Hersman, M. Holtrop, K. Johnston, R. Jones, K. Joo, S. Kowalski, C. Keppel, M. Kohl, E. Korkmaz, L. Lee, Y. Liang, A. Lung, D. Mack, S. Majewski, J. Mammei, D. Meekins, G. Mitchell, H. Mkrtchyan, N. Morgan, A. Opper, S. Page, S. Penttilla, M. Pitt, M. Poelker, T. Porcelli, W.D. Ramsay, M. Ramsey-Musolf, N. Simicevic, G.R. Smith, T. Smith, R. Suleiman, S. Taylor, E. Tsentalovich, W.T.H. van Oers, S. Wells, W.S. Wilburn, S. Wood, H. Zhu and C. Zorn, *The Q^p_{weak} tracking system. Measurement of the average Q^2 and the dilution by background events, ibid.* 159 [JLAB-PHY-04-75].

M. Agnello, G. Beer, L. Benussi, M. Bertani, S. Bianco, E. Botta, T. Bressani, L. Busso, D. Calvo, P. Camerini, P. Cerello, B. Dalena, F. De Mori, A. D'Erasmo, D. Di Santo, F.L. Fabbri, D. Faso, A. Feliciello, A. Filippi, V. Filippini, E.M. Fiore, H. Fujioka, P. Gianotti, N. Grion, A. Krasnoperov, V. Lucherini, S. Marcello, T. Maruta, N. Mirfakhrai, O. Morra, A. Olin, E. Pace, M. Pallotta, M. Palomba, A. Pantaleo, A. Panzarasa, V. Paticchio, S. Piano, F. Pompili, R. Rui, G. Simonetti, H. So, S. Tomassini, R. Wheadon and A. Zenoni, *First results from the FINUDA experiment*, Proc. **Int. Nuclear Physics Conf. (INPC 2004), Göteborg, Sweden, June 27–July 2, 2004**, eds. B. Jonson *et al.* (Nucl. Phys. **A752**, 2005) p.139.

A.A. Chen, R.E. Azuma, S. Bishop, L. Buchmann, M.L. Chatterjee, J.M. D'Auria, S. Engel, D. Gigliotti, U. Greife, D. Hunter, A. Hussein, D. Hutcheon, C.C. Jewett, J. José, J.D. King, A.M. Laird, M. Lamey, R. Lewis, W. Liu, A. Olin, D. Ottewell, P. Parker, J. Rogers, C. Ruiz, M. Trinczek and C. Wrede, *The ^{21}Na$(p,\gamma)^{22}$Mg reaction in novae and X-ray bursts, ibid.* 510.

A.C. Shotter, *Radioactive beams, ibid.* 532.

J. Mildenberger *et al.*, (E949 collaboration), *Latest results from the search for $K^+ \to \pi^+\nu\bar{\nu}$*, Proc. **6$^{\rm th}$ Int. Conf. on Hyperons, Charm and Beauty Hadrons (BEACH 2004), Chicago, IL, June 27–July 3, 2004**, eds. C.S. Kalman *et al.* (Nucl. Phys. **B142**, 2005) p.41.

L. Buchmann, M. Comyn and J. Thomson, eds., Proc. **8$^{\rm th}$ Symp. on Nuclei in the Cosmos (NICVIII), Vancouver, BC, July 19–23, 2004** (Nucl. Phys. **A758**, 2005).

C. Ruiz, M. Aliotta, R.E. Azuma, R.N. Boyd, L. Buchmann, A. Chen, N.M. Clarke, J.M. D'Auria, T. Davinson, B.R. Fulton, D. Groombridge, D. Hutcheon, A.M. Laird, A.S. Murphy, J. Pearson, I. Roberts, A. Robinson, F. Sarazin, A.C. Shotter, P. Walden and P.J. Woods, *Multichannel R-matrix analysis of elastic and inelastic resonances in the ^{20,21}Na+p compound systems, ibid.* 166c [TRI-PP-04-39].

G. Ruprecht, K. Czerski, D. Bemmerer, M. Hoeft and P. Heide, *Excitation of giant resonances in deuteron stripping reactions on ^{10}B far below the Coulomb barrier, ibid.* 170c [TRI-PP-04-40].

L. Buchmann, *Comments on the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate, ibid.* 355c [TRI-PP-04-35].

M. Trinczek, C.C. Jewett, J.M. D'Auria, S. Bishop, L. Buchmann, A.A. Chen, S. Engel, D. Gigliotti, U. Greife, D. Hunter, A. Hussein, D. Hutcheon, J. José, A.M. Laird, M. Lamey, R. Lewis, A. Olin, D. Ottewell, P. Parker, M.M. Pavan, J.E. Pearson, J. Rogers, C. Ruiz and C. Wrede, *Direct measurement of the $^{21}Na(p,\gamma)^{22}Mg$ reaction: resonance strengths and gamma-gamma analysis, ibid.* 729c [TRI-PP-04-43].

S.-M. Chen *et al.* (BNL E949 collaboration), *Rare kaon decay from E949 at BNL: $K^+ \to \pi^+\nu\bar{\nu}$*, Proc. **32$^{\rm nd}$ Int. Conf. on High-Energy Physics (ICHEP04), Beijing, China, August 16–22, 2004**, eds. H. Chen *et al.* (World Scientific, Hackensack, NJ, 2005) p.825 [hep-ex/0409064].

A. Sher *et al.* (E865 collaboration), *E865 result: an improved upper limit on the decay $K^+ \to \pi^+\mu^+e^-$*, Proc. **Annual Meeting of the Division of Particles and Fields (DPF 04), Riverside, CA, August 26–31, 2004** (Int. J. Mod. Phys. **A20**, 2005) p.3349.

R. Tacik (CHAOS collaboration), *Low energy pion-nucleon scattering*, Proc. **10$^{\rm th}$ Int. Symp. on Meson-Nucleon Physics and the Structure of the Nucleon (MENU 2004), Beijing, China, August 29–September 4, 2004**, ed. H.-C. Chiang (Int. J. Mod. Phys. **A20**, 2005) p.1639.

V.L. Ryjkov, L. Blomeley, M. Brodeur, P. Grothkopp, M. Smith, P. Bricault, F. Buchinger, J. Crawford, G. Gwinner, J. Lee, J. Vaz, G. Werth, J. Dilling and the TITAN collaboration, *TITAN project status report and a proposal for a new cooling method of highly charged ions*, Proc. **4$^{\rm th}$ Int. Conf. on Exotic Nuclei and Atomic Masses (ENAM04), Pine Mountain, GA, September 12–16, 2004** (Eur. Phys. J. **A25**, 2005) p.53.

G. Sikler, J.R. Crespo López-Urrutia, J. Dilling, S. Epp, C.J. Osborne and J. Ullrich, *A high-current EBIT for charge-breeding of radionuclides for the TITAN spectrometer, ibid.* 63.

R.S. Chakrawarthy, P.M. Walker, M.B. Smith, A.N. Andreyev, S.F. Ashley, G.C. Ball, J.A. Becker, J.J. Daoud, P.E. Garrett, G. Hackman, G.A. Jones, Y. Litvinov, A.C. Morton, C.J. Pearson, C.E. Svensson, S.J. Williams and E.F. Zganjar, *Discovery of a new 2.3 s isomer in neutron-rich ^{174}Tm, ibid.* 125.

J.A. Behr, A. Gorelov, D. Melconian, M. Trinczek, W.P. Alford, D. Ashery, P.G. Bricault, L. Courneyea, J.M. D'Auria, J. Deutsch, J. Dilling, M. Dombsky, P. Dubé, F. Glück, S. Gryb, S. Gu, O. Häusser, K.P. Jackson, B. Lee, A. Mills, E. Paradis, M.R.

Pearson, R. Pitcairn, E. Prime, D. Roberge and T.B. Swanson, *Weak interaction symmetries with atom traps, ibid.* 685.

M.T. Gericke, C. Blessinger, J.D. Bowman, R.D. Carlini, T.E. Chupp, K.P. Coulter, M. Dawkins, M. Dabaghyan, T.R. Gentile, R.C. Gillis, G.L. Greene, J. Hartfield, F.W. Hersman, T. Ino, G.L. Jones, B. Lauss, M. Leuschner, B. Losowski, R. Mahurin, Y. Masuda, G.S. Mitchell, S. Muto, H. Nann, S.A. Page, S.I. Penttilä, W.D. Ramsay, S. Santra, P.N. Seo, E.T. Shaparov, T.B. Smith, W.S. Wilburn, J. Tasson, W.M. Snow, T. Ino and Y. Masuda, *A low noise CsI detector array for the precision measurement of parity nonconservation in $\vec{n} + p \rightarrow d + \gamma$*, Proc. **Int. Conf. on Nuclear Data for Science and Technology 2004 (ND2004), Santa Fe, NM, September 26–October 1, 2004**, eds. R.C. Height *et al.* (AIP **769**, 2005) p.692.

P.-N. Seo, J.D. Bowman, R.D. Carlini, T.E. Chupp, K.P. Coulter, M. Dabaghyan, M. Dawkins, D. Desai, S.J. Freedman, T. Gentile, M.T. Gericke, R.C. Gillis, G.L. Greene, F.W. Hersman, T. Ino, S. Ishimoto, G.L. Jones, B. Lauss, M.B. Leuschner, B. Lozowski, R. Mahurin, Y. Masuda, G.S. Mitchell, S. Muto, H. Nann, S.A. Page, S.I. Penttilä, W.D. Ramsay, S. Santra, E.I. Sharapov, T.B. Smith, W.M. Snow, W.S. Wilburn, V. Yuan and H. Zhu, *The 2004 NPDGamma commissioning run – measurement of parity-violating gamma-ray asymmetries in neutron capture on Al, Cu, Cl, In, and B, ibid.* 696.

P.-N. Seo, J.D. Bowman, M. Dabaghyan, M. Gericke, R.C. Gillis, G.L. Greene, M.B. Leuschner, J. Long, R. Mahurin, G.S. Mitchell, H. Nann, S.A. Page, S.I. Penttila, G. Peralta, W.D. Ramsay, S. Santra, E.I. Sharapov and W.S. Wilburn, *FP12 pulsed cold neutron beam line for fundamental nuclear physics at LANSCE, ibid.* 700.

J.M. D'Auria, *Nuclear astrophysics at ISAC with DRAGON, ibid.* 1345.

R.D. Carlini *et al.* (Q_{weak} collaboration), *The Q^p_{weak} experiment: a search for new physics beyond the standard model and the TeV scale*, Proc. **16$^{\mathbf{th}}$ Int. Spin Symp. (SPIN 2004), Trieste, Italy, October 10–16, 2004**, eds. F. Bradamante *et al.* (World Scientific, Singapore, 2005).

M. Calderon de la Barca Sanchez, F. Retiere *et al.* (STAR collaboration), *Open charm production from d + Au collisions in STAR*, Proc. **Int. Conf. on Hard and Electromagnetic Probes of High Energy Nuclear Collisions (HP 2004), Ericeira, Portugal, November 4–10, 2004**, eds. C. Lourenco and H. Satz (Eur. Phys. J. **C43**, 2005) p.187.

A.A.P. Suaide, F. Retiere *et al.* (STAR collaboration), *Charm production in the STAR experiment at RHIC, ibid.* 193.

C.A. Gagliardi, F. Retiere *et al.* (STAR collaboration), *Recent high-p(T) results from STAR, ibid.* 263.

G.C. Ball, T. Achtzehn, D. Albers, J.S. Al Khalili, C. Andreoiu, A. Andreyev, S.F. Ashley, R.A.E. Austin, J.A. Becker, P. Bricault, S. Chan, R.S. Chakrawarthy, R. Churchman, H. Coombes, E.S. Cunningham, J. Daoud, M. Dombsky, T.E. Drake, B. Eshpeter, P. Finlay, P.E. Garrett, C. Geppert, G.F. Grinyer, G. Hackman, V. Hanemaayer, B. Hyland, G.A. Jones, K.A. Koopmans, W.D. Kulp, J. Lassen, J.P. Lavoie, J.R. Leslie, Y. Litvinov, J.A. Macdonald, C. Mattoon, D. Melconian, A.C. Morton, C.J. Osborne, C.J. Pearson, M. Pearson, A.A. Phillips, J.J. Ressler, F. Sarazin, M.A. Schumaker, J. Schwarzenberg, H.C. Scraggs, M.B. Smith, C.E. Svensson, J.J. Valiente-Dobón, J.C. Waddington, P.M. Walker, K. Wendt, S.J. Williams, J.L. Wood and E.F. Zganjar, *High-resolution γ-ray spectroscopy: a versatile tool for nuclear β-decay studies at TRIUMF-ISAC*, Proc. **Int. Conf. on Nuclear Structure, Astrophysics and Reactions (NUSTAR 05), Guildford, UK, January 5–8, 2005** (J. Phys. **G31**, 2005) p.S1491.

J.J. Ressler, C.W. Beausang, R.F. Casten, N.V. Zamfir, H. Ai, H. Amro, M. Babilon, R.B. Cakirli, J.A. Caggiano, G. Gürdal, A. Heinz, R.O. Hughes, S.D. Langdown, E.A. McCutchan, D.A. Meyer, C. Plettner, J. Qian, P.H. Regan, M.J.S. Sciacchitano, N.J. Thomas, E. Williams and A. Yamamoto, *Isomers and seniority in the trans-Pb nuclei, ibid.* S1605.

C.E. Svensson, P. Amaudruz, C. Andreoiu, A. Andreyev, R.A.E. Austin, G.C. Ball, D. Bandyopadhyay, A.J. Boston, R.S. Chakrawarthy, A.A. Chen, R. Churchman, T.E. Drake, P. Finlay, P.E. Garrett, G.F. Grinyer, G. Hackman, B. Hyland, B. Jones, R. Kanungo, R. Maharaj, J.P. Martin, D. Morris, A.C. Morton, C.J. Pearson, A.A. Phillips, J.J. Ressler, R. Roy, F. Sarazin, M.A. Schumaker, H.C. Scraggs, M.B. Smith, N. Starinsky, J.J. Valiente-Dobón, J.C. Waddington and L.M. Watters, *TIGRESS: TRIUMF-ISAC gamma-ray escape-suppressed spectrometer, ibid.* S1663.

K. Blaum, G. Audi, D. Beck, G. Bollen, M. Brodeur, P. Delahaye, S. George, C. Guénaut, F. Herfurth, A. Herlert, A. Kellerbauer, H-J. Kluge, D. Lunney, M. Mukherjee, D Rodriguez, S. Schwarz, L. Schweikhard and C. Yazidjian, *ISOLTRAP pins down masses of exotic nuclides, ibid.* S1775.

P.E. Garrett, W.D. Kulp, J.L. Wood, D. Bandyopadhyay, S. Christen, S. Choudry, A. Dewald, A. Fitzler, C. Fransen, K. Jessen, J. Jolie, A. Kloezer, P. Kudejova, A. Kumar, S.R. Lesher, A. Linnemann, A. Lisetskiy, D. Martin, M. Masur, M.T. McEllistrem, O. Möller, M. Mynk, J.N. Orce, P. Pejovic, T. Pissulla, J.M. Regis, A. Schiller, D. Tonev and S.W. Yates, *Octupole and hexadecapole bands in ^{152}Sm, ibid.* S1855.

B. Hyland, D. Melconian, G.C. Ball, J.R. Leslie, C.E. Svensson, P. Bricault, E. Cunningham, M. Dombsky, G.F. Grinyer, G. Hackman, K. Koopmans, F. Sarazin, M.A. Schumaker, H.C. Scraggs, M.B. Smith and P.M. Walker, *Precision half-life measurement of ^{62}Ga, ibid.* S1885.

S.J. Williams, P.M. Jenneson, P.E. Garrett, P.H. Regan, C. Andreoiu, G.C. Ball, R.S. Chakrawarthy, J.J. Daoud, G.F. Grinyer, G. Hackman, B. Hyland, N.A. Mlwilo, A.C. Morton, C.J. Pearson, M.A. Schumaker, M.B. Smith, C.E. Svensson and J.J. Valiente-Dubón, *Testing the integration of BaF_2 detectors into*

the 8π array – fast-timing measurements at TRIUMF, ibid. S1979.

G.M. Marshall, *New measurements of muon decay from TWIST*, Proc. **Int. Conf. on Exotic Atoms and Related Topics (EXA05), Vienna, Austria, February 21–25, 2005**, eds. A. Hirtl, J. Marton, E. Widmann and J. Zmeskal (Austrian Academy of Sciences Press, Vienna, 2005), p.269 [TRI-PP-05-22].

M.C. Fujiwara, *Detecting antihydrogen: the challenges and the applications*, Proc. **Physics with Ultra Slow Antiproton Beams, Wako, Japan, March 14–16, 2005** (AIP Conf. Proc. **793**, 2005) p.111 [TRI-PP-05-23, hep-ex/0507082].

A. Bellerive, K. Boudjemline, R.K. Carnegie, M.S. Dixit, J. Miyamoto, E. Neuheimer, A. Rankin, E. Rollin, K. Sachs, J.-P. Martin, V. Lepeltier, P. Colas, A. Giganon and I. Giomataris, *Spatial resolution of a micromegas-TPC using the charge dispersion signal*, Proc. **2005 Int. Linear Collider Workshop (LCWS 2005), Stanford, CA, March 18–22, 2005**, ed. J.L. Hewett (SLAC-R-772 eConf:C050318, 2005) p.829 [physics/0510085].

P.E. Garrett, C.E. Svensson, G.C. Ball, G. Hackman, E.F. Zganjar, C. Andreoiu, A. Andreyev, S.F. Ashley, R.A.E. Austin, D. Bandyopadhyay, J.A. Becker, S. Chan, H. Coombes, R. Churchman, R.S. Chakrawarthy, P. Finlay, G.F. Grinyer, B. Hyland, E. Illes, G.A. Jones, W.D. Kulp, J.R. Leslie, C. Mattoon, A.C. Morton, C.J. Pearson, A.A. Phillips, P.H. Regan, J.J. Ressler, F. Sarazin, M.A. Schumaker, J. Schwarzenberg, M.B. Smith, J.J. Valiente-Dubón, P.M. Walker, S.J. Williams, J.C. Waddington, L.M. Watters, J. Wong andJ.L. Wood, *Gamma-Ray Spectroscopy at TRIUMF-ISAC*, Proc. **Int. School on Contemporary Physics-III, ISCP2005, Ulaanbaatar, Mongolia, August, 2005**, eds. G. Khuukhenkhuu and J. Vanchinkhuu (University Press, Ulaanbaatar, 2005) p.104.

J.E. Carson *et al.*, *The spectrum of Markarian 421 above 100 GeV with STACEE*, Proc. **29$^{\text{th}}$ Int. Cosmic Ray Conf. (ICRC 2005), Pune, India, August 2–10, 2005** (Tata Inst. of Fundamental Research, 2005).

R. Mukherjee *et al.*, *STACEE observations of low-frequency peaked BL Lac objects, ibid.*

J. Kildea *et al.*, *Shower reconstruction techniques for STACEE, ibid.*

J. Kildea *et al.*, *Observations of the Crab Nebula and pulsar with STACEE, ibid.*

A. Jarvis *et al.*, *GRB observations around 100 GeV with STACEE, ibid.*

M. Dixit *et al.*, *Spatial resolution of a MPGD TPC using the charge dispersion signal*, Proc. **2$^{\text{nd}}$ ILC Accelerator Workshop, Snowmass, CO, August 14–27, 2005** (SLAC-R-798 eConf: C0508141, 2005).

P. Colas, M. Dixit *et al.*, *Micromegas TPC beam tests at KEK, ibid.*

V. Lepeltier, M. Dixit *et al.*, *Tests of Carleton and MPI TPC's with a resistive foil and a Micromegas readout at the KEK PS beam*, Proc. **ECFA Workshop on Physics and Detectors at the ILC, Vienna, Austria, November 15–17, 2005** (LAL 05-240, 2005).

Particle, Nuclear and Atomic Physics – *2006*

E. Accomando *et al.*, *Workshop on CP studies and non-standard Higgs physics*, Proc. **Meeting on CP Violation and Non-standard Higgs Physics (CPNSH), Geneva, Switzerland, December 2–3, 2004**, eds. S. Kraml, G. Azuelos *et al.* (CERN2006-009, Geneva, 2006) [hep-ph/0608079].

C. Andreoiu, C.E. Svensson, R.A.E. Austin, M.P. Carpenter, D. Dashdorj, P. Finlay, S.J. Freeman, P.E. Garrett, A. Görgen, J. Greene, G.F. Grinyer, B. Hyland, D. Jenkins, F. Johnston-Theasby, P. Joshi, A.O. Machiavelli, F. Moore, G. Mukherjee, A.A. Phillips, W. Reviol, D.G. Sarantites, M.A. Schumaker, D. Seweryniak, M.B. Smith, J.J. Valiente-Dobón and R. Wadsworth, *Lifetime measurements in $N = Z$ ^{72}Kr*, Proc. **Int. Conf. on Finite Fermionic Systems: Nilsson Model 50 Years, Lund, Sweden, June, 2005** (Phys. Scripta **T125**, 2006) p.127.

W. Murray, *Updated results from MuScat*, Proc. **7$^{\text{th}}$ Int. Workshop on Neutrino Factories and Superbeams (NuFact'05), Frascati, Italy, June 21–26, 2005**, eds. G. De Lellis *et al.* (Nucl. Phys. B Proc. Suppl. **155**, 2006) p.282.

J.J. Valiente-Dobón, T. Steinhardt, C.E. Svensson, I. Ragnarsson, A.V. Afanasjev, C. Andreoiu, M.P. Carpenter, G. de Angelis, F. Dönau, J. Eberth, S.J. Freeman, A. Gadea, P.E. Garrett, D. Jenkins, F. Johnston-Theasby, P. Joshi, A. Jungclaus, F. Moore, G. Mukherjee, D.R. Napoli, C. Plettner, W. Reviol, D.G. Sarantites, R. Schwengner, D. Seweryniak, I. Stefanescu, O. Thelen and R. Wadsworth, *Lifetimes of high-spin states in ^{74}Kr*, Proc. **Int. Conf. on Frontiers in Nuclear Structure, Astrophysics and Reactions, Kos, Greece, September, 2005** (AIP Conf. **831**, 2006) p.283.

P.-N. Seo, J.D. Bowman, R.D. Carlini, T.E. Chupp, M. Dabaghyan, S.J. Freedman, T.R. Gentile, M.T. Gericke, R.C. Gillis, G.L. Greene, F.W. Hersman, T. Ino, G.L. Jones, M. Kandes, B. Lauss, M.B. Leuschner, B. Losowski, R. Mahurin, M. Mason, Y. Masuda, G.S. Mitchell, S. Muto, H. Nann, S.A. Page, S.I. Penttila, W.D. Ramsay, S. Santra, E.I. Sharapov, T.B. Smith, W.M. Snow, W.S. Wilburn, V. Yuan and H. Zhu, *Measurement of parity-violating gamma-ray asymmetry on compound nuclei with cold neutrons*, Proc. **12$^{\text{th}}$ Int. Symp. on Capture Gamma-ray Spectroscopy and Related Topics (CGS-12), Notre Dame, IN, September 4–9, 2005**, eds. A. Woehr and A. Aprahamian (AIP **819**, 2006) p.81.

B. Hyland, C.E. Svensson, G.C. Ball, J.R. Leslie, D. Albers, C. Andreoiu, P. Bricault, R. Churchman, D. Cross, M. Dombsky, P.E. Garrett, C. Geppert, G.F. Grinyer, G. Hackman, V. Hanemaayer, J. Lassen, J.P. Lavoie, D. Melconian, A.C. Morton, C.J.

Pearson, M. Pearson, A.A. Phillips, M.A. Schumaker and J.J. Valiente-Dobón, *Gamma-ray transitions in the decay of the superallowed beta emitter ^{62}Ga, ibid.* 105.

P.E. Garrett, C.E. Svensson, G.C. Ball, G. Hackman, E.F. Zganjar, C. Andreoiu, A. Andreyev, S.F. Ashley, R.A.E. Austin, D. Bandyopadhyay, J.A. Becker, S. Chan, H. Coombes, R. Churchman, R.S. Chakrawarthy, P. Finlay, G.F. Grinyer, B. Hyland, E. Illes, G.A. Jones, W.D. Kulp, J.R. Leslie, C. Mattoon, A.C. Morton, C.J. Pearson, A.A. Phillips, P.H. Regan, J.J. Ressler, F. Sarazin, M.A. Schumaker, J. Schwarzenberg, M.B. Smith, J.J. Valiente-Dobón, P.M. Walker, S.J. Williams, J.C. Waddington, L.M. Watters, J. Wong and J.L. Wood, *Gamma-ray spectroscopy at TRIUMF-ISAC, ibid.* p.249.

C. Bryman, J. Ives, P. Amaudruz, Y. Davydov, C. Lim, R. Henderson, N. Khan, A. Miller, T. Numao and A. Sher, *Pointing calorimeter for measuring decay and development of extruded scintillator*, Proc. **9$^{\mathbf{th}}$ Conf. on Astroparticle, Particle and Space Physics, Detectors and Medical Physics Applications, Como, Italy, October 17–21, 2005**, eds. M. Barone *et al.* (World Scientific, New Jersey, 2006).

E. Friedman, G. Yaari, S. Kritchman M. Bauer, J. Breitschopf, H. Clement, H. Denz, E. Doroshkevich, A. Erhardt, R. Meier, G.J. Wagner and G.J. Hofman, *Elastic scattering of low energy pions by nuclei and the in-medium isovector πN amplitude*, Proc. **Particles and Nuclei Int. Conf. (PANIC05), Santa Fe, NM, October 24–28, 2005** (AIP Conf. Proc. **842**, 2006) p.437.

M. Nozar *et al.* (CLAS collaboration), *Partial wave analysis of the $\pi^+\pi^+\pi^-$ system in photo-production at CLAS, ibid.* 443.

B. Lauss, J.D. Bowman, R.D. Carlini, T.E. Chupp, W. Chen, S. Covrig, M. Dabaghyan, D. Desai, S.J. Freedman, T.R. Gentile, M.T. Gericke, R.C. Gillis, G.L. Greene, F.W. Hersman, T. Ino, G.L. Jones, M. Kandes, M.B. Leuschner, B. Losowski, R. Mahurin, M. Mason, Y. Masuda, J. Mei, G.S. Mitchell, S. Muto, H. Nann, S.A. Page, S.I. Penttila, W.D. Ramsay, S. Santra, P.-N. Seo, E.I. Sharapov, T.B. Smith, W.M. Snow, W.S. Wilburn, V. Yuan and H. Zhu, *Precision measurement of parity violation in polarized cold neutron capture on the proton: the NPDγ experiment, ibid.* 790 [nucl-ex/0601004].

J. Hu *et al.* (TWIST collaboration), *High precision measurements of muon decay at TWIST, ibid.* 900.

A.A. Chen (DRAGON collaboration), *Probing galactic Al-26 with exotic ion beams*, Proc. **Conf. on the Origin of Matter and the Evolution of Galaxies (OMEG05), Tokyo, Japan, November 8–11, 2005** (AIP Conf Proc. 847, 2006) p.298.

R. Sanchez, W. Noertershaeuser, A. Dax, G. Ewald, S. Goette, R. Kirchner, H.-J. Kluge, T. Kuehl, A. Wojtaszeky, B.A. Bushaw, G.W.F. Drake, Z.-Ch. Yan, C. Zimmermann, D. Albers, J. Behr, P. Bricault, J. Dilling, M. Dombsky, J. Lassen, C.D.P. Levy, M.R. Pearson, E.J. Prime and V. Ryjkov, *Nuclear charge radius of lithium-11*, Proc. **Application of Lasers in Atomic Nuclei Research VII Int. Workshop, Poznan, Poland, May 29–June 1, 2006** (Hyp. Int. **171**, 2006) p.181.

G.M. Marshall, *Measuring muon decay with TWIST*, Proc. **9$^{\mathbf{th}}$ Conf. on Intersections of Particle and Nuclear Physics (CIPANP'06), Puerto Rico, May 30 – June 3, 2006**, ed. T.M. Liss (AIP Conf. Proc. 870, 2006).

C. Ruiz, A. Parikh, J. José, L. Buchmann, J.A. Caggiano, A.A. Chen, J.A. Clark, H. Crawford, J. D'Auria, B. Davids, C. Davis, C. Deibel, L. Erikson, L. Fogarty, D. Frekers, U. Greife, A. Hussein, D.A. Hutcheon, M. Huyse, C. Jewett, A.M. Laird, R. Lewis, P. Mumby-Croft, A. Olin, D.F. Ottewell, C.V. Ouellet, P. Parker, J. Pearson, G. Ruprecht, M. Trinczek, C. Vockenhuber and C. Wrede, *The ^{26g}Al $(p,\gamma)^{27}$Si reaction in novae*, Proc. **Int. Symp. Nuclear Astrophysics – Nuclei in the Cosmos IX (NIC-IX), Geneva, Switzerland, June 25–30, 2006** (Proc. of Science, 2006) p.004.

M. Lindroos, J. D'Auria, J. José and L. Buchmann, *Measuring difficult reaction rates involving radioactive beams: a new approach, ibid.* 006.

C. Vockenhuber, C.O. Ouellet, L. Buchmann, J. Caggiano, A.A. Chen, H. Crawford, J. D'Auria, B. Davids, L. Fogarty, D. Frekers, A. Hussein, D.A. Hutcheon, W. Kutschera, A.M. Laird, R. Lewis, E. O'Connor, D. Ottewell, M. Paul, M.M. Pavan, J. Pearson, C. Ruiz, G. Ruprecht, M. Trinczek, B. Wales and A. Wallner, *Study of the ^{40}Ca$(\alpha,\gamma)^{44}$Ti reaction at stellar temperatures with DRAGON, ibid.* 030.

G. Ruprecht, L. Buchmann, K. Czerski, D. Hutcheon, D. Ottewell, C. Ruiz, C. Vockenhuber and P. Walden, *The influence of electron screening on half-lives, ibid.* 171.

J.C. Batchelder, H.K. Carter, E.H. Spejewski, J.-C. Bilheux, K.P. Rykaczewski, D.W. Stracener, C.R. Bingham, R. Grzywacz, M.N. Tantawy, Y. Larochelle, J.H. Hamilton, W. Krolas, D. Fong, A.V. Ramayya, J.K. Hwang, P.E. Garrett, D.J. Hartley, D. Kulp, J.L. Wood, A. Piechaczek, E.F. Zganjar and J.A. Winger, *Beta decay strengths from the decay of ^{116m1,m2,gs}Ag*, Proc. **Annual Meeting of the Division of Nuclear Physics of the American Physical Society (APS DNP) Nashville, TN, October 25–28, 2006** (Bull. Am. Phys. Soc. **51**, 2006) p.38.

Particle, Nuclear and Atomic Physics – *2007*

C. Vockenhuber, A. Bergmaier, T. Faestermann, K. Knie, G. Korschinek, G. Rugel, W. Kutschera, P. Steier, K. Vorderwinkler and A. Wallner, *Development of isobar separation for ^{182}Hf AMS measurements of astrophysical interest*, Proc. **10$^{\mathbf{th}}$ Int. Conf. on Accelerator Mass Spectrometry (AMS-10), Berkeley, CA, September 5–10, 2005**, eds. J. Knezovich *et al.* (Nucl. Instrum. Methods **B259**, 2007) p.250.

A. Wallner, I. Dillmann, R. Golser, F. Käppeler, W. Kutschera, M. Paul, A. Priller, P. Steier and C. Vockenhuber, *Nuclear astrophysics with AMS – new nuclides measured at VERA, ibid.* 677.

C. Vockenhuber, C.O. Ouellet, L. Buchmann, J. Caggiano, A.A. Chen, J.M. D'Auria, D. Frekers, A. Hussein, D.A. Hutcheon, W. Kutschera, K. Jayamanna, D. Ottewell, M. Paul, J. Pearson, C. Ruiz, G. Ruprecht, M. Trinczek and A. Wallner, *The* $^{40}Ca(\alpha,\gamma)^{44}Ti$ *reaction at DRAGON, ibid.* 688.

P.E. Garrett, A. Andreyev, R.A.E. Austin, G.C. Ball, D. Bandyopadhyay, J.A. Becker, A.J. Boston, H.C. Boston, R.C. Chakrawarthy, R. Churchman, D. Cline, R.J. Cooper, D. Cross, D. Dashdorj, G. Demand, M.R. Dimmock, T. Drake, P. Finlay, F. Gagnon, A.T. Gallant, K.L. Green, A.N. Grint, G.F. Grinyer, G. Hackman, L.J. Harkness, A.B. Hayes, R. Kanungo, K.G. Leach, G. Lee, J.R. Leslie, R. Maharaj, J.-P. Martin, C. Mattoon, W.J. Mills, A.C. Morton, L. Nelson, O. Newman, P.J. Nolan, E. Padilla-Rodal, C.J. Pearson, A.A. Phillips, M. Porter-Peden, J.J. Ressler, C. Ruiz, F. Sarazin, M.A. Schumaker, D.P. Scraggs, M.T. Strange, M. Subramanian, C.E. Svensson, J.C. Waddington, J.M. Wan, A. Whitbeck, S.J. Williams, J.L. Wood, J.C. Wong, C.Y. Wu and E.F. Zganjar, *The TRIUMF nuclear structure program and TIGRESS*, Proc. **19$^{\text{th}}$ Int. Conf. on the Application of Accelerators in Research and Industry (CAARI), Fort Worth, TX, August 20–25, 2006**, eds. F. Del McDaniel *et al.* (Nucl. Instrum. Methods **B261**, 2007) p.1084.

U. Greife, J. Livesay, C. Jewett, K. Chipps, F. Sarazin, D. Bardayan, J. Blackmon, C. Nesaraja, M.S. Smith, A. Champagne, R. Fitzgerald, K. Jones, J. Thomas, R. Kozub, L. Buchmann, J. Caggiano, D. Hunter, D. Hutcheon, A. Olin, D. Ottewell, J. Rogers, C. Ruiz, G. Ruprecht, M. Trinczek, C. Vockenhuber, S. Bishop, J. D'Auria, M. Lamay, W. Liu, C. Wrede, M.L. Chatterjee, A.A. Chen, J. Pearson, S. Engel, A.M. Laird, D. Gigliotti and A. Hussein, *Recent results of experiments with radioactive* ^{21}Na *and* ^{7}Be *ion beams, ibid.* 1089.

W.T.H. van Oers *et al.* (Qweak collaboration), *The Qweak experiment: a search for physics and the TeV scale*, Proc. **18$^{\text{th}}$ Int. IUPAP Conf. on Few-Body Problems in Physics (FB18), Sao Paulo, Brazil, August 21–26, 2006** (Nucl. Phys. **A790**, 2007) p.81 [TRI-PP-06-16].

E.F. Zganjar, T. Achtzehn, D. Albers, C. Andreoiu, A.N. Andreyev, R.A.E. Austin, G.C. Ball, J.A. Behr, G.C. Biosvert, P. Bricault, S. Bishop, R.S. Chakrawarthy, R. Churchman, D. Cross, E. Cunningham, J.M. D'Auria, M. Dombsky, P. Finlay, P.E. Garrett, G.F. Grinyer, G. Hackman, V. Hanemaayer, J.C. Hardy, D.F. Hodgson, B. Hyland, V. Iacob, P. Klages, K.A. Koopmans, W.D. Kulp, J. Lassen, J.P. Lavoie, J.R. Leslie, T. Linder, J.A. MacDonald, H.-B. Mak, D. Melconian, A.C. Morton, W.E. Ormand, C.J. Osborne, C.J. Pearson, M.R. Pearson, A.A. Phillips, A. Piechaczek, J. Ressler, F. Sarazin, G. Savard, M.A. Schumaker, H.C. Scraggs, C.E. Svensson, J.J. Valiente-Dobón, I.S. Towner, J.C. Waddington, P.M. Walker, K. Wendt and J.L. Wood, *Superallowed beta decay studies at TRIUMF – nuclear structure and funadmental symmetries*, Proc. **Int. Symp. Trends in Nuclear Physics, Zakopane, Poland, September 4–11, 2006** (Acta Phys. Polonica **B38**, 2007) 1179.

P.E. Garrett, A. Andreyev, R.A.E. Austin, G.C. Ball, D. Bandyopadhyay, J.A. Becker, A.J. Boston, H.C. Boston, R.S. Chakrawarthy, D. Cline, R.J. Cooper, R. Churchman, D. Cross, D. Dashdorj, G.A. Demand, M.R. Dimmock, T. Drake, P. Finlay, K. Gagnon, A. Gallant, K.L. Green, A.N. Grint, G.F. Grinyer, G. Hackman, L.J. Harkness, A.B. Hayes, R. Kanungo, W.D. Kulp, K.G. Leach, G. Lee, J.R. Leslie, R. Maharaj, J.-P. Martin, C. Mattoon, W.J. Mills, A.C. Morton, L. Nelson, O. Newman, P.J. Nolan, E. Padilla-Rodal, C.J. Pearson, A.A. Phillips, M. Porter-Peden, J.J. Ressler, C. Ruiz, F. Sarazin, M.A. Schumaker, D.P. Scraggs, M.D. Strange, M. Subramanian, C.E. Svensson, J.C. Waddington, J. Wan, A. Whitbeck, S.J. Williams, J. Wong, J.L. Wood, C.Y. Wu and E.F. Zganjar, *Nuclear structure research at TRIUMF, ibid.*

I. Kato *et al.* (K2K and T2K collaborations), *The K2K and T2K experiments*, Proc. **Neutrino Oscillation Workshop (NOW 2006), Otranto, Italy, September 9–16, 2006** (Nucl. Phys. **B168**, 2007) p.199.

T. Nagatomo, K. Minamisono, K. Matsuta, C.D.P. Levy, T. Sumikama, A. Ozawa, Y. Tagishi, M. Mihara, M. Ogura, R. Matsumiya, M. Fukuda, M. Yamaguchi, J.A. Behr, K.P. Jackson, H. Fujiwara, H. Ohta, T. Yasuno, Y. Hashizume and T. Minamisono, *Alignment correlation terms in* β*-ray angular distributions from spin aligned* ^{20}F *and* ^{20}Na, Proc. **17$^{\text{th}}$ Int. Spin Physics Symp. (SPIN06), Kyoto, Japan, October 2–7, 2006** (AIP Conf. Proc. **915**, 2007), p.226.

L. De Nardo, *The final HERMES data on* g_1^p *and* g_1^d, *ibid.* 404.

K. Matsuta, T. Nagatomo, M. Mihara, R. Matsumiya, S. Momota, T. Ohtsubo, T. Izumikawa, H. Hirano, S. Takahashi, A. Kitagawa, M. Kanazawa, M. Torikoshi, S. Sato, M. Fukuda, T. Minamisono, A. Ozawa, K. Yamada, T. Suzuki, T. Yamaguchi, S. Nakajima, T. Sumikama, K. Tanaka, K. Yoshida, Y. Nakashima, H. Fujiwara, S. Kumashiro, M. Ota, D. Shinojima, H. Tanaka, T. Yasuno, K. Muranaka, T. Maemura, A. Chiba, S.A. Pahlovy, M. Nagao, I. Tanihata, K. Minamisono, Y. Nojiri, J.R. Alonso, G.F. Krebs and T.J.M. Symons, *Polarization and momentum distribution of* ^{23}Ne *and* ^{25}Al *produced in one nucleon pickup reactions at 10A MeV, ibid.* 837.

D. Gabbert and L. De Nardo, *New global fit to the total photon-proton cross-section* σ_{L+T} *and to the structure function* F_2, Proc. **15$^{\text{th}}$ Int. Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2007), Munich, Germany, April 16–20, 2007**, eds. G. Grindhammer and K. Sachs (ScienceWisePublishing, 2007) DOI 10.3360/dis.2007.44.

D. Bryman, *Prospects for measurements of the* $\pi \to e\nu$ *branching ratio*, Proc. **Kaon Int. Conf. (KAON'07), Frascati, Italy, May 21–25, 2007** (Proc. of Science, 2007) PoS(KAON)052.

Particle, Nuclear and Atomic Physics – *presented*

W.T.H. van Oers *et al.* (Qweak collaboration), *The Qweak experiment – a search for new physics at the TeV scale*, Proc. **23rd Int. Nuclear Physics Conf. (INCP 2007), Tokyo, Japan, June 3–8, 2007** (Nucl. Phys. A, in press) [TRI-PP-07-17, JLAB-PHY-07-688, arXiv:0708.1972].

M.A. Schumaker, D. Cline, G. Hackman, A.C. Morton, C.J. Pearson, C.E. Svensson, C.Y. Wu, A. Andreyev, R.A.E. Austin, G.C. Ball, D. Bandyopadhyay, J.A. Becker, A.J. Boston, H.C. Boston, R. Churchman, F. Cifarelli, R.J. Cooper, D.S. Cross, D. Dashdorj, G.A. Demand, M.R. Dimmock, T.E. Drake, P. Finlay, A.T. Gallant, P.E. Garrett, K.L. Green, A.N. Grint, G.F. Grinyer, L.J. Harkness, A.B. Hayes, R. Kanungo, K.G. Leach, G. Lee, R. Maharaj, J-P. Martin, F. Moisan, S. Mythili, L. Nelson, O. Newman, P.J. Nolan, E. Padilla-Rodal, A.A. Phillips, M. Porter-Peden, J.J. Ressler, R. Roy, C. Ruiz, F. Sarazin, D.P. Scraggs, J.C. Waddington, J.M. Wan, A. Whitbeck, S.J. Williams and J.C. Wong, *Coulomb excitation of radioactive* ^{21}*Na, ibid.*

G. Brooijmans *et al.*, *New physics at the LHC*, Proc. **5th Workshop on Physics at TeV Colliders, Les Houches, France, June 11–29, 2007** [arXiv:0802.3715].

D. Bryman, L. Kurchaninov, P. Lu, F. Retière and V. Sossi, *Simulation of Compton reconstruction in liquid xenon PET*, Proc. **2007 IEEE Nuclear Science Symp. and Medical Imaging Conf., Honolulu, HI, October 27– November 3, 2007** (IEEE, in press).

P. Amaudruz, D. Bryman, L. Kurchaninov, P. Lu, C. Marshall, J.-P. Martin, A. Muennich, F. Retière and A. Sher, *Simultaneous reconstruction of light and charge signals from 511 keV photons, ibid.*

W. van Oers *et al.*, *From hadronic parity violation to parity-violating electron scattering and tests of the standard model*, Proc. **Int. Symp. on Cosmology and Particle Astrophysics (CoSpa 2007), Taipei, Taiwan, November 13–15, 2007** [TRI-PP-07-46].

M.C. Fujiwara, G.B. Andresen, W. Bertsche, P.D. Bowe, C.C. Bray, E. Butler, C.L. Cesar, S. Chapman, M. Charlton, J. Fajans, R. Funakoshi, D.R. Gill, J.S. Hangst, W.N. Hardy, R.S. Hayano, M.E. Hayden, A.J. Humphries, R. Hydomako, J.J. Jenkins, L.V. Jorgensen, L. Kurchaninov, W. Lai, R. Lambo, N. Madsen, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, S. Seif El Nasr, D.M. Silveira, J.W. Storey, R.I. Thompson, D.P. van der Werf, L. Wasilenko, J.S. Wurtele and Y. Yamazaki, *Particle physics aspects of antihydrogen studies with ALPHA at CERN*, Proc. **Workshop on Cold Antimatter Plasmas and Application to Fundamental Physics (pbar08), Naha, Japan, February 20–22, 2008** (AIP Conf. Proc., in press) [TRI-PP-08-01].

Instrumentation / Accelerator Physics / Computing Sciences – *2003*

D. Gray and B. Minato, *Simple "package design" ion chamber monitors for TRIUMF's proton beamlines*, Proc. **10th Beam Instrumentation Workshop (BIW 2002), Upton, NY, May 6–9, 2002** (AIP Conf. Proc. **648**, 2003) p.439 [TRI-PP-02-06].

W. Andersson, R.E. Laxdal, I. Sekachev and G. Stanford, *Overview of the cryogenic system for the ISAC-II superconducting linac at TRIUMF*, Proc. **19th Int. Cryogenic Engineering Conf. (ICEC 19), Grenoble, France, July 22–26, 2002**, eds. G. Gistau Baguer, P. Seyfert (Narosa, New Delhi, 2003) p.47 [TRI-PP-02-34].

C. Kost, S. McDonald, B. Caron and W. Hong, *ATLAS Canada lightpath data transfer trial*, Proc. **iGrid2002, Amsterdam, Netherlands, September 23–26, 2002** (J. Future Generation of Computer Systems **19**, 2003) p.1051.

L. Moritz, *Radiation safety at ISAC*, Proc. **SAFERIB Workshop at CERN, Geneva, Switzerland, October 30–November 1, 2002** (CERN-2003-004).

E. Calvo, C. Boccard, D. Cocq, L. Jensen, R. Jones, J.J. Savioz, D. Bishop and G. Waters, *The LHC orbit and trajectory system*, Proc. **6th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC 2003), Mainz, Germany, May 5–7, 2003** [CERN-AB-2003-057-BDI].

P. Schmor, *Recently commissioned and future RNB facilities*, Proc. **Particle Accelerator Conf. (PAC2003), Portland, OR, May 12–16, 2003** (Piscataway, NJ, IEEE, 2003) p.6 [TRI-PP-03-23].

R. Assmann, O. Aberle, M. Brugger, L. Bruno, E. Chiaveri, B. Dehning, A. Ferrari, B. Goddard, J.B. Jeanneret, M. Jimenez, V. Kain, M. Lamont, F. Ruggiero, F. Schmidt, P. Sievers, J. Uythoven, V. Vlachoudis, L. Vos, J. Wenninger, I. Baishev and D. Kaltchev, *Designing and building a collimation system for the high-intensity LHC beam, ibid.* 45 [TRI-PP-03-17, CERN-LHC-PROJECT-REPORT-640].

P.G. Bricault, M. Dombsky, P.W. Schmor and A. Dowling, *High power targets for ISOL radioactive ion beams facility, ibid.* 439 [TRI-PP-03-10].

R. Laxdal, G. Clark, G. Dutto, K. Fong, G. Stanford, Z.H. Peng, R. Poirier, W. Rawnsley, T. Ries and I. Sekachev, *The ISAC-II upgrade at TRIUMF – progress and developments, ibid.* 601 [TRI-PP-03-20, PAC-2003-ROPA010].

L. Moritz, J. Drozdoff, G. Dutto, F. Mammarella, M. Mouat and R. Ruegg, *Safety critical monitoring for prompt radiation hazards, ibid.* 638 [TRI-PP-03-21].

L. Ducimetiére, N. Garrel, M.J. Barnes and G.D. Wait, *The LHC injection kicker magnet, ibid.* 1162 [TRI-PP-03-24].

I. Bylinsky, Z. Ang, S. Fang, K. Fong, R. Kumaran, J. Lu and R. Poirier, *TRIUMF ISAC RF system improvements after 2 years of operational experience, ibid.* 1285 [TRI-PP-03-11, PAC-2003-TPAB040]

K. Fong, S. Fang, M. Laverty and Q. Zheng, *RF control system for ISAC-II superconducting cavities, ibid.* 1404 [TRI-PP-03-14, PAC-2003-TPAB088]

T. Ries, K. Fong, S. Koscielniak, R.E. Laxdal and G. Stanford, *A mechanical tuner for the ISAC-II quarter wave superconducting acities, ibid.* 1488 [TRI-PP-03-22, PAC-2003-TPAG027].

R. Baartman and Y.-N. Rao, *Investigation of space charge effect in TRIUMF injection beamline, ibid.* 1578 [TRI-PP-03-09].

M.K. Craddock and D. Kaltchev, *Feasibility studies for a radioactive-ion storage ring, ibid.* 1581 [TRI-PP-03-12]

R. Baartman, P. Bricault, I. Bylinsky, M. Dombsky, G. Dutto, R. Laxdal, R. Poirier, Y. Rao, L. Root, R. Ruegg, P. Schmor, M. Stenning and G. Stinson, *The TRIUMF 500 MeV cyclotron: Present operation and intensity upgrade, ibid.* 1584 [TRI-PP-03-13, PAC03-TPPE016].

G. Stinson and P. Bricault, *A proposal for an additional beamline to the TRIUMF ISAC Facility, ibid.* 1670 [TRI-PP-03-08, PAC03-TPPE014].

S. Koscielniak *et al.*, *Longitudinal dynamics in an FFAG accelerator under conditions of rapid acceleration and fixed, high rf, ibid.* 1831 [TRI-PP-03-18].

F.W. Jones and W. Herr, *Parallel computation of beam-beam interactions including longitudinal motion, ibid.* 3404 [TRI-PP-03-15, CERN-AB-2003-019-ABP].

J.S. Berg, S. Kahn, R. Palmer, D. Trbojevic, C. Johnstone, E. Keil, M. Aiba, S. Machida, Y. Mori, T. Ogitsu, C. Ohmori, A. Sessler and S. Koscielniak, *FFAGS for muon acceleration, ibid.* 3413 [TRI-PP-03-19].

R. Assmann, M. Brugger, M. Hayes, J.B. Jeanneret, F. Schmidt, I. Baichev and D. Kaltchev, *Tools for predicting cleaning efficiency in the LHC, ibid.* 3494 [TRI-PP-03-16, CERN-LHC-PROJECT-REPORT-639].

E.W. Blackmore, P.E. Dodd and M.R. Shaneyfelt, *Improved capabilities for proton and neutron irradiations at TRIUMF*, Proc. **IEEE Radiation Effects Data Workshop, July 21–25, 2003** (IEEE, 2003) p.149.

C.E. Covault *et al.*, *Observations of active galactic nuclei bythe solar tower atmospheric Cherenkov effect experiment (STACEE)*, Proc. **28th Int. Cosmic Ray Conf., Tsukuba, Japan, July 31– August 7, 2003** (UAP, Tsukuba, 2003) p.2551.

J.A. Zweerink *et al.*, *Using GHz FADCs to reject hadrons from STACEE data, ibid.* 2795.

R.A. Scalzo *et al. Optimized pointing strategies for solar tower ACTs, ibid.* 2799.

Instrumentation / Accelerator Physics / Computing Sciences – *2004*

D.A. Williams *et al.*, *Astrophysics around 100 GeV with STACEE*, Proc. **2nd VERITAS Symp. on TeV Astrophysics of Extragalactic Sources, Chicago, IL, April 24–26, 2003** (New Astron. Rev. **48**, 2004) p.359.

T. Yoshioka, M. Nomachi, A. Artamanov, B. Bhuyan, J.S. Frank, T. Fujiwara, K. Higa, S.H. Kettell, T.K. Komatsubara, A. Konaka, A Kozjevnikov, A. Kushnirenko, N. Muramatsu, T. Nakano, T. Nomura, S. Petrenko, R. Poutissou, G. Redlinger, T. Sekiguchi, T. Shinkawa, S. Sugimoto and T. Tsunemi, *Upgrade of the level-0 trigger system for BNL-E949*, Proc. **13th IEEE – NPSS Real Time Conf. (RT 2003), Montreal, PQ, May 18–23, 2003** (IEEE Trans. Nucl. Sci. **51**, 2004) p.334 [KEK-PREPRINT-2003-109, OULNS-03-02, BNL-71879-2003-JA].

D.M. Gingrich, N.J. Buchanan, S. Liu, S. Boettcher, J.A. Parsons and B.W. Sippach, *Radiation tolerant ASIC for controlling switched-capacitor arrays, ibid.* 1324.

R. Poutissou, P.-A. Amaudruz, A. Gaponenko, P. Green, K. Olchanski and A. Olin, *The TWIST data acquisition system at TRIUMF, ibid.* [TRI-PP-04-16].

J.B. Jeanneret *et al.*, *Beam loss and collimation in the LHC*, Proc. **29th ICFA Advanced Beam Dynamics Workshop (HALO'03), Montauk, NY, May 19–23, 2003** (AIP **693**, 2004) p.180.

S. Koscielniak and C.J. Johnstone, *Nonlinear acceleration modes in FFAGs with fixed rf*, Proc. **5th Int. Workshop on Neutrino Factories and Superbeams (NuFact03), New York, NY, June 5–11, 2003** (AIP **721**, 2004) p.467.

M.J. Barnes and G.D. Wait, *A 25 kV, 75 kHz kicker for measurement of muon lifetime*, Proc. **IEEE Int. Pulsed Power Conf., Dallas, TX, June 15–18, 2003** (IEEE Trans. Plasma Sci. **32**, 2004) p.1932 [TRI-PP-03-28].

M.J. Barnes, G.D. Wait, J. Dilling, J.V. Vaz, L. Blomeley, O. Hadary and M.J. Smith, *A high frequency MOSFET driver for the TITAN facility at TRIUMF, ibid.*

K. Jayamanna, D. Yuan, M. Olivo, R. Baartman, G. Dutto, M. McDonald, A. Mitra, P. Schmor and G. Stanford, *Commissioning the TRIUMF/ISAC ECR source for radioactive ion beams*, Proc. **10th Int. Conf. on Ion Sources (ICIS 2003), Dubna, Russia, September 8–13, 2003** (Rev. Sci. Instrum. **75**, 2004) p.1621 [TRI-PP-03-42].

G. Stanford, R.E. Laxdal, C. Marshall, T. Ries and I. Sekatchev, *Design of the medium-beta cryomodule for the ISAC-II superconducting heavy ion accelerator*, Proc. **2003 Cryogenic Engineering Conf. (CEC) and Int. Cryogenic Materials Conf. (ICMC), Anchorage, AL, September 22–26, 2003** (AIP, New York, Advances in Cryo. Eng. **49**, 2004) p.552 [TRI-PP-03-30].

K.S. Lee, E.M. Tikhomolov, J.E. Richards, E. Klassen and T. Tateyama, *TRIUMF secondary beam line control system upgrade using EPICS*, Proc. **IX Int. Conf. on Accelerator and**

Large Experimental Physics Control Systems (ICALEPCS 2003), Gyeongju, South Korea, October 13–17, 2003 (Pohang Accelerator Laboratory, 2004, ISBN:89-954175-2-8 98420 (CD-ROM)) p.199.

R. Keitel, J. Richards and E. Tikhomolov, *Upgrade of the ISAC device database from Paradox to PostgreSQL, ibid.* 202.

J.J. Pon, E. Klassen, K.S. Lee, M.M. Mouat and P.J. Yogendran, *Preliminary use of PDAs in TRIUMF's central control system, ibid.* 380.

J.J. Pon, E. Klassen, K.S. Lee, M.M. Mouat and P.J. Yogendran, *Early control system applications using PDAs at TRIUMF, ibid.* 383.

G. Waters and R. Nussbaumer, *TRIUMF/ISAC EPICS IOCs using a PC104 platform, ibid.* 466.

R. Nussbaumer and G. Waters, *Inexpensive IOCs for GPIB support in the TRIUMF/ISAC control system, ibid.* 515.

E. Tikhomolov, G. Waters and R. Keitel, *EPICS portable channel access server for multiple Windows applications, ibid.* 518.

M.J. Barnes, G.D. Wait, Y. Shirakabe and Y. Mori, *Conceptual design of a bipolar kicker magnet for the J-PARC-Kamioka neutrino project*, Proc. **18$^{\text{th}}$ Int. Conf. on Magnet Technology (MT18), Morioka, Japan, October 20–24, 2003** (IEEE Trans. Applied Superconductivity, 2004) p.465.

M.J. Barnes, E.W. Blackmore, G.D. Wait, J. Lemire-Elmore, B. Rablah, G. Leyh, M. Nguyen and C. Pappas, *Analysis of high power IGBT short circuit failures*, Proc. **26$^{\text{th}}$ Int. Power Modulator Symp. and High-Voltage Workshop, San Francisco, CA, May 23–26, 2004** (IEEE conference record, 2004) p.424.

J. Kildea *et al.* (STACEE collaboration), *The solar tower atmospheric Cherenkov effect experiment*, Proc. **3$^{\text{rd}}$ Int. Conf. on Frontier Science, Physics and Astrophysics in Space, Frascati, Italy, June 14–19, 2004** (Frascati Physics Ser. **VVV**, 2004).

R.W. Assmann, O. Aberle, A. Bertarelli, H.-H. Braun, M. Brugger, L. Bruno, O.S. Brüning, S. Calatroni, E. Chiaveri, B. Dehning, A. Ferrari, B. Goddard, E.B. Holzer, J.-B. Jeanneret, J.M. Jimenez, V. Kain, M. Lamont, M. Mayer, E. Mëtral, R. Perret, S. Redaelli, T. Risselada, G. Robert-Demolaize, S. Roesler, F. Ruggiero, R. Schmidt, D. Schulte, P. Sievers, V. Vlachoudis, L. Vos, G. Vossenberg, J. Wenninger, I.L. Ajguirei, I. Baishev, I.L. Kurochkin, D. Kaltchev and H. Tsutsui, *An improved collimation system for the LHC*, Proc. **9$^{\text{th}}$ European Particle Accelerator Conf. (EPAC 2004), Lucerne, Switzerland, July 5–9, 2004** (EPS Accel. Group, Geneva, 2004) p.536 [EPAC-2004-MOPLT005, CERN-LHC-PROJECT-REPORT-773].

R.W. Assmann, O. Aberle, O.S. Brüning, S. Chemli, D. Gasser, J.-B. Jeanneret, J.M. Jimenez, V. Kain, E. Mëtral, G. Peon, S. Ramberger, C. Rathjen, T. Risselada, F. Ruggiero, L. Vos and D. Kaltchev, *The new layout of the LHC cleaning insertions, ibid.* 539 [EPAC-2004-MOPLT006, CERN-LHC-PROJECT-REPORT-774].

C. Johnstone and S.R. Koscielniak, *Optimizing non-scaling FFAG lattices for rapid acceleration, ibid.* 800 [EPAC-2004-MOPLT112].

M.P. Laverty, S.F. Fang and K. Fong, *TRIUMF ISAC-II rf control system design and testing, ibid.* 953 [EPAC-2004-TUPKF002].

A. Facco, W. Lu, F. Scarpa, E. Chiaveri, R. Losito and V. Zviagintsev, *Construction and testing of the beta=0.31, 352 MHz superconducting half-wave resonator for the SPES Project, ibid.* 1012 [EPAC-2004-TUPKF022].

A. Facco, W. Lu, F. Scarpa, E. Chiaveri, R. Losito, T.L. Grimm, W. Hartung, F. Marti, R.C. York and V. Zviagintsev, *Construction of a 161 MHz, beta = 0.16 superconducting QWR with steering correction for RIA, ibid.* 1015 [EPAC-2004-TUPKF023].

S.R. Koscielniak and M.K. Craddock, *Simple analytic formulae for the properties of nonscaling FFAG lattices, ibid.* 1138 [EPAC-2004-TUPLT006].

L. Ahrens, J.M. Brennan, K.A. Brown, J. Glenn, M. Sivertz, N. Tsoupas and S.R. Koscielniak, *Mini-bunched and micro-bunched slow extracted beams from the AGS, ibid.* 1544 [EPAC-2004-TUPLT179].

D. Kaltchev, *Building truncated Taylor maps with Mathematica and applications to FFAG, ibid.* 1822 [EPAC-2004-WEPLT005].

S.R. Koscielniak, *A comparison of COSY DA maps with analytic formulae for orbit functions of a non-scaling FFAG accelerator, ibid.* 2469 [EPAC-2004-THPLT006].

Instrumentation / Accelerator Physics / Computing Sciences – *2005*

D.A. Williams *et al.* (STACEE collaboration), *Follow-up observations of gamma-ray bursts with STACEE*, Proc. **3$^{\text{rd}}$ Int. Symp. on High-Energy Gamma-ray Astronomy, Heidelberg, Germany, July 26–30, 2004** (AIP Conf. Proc. **745**, 2005) p.603.

J. Kildea *et al.*, *Recent AGN observations by the solar tower atmospheric Cherenkov effect experiment, ibid.*

R.E. Laxdal, Y. Bylinskii, G.S. Clark, K. Fong, A.K. Mitra, R.L. Poirier, B. Rawnsley, T. Ries, I. Sekatchev, G. Stanford and V. Zvyagintsev, *Cold test results of the ISAC-II medium beta high gradient cryomodule*, Proc. **XXII Int. Linear Accelerator Conf. (LINAC 2004), Lübeck, Germany, August 16–24, 2004** (GSI, Germany, 2005) p.222 [http://bel.gsi.de/linac2004/INDEX.html].

R.L. Poirier, K. Fong, P. Harmer, R.E. Laxdal, A.K. Mitra, I. Sekatchev, B. Waraich and V. Zvyagintsev, *RF coupler design* *for the TRIUMF ISAC-II superconducting quarter wave resonator, ibid.* 228.

W. Rawnsley, Y. Bylinski, G. Dutto, K. Fong, R. Laxdal, T. Ries and D. Giove, *A wire position monitor system for the ISAC-II cryomodule components alignment, ibid.* 231.

P. Schmor, *Developments and future plans at ISAC/TRIUMF, ibid.* 251.

K. Fong, S. Fang and M.P. Laverty, *Status of rf control system for ISAC-II superconducting cavities, ibid.* 450.

R.E. Laxdal and Z.H. Peng, *High beta cavity optimization for ISAC-II, ibid.* 627.

G. Stanford, Y. Bylinskii, R.E. Laxdal, B. Rawnsley, T. Ries and I. Sekatchev, *Engineering and cryogenic testing of the ISAC-II medium beta cryomodule, ibid.* 630.

F. Ames, K. Jayamanna, D.H.L. Yuan, M. Olivo, R. Baartman, P. Bricault, M. McDonald, P. Schmor and T. Lamy, *Charge state breeding with an ECRIS for ISAC at TRIUMF*, Proc. **16$^{\mathrm{th}}$ Int. Workshop on Electron Cyclotron Resonance Ion Sources (ECRIS'04), Berkeley, CA, September 26–30, 2004**, ed. M. Leitner (AIP **749**, 2005) p.147.

L. Chen and D.M. Gingrich, *Study of n-channel MOSFETs with an enclosed-gate layout in a 0.18 micron CMOS technology*, Proc. **IEEE Nuclear Science Symp. and Medical Imaging Conf. (NSS/MIC), Rome, Italy, October 16–22, 2004**, ed. J.D. Valentine (IEEE Trans. Nucl. Sci. **52**, 2005) p.861.

D.M. Gingrich *et al.* (STACEE collaboration), *The STACEE ground-based gamma-ray detector, ibid.* 2977 [astro-ph/0506613].

G. Dutto, *TRIUMF high intensity cyclotron development for ISAC*, Proc. **17$^{\mathrm{th}}$ Int. Conf. on Cyclotrons and Their Applications, Tokyo, Japan, October 18–22, 2004**, eds. A. Goto and Y. Yano (Part. Accel. Soc. Japan, Tokyo, 2005) p.82 [TRI-PP-04-28].

J.S. Berg, R. Palmer, A. Ruggiero, D. Trbojevic, E. Keil, C. Johnstone, A. Sessler, S.R. Koscielniak and M. Craddock, *Review of current FFAG lattice studies in North America, ibid.* 222.

S. Koscielniak, *Novel constant-frequency acceleration technique for non-scaling muon FFAGs, ibid.* 227 [TRI-PP-04-29].

I. Bylinski, S. Calic, K. Fong and R. Poirier, *TRIUMF cyclotron rf system refurbishing, ibid.* 327 [TRI-PP-04-30].

A.K. Mitra, Y. Bylinski, N. Mehboob, R.L. Poirier and V. Zvyagintsev, *Simulation of rf structure of TRIUMF cyclotron with HFSS, ibid.* 365 [TRI-PP-04-31].

P. Schmor, *TRIUMF ISAC-II and beyond, ibid.* 523 [TRI-PP-04-32].

M.K. Craddock, *Cyclotrons and FFAGs in 2004, ibid.* 537 [TRI-PP-04-33].

R. Baartman and S. Martin, *Summary of session H: FFAGs and cyclotrons*, Proc. **33$^{\mathrm{rd}}$ ICFA Advanced Beam Dynamics Workshop: High Intensity High Brightness Hadron Beams (ICFA HB2004), Bensheim, Darmstadt, Germany, October 18–22, 2004** (AIP Conf. Proc. **773**, 2005) p.461.

L. Chen and D.M. Gingrich, *Configurable SRAM macro design to resist total dose effects*, Proc. **18$^{\mathrm{th}}$ Annual Canadian Conf. on Electrical and Computer Engineering (CCECE05), Saskatoon, SK, May 1–4, 2005** (IEEE, 2005) p.690.

Y.-N. Rao and D. Reistad, *Monte Carlo simulations of thin internal target scattering in CELSIUS*, Proc. **2005 Particle Accelerator Conf. (PAC 2005), Knoxville, TN, May 16–20, 2005**, ed. C. Horak (IEEE ISBN 0-7803-8859-3, 2005) p.1 [TRI-PP-05-13].

M.K. Craddock, *New concepts in FFAG design for secondary beam facilities and other applications, ibid.* 261 [PAC-2005-FOAC003, TRI-PP-05-11].

I. Hofmann *et al. Benchmarking of simulation codes based on the Montague resonance in the CERN proton synchrotron, ibid.* 330 [PAC-2005-MOPC003].

R.E. Laxdal, K. Fong, M. Marchetto, W.R. Rawnsley and V. Verzilov, *First acceleration with superconducting rf cavities at ISAC-II, ibid.* 662 [PAC-2005-ROPC009, TRI-PP-05-17].

V. Zviagintsev and Yu. Bylinsky, *HFSS simulation of vacuum tube rf power amplifiers, ibid.* 767 [PAC-2005-WPAT001].

Y.N. Rao, G.H. Mackenzie and T.C. Ries, *Redesign of a low energy probe head, ibid.* 1105 [PAC-2005-WPAE008, TRI-PP-05-14].

R.B. Armenta, M.J. Barnes, E.W. Blackmore, O. Hadary, G.D. Wait, L. Ahrens, C.J. Gardner and W. Zhang, *Design concept for AGS injection kicker upgrade to 2 GeV, ibid.* 1380 [PAC-2005-MPPT014, TRI-PP-05-12].

E.W. Blackmore, A.S. Dowling, R. Ruegg and M. Stenning, *Operating experience with meson production targets at TRIUMF, ibid.* 1919 [PAC-2005-RPPE026, TRI-PP-05-31].

R.E. Laxdal, W. Andersson, P. Bricault, I. Bylinskii, K. Fong, M. Marchetto, A.K. Mitra, R.L. Poirier, W.R. Rawnsley, P. Schmor, I. Sekachev, G. Stanford, G. Stinson and V. Zviagintsev, *Status of the ISAC-II accelerator at TRIUMF, ibid.* 2003 [PAC-2005-FPAE027, TRI-PP-05-15].

S.R. Koscielniak and C. Johnstone, *Electron model of linear-field FFAG, ibid.* 3173 [PAC-2005-RPPT051].

R.E. Laxdal, K. Fong, K. Mitra, T.C. Ries, I. Sekachev, G. Stanford and V. Zviagintsev, *Cryogenic, magnetic and rf performance of the ISAC-II medium beta cryomodule at TRIUMF, ibid.* 3191 [PAC-2005-TPPT052, TRI-PP-05-16].

S.R. Koscielniak and R. Baartman, *Analysis of rapid betatron resonance crossing, ibid.* 3206 [PAC-2005-RPPT052].

M.J. Barnes, G.D. Wait and L. Ducimetiere, *High voltage measurements on nine PFNs for the LHC injection kicker systems, ibid.* 3402 [PAC-2005-WPAE058, TRI-PP-05-19].

A. Facco, F. Scarpa, D. Zenere and V. Zviagintsev, *Prototyping of a 352 MHz, β = 0.17 superconducting coaxial half wave resonator, ibid.* 3547 [PAC-2005-TPPT061].

V. Blideanu, G. Bollen, D. Lawton, P. Mantica, D. Morrissey, R. Ronningen, B. Sherrill, A. Zeller, T. Bredeweg, F.M. Nortier, D. Vieira, L. Heilbronn, L. Ahle, J. Boles, S. Reyes, W. Stein, J.R. Beene, T. Burgess, K. Carter, D. Conner, T. Gabriel, L. Mansur, I. Remec, M. Rennich, D. Stracener, M. Wendel and P. Bricault, *Radiation simulations for the proposed ISOL stations for RIA, ibid.* 3561 [PAC-2005-RPPT062].

S. Bassanese, M. Ferianis, F. Iazzourene and V. Verzilov, *Linac and transfer line beam position monitor at ELETTRA*, Proc. **7th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC 2005), Lyon, France, June 6–8, 2005** (2005) p.252 [POW005].

M.J. Barnes, G.D. Wait, J. Dilling, J.V. Vaz, L. Blomeley, O. Hadary and M.J. Smith, *A high frequency MOSFET driver for the TITAN facility at TRIUMF*, Proc. **15th IEEE Int. Pulsed Power Conf., Monterey, CA, June 13–17, 2005** (IEEE, DOI 10.1109/PPC.2005.300554, 2005) p.178 [TRI-PP-05-21].

R.B. Armenta, M.J. Barnes and G.D. Wait, *Precision 25 kV pulse and rf suppression in a 75 kHz kicker, ibid.* 676 [TRI-PP-05-20].

Instrumentation / Accelerator Physics / Computing Sciences – *2006*

J. Lassen, P. Bricault, M. Dombsky, J.P. Lavoie, Ch. Geppert and K. Wendt, *Resonant ionization laser ion source project at TRIUMF*, Proc. **6th Int. Workshop on Application of Lasers in Atomic Nuclei Research (LASER 2004), Poznan, Poland, May 24–27, 2004** (Springer, Berlin, Heidelberg, 2006) p.69.

G. Ruprecht, D. Gigliotti, P. Amaudruz, L. Buchmann, S.P. Fox, B.R. Fulton, T. Kirchner, A.M. Laird, P.D. Mumby-Croft, R. Openshaw, M.M. Pavan, J. Pearson, G. Sheffer and P. Walden, *Status of the TRIUMF annular chamber for the tracking and identification of charged particles (TACTIC)*, Proc. **2nd Int. Conf. on Nuclear Physics in Astrophysics, Debrecen, Hungary, May 16–20, 2005**, eds. Z. Fülöp *et al.* (Eur. Phys. J. **A27**, 2006) p.315.

M.J. Barnes, T. Fowler, K. Metzmacher and L. Sermeus, *Pulse forming network conceptual design for the proposed PS multi-turn extraction system*, Proc. **Power Modulator Symp., Washington, DC, May 14–18, 2006** (IEEE, 2006) p.260.

J.P. Martin and P.A. Amaudruz, *A 48 channel pulse shape digitizer with DSP*, Proc. **14th IEEE-NPSS Real Time Conf. (RT2005), Stockholm, Sweden, June 4–10, 2005** (IEEE Trans. Nucl. Sci. **53**, 2006) p.715.

D. Morris, P.A. Amaudruz, F. Berghaus, Shao-Min Chen, R. Helmer, C. Holmberg, K. Hoyle, I. Kato, P. Kitching, A. Konaka, M. Lenckowski and S. Oser, *An optical calibration manipulator system, ibid.* 956.

A. Vandenbroucke, C.A. Miller *et al.* (HERMES collaboration), *Simulation of the HERMES lead glass calorimeter using a look-up table*, Proc. **12th Int. Conf. on Calorimetry in High Energy Physics (CALOR 06), Chicago, IL, June 5–9, 2006**, eds. S.R. Magill *et al.* (AIP Conf. Proc. **867**, 2006) p.495.

R.B. Armenta, M.J. Barnes, E.W. Blackmore, O. Hadary, D.T. Norn and G.D. Wait, *Electromagnetic modelling of the AGS A10 injection kicker magnet*, Proc. **19th Int. Conf. on Magnet Technology (MT-19), Genoa, Italy, September 18–23, 2005** (IEEE Trans. Applied Superconductivity **16**, 2006) p.293.

D. Karlen *Near detectors for the T2K experiment*, Proc. **4th Int. Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region (NuInt05), Okayama, Japan, September 26–29, 2005** (Nucl. Phys. Proc. Suppl. **159**, 2006) p.91.

W.R. Rawnsley, R.J. Potter, V.A. Verzilov and L. Root, *Wide dynamic range front-end electronics for beam current and position measurement*, Proc. **12th Beam Instrumentation Workshop (BIW06), Batavia, IL, May 1–4, 2006**, eds. T.S. Meyer and R.C. Webber (AIP Conf. Proc. **868**, 2006) p.454.

E.J. Prime, J. Lassen, T. Achtzehn, D. Albers, P. Bricault, T. Cocolios, M. Dombsky, F. Labrecque, J.P. Lavoie, M.R. Pearson, T. Stubbe, N. Lecesne, Ch. Geppert and K.D.A. Wendt, *TRIUMF resonant laser ion source; Ga, Al and Be radioactive ion beam development*, Proc. **Application of Lasers in Atomic Nuclei Research VII Int. Workshop, Poznan, Poland, May 29–June 1, 2006** (Hyp. Int. **171**, 2006) p.127.

G. Ruprecht, P. Amaudruz, P. Mumby-Croft, L. Buchmann, S. Fox, B. Fulton, A.M. Laird, R. Openshaw, M.M. Pavan, J. Pearson and P. Walden, *The TRIUMF annular chamber of tracking and identification of charged particles (TACTIC)*, Proc. **Int. Symp. Nuclear Astrophysics – Nuclei in the Cosmos IX (NIC-IX), Geneva, Switzerland, June 25–30, 2006** (Proc. of Science, 2006) p.170.

V. Zviagintsev *et al.*, *Results and experience with single cavity tests of medium beta superconducting quarter wave resonators at TRIUMF*, Proc. **10th European Particle Accelerator Conf. (EPAC'06), Edinburgh, UK, June 26–30, 2006** (JACoW, 2006) p.375.

A. Facco, F. Scarpa, D. Zenere, R. Losito and V. Zviagintsev, *Low- and intermediate-beta, 352-MHz superconducting half-wave resonators for high power hadron acceleration, ibid.* 448.

W. Herr *et al.*, *Large scale beam-beam simulations for the CERN LHC using distributed computing resources, ibid.* 526.

V.A. Verzilov *et al.*, *A wideband intercepting probe for the TRIUMF cyclotron, ibid.* 1001.

R.E. Laxdal *et al.*, *Commissioning of the ISAC-II heavy ion superconducting linac at TRIUMF, ibid.* 1556.

S.R. Koscielniak, *Chromaticity control in linear-field nonscaling FFAGs by sextapoles, ibid.* 1657.

S.R. Koscielniak, *Minimum cost lattices for nonscaling FFAGs, ibid.* 1660.

S.R. Koscielniak, *Nonscaling FFAG with equal longitudinal and transverse reference momenta, ibid.* 1663.

M.K. Craddock and S.R. Koscielniak, *Formulae for linear-field non-scaling FFAG accelerator orbits, ibid.* 1666.

D. Kalchev, *Implementation of TPSA in the Mathematica code LieMath, ibid.* 2077.

F. Zimmermann *et al.*, *Accelerator physics code web repository, ibid.* 2254.

C. Johnstone and S.R. Koscielniak, *Tune-stabilized linear-field FFAG for carbon therapy, ibid.* 2290.

B. Guo, W.P. Liu, M. Trinczek, S. Lapi, F. Ames, K.R. Buckley, J.M. D'Auria, K. Jayamanna, C. Ruiz and T.J. Ruth, *Production of intense radioactive beams using low energy protons*, Proc. **17^{th} Int. Workshop on ECR Ion Sources (ECRIS06), Lanzhou, China, September 17–21, 2006** (High Energy Phys. Nucl. Phys. (Chinese ed.) **30**, 2006) p.679.

F. Ames, R. Baartman, P. Bricault, K. Jayamanna, M. McDonald, M. Olivo, P. Schmor, D.H.L. Yuan and T. Lamy, *ECRIS charge breeding at ISAC, ibid.*

Instrumentation / Accelerator Physics / Computing Sciences – *2007*

M.A. Schumaker, C.E. Svensson, C. Andreoiu, A. Andreyev, R.A.E. Ausin, G.C. Ball, D. Bandyopadhyay, A.J. Boston, R.S. Chakrawarthy, R. Churchman, T.E. Drake, P. Finlay, P.E. Garrett, G.F. Grinyer, G. Hackman, B. Hyland, B. Jones, R. Maharaj, A.C. Morton, C.J. Pearson, A.A. Phillips, F. Sarazin, H.C. Scraggs, M.B. Smith, J.J. Valiente-Dobón, J.C. Waddington and J.M. Watters, *Optimization of Compton-suppression and summing schemes for the TIGRESS HPGe detector array*, Proc. **$7^{\rm th}$ Position Sensitive Detectors Conf., Liverpool, UK, September 12–16, 2005** (Nucl. Instrum. Methods **A573**, 2007) p.157.

S. Baranov, A. Barashkou, N. Benekos, L. Chevalier, J.-F. Laporte, D. Pomarede, S. Goldfarb, T. Moore, D. Rebuzzi, M. Schott, S. Spagnolo and I. Trigger, *Muon detector description as built and its simulation for the ATLAS experiment*, Proc. **$10^{\rm th}$ Pisa Meeting on Advanced Detectors: Frontier Detectors for Frontier Physics, La Biodola, Elba, Italy, May 21–27, 2006** (Nucl. Instrum. Methods **A572**, 2007) p.14.

R.E. Laxdal, W. Andersson, I Sekachev and G. Stanford, *Performance and early operating experience with the ISAC-II cryogenic system*, Proc. **2006 Linear Accelerator Conf. (LINAC06), Knoxville, TN, August 21–25, 2006**, ed. C. Horak (www.JACoW.org, 2007) p.306 [TUP029].

R.E. Laxdal, I. Bylinskii, K. Fong, M.P. Laverty, A.K. Mitra, T.C. Ries, Q. Zheng and V. Zviagintsev, *RF cavity performance and rf infrastructure for the ISAC-II superconducting linac, ibid.* 309 [TUP030].

M. Marchetto, A. Bylinskii and R.E. Laxdal, *Beam dynamics studies on the ISAC II superconducting linac, ibid.* 312 [TUP031].

J. Rodnizki, D. Berkovits, K. Lavie, I. Mardor, A. Shor, Y. Yanai, K. Dunkel, C. Piel, A. Facco and V. Zviagintsev, *Beam dynamics simulations of SARAF accelerator including error propagation and implications for the EURISOL driver, ibid.* 426 [TUP074]

R.E. Laxdal, *Initial commissioning results from the ISAC-II SC linac, ibid.* 521 [TH1003].

K. Fong, M. Laverty and Q.W. Zheng, *Adaptive tuner control in TRIUMF ISAC-II superconducting linac using Kalman filter, ibid.* 592 [THP012].

P. Bricault, *Targets and ion sources development at ISAC-TRIUMF, ibid.* 823 [FR2001].

J. Dilling, M. Comyn, J. Thomson and G. Gwinner, eds., Proc. **$4^{\rm th}$ Int. Conf. on Trapped Charged Particles and Fundamental Physics (TCP 2006), Parksville, BC, September 3–8, 2006** (Springer, The Netherlands, 2007) (also Hyp. Int. **172-174**, 2006-2007).

M.C. Fujiwara, G. Andresen, W. Bertsche, A. Boston, P.D. Bowe, C.L. Cesar, S. Chapman, M. Charlton, M. Chartier, A. Deutsch, J. Fajans, R. Funakoshi, D.R. Gill, K. Gomberoff, J.S. Hangst, W.N. Hardy, R.S. Hayano, R. Hydomako, M.J. Jenkins, L.V. Jorgensen, L. Kurchaninov, N. Madsen, P. Nolan, K. Olchanski, A. Olin, R.D. Page, A. Povilus, F. Robicheaux, E. Sarid, D.M. Silveira, J.W. Storey, R.I. Thompson, D.P. van der Werf, J.S. Wurtele and Y. Yamazaki, *Towards antihydrogen confinement with the ALPHA antihydrogen trap, ibid.* 81 [TRI-PP-07-03].

J.A. Behr, J.R.A. Pitcairn, D.G. Roberge, M.R. Pearson, C. Höhr, G. Gwinner, D. Ashery, B. Dej, A. Gaudin, K.P. Jackson and A. Gorelov, *Ion detection from beta and electron capture decay experiments with laser-cooled atoms, ibid.* 197 [TRI-PP-07-06].

M. Froese, C. Champagne, J.R. Crespo López-Urrutia, S. Epp, G. Gwinner, A. Lapierre, J. Pfister, G. Sikler, J. Ullrich and J. Dilling, *A high-current electron beam ion trap as an on-line charge breeder for the high precision mass measurement TITAN experiment, ibid.* 241.

Z. Ke, W. Shi, G. Gwinner, K. Sharma, S. Toews, J. Dilling, V.L. Ryjkov *et al.* (TITAN collaboration), *A cooler ion trap for the TITAN on-line trapping facility at TRIUMF, ibid.* 259 [TRI-PP-07-07].

P. Delheij, L. Blomeley, M. Froese, G. Gwinner, V. Ryjkov, M. Smith and J. Dilling, *The TITAN mass measurement facility at TRIUMF-ISAC, ibid.* 279 [TRI-PP-07-05].

M. Smith, L. Blomeley, P. Delheij and J. Dilling, *First tests of the TITAN digital RFQ beam cooler and buncher, ibid.* 327 [TRI-PP-07-26].

R. Ringle, G. Bollen, P. Schury, S. Schwarz and T. Sun, *Octupolar excitation of ion motion in a penning trap, ibid.* 365 [TRI-PP-07-08].

T. Achtzehn, J. Lassen, P. Bricault, D. Albers, T. Cocolios, M. Dombsky, V. Hanemaayer, J.P. Lavoie, N. Lecesne, M.R. Pearson, E.J. Prime and K.D.A. Wendt, ^{26}*Al beam production by a solid state laser ion source at TRIUMF, ibid.* 383 [TRI-PP-07-09].

J.P. Lavoie, P. Bricault, J. Lassen and M.R. Pearson, *Segmented linear radiofrequency quadrupole/laser ion source project at TRIUMF, ibid.* 389 [TRI-PP-07-10].

M. Dixit, D. Attie, A. Bellerive, K. Boudjemline, P. Colas, A. Giganon, I. Giomataris, V. Lepeltier, S. Liu, J.-P. Martin, K. Sachs, Y. Shin and S. Turnbull, *Micromegas TPC studies at high magnetic fields using the charge dispersion signal*, Proc. **11th Vienna Conf. on Instrumentation (VCI 2007), Vienna, Austria, February 19–24, 2007** (Nucl. Instrum. Methods **A581**, 2007) p.254 [CARLETON-HP-732, DAPNIA-07-36, LAL-0721].

M. Kobayashi, T. Araki, D.C. Arogancia, A.M. Bacala, K. Boudjemline, D. Burke, P. Colas, M. Dixit, K. Fujii, H. Fujishima, A. Giganon, I. Giomataris, H.C. Gooc Jr., M. Habu, T. Higashi, K. Ikematsu, K. Kadomatsu, Y. Kato, H. Kuroiwa, V. Lepeltier, T. Matsuda, S. Matsushita, K. Nakamura, O. Nitoh, J. Pouthas, R.L. Reserva, P. Rosier, R.D. Settles, A. Sugiyama, T. Takahashi, Y. Tanaka, T. Watanabe, A. Yamaguchi, T. Yamamoto, H. Yamaoka and T. Zerguerras, *Performance of MPGD-based TPC prototypes for the linear collider experiment, ibid* 265.

P.A. Amaudruz, C.J. Pearson, J.P. Martin, C. Mercier and N. Starinski, *The TIGRESS DAQ/trigger system*, Proc. **15th IEEE Real Time Conf. 2007 (RT 07), Batavia, IL, April 29 – May 4, 2007** (IEEE Trans Nucl. Sci. **55**, 2007) p.84 [RT2007-TDAQ-SYS05].

R.E. Laxdal, A.K. Mitra and W.R. Rawnsley, *A nonintercepting beam current monitor for the ISAC-II SC linac*, Proc. **22nd Particle Accelerator Conf. (PAC 07), Albuquerque, NM, June 25–29, 2007**, ed. C. Petit-Jean-Genaz (IEEE, Piscataway, and www.JACoW.org, 2007) p.155 [MOPAN007].

A. Grassellino, J.K. Keung, F.M. Newcomer and N. Lockyer, *FPGA based ILC cavity simulator, ibid.* 632 [MOPAS086].

M.J. Barnes and G.D. Wait, *Design and measurements of a damping ring kicker for the ILC, ibid.* 846 [TUOAC01, TRI-PP-07-23].

S.R. Koscielniak and C. Johnstone, *Analytic model for quadrupole fringe-field effects, ibid.* 1386 [TUPAN001].

S.R. Koscielniak, *Large displacement and divergence analytic transfer maps through quadrupoles, ibid.* 1389 [TUPAN002].

M. Marchetto, R.E. Laxdal and V. Zviagintsev, *Beam quality and operational experience with the superconducting LINAC at the ISAC II RIB facility, ibid.* 1392 [TUPAN003, TRI-PP-07-15].

K. Fong, M.P. Laverty and Q. Zheng, *Tuner control in TRIUMF ISAC II superconducting RF system, ibid.* 2047 [WEPMN002].

M.J. Barnes and G.D. Wait, *Low power measurements on an AGS injection kicker magnet, ibid.* 2188 [WEPMN069, TRI-PP-07-20].

J.K. Keung, M. Newcomer, S. Nagaitsev and N. Lockyer, *PVC – an ILC rf cryomodule software simulator, ibid.* 2523 [WEPMS082].

R.E. Laxdal, *Commissioning and early experiments with ISAC II, ibid.* 2593 [THXAB01].

C. Johnstone and S. Koscielniak, *New nonscaling FFAG for medical applications, ibid.* 2951 [THPMN103].

J.S. Berg, A. Ruggiero, S. Machida and S. Koscielniak, *The EMMA lattice design, ibid.* 3181 [THPMS083].

A. Baartman and D. Kaltchev, *Runge-Kutta DA integrator in Mathematica language, ibid.* 3226 [THPAN004].

A. Baartman and D. Kaltchev, *Short quadrupole parametrization, ibid.* 3229 [THPAN005].

F.W. Jones and E.Y. Wildner, *Simulation of decays and secondary ion losses in a betabeam decay ring, ibid.* 3232 [THPAN006].

F.W. Jones, W. Herr and T. Pieloni, *Parallel beam-beam simulation incorporating multiple bunches and multiple interaction regions, ibid.* 3235 [THPAN007].

Y.-N. Rao and A. Baartman, *TRIUMF extraction and 500 MeV beamline optics, ibid.* 3238 [THPAN008, TRI-PP-07-16].

M.K. Craddock and S.R. Koscielniak, *Orbit properties of nonscaling FFAG accelerators using constant-gradient magnets, ibid.* 3241 [THPAN009, TRI-PP-07-14].

I.V. Bylinskii, K. Fong, J. Lu, A.K. Mitra and C. Owen, *RF amplifier choice for the ISAC superconducting linac, ibid.* 3798 [FROAC02].

P. Bricault, *ISAC-I and ISAC-II: present status and future perspectives*, Proc. **7th Int. Conf. on Radioactive Nuclear Beams (RNB7), Cortina d'Ampezzo, Italy, July 3–7, 2006** (Eur. Phys. J. ST **150**, 2007) p.227.

M. Marchetto, Z.T. Ang, K. Jayamanna, R.E. Laxdal, A. Mitra and V. Zvyagintsev, *Radioactive ion beam post-acceleration at ISAC, ibid.* 241.

J. Lassen, T. Achtzehn, D. Albers, P. Bricault, M. Dombsky, Ch. Geppert, J.P. Lavoie, P. Levy, M. Pearson, E. Prime and K. Wendt, *On-line ^{26}Al and ^{62}Ga beams with the TRIUMF-ISAC resonant ionization laser ion source, ibid.*

A.C. Morton, P. Bricault, M. Dombsky, R.E. Laxdal, C.R. Mark, L.E. Moritz, G. Stanford and A. Trudel, *Actinide target development for RIB production at TRIUMF's ISAC facility, ibid.*

G.C. Ball, A. Andreyev, R.A.E. Austin, D. Bandyopadhyay, J.A. Becker, A.J. Boston, H.C. Boston, A. Chen, R. Churchman, F. Cifarelli, D. Cline, R.J. Cooper, D.S. Cross, D. Dashdorj, G. Demand, M.R. Dimmock, T.E. Drake, P. Finlay, F. Gagnon-Moisan, A.T. Gallant, P.E. Garrett, K.L. Green, A.N. Grint, G. Hackman, L.J. Harkness, A.B. Hayes, R. Kanungo, K.G. Leach, G. Lee, R. Maharaj, J.-P. Martin, A.C. Morton, S. Mythili, L. Nelson, O. Newman, P.J. Nolan, E. Padilla-Rodal, C.J. Pearson, A.A. Phillips, M. Porter-Peden, J.J. Ressler, R. Roy, C. Ruiz, H. Savajols, F. Sarazin, M.A. Schumaker, D.P. Scraggs, C.E. Svensson, J.C. Waddington, J.M. Wan, A. Whitbeck, S.J. Williams, J. Wong and C.Y. Wu, *TRIUMF-ISAC gamma-ray escape suppressed spectrometer (TIGRESS): a versatile tool for radioactive beam physics*, Proc. **IX Int. Conf. on Nucleus Nucleus Collisions, Rio de Janeiro, Brazil, August 28–September 1, 2006** (Nucl. Phys. **A787**, 2007) p.118.

Instrumentation / Accelerator Physics / Computing Sciences – *2008*

M.K. Craddock and Y.-N. Rao, *High-energy cyclotrons without spiral*, Proc. **18th Int. Conf. on Cyclotrons and their Applications (CYCLOTRONS 07), Giardini Naxos, Italy, September 30 – October 5, 2007** (www.JACoW.org, 2008) [TUPPRB06, TRI-PP-07-29].

I. Bylinskii, R.A. Baartman, G. Dutto, K. Fong, A. Hurst, M. Laverty, C. Mark, F. Mammarella, M. McDonald, A.K. Mitra, M. Mouat, D. Pearce, K. Reiniger, R. Ruegg, P. Schmor, I. Sekachev, M. Stenning and V.A. Verzilov, *TRIUMF 500 MeV cyclotron refurbishment, ibid.* [MOPPRA05, TRI-PP-07-30].

P.G. Bricault, M. Dombsky, J. Lassen and F. Ames, *Progress in development of ISOL RIB ion sources and targets for highpower, ibid.* [MOZCR02, TRI-PP-07-31].

K. Fong, *New technologies in the design of rf controls for accelerators, ibid.* [TUXCR02], TRI-PP-07-32].

P.W. Schmor, *New achievements at TRIUMF and future plans, ibid.* [TUYCR01, TRI-PP-07-33].

T. Kuo, R. Baartman, B. Milton, W. Uzat, P. Schmor, G. Dutto, V. Sabaiduc, R. Johnson, K. Erdman, W. Gyles, R. Watt, T.S. Duh and T.J. Zhang, *Review on beam characteristics of high current H^- cyclotrons, ibid.* [WEPPRB01, TRI-PP-07-34].

V.A. Verzilov, D.T. Gray, R. Potter and W.R. Rawnsley, *A new beam position monitor for the TRIUMF cyclotron beamlines, ibid.* [WEPPRB17, TRI-PP-07-35].

A. Shotter, *Radioactive beams – pathway to exotic regions of the nuclear landscape, ibid.* [FRZCR01, TRI-PP-07-36].

H. Yao, R. Baartman, Y.-N. Rao, T. Zhang and Y. Lin, *Gap-crossing resonance in CYCIAE-100 cyclotron, ibid.* [MOPPRA11].

E. Tikhomolov, *Interfacing of peripheral systems to EPICS using shared memory*, Proc. **11th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS 07), Knoxville, TN, October 15–19, 2007**, ed. C. Horak (www.JACoW.org, 2008) p.152 [TPPA29, TRI-PP-07-39].

R. Keitel, D. Bishop, D. Dale, T. Howland, H. Hui, K. Langton, M. Leross, R. Nussbaumer, C. Payne, K. Pelzer, J. Richards, W. Roberts, E. Tikhomolov and G. Waters, *ISAC control system update, ibid.* 235 [TPPB34, TRI-PP-07-40].

D. Dale, R. Nussbaumer, T. Howland, H. Hui, R. Keitel, K. Langton, M. Leross, K. Pelzer, J. Richards, W. Roberts and E. Tikhomolov, *The control system for the TITAN experiment at ISAC, ibid.* 238 [TPPB35, TRI-PP-07-41].

M.M. Mouat, I.A. Aguilar, E. Klassen, K.S. Lee, D. Pearce, J.J. Pon, T.M. Tateyama and P.J. Yogendran, *Commissioning TRIUMF's 2C solid target facility controls, ibid.* 371 [WPPA27, TRI-PP-07-42].

E. Tikhomolov, *Processing and visualization of EPICS data with MATLAB, ibid.* 659 [RPPB24, TRI-PP-07-43].

R. Nussbaumer, *Live Capfast schematics in the ISAC control system, ibid.* 662 [RPPB25, TRI-PP-07-44].

Instrumentation / Accelerator Physics / Computing Sciences – *presented*

R. Mukherjee *et al.* (STACEE collaboration), *STACEE observations of 1ES 1218+304*, Proc. **30th Int. Cosmic Ray Conf. (ICRC 2007), Merida, Mexico, July 3–11, 2007** [arXiv:0710.4170].

D.D. Driscoll *et al.*, *Search for dark matter annihilation in Draco with STACEE, ibid.* [arXiv:0710.3545].

J. Kildea *et al.*, *Observations of the pulsar PSR B1951+32 with the solar tower atmospheric Cherenkov effect experiment, ibid.* [arXiv:0710.4623].

A. Jarvis *et al.*, *Gamma-ray burst follow-up observations with STACEE during 2003-2007, ibid.* [arXiv:0710.4149].

Molecular and Materials Science – *2003*

P.W. Percival, *Muonium chemistry*, Pre-conference tutorial on μSR, Proc. **9th Int. Conf. on Muon Spin Rotation/Relaxation/Resonance (MuSR 2002), Williamsburg, VA, June 3–7, 2002** (Physica **B326**, 2003).

D.R. Noakes, R.H. Heffner and P.W. Percival (editors), Proc. **9th Int. Conf. on Muon Spin Rotation/Relaxation/Resonance (MuSR 2002), Williamsburg, VA, June 3–7, 2002** (Physica **B326**, 2003).

S. Kreitzman, *An overview of high field/timing resolution and RF/μwave μSR methods, ibid.*

J.C. Brodovitch, B. Addison-Jones, K. Ghandi, I.D. McKenzie and P.W. Percival, *^{13}C hyperfine coupling constants of MuC_{70} in solution, ibid.*

J.H. Brewer, *More μ^-SR in nuclei with spin, ibid.*

K. Ghandi, B. Addison-Jones, J.-C. Brodovitch, S. Kecman, I. McKenzie and P.W. Percival, *Muonium kinetics in sub- and supercritical water, ibid.* 55.

V.G. Storchak, D.G. Eshchenko, J.H. Brewer, G.D. Morris, S.P. Cottrell and S.F.J. Cox, *Coherent tunnelling dynamics of muonium in a disordered medium, ibid.* 61.

D.J. Arseneau, D.G. Fleming, C.A. Fyfe and M. Senba, *Observation of muonium in zeolites, ibid.* 64.

P.W. Percival, J.C. Brodovitch, D.J. Arseneau, M. Senba and D.G. Fleming, *Formation of the muoniated ethyl radical in the gas phase, ibid.* 72.

I. McKenzie, J.C. Brodovitch, K. Ghandi, S. Kecman and P.W. Percival, *Formation and spectroscopy of α-muoniated radicals, ibid.* 76.

D.G. Eshchenko, V.G. Storchak, J.H. Brewer, S.P. Cottrell, S.F.J. Cox, E. Karlsson and R. Wäppling, *Ionization of a shallow muonium state in a semiconductor, ibid.* 120.

R.L. Lichti, *Properties of muonium defect centers in III-V nitrides, ibid.* 139.

K.H. Chow, *Isolated positively charged muonium and the analog of hydrogen passivation, ibid.* 145.

K.H. Chow, B. Hitti, D.G. Eshchenko, V.G. Storchak, S.R. Kreitzman and J.H. Brewer, *Avoided level crossing measurements of electric field enhanced diamagnetic states in gallium arsenide, ibid.* 157.

D.G. Eshchenko, V.G. Storchak, R.L. Lichti and J.H. Brewer, *Short range electron transport in GaAs, ibid.* 160.

V.G. Storchak, D.G. Eshchenko, R.L. Lichti and J.H. Brewer, *Weakly bound muonium state in a semiconductor, ibid.* 164.

R.L. Lichti, K.H. Chow, E.A. Davis, B. Hitti, Y.G. Celebi and S.F.J. Cox, *Muonium–acceptor interactions in gallium phosphide, ibid.* 167.

P.J.C. King, R.L. Lichti and I. Yonenaga, *Muonium behaviour in Czochralski $Si_{1-x}Ge_x$ alloys, ibid.* 171.

K.L. Hoffman, K.H. Chow, R.F. Kiefl, B. Hitti, T.L. Estle and R.L. Lichti, *Frequency shifts and local spin susceptibility of muonium in heavily-doped Si and GaAs, ibid.* 175.

B. Hitti and S.R. Kreitzman, *Muonium dynamics in silicon at high temperature, ibid.* 178.

R.F. Kiefl, W.A. MacFarlane, G.D. Morris, P. Amaudruz, D. Arseneau, H. Azumi, R. Baartman, T.R. Beals, J. Behr, C. Bommas, J.H. Brewer, K.H. Chow, E. Dumont, S.R. Dunsiger, S. Daviel, L. Greene, A. Hatakeyama, R.H. Heffner, Y. Hirayama, B. Hitti, S.R. Kreitzman, C.D.P. Levy, R.I. Miller, M. Olivo and R. Poutissou, *Low-energy spin-polarized radioactive beams as a nano-scale probe of matter, ibid.* 189.

T.R. Beals, R.F. Kiefl, W.A. MacFarlane, K.M. Nichol, G.D. Morris, C.D.P. Levy, S.R. Kreitzman, R. Poutissou, S. Daviel, R.A. Baartman and K.H. Chow, *Range straggling of low energy $^8Li^+$ in thin metallic films using β-NMR, ibid.* 205.

W.A. MacFarlane, G.D. Morris, K.H. Chow, R.A. Baartman, S. Daviel, S.R. Dunsiger, A. Hatakeyama, S.R. Kreitzman, C.D.P. Levy, R.I. Miller, K.M. Nichol, R. Poutissou, E. Dumont, L.H. Greene and R.F. Kiefl, *Quadrupolar split ^{8}Li β-NMR in $SrTiO_3$, ibid.* 209.

W.A. MacFarlane, G.D. Morris, T.R. Beals, K.H. Chow, R.A. Baartman, S. Daviel, S.R. Dunsiger, A. Hatakeyama, S.R. Kreitzman, C.D.P. Levy, R.I. Miller, K.M. Nichol, R. Poutissou and R.F. Kiefl, *^{8}Li β-NMR in thin metal films, ibid.* 213.

D.G. Eshchenko, V.G. Storchak, B. Hitti, S.R. Kreitzman, J.H. Brewer and K.H. Chow, *Radio-frequency μSR experiments in an applied electric field, ibid.* 244.

G.D. Morris and R.H. Heffner, *A method of achieving accurate zero field conditions using muonium, ibid.* 252.

K.H. Chow, R.F. Kiefl, S. Chan, R.I. Miller, P. Amaudruz, R. Poutissou, B. Hitti and D. Arseneau, *MULTI – new detector, new logic, new science, ibid.* 279.

R.I. Miller, R.F. Kiefl, J.H. Brewer, J.C. Chakhalian, S. Dunsiger, A.N. Price, D.A. Bonn, W.H. Hardy, R. Liang and J.E. Sonier, *Penetration depth and core radius μSR measurements in the vortex state near the lower critical field, ibid.* 296.

J.E. Sonier, J.H. Brewer, R.F. Kiefl, R.I. Miller, R.H. Heffner, K.F. Poon, G.D. Morris, W.N. Hardy, R. Liang, D.A. Bonn, J.S. Gardner and C.E. Stronach, *Zero field μSR study of $YBa_2Cu_3O_{6+x}$, $x \geq 0.67$: evidence for charge ordering, ibid.* 312.

K.M. Kojima, S. Uchida, Y. Fudamoto, I.M. Gat, M.I. Larkin, Y.J. Uemura and G.M. Luke, *Superfluid density and volume fraction of static magnetism in stripe-stabilized $La_{1.85-y}Eu_ySr_{0.15}CuO_4$, ibid.* 316.

D. Baabe, H.-H. Klauss, D. Mienert, M. Birke, P. Adelmann, B. Hitti, U. Zimmermann, A. Amato and F.J. Litterst, *Inhomogeneous spin order in the magnetic phase of electron-doped high-T_c superconductors, ibid.* 338.

H. Takagiwa, A. Kawano, Y. Mizuta, T. Yamamoto, M. Yamada, K. Ohishi, T. Muranaka, J. Akimitsu, W. Higemoto and R. Kadono, *Magnetic penetration depth of a new boride superconductor Re_3B, ibid.* 355.

K. Ohishi, K. Kakuta, J. Akimitsu, A. Koda, W. Higemoto, R. Kadono, J.E. Sonier, A.N. Price, R.I. Miller, R.F. Kiefl, M. Nohara, H. Suzuki and H. Takagi, *Anomalous quasiparticle excitations in Y(Ni$_{1-x}Pt_x)_2B_2C$, ibid.* 364.

G.M. Luke, M.T. Rovers, A. Fukaya, I.M. Gat, M.I. Larkin, A.T. Savici, Y.J. Uemura, K.M. Kojima, P.M. Chaikin, I.J. Lee and M.J. Naughton, *Unconventional superconductivity in (TMTSF)$_2ClO_4$, ibid.* 378.

D.E. MacLaughlin, M.S. Rose, B.-L. Young, O.O. Bernal, R.H. Heffner, G.D. Morris, K. Ishida, G.J. Nieuwenhuys and J.E. Sonier, *μSR and NMR in f-electron non-Fermi liquid materials, ibid.* 381.

D.E. MacLaughlin, M.S. Rose, B.-L. Young, O.O. Bernal, R.H. Heffner, G.J. Nieuwenhuys, R. Pietri and B. Andraka, *μSR in $Ce_{1-x}La_xAl_3$: anisotropic Kondo effect?, ibid.* 387.

G.D. Morris, R.H. Heffner, J.E. Sonier, D.E. MacLaughlin, O.O. Bernal, G.J. Nieuwenhuys, A.T. Savici, P.G. Pagliuso and J.L. Sarrao, *Magnetism and superconductivity in $CeRh_{1-x}Ir_xIn_5$ heavy fermion materials, ibid.* 390.

D.R. Noakes, G.M. Kalvius, H. Nakotte, E. Schreier and R. Wäppling, *μSR magnetic response in UPdSn, ibid.* 406.

D.R. Noakes, G.M. Kalvius, H. Nakotte, E.J. Ansaldo and A.V. Andreev, *$U_{0.94}Y_{0.06}CoAl$: a dilute-moment ferromagnet, ibid.* 410.

J.E. Sonier, R.H. Heffner, G.D. Morris, D.E. MacLaughlin, O.O. Bernal, J. Cooley, J.L. Smith and J.D. Thompson, *μ^+-Knight shift in the superconducting state of $U_{1-x}Th_xBe_{13}$, x = 0 and 0.035 single crystals, ibid.* 414.

J.A. Chakhalian, R.F. Kiefl, R. Miller, S.R. Dunsiger, G. Morris, S. Kreitzman, W.A. MacFarlane, J. Sonier, S. Eggert, I. Affleck and I. Yamada, *Local magnetic susceptibility of the positive muon in the quasi-1D S = 1/2 antiferromagnet $KCuF_3$, ibid.* 422.

D. Mienert, H.-H. Klauss, A. Bosse, D. Baabe, H. Luetkens, M. Birke, F.J. Litterst, B. Büchner, U. Ammerahl, A. Revcolevschi, A. Amato, U. Zimmermann, B. Hitti and S. Kreitzman, *The interplay of charge order and magnetism in the one-dimensional quantum spin system $Sr_{14}Cu_{24}O_{41}$, ibid.* 440.

A. Fukaya, Y. Fudamoto, I.M. Gat, T. Ito, M.I. Larkin, A.T. Savici, Y.J. Uemura, P.P. Kyriakou, G.M. Luke, M. Rovers, H. Kageyama and Y. Ueda, *Spin dynamics in the two-dimensional spin system $SrCu_2(BO_3)_2$, ibid.* 446.

D.H. Ryan, J. van Lierop and J.M. Cadogan, *μSR and Mössbauer studies of transverse spin freezing, ibid.* 450.

G.M. Kalvius, D.R. Noakes, R. Wäppling, G. Grosse, W. Schäfer, W. Kockelmann, J.K. Yakinthos and P.A. Kotsanides, *Spin dynamics and spin disorder in frustrated $TbCo_xNi_{1-x}C_2$, ibid.* 465.

G.M. Kalvius, D.R. Noakes, R. Wäppling, E. Schreier, N. Büttgen, A. Krimmel, M. Klemm, S. Horn and A. Loidl, *Magnetic properties of geometrically frustrated $Zn_xLi_{1-x}V_2O_4$, ibid.* 470.

S.R. Dunsiger, R.F. Kiefl, J.A. Chakhalian, K.H. Chow, J.S. Gardner, J.E. Greedan, W.A. MacFarlane, R.I. Miller, G.D. Morris, A.N. Price, N.P. Raju and J.E. Sonier, *A comparison of the local magnetic susceptibility in rare earth pyrochlores, ibid.* 475.

R.H. Heffner, J.E. Sonier, D.E. MacLaughlin, G.J. Nieuwenhuys, F. Mezei, G. Ehlers, J.F. Mitchell and S.-W. Cheong, *Inhomogeneity in the spin channel of ferromagnetic CMR manganites, ibid.* 494.

J. Sugiyama, J.H. Brewer, E.J. Ansaldo, H. Itahara, M. Bayer and T. Tani, *μSR studies on layered cobalt oxides, ibid.* 518.

P.W. Percival, *Closing remarks, ibid.*

R.L. Lichti, *Sites and dynamics for muonium in III-V semiconductors*, Proc. **Int. Workshop on Hydrogen in Materials and Vacuum Systems (Hydrogen Workshop 2002), Newport News, VA, November 11–13, 2002**, eds. G.R. Myneni and S. Ghattopadhyay (AIP Conf. Proc. **671**, 2003) p.55.

D.R. Harshman, W.J. Kossler, X. Wan, A.T. Fiory, A.J. Greer, D.R. Noakes, C.E. Stronach, E. Koster, A. Erb and J.D. Dow, *Verification of nodeless superconductivity pairing in single-crystal $YBa_2Cu_3O_7$*, Proc. **4$^{\mathbf{th}}$ Int. Conf. on New Theories, Discoveries, and Applications of Superconductors and Related Materials (New4SC-3), San Diego, CA, January 16–21, 2003** (Int. J. Mod. Phys. **B17**, 2003) p.3582.

J.D. Dow and D.R. Harshman, *Locus of high-temperature superconductivity, ibid.*

D.E. MacLaughlin, *Critical and glassy dynamics in non-fermi-liquid heavy-fermion metals*, **Am. Phys. Soc. March Meeting, Austin, TX, March, 2003** (Bull Am. Phys. Soc. **48**, 2003) p.60.

J. Sugiyama, H. Itahara, J.H. Brewer, E.J. Ansaldo, K. Dohmae, C. Xia, Y. Seno, B. Hitti and T. Tani, *A common behavior of*

thermoelectric layered cobaltites: incommensurate spin density wave states, Proc. **Int. Conf. on Thermoelectrics, La Grande-Motte, France, August 17–21, 2003** (IEEE, Piscataway, 2003) p.215.

Molecular and Materials Science – *2004*

J. Sugiyama, J.H. Brewer, E.J. Ansaldo, H. Itahara, K. Dohmae, Y. Seno, C. Xia and T. Tani, *Successive magnetic transitions in thermoelectric layered cobaltite, $[Ca_2CoO_3]_{0.62}[CoO_2]$*, Proc. **8th IUMRS Int. Conf. on Advanced Materials, Yokohama, Japan, October 8–13, 2003** (Trans. MRS-Japan **29**, 2004) p.2737.

J. Sugiyama, H. Itahara, J.H. Brewer, E.J. Ansaldo, T. Motohashi, M. Karppinen and H. Yamauchi, *Magnetism in $Na_{0.75}CoO_2$ detected by μSR, ibid.* 2745.

J. Sugiyama, J.H. Brewer, E.J. Ansaldo, B. Hitti, M. Mikami, Y. Mori and T. Sasaki, *μSR studies on thermoelectric cobalt oxides V: Na_xCoO_2 crystals*, Proc. **Physical Society Japan March Meeting, Fukuoka, Japan, 2004** (Meeting Abstracts Phys. Soc. Jpn. **59**(1), 2004) p.549 (in Japanese).

Molecular and Materials Science – *2005*

I. McKenzie, P.W. Percival and J.A.C. Clyburne, *A computational study of the reactions of a beta-diketiminatoaluminium(I) complex with the hydrogen atom and the electron*, Proc. **American Chemical Society National Meeting, Anaheim, CA, March 28–30, 2004** (Chem. Comm. **9**, 2005) p.1134.

I. McKenzie, *Organic free radicals probed by muonium, ibid.*

J. Sugiyama, J.H. Brewer, E.J. Ansaldo, J.A. Chakhalian, H. Nozaki, H. Hazama, R. Asahi, T. Tani, Y. Ono and T. Kajitani, *Spin state transition in Ca-doped $Na_{0.7}CoO_2$: muon spin rotation and relaxation in the layered cobaltites with the nominal Co valence below 3.16*, Proc. **Int. Conf. on Thermoelectrics, Adelaide, Australia, July 25–29, 2004** (IEEE, Piscataway, 2005).

J. Sugiyama, J.H. Brewer, E.J. Ansaldo, B. Hitti, M. Mikami, Y. Mori and T. Sasaki, *Electron correlation in the two-dimensional triangular lattice of Na_xCoO_2 with $x \geq 0.6$*, Proc. **Int. Conf. on Strongly Correlated Electron Systems, Karlsruhe, Germany, July 26–30, 2004**, (Physica **B359-361**, 2005) p.1345.

J. Sugiyama, H. Nozaki, H. Itahara, T. Tani, J.H. Brewer, E.J. Ansaldo, J.A. Chakhalian and H. Hazama, *μSR studies on thermoelectric cobalt oxides VI: muonic Knight shift*, Proc. **Physical Society Japan Autumn Meeting, Aomori, Japan, 2004** (Meeting Abstracts Phys. Soc. Jpn. **59**(2), 2005) p.498 (in Japanese).

H. Nozaki, J. Sugiyama, J.H. Brewer, E.J. Ansaldo, T. Takami, H. Ikuta and H. Hazama, *μSR studies on thermoelectric cobalt oxides VII: one-dimensional system, ibid.* 498 (in Japanese).

H. Nozaki, J. Sugiyama, J.H. Brewer, E.J. Ansaldo, T. Takami, H. Ikuta and U. Mizutani, *μSR studies on thermoelectric cobalt oxides VIII: one-dimensional system, ibid. **60**(1)* (in Japanese).

J. Sugiyama, H. Nozaki, J.H. Brewer, E.J. Ansaldo, G.D. Morris and C. Delmas, *μSR studies on cobalt oxides IX: Li_xCoO_2, ibid.*

J. Sugiyama, H. Nozaki, J.H. Brewer, E.J. Ansaldo, Y. Miyazaki, X. Huang and T. Kajitani, *μSR studies on cobalt oxides X: $Ca_{0.5}CoO_2$, ibid.*

J. Sugiyama, H. Nozaki, J.H. Brewer, E.J. Ansaldo, G.D. Morris, T. Fujii and A. Asamitsu, *μSR studies on cobalt oxides XI: $K_{0.4}CoO_2$ crystal, ibid.*

H. Nozaki, J. Sugiyama, T. Takami, H. Ikuta, U. Mizutani, G.D. Morris, E.J. Ansaldo and J.H. Brewer, *μSR studies on cobalt oxides XII: pure and doped $BaCoO_3$, ibid.*

H. Imao, N. Kawamura, K. Ishida, T. Matsuzaki, Y. Matsuda, A. Toyoda and K. Nagamine, *Study of ortho-para effects on muonic-atomic and muonic-molecular processes in dd-μCF*, Proc. **Int. Conf. on Exotic Atoms and Related Topics, Vienna, Austria, February 21–25, 2005**, eds. A. Hirtl, J. Marton, E. Widmann and J. Zmeskal (Austrian Academy of Sciences Press, Vienna, 2005) p.279.

Molecular and Materials Science – *2006*

K. Mukai, Y. Ikedo, H. Nozaki, J. Sugiyama, K. Ariyoshi, T. Ohzuku, J.H. Brewer, E.J. Ansaldo and G.D. Morris, *μSR (muon spin relaxation & rotation) measurements on lithium insertion materials, $LiNi_xCo_{1-x}O_2$ (x=0, 1/4, 1/2, 3/4, 1)*, Meeting Abstracts of Phys. Soc. of Japan **61**, 320 (2006) (in Japanese).

K. Mukai, J. Sugiyama, Y. Ikedo, H. Nozaki, K. Ariyoshi, T. Ohzuku, K. Shimomura, K. Nishiyama, J.H. Brewer, E.J. Ansaldo and G.D. Morris, *μSR studies on cobalt oxides XVI: Li_xCoO_2 and $Li(CoNi)O_2$, ibid.* 447 (in Japanese).

J. Sugiyama, Y. Ikedo, K. Mukai, H. Yoshida, Z. Hiroi, J.H. Brewer, E.J. Ansaldo, G.D. Morris and K.H. Chow, *μSR studies on nickel oxides: Ag_2NiO_2 powder, ibid.* 453 (in Japanese).

J. Sugiyama, *μSR for industrial world, ibid.* 473 (in Japanese).

J. Sugiyama, Y. Ikedo, K. Mukai, T. Fujii, A. Asamitsu, J.H. Brewer, E.J. Ansaldo and G.D. Morris, *μSR studies on cobalt oxides XV: $Na_{0.5}CoO_2$ crystals, ibid.* 474 (in Japanese).

Y. Ikedo, J. Sugiyama, H. Nozaki, H. Itahara, J.H. Brewer, E.J. Ansaldo, D. Andreica and A. Amato, *μSR studies on cobalt oxides XIV: Co_3O_4 spinel, ibid.* 477 (in Japanese).

J. Sugiyama, H. Nozaki, T.J. Sato, J.H. Brewer, E.J. Ansaldo and G.D. Morris, *μSR studies on quasicrystals: i-ZnMgHo, CdMgHo, CdMgGd, ibid.* 498 (in Japanese).

K. Shimomura, *Origin of n type conductivity in wide gap semiconductors studied by muSR*, Proc. **7$^{\mathbf{th}}$ Int. Workshop on Neutrino Factories and Superbeams (NuFact'05), Frascati, Italy, June 21–26, 2005**, eds. G. De Lellis *et al.* (Nucl. Phys. B Proc. Suppl. **155**, 2006) p.378.

R.H. Heffner, E.D. Bauer, B. Chung, M.J. Fluss, W. Higemoto, T. Ito, D.E. MacLaughlin, L.A. Morales, G.D. Morris, K. Ohishi, J.L. Sarrao and L. Shu, *μSR studies of Pu metal and the Pu-based superconductor PuCoGa5*, Proc. **5$^{\mathbf{th}}$ Int. Symp. on Advanced Science Research in Celebration of the World Year of Physics (ASR-WYP-2005) "Advances in the Physics and Chemistry of Actinide Compounds", Tokai, Japan, September 27–29, 2005** (J. Phys. Soc. Japan **75**, 2006 supplement) p.14.

R.L. Lichti, K.H. Chow, J.M. Gil, D.L. Stripe, R.C. Vilao and S.F.J. Cox, *Location of the H[+/-] level: experimental limits for muonium*, Proc. **23$^{\mathbf{rd}}$ Int. Conf. on Defects in Semiconductors, Awaji Island, Japan, July 24–29, 2005** (Physica **B376/377**, 2006) p.587.

D.E. MacLaughlin, L. Shu, J.E. Anderson, R.H. Heffner, G.D. Morris, O.O. Bernal, J.S. Kim and G.R. Stewart, *Spin freezing and non-glassy dynamics in $Ce_{0.2}La_{0.8}RhIn_5$*, Proc. **Int. Conf. on Strongly Correlated Electron Systems (SCES2005), Vienna, Austria, July 26–30, 2005** (Physica **B378-380**, 2006) p.144.

Y.J. Uemura, *Twin spin/charge roton mode and superfluid density: primary determining factors of T_c in high-T_c superconductors observed by neutron, ARPES, and μSR*, Proc. **10$^{\mathbf{th}}$ Int. Conf. on Muon Spin Rotation, Relaxation and Resonance (μSR2005), Oxford, UK, August 8–12, 2005** (Physica **B374-375**, 2006) p.1.

J. Rodriguez, S.R. Dunsiger, J.B. Kycia, G.J. MacDougall, J.A. Quilliam, P.L. Russo, A.T. Savici, Y.J. Uemura, C.R. Wiebe and G.M. Luke, *μSR study of the "anti-glass" $LiHo_{0.045}Y_{0.955}F_4$*, *ibid* 13.

R.I. Miller, D. Arseneau, K.H. Chow, S. Daviel, A. Engelbertz, M.D. Hossain, T. Keeler, R.F. Kiefl, S. Kreitzman, C.D.P. Levy, P. Morales, G.D. Morris, W.A. MacFarlane, T.J. Parolin, R. Poutissou, H. Saadaoui, Z. Salman, D. Wang and J.Y.T. Wei, *Nuclear spin relaxation of ^{8}Li in a thin film of $La_{0.67}Ca_{0.33}MnO_3$, ibid.* 30.

T.A. Keeler, Z. Salman, K.H. Chow, B. Heinrich, M.D. Hossain, B. Kardasz, R.F. Kiefl, S.R. Kreitzman, W.A. MacFarlane, O. Mosendz, T.J. Parolin and D. Wang, *Hyperfine fields in a Ag/Fe magnetic multilayer probed with low energy spin polarized $^8Li^+$, ibid.* 31.

K.H. Satoh, T. Goko, S. Takeshita, Y. Hayashi, J. Arai, W. Higemoto, K. Nishiyama and K. Nagamine, *μSR study of magnetic order in $La_{2x}Ba_xCuO_4$ under high pressure, ibid.* 40.

W.A. MacFarlane, K.H. Chow, Z. Salman, A.V. Tkachuk and A. Mar, *A μSR study of the unusual magnetism of $LaCrSb_3$, ibid.* 71.

S. Kuroiwa, Y. Zenitani, M. Yamazawa, Y. Tomita, J. Akimitsu, K. Ohishi, A. Koda, S.R. Saha, R. Kadono, I. Watanabe and S. Ohira, *Magnetic and superconducting phase diagram in oxybromite cuprate $Ca_{2x}Na_xCuO_2Br_2$, ibid.* 75.

T.A. Keeler, Z. Salman, K.H. Chow, B. Heinrich, M.D. Hossain, B. Kardasz, R.F. Kiefl, S.R. Kreitzman, W.A. MacFarlane, O. Mosendz, T.J. Parolin and D. Wang, *Hyperfine fields in a Ag/Fe magnetic multilayer probed with low energy spin polarized ^{8}Li, ibid.* 79.

K. Satoh, H. Taniguchi, A. Kawamoto and W. Higemoto, *μSR Study of an Antiferromagnetic Mott Insulator β'-(BEDT-TTF)$_2$ICl$_2$, ibid.* 99.

K. Satoh, H. Fujita, R. Sato, H. Taniguchi and W. Higemoto, *μSR Study of an Antiferromagnetic Insulator (BEDT-TTF)(TCNQ), ibid.* 102.

Z. Salman, T.J. Parolin, K.H. Chow, T.A. Keeler, R.I. Miller, D. Wang, J. Chakhalian and W.A. MacFarlane, *A μSR study of the magnetism in Prussian Blue analogue photomagnets, ibid.* 130.

D.E. MacLaughlin, M.S. Rose, J.E. Anderson, L. Shu, R.H. Heffner, T. Kimura, G.D. Morris and O.O. Bernal, *Critical slowing down in the geometrically frustrated pyrochlore antiferromagnet $Gd_2Ti_2O_7$, ibid.* 142.

J. Sugiyama, H. Nozaki, J.H. Brewer, E.J. Ansaldo, G.D. Morris and C. Delmas, *Frustrated magnetism in the two-dimensional triangular lattice of Li_xCoO_2, ibid.* 148.

X.G. Zheng and K. Nishiyama, *Geometric frustration in a new material system $M_2X(OH)_3$, ibid.* 156.

R.H. Heffner, G.D. Morris, M.J. Fluss, B. Chung, D.E. MacLaughlin, L. Shu and J.E. Anderson, *New limits on the ordered moments in α-Pu and Ga-stabilized δ-Pu, ibid.* 163.

D.E. MacLaughlin, O.O. Bernal, R.H. Heffner, J.E. Sonier, G.J. Nieuwenhuys, R. Chau and M.B. Maple, *Susceptibility inhomogeneity and non-Fermi liquid behavior in $UCu_{5-x}Pt_x$, ibid.* 174.

D.E. MacLaughlin, M.S. Rose, J.E. Anderson, O.O. Bernal, R.H. Heffner, J.E. Sonier, G.J. Nieuwenhuys, R.E. Baumbach, N.P. Butch and M.B. Maple, *Effect of annealing on glassy dynamics and non-Fermi liquid behavior in UCu_4Pd, ibid.* 177.

G.D. Morris, R.H. Heffner, E.D. Bauer, L.A. Morales, J.L. Sarrao, M.J. Fluss, D.E. MacLaughlin, L. Shu and J.E. Anderson, *μSR studies of the superconducting order parameter in $PuCoGa_5$, ibid.* 180.

R.H. Heffner, G.D. Morris, E.D. Bauer, J.L. Sarrao, J.D. Thompson, D.E. MacLaughlin and L. Shu, *Evolution of the heavy fermion state in Ce_2IrIn_8, ibid.* 184.

F.D. Callaghan, M. Laulajainen, C.V. Kaiser and J.E. Sonier, *Effect of quasiparticle delocalization on μSR measurements of a multiband superconductor in the vortex state, ibid.* 195.

K.M. Kojima, K. Kawashima, M. Fujita, K. Yamada, M. Azuma, M. Takano, A. Koda, K. Ohishi, W. Higemoto, R. Kadono and Y.J. Uemura, *Magnetism and superconductivity of an electron-doped superconductor* $(Sr_{1x}La_x)CuO_2$*, ibid.* 207.

G.J. MacDougall, R.J. Birgeneau, H. Kim, S.-J. Kim, J. Rodriguez, P.L. Russo, A.T. Savici, Y.J. Uemura, S. Wakimoto, C.R. Wiebe and G.M. Luke, *Muon spin rotation study of field-induced magnetism in heavily overdoped* $La_{2-x}Sr_xCuO_4$*, ibid.* 211.

R.I. Miller, R.F. Kiefl, J.H. Brewer, Z. Salman, J.E. Sonier, F. Callaghan, D.A. Bonn, W.N. Hardy and R. Liang, *Coexistence of antiferromagnetism and superconductivity in single crystal underdoped* $YBa_2Cu_3O_{6+x}$*, ibid.* 215.

D. Wang, M.D. Hossain, Z. Salman, D. Arseneau, K.H. Chow, S. Daviel, T.A. Keeler, R.F. Kiefl, S.R. Kreitzman, C.D.P. Levy, G.D. Morris, R.I. Miller, W.A. MacFarlane, T.J. Parolin and H. Saadaoui, β*-detected NMR of* ^8Li *in the normal state of 2H-*$NbSe_2$*, ibid.* 239.

L. Shu, D.E. MacLaughlin, R.H. Heffner, F.D. Callaghan, J.E. Sonier, G.D. Morris, O.O. Bernal, A. Bosse, J.E. Anderson, W.M. Yuhasz, N.A. Frederick and M.B. Maple, *Penetration depth study in the heavy-fermion superconductor* $PrOs_4Sb_{12}$*, ibid.* 247.

S. Kuroiwa, H. Takagiwa, M. Yamazawa, Y. Tomita, J. Akimitsu, K. Ohishi, A. Koda, S.R. Saha, R. Kadono and W. Higemoto, *Magnetic response in the superconducting state of 1H-*$Ca(Al_{0.5}Si_{0.5})_2$ *studied by* μ*SR, ibid.* 251.

M. Laulajainen, F.D. Callaghan, C.V. Kaiser and J.E. Sonier, *Muon spin rotation measurements on vanadium analyzed using an iterative Ginzburg Landau solution, ibid.* 259.

G.J. MacDougall, R.J. Cava, S.-J. Kim, P.L. Russo, A.T. Savici, C.R. Wiebe, A. Winkels, Y.J. Uemura and G.M. Luke, *Muon spin rotation study of* $MgCNi_3$*, ibid.* 263.

J. Sugiyama, H. Itahara, H. Nozaki, J.H. Brewer, E.J. Ansaldo, G.D. Morris, S. Hébert and A. Maignan, *Incommensurate spin density wave state in layered cobaltites, ibid.* 282.

J. Sugiyama, H. Nozaki, J.H. Brewer, E.J. Ansaldo, G.D. Morris, T. Takami, H. Ikuta and U. Mizutani, *Two dimensionality in quasi-one-dimensional cobalt oxides, ibid.* 286.

I. McKenzie, J.-C. Brodovitch, K. Ghandi and P.W. Percival, *Muoniated acyl and thioacyl radicals, ibid.* 299.

K. Ghandi, S.P. Cottrell, D. Fleming and C. Johnson, *The first report of a muoniated free radical formed from reaction of Mu with* Br_2*, ibid.* 303.

J.-C. Brodovitch, K. Ghandi, I. McKenzie, P.W. Percival and J. Schüth, *Free radicals formed by H(Mu) addition to triphenylene and dodecahydrotriphenylene, ibid.* 310.

J.-C. Brodovitch, *Apparatus for* μ*SR and* μ*LCR experiments on fluids at high pressure and temperature, ibid.* 314.

V.G. Storchak, D.G. Eshchenko and J.H. Brewer, *Quantum diffusion of muonium atoms in solids: localization vs. band-like propagation, ibid.* 347.

H.N. Bani-Salameh, Y.G. Celebi, K.H. Chow, B.E. Coss, S.F.J. Cox and R.L. Lichti, *Muonium states and dynamics in 4H and 6H silicon carbide, ibid.* 368.

P. King, R. Lichti, S. Cottrell and I. Yonenaga, *Muonium hyperfine parameters in* $Si_{1-x}Ge_x$ *alloys, ibid.* 376.

R.C. Vilão, H.V. Alberto, J. Piroto Duarte, J.M. Gil, N. Ayres de Campos, A. Weidinger, R.L. Lichti, K.H. Chow, S.P. Cottrell and S.F.J. Cox, *Muonium states in II-VI zinc chalcogenide semiconductors, ibid.* 383.

V.G. Storchak, D.G. Eshchenko, J.H. Brewer, B.A. Aronzon, S.P. Cottrell, R.L. Lichti, A.T. Savici and Y.J. Uemura, *Deep muonium state in InSb: Recombination center vs. trapping center, ibid.* 387.

V.G. Storchak, D.G. Eshchenko, J.H. Brewer and S.P. Cottrell, *Formation and dynamics of muonium centers in semiconductors, ibid.* 398.

B.E. Schultz, B. Hitti, Z. Salman, W.A. MacFarlane, H.N. Bani-Salameh, R.L. Lichti, I. Fan, J. Jung and K.H. Chow, *Study of muonium precession signals in optically excited silicon, ibid.* 412.

K.H. Chow, Z. Salman, W.A. MacFarlane, B. Campbell, T.A. Keeler, R.F. Kiefl, S.R. Kreitzman, C.D.P. Levy, G.D. Morris, T.J. Parolin, S. Daviel and Z. Yamani, *Early* $^8Li^+$ β*-NMR investigations in GaAs and Ge, ibid.* 415.

T.J. Parolin, Z. Salman, J. Chakhalian, D. Wang, T.A. Keeler, M.D. Hossain, R.F. Kiefl, K.H. Chow, G.D. Morris, R.I. Miller and W.A. MacFarlane, β*-NMR of palladium foil, ibid.* 419.

V.G. Storchak, D.G. Eshchenko, H. Luetkens, E. Morenzoni, R.L. Lichti, S.F. Marenkin, O.N. Pashkova and J.H. Brewer, *Room temperature ferromagnetism in III-V and II-IV-*V_2 *dilute magnetic semiconductors, ibid.* 430.

B.E. Schultz, I. Fan, B. Hitti, R.F. Kiefl and K.H. Chow, *ZeroX: A technique for studying weak dipolar relaxations at continuous muon facilities, ibid.* 464.

Z. Salman, R.F. Kiefl, K.H. Chow, W.A. MacFarlane, S.R. Kreitzman, D.J. Arseneau, S. Daviel, C.D.P. Levy, Y. Maeno and R. Poutissou, *Beta-detected NQR in zero field with a low energy beam of* $^8Li^+$*, ibid.* 468.

Y. Miyake, K. Nishiyama, N. Kawamura, S. Makimura, P. Strasser, K. Shimomura, J.L. Beveridge, R. Kadono, K. Fukuchi, N. Sato, K. Ueno, W. Higemoto, K. Ishida, T. Matsuzaki, I.

Watanabe, Y. Matsuda, M. Iwasaki, S.N. Nakamura, J. Doornbos and K. Nagamine, *Status of J-PARC muon science facility at the year of 2005, ibid.* 484.

I. Tucakov, J. Cosman and J.H. Brewer, *Data display and analysis with μView, ibid.* 488.

I. Tucakov, J.H. Brewer, A. Froese and A. Lau, *μSR data analysis with XYfit, ibid.* 492.

Molecular and Materials Science – *2007*

W. Higemoto, Y. Aoki, K. Ohishi, T.U. Ito, R.H. Heffner, S.R. Saha, A. Koda, K.H. Satoh, R. Kadono, D. Kikuchi H. Sugawara and H. Sato, *Knight shift measurements in superconducting state of $Pr_{1-x}La_xOs_4Sb_{12}$ ($x = 0.4$) probed by μSR*, Proc. **17^{th} Int. Conf. on Magnetism, Kyoto, Japan, August 20–25, 2006**, eds. H. Harima *et al.* (J. Magn. Mag. Mat. **310**, 2007) p.620.

T.U. Ito, N. Nishida, W. Higemoto, K. Ohishi, R.H. Heffner, Y. Aoki, T. Onimaru and H.S. Suzuki, *Muon Knight shift measurements on $PrPb_3$ in paraquadrupolar state, ibid.* 743.

D.E. MacLaughlin, R.H. Heffner, S. Nakatsuji, Y. Nambu, K. Ishida, O.O. Bernal and L. Shu, *Slow inhomogeneous spin dynamics in the frustrated antiferromagnet $NiGa_2S_4$, ibid.* 1300.

J. Sugiyama, H. Nozaki, Y. Ikedo, K. Mukai, D. Andreica, A. Amato, J.H. Brewer, E.J. Ansaldo, G.D. Morris, T. Takami and H. Ikuta, *Two dimensionality in quasi-one-dimensional cobalt oxides confirmed by muon-spin spectroscopy, ibid.* 2719.

T. Takami, H. Nozaki, J. Sugiyama, T. Takeuchi and H. Ikuta, *Magnetic properties of one-dimensional compounds $A_{n+2}Co_{n+1}O_{3n+3}$ (A = Ca, Sr, Ba; n = 1–5), ibid.* e438.

P.W. Percival, J.-C. Brodovitch, K. Ghandi, B. McCollum and I. McKenzie, *H atom kinetics in superheated water studied by muon spin spectroscopy*, Proc. **11^{th} Tihany Symp. on Radiation Chemistry, Eger, Hungary, August 26–31, 2006** (Radiation Phys. and Chem. **76**, 2007) p.1231.

Life Sciences – *2003*

R.L. Watts, C.D. Raiser, N.P. Stover, M.L. Cornfeldt, A.W. Schweikert, R.C. Allen, T. Subramanian, D.J. Doudet, C. Honey and R.A.E. Bakay, *Human retinal pigment epithelial cells attached to gelatin microcarriers: a promising new cell therapy for Parkinson's disease*, Proc. **10^{th} Int. Winter Conf. on Neurodegeneration, Berlin, Germany, February, 2002** (J. Neural Transm. **65**, 2003) p.1.

G.-J. Beyer and T.J. Ruth, *The role of electromagnetic separators in the production of radiotracers for bio-medical research and nuclear medical application*, Proc. **14^{th} Int. Conf. on Electromagnetic Isotope Separators and Techniques Related to Their Applications (EMIS-14), Victoria, BC, May 6–10, 2002** (Nucl. Instrum. Methods **B204**, 2003) p.694 [TRI-PP-02-26].

V. Astakhov, P. Gumplinger, C. Moisan, T.J. Ruth and V. Sossi, *Effect of depth of interaction decoding on resolution in PET: a simulation study*, Proc. **2002 IEEE/Medical Imaging Conf., Norfolk, VA, November 13–16, 2002** (IEEE Trans. Med. Imaging **NS50**, 2003) p.1373.

V. Sossi, O. Morin, A. Celler, A. Belzberg, T.D. Rempel and C. Carhart, *PET and SPECT performance evaluation of the Siemens HD3 e.camduet: a 1 in. Na(I) hybrid camera, ibid.* 1504.

M. Zamburlini, R. de la Fuente-Fernandez, A.J. Stoessl, T.J. Ruth and V. Sossi, *Impact of different realignment algorithms on the SPM analysis of ^{11}C-raclopride PET studies, ibid.*

A.R. Studenov, S. Jivan, M.J. Adam, T.J. Ruth and K.R. Buckley, *Studies of the mechanism of the in-loop synthesis of radiopharmaceuticals*, Proc. **15^{th} Int. Symp. Radiopharmaceutical Chemistry, Sydney, Australia, August, 2003** (J. Labelled Cmpds. Radiopharm. **46** Suppl 1, 2003) p.S72.

S. Lu, M.J. Adam, J. Lu and T.R. Ruth, *Simplified synthesis of desmethyl-FLB457 in two steps, ibid.* S234.

C.L. Fisher, S.R. Bayly, C.B. Ewart, M.J. Adam and C. Orvig, *Synthesis of rhenium and technetium complexes of glucose derivatives, ibid.* S246.

Life Sciences – *2004*

M.J. Adam, C.L. Fisher, S.R. Bayly, C.B. Ewart, C. Orvig and S. Lapi, *Synthesis of radiometal complexes of glucose*, Proc. **51^{st} Annual Meeting of the Society of Nuclear Medicine, Philadelphia, PA, June 19–23, 2004** (J. Nucl. Med. **45**, 2004) p.467P.

S. Lu, M.J. Adam, V. Kennedy, J. Lu and T.J. Ruth, *Preparation of iodo-TZDM for PET/SPECT imaging, ibid.* 467P.

A.R. Studenov, M.J. Adam, T.J. Ruth and J.S. Wilson, *Exploring new radiolabelling chemistry: synthesis of the compounds with phosphorus-fluorine-18 bonds, ibid.* 469P.

Life Sciences – *2005*

A.R. Studenov, S. Jivan, J. Lu, M.J. Adam, S.B. Jensen and Y.-S. Ding, *Routine radiosynthesis of [^{11}C]methylphenidate: can it be improved?*, Proc. **16^{th} Int. Symp. Radiopharmaceutical Chemistry, Iowa City, IW, June 24–28, 2005** (J. Lab. Cmpds. and Rad. **48**, 2005) p.S 199.

Life Sciences – *2006*

S. Lapi, J.J. Ressler, M.E. Cox and T.J. Ruth, *High-specific activity ^{186}Re-labeled antibodies for radioimmunotherapy*, Proc.

$7^{\rm th}$ **Int. Symp. on Technetium in Nuclear Medicine, Bressanone, Italy, September 6–9, 2006**, ed. U. Mazzi (in Technetium, Rhenium and Other Metals in Chemistry and Nuclear Medicine, Padova, 2006) p.593.

A. Rahmim, J.C. Cheng, K. Dinelle, M.A. Shilov, W.P. Segars, O.G. Rousset, B.M.W. Tsui, D.F. Wong and V. Sossi, *System matrix modeling of externally tracked motion*, Proc. **2006 IEEE Nuclear Science Symp. and Medical Imaging Conf., San Diego, CA, October 29–November 4, 2006** (IEEE Conf. Record, 2006) p.2137.

V. Sossi, S. Blinder, K. Dinelle, S. Lidstone, K. Cheng, A. Rahmim, S. McCormick, D. Doudet and T. Ruth, *Comparison between the ROI based and pixel based analysis for neuroreceptor studies performed on the high resolution research tomograph (HRRT), ibid.* 2653.

J.-C. Cheung, A. Rahmim, S. Blinder, K. Dinelle and V. Sossi, *The quantitative accuracy and efficiency of the dual reconstruction scheme including a practical scatter/random approximation in dynamic PET imaging, ibid.* 2744.

K. Dinelle, S. Blinder, J.C. Cheng, S. Lidstone, K. Buckley, T. Ruth and V. Sossi, *Investigation of subject motion encountered during a typical positron emission tomography scan, ibid.* 3283.

E. Vandervoort and V. Sossi, *An analytical scatter correction for singles-mode transmission data in PET, ibid.* 3310.

A. Rahmim, K. Dinelle, J.C. Cheng, M.A. Shilov, W.P. Segars, O.G. Rousset, B.M.W. Tsui, D.F. Wong and V. Sossi, *Accurate motion compensation incorporating all detected events in the HRRT scanner, ibid.* 3331.

Life Sciences – *2007*

M.P. Dehnel, P. Jackle, M. Roeder, T. Stewart, J. Theroux, J.P. Brasile, P. Sirot, K.R. Buckley and M. Bedue, *A compact cost-effective beamline for a PET cyclotron*, Proc. $19^{\rm th}$ **Int. Conf. on the Application of Accelerators in Research and Industry (CAARI), Fort Worth, TX, August 20–25, 2006**, eds. F. Del McDaniel *et al.* (Nucl. Instrum. Methods **B261**, 2007) p.809 [TRI-PP-07-37].

Theoretical Program – *2003*

D.H. Wilkinson, *Super-allowed fermi beta-decay: CKM unitarity*, Proc. **Fifty Years of Electroweak Physics: A Symposium in Honor of Professor Alberto Sirlin's $70^{\rm th}$ Birthday, New York, NY, October 27–28, 2000**, eds. A. Sirlin *et al.* (J. Phys. **G29**, 2003), p.189 [TRI-PP-02-14].

A. Astbury, B. Campbell, F.C. Khanna and M. Vincter, eds., Proc. **Lake Louise Winter Inst. on Fundamental Interactions (LLWI02), Lake Louise, AB, February 17–23, 2002** (World Scientific, Singapore, 2003).

F.C. Khanna and D.U. Matrasulov, *Properties of hadrons in nuclear matter*, Proc. **Joint CCSM/JHF/NITP Workshop on Physics at the Japan Hadron Facility, Adelaide, Australia, March 14–21, 2002**, eds. V. Guzey *et al.* (World Scientific, Singapore, 2003) p.255.

R. Lewis, W. Wilcox and R.M. Woloshyn, *Strange matrix elements of the nucleon*, Proc. $20^{\rm th}$ **Int. Symp. on Lattice Field Theory (LATTICE 2002), Cambridge, MA, June 24–29, 2002** (Nucl. Phys. B Proc. Supp. **119**, 2003) p.119 [hep-lat/0208063].

C.S. Kalman, J. McKenna, M. Bozzo, Z. Ligeti, T. Mattison, J. Ng, M.A. Sanchis-Lozano and P. Singer, eds., Proc. $5^{\rm th}$ **Int. Conf. on Hyperons, Charm and Beauty Hadrons (BEACH 2002), Vancouver, BC, June 25–29, 2002** (Nucl. Phys. **115**, 2003).

D.U. Matrasulov, F.C. Khanna, Kh.Yu. Rakhimov and H. Yusupov, *Spectra of heavy flavored hadrons in the relativistic approach, ibid.* 195.

T. Numao (for the E787/949 and KOPIO collaborations at BNL), *Status of $K \to \pi\nu\overline{\nu}$, ibid.* 238.

C.-H. Chen, C.Q. Geng and J.N. Ng, *T violation in $\Lambda_b \to \Lambda\ell^+\ell^-$ decays, ibid.* 263 [hep-ph/-0210067].

J. Escher and B.K. Jennings, *A new signature for nuclear shell closures*, Proc. $7^{\rm th}$ **Int. Symp. on Nuclei in the Cosmos (NIC7), Fuji-Yoshida, Japan, July 8–12, 2002**, eds. S. Kubono *et al.* (Nucl. Phys. **A718**, 2003) p.694 [TRI-PP-02-12].

L. Theussl, A. Amghar, B. Desplanques and S. Noguera, *Comparison of different boost transformations for the calculation of form factors in relativistic quantum mechanics*, Proc. $18^{\rm th}$ **European Conf. on Few-Body Problems in Physics, Bled, Slovenia, September 8–14, 2002** (Few Body Syst. Suppl. **14**, 2003) p.393 [hep-ph/0301137].

C.-P. Liu, *Nuclear anapole moments and the parity nonconserving nuclear interaction*, Proc. $15^{\rm th}$ **Int. Spin Physics Symp. (SPIN 2002), Long Island, NY, September 9–14, 2002** (AIP Conf. Proc. **675**, 2003) p.262 [nucl-th/0211095].

K. Tsushima and F.C. Khanna, *Properties of charmed and bottom hadrons in nuclear medium: results for Λ_c^+ and Λ_b hypernuclei*, Proc. **YITP-RCNP Workshop on Chiral Restoration in Nuclear Medium, Kyoto, Japan, October 7–9, 2002** (Prog. Theor. Phys. Suppl. **149**, 2003) p.160 [nucl-th/0212100].

C. Barbieri and W.H. Dickhoff, *Effects of nuclear fragmentation on single particle and collective motions at low energy*, Proc. $10^{\rm th}$ **Int. Conf. on Nuclear Reaction Mechanisms, Varenna, Italy, June 9–13, 2003**, ed. E. Gadioli (Ricerca Scientifica ed Educazione Permanente, Suppl. **122**, 2003) p.89 [TRI-PP-03-26, nucl-th/0307037].

S.-I. Ando, *Solar-neutrino reactions on deuteron in EFT and radiative corrections of neutron beta decay*, Proc. $4^{\rm th}$ **Int. Workshop on Chiral Dynamics (CD2003), Bonn, Germany, September 8–13, 2003**, eds. U.-G. Meissner *et al.* ("Chiral Dynamics: Theory and Experiment (CD2003)", HISKP-TH-03/23, 2003) [TRI-PP-03-34, hep-ph/0311212].

Theoretical Program – *2004*

C. Barbieri, L. Lapikas and D. Rohe, *Rescattering contributions to final state interactions in $(e, e'p)$ reactions*, Proc. **2$^{\mathrm{nd}}$ Conf. on Nuclear and Particle Physics with CEBAF at JLab (NAPP 2003), Dubrovnik, Croatia, May 26–31, 2003** (Croatian Phys. Soc. Fizika **B13**, 2004) p.185 [TRI-PP-03-29, nucl-th/0309024].

B. Desplanques, A. Amghar and L. Theussl, *'Point-form' estimate of the pion form factor revisited*, Proc. **17$^{\mathrm{th}}$ Int. IUPAP Conf. on Few-Body Problems in Physics (FB 17), Durham, NC, June 5–10, 2003**, eds. W. Gloeckle and W. Tomow (Nucl. Phys. **A737**, 2004) p.3 [hep-ph/0308219].

W.T.H. van Oers, *Symmetries and symmetry breaking, ibid.* 267 [TRI-PP-03-27, hep-ph/0307285].

M. de Montigny, F.C. Khanna and A. Santana, *Some Lorentz-like formulation of Galilean invariance*, Proc. **Int. Conf. on Symmetry in Non-Linear Mathematical Physics (SNMP'03), Kyiv, Ukraine, June 23–29, 2003**, eds. A.G. Nikitin *et al.* (Inst. of Mathematics of Ukraine **50**, 2004) p.677.

F. Okiharu and R.M. Woloshyn, *A study of color field distributions in the baryon*, Proc. **21$^{\mathrm{st}}$ Int. Symp. on Lattice Field Theory (LATTICE 2003), Tsukuba, Ibaraki, Japan, July 15–19, 2003** (Elsevier, Nucl. Phys. Proc. Suppl. **129**, 2004) p.745 [hep-lat/0310007].

C. Barbieri and L. Lapikas, *Rescattering contributions to final state interactions in $(e, e'p)$ reactions at high (p_m, E_m)*, Proc. **6$^{\mathrm{th}}$ Workshop on Electromagnetically Induced Two Hadron Emission, Pavia, Italy, September 24–27, 2003**, eds. A. Braghieri *et al.* (CD, ISBN:88-85159-20-6, 2004) p.68 [TRI-PP-03-39, nucl-th/0401010].

J.N. Ng, *Neutrino mass models in extra dimensions*, Proc. **2$^{\mathrm{nd}}$ Int. Conf. on Flavor Physics (ICFP 2003), Seoul, Korea, October 6–11, 2003** (J. Korean Phys. Soc. **45**, 2004) p.S341 [hep-ph/0311352].

J.-M. Sparenberg and B. Jennings, *On the practical interest of one-body overlap functions*, Proc. **Int. Symp.: A New Era of Nuclear Structure Physics, Niigata, Japan, November 19–22, 2003**, eds. Y. Suzuki *et al.* (World Scientific, Singapore, 2004) [nucl-th/0401049].

Y. Fujiwara, K. Miyagawa, M. Kohno, Y. Suzuki, D. Baye and J.-M. Sparenberg, *A realistic baryon-baryon interaction in the SU_6 quark model and its applications to few-body systems, ibid.*

J.-M. Sparenberg, *Deducing the asymptotic normalization constant of the 2^+ subthreshold state in ^{16}O from $^{12}C + \alpha$ elastic scattering*, Proc. **8$^{\mathrm{th}}$ Int. Conf. on Clustering Aspects of Nuclear Structure and Dynamics (CLUSTER 03), Nara, Japan, November 24–29, 2003**, eds. K. Ikeda *et al.* (Nucl. Phys. **A738**, 2004) p.416.

Y. Hirayama T. Shimoda, H. Izumi, H. Yano, M. Yagi, A. Hatakeyama, C.D.P. Levy, K.P. Jackson and H. Miyatake, *Spectroscopic study of ^{11}Be through β-delayed neutron- and γ-decays of spin-polarized ^{11}Li, ibid.*

Y. Fujiwara, K. Miyagawa, M. Kohno, Y. Suzuki, D. Baye and J.-M. Sparenberg, *A consistent 3α and $2\alpha\Lambda$ Faddeev calculation using the 2α RGM kernel, ibid.* 495.

Y. Fujiwara, K. Miyagawa, M. Kohno, Y. Suzuki, D. Baye and J.-M. Sparenberg, *$2\alpha\Lambda$ Faddeev calculation using the quark-model $S = -2$ hyperon hyperon interaction, ibid.*

Theoretical Program – *2005*

A. Astbury, B.A. Campbell, F.C. Khanna and M.G. Vincter, eds., Proc. **Lake Louise Winter Institute: Fundamental Interactions (LLWI04), Lake Louise, AB, February 15–21, 2004** (World Scientific, Hackensack, NJ, 2005).

E. Santos, F. Khanna and M. de Montigny, *Lorentz-like formulation of Galilean field theories*, Proc. **XI Int. Conf. Symmetry Methods in Physics, Prague, Czech Rep., June 21–24, 2004**, eds. C. Burdik *et al.* (JINR Dubna, 2005).

C. Barbieri and L. Lapikás, *Two-step rescattering in $(e, e'p)$ reactions*, Proc. **VIII Conf. on Electron-Nucleus Scattering, Isola d'Elba, Italy, June 21–25, 2004** (Eur. Phys. J. **A24**, 2005) [TRI-PP-04-18].

S.R. Sharpe and J.M.S. Wu, *Applying chiral perturbation to twisted mass lattice QCD*, Proc. **22$^{\mathrm{nd}}$ Int. Symp. on Lattice Field Theory (Lattice 2004), Batavia, IL, June 21–26, 2004** (Nucl. Phys. Proc. Suppl. **140**, 2005) p.323 [UW-PT-04-09, hep-lat/0407035].

K.Y. Wong and R.M. Woloshyn, *Topology and staggered fermion action improvement, ibid.* 620 [hep-lat/0407003].

R.H. Cyburt, *Creating nuclear data representations and error budget accounting*, Proc. **8$^{\mathrm{th}}$ Symp. on Nuclei in the Cosmos (NICVIII), Vancouver, BC, July 19–23, 2004**, eds. L. Buchmann, M. Comyn, J. Thomson (Nucl. Phys. **A758**, 2005) p.122c [TRI-PP-04-37].

C. Barbieri and B.K. Jennings, *Study of the $^{16}O(p, \gamma)$ reaction at astrophysical energies, ibid.* 395c [TRI-PP-04-34, nucl-th/0408017].

J.-M. Sparenberg, *Hybrid potential/R-matrix models for the $^{12}C + \alpha$ system, ibid.* 423c [TRI-PP-04-41].

R.H. Cyburt, *The $^7Be(p, \gamma)^8B$ reaction and its future, ibid.* 693c [TRI-PP-04-38].

E. Tikhomolov, *Large-scale vortical flows and penetrative convection in the sun, ibid.* 709c [TRI-PP-04-42].

R.H. Cyburt, *What's next for big bang nucleosynthesis?, ibid.* 771c [TRI-PP-04-36].

W. Liao, *Toward precision measurements in solar neutrinos*, Proc. **32nd Int. Conf. on High-Energy Physics (ICHEP04), Beijing, China, August 16–22, 2004**, eds. H. Chen *et al.* (World Scientific, Hackensack, NJ, 2005) p.271.

B.R. Barrett, P. Navratil, A. Nogga, W.E. Ormand, I. Stetcu, J.P. Vary and H. Zhan, *Ab initio large-basis no-core shell model*, Proc. **Int. Conf. on Nuclear Data for Science and Technology 2004 (ND2004), Santa Fe, NM, September 26–October 1, 2004**, eds. R.C. Haight *et al.* (AIP **769**, 2005) p.1257.

C. Barbieri and W.H. Dickhoff, *Self-consistent Green's function calculation of ^{16}O at small missing energies*, Proc. **Workshop on Nuclear Forces and Many-Body Problems, Seattle, WA, October 4–8, 2004**, eds. B.R. Barrett *et al.* (J. Phys. **G31**, 2005) p.S1301 [TRI-PP-04-24, nucl-th/0410082].

L. Theussl, S. Noguera and V. Vento, *Generalized parton distributions of the pion in a Bethe-Salpeter approach*, Proc. **Int. Conf. on the Structure of Baryons, Palaiseau, France, October 25–29, 2004** (Nucl. Phys. **A755**, 2005) p.545.

S.X. Nakamura, H. Toki, K. Ikeda and S. Sugimoto, *Study of nuclear structure using low-momentum NN-interaction*, Proc. **Int. Symp. on Correlation Dynamics in Nuclei (CDN05), Tokyo, Japan, January 31–February 4, 2005** (J. Phys. Conf. Series **20**, 2005) p.165.

C.H. Hyung, S. Ando, R.H. Cyburt and S.W. Hong, *Low energy $np \to d\gamma$ and $d\gamma \to np$ cross section for big bang nucleosynthesis*, Proc. **Int. Workshop on Quark Nuclear Physics, Pyoungchang, Korea, February 22–24, 2005**, ed. J.K. Ahn *et al.* (Pusan Nat. Univ. Press, 2005) [TRI-PP-05-26].

P. Capel, D. Baye and G. Goldstein, *Time-dependent analysis of the nuclear and Coulomb dissociation of ^{11}Be*, Proc. **Reaction Mechanisms for Rare Isotope Beams, 2nd Argonne/MSU/JINA/INT RIA Workshop, East Lansing, MI, March 9–12, 2005** (AIP **791**, 2005), p.12 [nucl-th/0506008].

W. Bertsche *et al.*, *The ALPHA experiment: a cold antihydrogen trap*, Proc. **Int. Conf. on Low Energy Antiproton Physics (LEAP'05), Bonn, Germany, May 16–22, 2005** (AIP Conf. Proc. **796**, 2005) p.301.

C. Barbieri, *On the meaning and usefulness of spectroscopic factors, ibid.* 57 [TRI-PP-05-18].

C.Y. Ryu, C.H. Hyun, S.W. Hong and B.T. Kim, *Kaon optical potential in nuclei and kaon condensation in neutron star*, Proc. **29th Johns Hopkins Workshop on Current Problems in Particle Physics: Strong Matter in the Heavens, Budapest, Hungary, August 1–3, 2005** (Proc. Sci., 2005) p.027 [JHW2005].

Theoretical Program – *2006*

F.C. Khanna and D. Matrasulov, eds., *Non-Linear Dynamics and Fundamental Interactions*, Proc. **NATO Advanced Research Workshop (NATO-ARW), Tashkent, Uzbekistan, October 11–16, 2004** (NATO Science Series II: Mathematics, Physics and Chemistry, **213**, Springer, 2006).

U.R. Salomov, D.U. Matrasulov, F.C. Khanna and G.M. Milibaeva, *Finite temperature quantum billiards, ibid.* 167.

A.E. Santana, A.P.C. Malbouisson, J.M.C. Malbouisson and F.C. Khanna, *Thermofield dynamics and confined systems: applications to physical systems, ibid.* 187.

F.C. Khanna, J.M.C. Malbouisson and A.E. Santana, *Thermofield dynamics: generalised Bogoliubov transformations and Casimir effect, ibid.* 215.

D. Ontajanov, F. Khanna and D. Matrasulov, *Chaotisation of the periodic driven quarkonia, ibid.* 335.

K.T. Butanov, D.U. Matrasulov, Kh.Yu. Rakhimov and F.C. Khanna, *Spectra of quarkonia at finite temperature, ibid.* 329.

D.U. Matrasulov, U.G. Salomov, F.C. Khanna and A.E. Santana, *Quantum chaos at finite temperature, ibid.* 341.

A. Astbury, B. Campbell, F. Khanna, R. Moore and M. Vincter, eds., Proc. **20th Lake Louise Winter Institute: Fundamental Interactions, Lake Louise, AB, February 20–26, 2005** (World Scientific, Singapore, 2006).

J.M.C. Malbouisson, F.C. Khanna, A.E. Santana and A.P.C. Malbouisson, *Spatial confinement and thermal deconfinement in the compactified Gross-Neveu model, ibid.* 214.

E.S. Santos, M. de Montigny and F.C. Khanna, *Quantization of Galilean covariant fields, ibid.* 280.

B.C. Allanach *et al.*, *Les Houches physics at TeV colliders 2005 beyond the standard model working group: summary report*, Proc. **Les Houches Workshop on Physics at TeV Colliders, Les Houches, France, May 2–20, 2005**, ed. G. Belanger *et al.* (Annecy, LAPP, 2006) [FERMILAB-CONF-06-338-T, SLAC-PUB-11770, hep-ph/0602198].

A.M. Abdel-Rehim, R. Lewis and R.M. Woloshyn, *The hadron spectrum from twisted mass QCD with a strange quark*, Proc. **23rd Int. Symp. on Lattice Field Theory, Dublin, Ireland, July 25–30, 2005**, eds. A. Irving *et al.* (Proc. Sci. LAT2005, 2006) p.032 [hep-lat/0509056].

A.M. Abdel-Rehim, R. Lewis and R.M. Woloshyn, *Maximal twist and the spectrum of quenched twisted mass lattice QCD, ibid.* 051 [hep-lat/0509098].

P. Capel and F.M. Nunes, *Influence of the projectile description on breakup calculations*, Proc. **12$^{\mathrm{th}}$ Int. Conf. on Capture Gamma-ray Spectroscopy and Related Topics (CGS-12), Notre Dame, IN, September 4–9, 2005**, eds. A. Woehr and A. Aprahamian (AIP **819**, 2006) p.528.

K. Kubodera, S. Nakamura and T. Sato, *Neutrino-nucleus reactions in the energy range 1 MeV to 100 MeV*, Proc. **4$^{\mathrm{th}}$ Int. Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region (NuInt05), Okayama, Japan, September 26–29, 2005** (Nucl. Phys. Proc. Suppl. **159**, 2006) p.21 [nucl-th/0601068].

C. Barbieri, *Final state interactions in electron scattering at high missing energies and momenta, ibid.* 174 [nucl-th-0604004].

F.C. Khanna, *Ward-Takahashi relations: longitudinal and transverse*, Proc. **5$^{\mathrm{th}}$ Int. Conf. on Mathematical Methods in Physics, Rio de Janeiro, Brazil, April 24–28, 2006** (Proc. of Science PoS(IC2006), 2006) p.003.

J.M.C. Malbouisson, F.C. Khanna, A.P.C. Malbouisson and A.E. Santana, *Application of zeta-function techniques to the compactified Gross-Neveu model, ibid.* 023.

A.M. Abdel-Rehim, R. Lewis, R.G. Petry and R.M. Woloshyn, *The spectrum of tmLQCD with quark and link smearing*, Proc. **24$^{\mathrm{th}}$ Int. Symp. on Lattice Field Theory (Lattice 2006), Tucson, AZ, July 23–28, 2006** (Proc. of Science, 2006) p.164 [hep-lat/0610004].

Theoretical Program – *2007*

B.K. Jennings and A. Schwenk, *Modern topics in theoretical nuclear physics*, Proc. **Nuclear Physics Town Hall Meeting, Vancouver, BC, September 9, 2005** (Can. J. Phys. **85**, 2007) p.219 [TRI-PP-06-19, nucl-th/0512013].

A. Astbury, B. Campbell, F. Khanna and R. Moore, eds., Proc. **21$^{\mathrm{st}}$ Lake Louise Winter Institute: Fundamental Interactions, Lake Louise, AB, February 17–23, 2006** (World Scientific, Singapore, 2007).

A.M. Abdel-Rehim, R. Lewis, R.M. Woloshyn and J.M.S. Wu, *Lattice QCD with a twisted mass term and a strange quark*, Proc. **4$^{\mathrm{th}}$ Int. Conf. on Quarks and Nuclear Physics (QNP06), Madrid, Spain, June 5–10, 2006** (Eur. Phys. J. **A31**, 2007) p.773 [hep-lat/0610090].

S.X. Nakamura, *Renormalization group analysis of nuclear force*, Proc. **18$^{\mathrm{th}}$ Int. IUPAP Conf. on Few-Body Problems in Physics (FB18), Sao Paulo, Brazil, August 21–26, 2006** (Nucl. Phys. **A790**, 2007) p.422 [nucl-th/0610034].

A. Schwenk, *Superfluidity in neutron stars and cold atoms*, Proc. **Quark Confinement and the Hadron Spectrum VII, Ponta Delgada, Portugal, September 2–7, 2006** (AIP Conf Proc. **892**, 2007) p.502 [TRI-PP-06-22, nucl-th/0611046].

L. Tolos, B. Friman and A. Schwenk, *The neutron matter equation of state from low-momentum interactions, ibid.* 508 [TRI-PP-06-23, nucl-th/0611070].

B. Friman, K. Hebeler, A. Schwenk and L. Tolos, *Neutron matter from low-momentum interactions*, Proc. **YKIS Seminar on New Frontiers in QCD: Exotic Hadrons and Hadronic Matter, Kyoto, Japan, November 20–December 8, 2006** (Prog. Theor. Phys. Suppl. **168**, 2007) p.639 [TRI-PP-06-27, arXiv:0704.1404].

B. Klein and J. Braun, *Finite-size scaling from the non-perturbative renormalization group*, Proc. **QCD WORK 2007: Int. Workshop on Quantum Chromodynamics: Theory and Experiment, Martina Franca, Italy, June 16–20, 2007** (AIP Conf. Proc. **964**, 2007) p.330 [arXiv:0710.1038].

K.Y. Wong and R.M. Woloshyn, *Dynamical simulations with highly improved staggered quarks*, Proc. **25$^{\mathrm{th}}$ Int. Symp. on Lattice Field Theory, Regensburg, Germany, July 30 – August 4, 2007** (PoS LAT2007, 2007) p.047 [arXiv:0710.0737].

B. Klein and J. Braun, *Finite size scaling for the O(N) universality class from renormalization group methods, ibid.* 198 [arXiv:0710.1161].

Theoretical Program – *2008*

D.M. Gingrich, *Black hole production at the Large Hadron Collider*, Proc. **CTP Symp. on Supersymmetry at LHC: Theoretical and Experimental Prospectives, Cairo, Egypt, March 11–14, 2007** (Int. J. Mod. Phys. **A22**, 2008) p.5685 [arXiv:0706.0627].

Theoretical Program – *presented*

S.X. Nakamura and S.-I. Ando, *Renormalization group analysis of nuclear current operators*, Proc. **5$^{\mathrm{th}}$ Int. Workshop on Chiral Dynamics, Theory and Experiment (CD 2006), Durham, NC, September 18–22, 2006** (World Scientific, Singapore, in press) [TRI-PP-06-15, nucl-th/0611052].

W.-F. Chang, J.N. Ng and J.M.S. Wu, *Phenomenology from a U(1) gauged hidden sector*, Proc. **Lake Louise Winter Institute, Lake Louise, AB, February 19–24, 2007** [arXiv:0706.2345].

S.X. Nakamura and A. Gardestig, *Renormalization group analysis of the chiral pion production operator for $NN \to d\pi$*, Proc. **11$^{\mathrm{th}}$ Int. Conf. on Meson-Nucleon Physics and the Structure of the Nucleon (MENU2007), Jülich, Germany, September 10–14, 2007** (SLAC econf, in press) [TRI-PP-07-28, arXiv:0704-3757].

S.X. Nakamura, *Bridging over p-wave π-production and weak processes in few-nucleon systems with chiral perturbation theory, ibid.* [TRI-PP-07-25, arXiv:0709.2925].

TRIUMF Reports

TRIUMF Annual Reports

TRIUMF Annual Report Scientific Activities 2003 (TRIUMF, Vancouver, 2004).

TRIUMF Annual Financial & Administrative Report 2003-2004 (TRIUMF, Vancouver, 2004).

TRIUMF Annual Report Scientific Activities 2004 (TRIUMF, Vancouver, 2005).

TRIUMF Annual Financial & Administrative Report 2004-2005 (TRIUMF, Vancouver, 2005).

TRIUMF Annual Report Scientific Activities 2005 (TRIUMF, Vancouver, 2006).

TRIUMF Annual Financial & Administrative Report 2005-2006 (TRIUMF, Vancouver, 2006).

TRIUMF Annual Report Scientific Activities 2006 (TRIUMF, Vancouver, 2007).

TRIUMF Annual Financial & Administrative Report 2006-2007 (TRIUMF, Vancouver, 2007).

TRIUMF Annual Financial & Administrative Report 2007-2008 (TRIUMF, Vancouver, 2008).

Proceedings of TRIUMF Hosted Conferences and Workshops

J.M. D'Auria, J. Thomson and M. Comyn, eds., Proc. **14^{th} Int. Conf. on Electromagnetic Isotope Separators and Techniques Related to Their Applications (EMIS-14), Victoria, BC, May 6–10, 2002** (Nucl. Instrum. Methods **B204**, 2003).

C.S. Kalman, J. McKenna, M. Bozzo, Z. Ligeti, T. Mattison, J. Ng, M.A. Sanchis-Lozano and P. Singer, eds., Proc. **5^{th} Int. Conf. on Hyperons, Charm and Beauty Hadrons (BEACH 2002), Vancouver, BC, June 25–29, 2002** (Nucl. Phys. **115**, 2003).

L. Buchmann, M. Comyn and J. Thomson, eds., Proc. **8^{th} Symp. on Nuclei in the Cosmos (NICVIII), Vancouver, BC, July 19–23, 2004** (Nucl. Phys. **A758**, 2005).

E. Accomando, G. Azuelos *et al.*, eds., Proc. **Workshop on CP Studies and Non-Standard Higgs Physics, Geneva, Switzerland, December 2–3, 2004** (CERN-2006-009, 2006) [hep-ph/0608079].

J. Dilling, M. Comyn, J. Thomson and G. Gwinner, eds., Proc. **4^{th} Int. Conf. on Trapped Charged Particles and Fundamental Physics (TCP 2006), Parksville, BC, September 3–8, 2006** (Springer, The Netherlands, 2007).

Books

Books – *2003*

K. Nagamine, *Introductory muon science* (Cambridge Univ. Press, Cambridge, 2003).

T.J. Ruth, *Criteria for the selection, production, and use of radionuclides for diagnosis and radiotherapy* in Technetium, Rhenium and other Metals in Chemistry and Nuclear Medicine, eds. M. Nicolini, U. Mazzi (SG Editorial, Padova, 2003) p.297.

A.J. Stoessl and S. Furtado, *Positron emission tomography in movement disorders*, in Positron Emission Tomography: Basic Science and Clinical Practice, eds. P.E. Valk *et al.* (Springer-Verlag, London, 2003).

Books – *2005*

J. Sugiyama, *Correlation between thermopower and magnetism detected by μSR in layered cobaltites* in Muons: New Research, ed. J. Caparthy (Nova Science, New York, 2005), p.221.

Books – *2006*

M.K. Craddock, *FFAG accelerators*, in Handbook of Accelerator Physics and Engineering, eds. A.W. Chao and M. Tigner (World Scientific, 3rd ed., 2006) p.18.

J. Hanlon, *Human resources in a research environment* in Research Administration and Management (Jones and Bartlett, Sudbury, MA, 2006).

Theses

Theses – *2003*

M.D. Bridges, *Room-temperature hyperfine coupling constants of the Mu-ethyl and Mu-t-butyl radicals in faujasites* (B.Sc. Hon., Chemistry, University of British Columbia).

T. Warner, *Collection and manipulation of radioactive xenon isotopes: progress towards a radon EDM search at TRIUMF* (B.Sc. Hon., Engineering Physics, Simon Fraser University).

C.J. Osborne, *High-precision measurements of the half-life of ^{26}Na* (M.Sc., Physics, University of Surrey).

K.F. Poon, *μSR studies of the electron-doped high-T_c superconductor $Pr_{2-x}Ce_xCuO_4$* (M.Sc., Physics, Simon Fraser University).

N. Buchanan, *The radiation qualification of a switch capacitor array controller for use in ATLAS* (Ph.D., Physics, University of Alberta). 2003

D. Waller, *A study of charm quark production in beauty quark decays with the OPAL detector at LEP* (Ph.D., Carleton University).

J. Wendland, *Polarized parton distributions measured at the HERMES experiment* (Ph.D., Physics, Simon Fraser University).

Theses – *2004*

L.A. Courneyea, *Photoionization of the $5P_{1/2}$ state of cooled and trapped potassium atoms* (B.Sc., Physics, University of British Columbia).

A. Bebington, *Investigating the $^{13}C(p,\gamma)^{14}N$ reaction and using GEANT to test the DRAGON's acceptance* (M.Sc., Physics, University of Surrey, UK).

E.S. Cunningham, *The development of SCEPTAR, the new scintillator array for the 8π spectrometer and its use in the study of the ^{32}Na decay* (M.Sc., Physics, University of Surrey, UK).

D. Gigliotti, *Efficiency calibration measurement and GEANT simulation of the DRAGON BGO gamma array at TRIUMF* (M.Sc., Physics, University of Northern British Columbia).

G.F. Grinyer, *High precision measurements of ^{26}Na β^- decay* (M.Sc., Physics, University of Guelph).

S. Kecman, *Muonium kinetics and free radical formations in solutions of fullerenes* (M.Sc., Chemistry, Simon Fraser University).

M. Lamey, *A microchannel detection system for DRAGON* (M.Sc., Physics, Simon Fraser University).

J.G. Publicover, *Energy mapping of scattered protons within a gas target* (M.Sc., Physics and Astronomy, University of Victoria).

P.-H. Beauchemin, *Phenomenology of bulk scalar production at the LHC* (Ph.D., Physics, University of McGill).

L. Chen, *EE radiation tolerant design with 0.18-micron CMOS technology* (Ph.D., Physics, University of Alberta).

M. Gericke, *The NPDGamma experiment – the weak interaction between nucleons and parity violation in cold neutron capture* (Ph.D., Physics, Indiana University).

H. Itahara, *Processing design, synthesis and thermoelectric properties of textured cobaltite ceramics* (Ph.D., Engineering, Nagoya University).

I. McKenzie, *Investigations of the structure and dynamics of novel muoniated radicals* (Ph.D., Chemistry, Simon Fraser University).

Theses – *2005*

R. Prest, *Pulse shape characterization and simulation for the TIGRESS gamma-ray detector* (B.Sc., Engineering Science, Simon Fraser University).

J.D. Schultz, *Point charge simulations of the electric field gradient* (B.Sc., Physics, University of British Columbia).

J. Valiani, *Spectroscopic determination of the interaction between endohedral lithium and buckminster fullerene using β-detected NMR* (B.Sc., Chemistry, University of British Columbia).

T.E. Cocolios, *Collinear fast-beam laser spectroscopy at ISAC* (M.Sc., Physics, McGill University).

J.J. Daoud, *High precision measurements of the half-life of ^{18}Ne using SCEPTAR and the 8π spectrometer* (M.Sc., Physics, University of Surrey, UK).

B. Hyland, *Precision half-life and branching ratio measurements for the superallowed β emitter ^{62}Ga* (M.Sc., Physics, University of Guelph).

J.A. Klug, *Heat transfer and fluid flow modelling of high current solid isotope production targets* (M.Sc., Mechanical Engineering, University of Applied Sciences, Mannheim, Germany).

K. Leung, *EE effects of ionizing radiation on IDDQ testing* (M.Sc., Physics, University of Alberta).

A.A. Phillips, *Diffusion and transport of radioactive* ^{120}Xe*: towards Rn electric-dipole moment measurements* (M.Sc., Physics, University of Guelph).

E. Prime, *Loading of a far-off resonance dipole force trap for stable* ^{39}K (M.Sc., Physics, University of British Columbia).

G. Rosenbaum, *Measuring the resolution of a GEM-TPC in a magnetic field* (M.Sc., Physics and Astronomy, University of Victoria).

B.E. Schultz, *Diamagnetic muonium centers in GaAs* (M.Sc., Physics, University of Alberta).

M.A. Schumaker, *Measurement and simulation-based optimization of TIGRESS HPGe detector array performance* (M.Sc., Physics, University of Guelph).

M.J. Smith, *A square-wave-driven radiofrequency quadrupole cooler and buncher for TITAN* (M.Sc., Physics and Astronomy, University of British Columbia).

D. Wakeford, *STACEE observations of BL Lacertae using the Solar Tower Atmospheric Cherenkov Effect Experiment* (M.Sc., Physics, University of Alberta).

A. Gaponenko, *A precision measurement of the muon decay parameter delta* (Ph.D., Physics, University of Alberta).

B. Jamieson, *Measurement of the muon decay asymmetry parameter with the TWIST spectrometer* (Ph.D., Physics, University of British Columbia).

C.C. Jewett, *Excited states in* ^{22}Mg *and the* $^{21}Na(p,\gamma)^{22}Mg$ *reaction* (Ph.D., Physics, Colorado School of Mines).

R. Mazini, *Étude du potentiel de découverte du boson de Higgs produit via la fusion de bosons vectoriels* $qq\overline{qq}H \rightarrow \tau^+\tau^-$ *par le détecteur ATLAS au LHC* (Ph.D., Physics, Université de Montréal).

D.G. Melconian, *Measurement of the neutrino asymmetry in the decay of polarized, laser-cooled* ^{37}K (Ph.D., Physics, Simon Fraser University).

J.R. Musser, *Measurement of the Michel parameter* ρ *in muon decay* (Ph.D., Physics, Texas A&M University).

P.L. Russo, *Muon spin relaxation study of superconducting* $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (Ph.D., Physics, Columbia University).

A.T. Savici, *Muon spin relaxation study of coexisting superconductivity and magnetic ordering in* La_2CuO_4 *based systems* (Ph.D., Physics, Columbia University).

Theses – *2006*

S. Wright, *ANC for the valence neutron in* ^8Li *from a study of* $^7Li(^8Li,^7Li)^8Li$ *a mirrored approach to* $S_{17}(0)$ (M.Phys., Physics, University of Surrey, UK).

S.J. Heath, *Observations of the flow of a fibre suspension through a sudden expansion using positron emission tomography* (M.App.Sc., Mechanical Engineering, University of British Columbia).

R. Bayes, *A search for exotic muon decays in the TWIST muon decay spectrum* (M.Sc., Physics and Astronomy, University of Victoria).

F. Berghaus, *K2K near detector laserball calibration: manipulator motivaton, design and results* (M.Sc., Physics and Astronomy, University of British Columbia).

M. Bieri, *Study of the 2004 end-cap beam tests of the ATLAS detector* (M.Sc., Physics, Simon Fraser University).

M. Brodeur, *Towards high precision mass measurements of short-lived exotic isotopes using highly charged ions at the TITAN Penning trap system* (M.Sc., Physics and Astronomy, University of British Columbia).

M.W. Froese, *The TITAN electron beam ion trap: assembly, characterization, and first tests* (M.Sc., Physics, University of Manitoba).

M.D. Hossain, *Measurement of the London penetration depth in the Meissner state of* $NbSe_2$ *using low energy polarized* ^8Li (M.Sc., Physics and Astronomy, University of British Columbia).

T. Keeler, *Investigation of Ag/Fe magnetic multilayers with* β*-NMR* (M.Sc., Physics and Astronomy, University of British Columbia).

D.G. Roberge, *Polarization diagnostics for rubidium-80 in a spin-polarized beta decay experiment* (M.Sc., Physics and Astronomy, University of British Columbia).

D. Wang, *Near surface vortex lattice in* $NbSe_2$ *studied with low energy beta-NMR* (M.Sc., Physics and Astronomy, University of British Columbia).

H. Imao, *Muon catalyzed fusion in gas/liquid/solid deuterium under the controlled ortho-para ratio* (Ph.D., Physics, University of Tokyo).

C. Matei, *Nucleosynthesis of* ^{16}O *under helium burning* (Ph.D., Physics, Ohio University).

Theses – *2007*

C. Adams, *Large extra dimensions* (M.Sc., Physics, University of Toronto).

L.G. Blomeley, *First tests of a square wave radio frequency quadrupole cooler and buncher for TITAN* (M.Sc., Physics, McGill University).

P.E.J. Finlay, *High-precision branching ratio measurement for the superallowed β emitter ^{62}Ga* (M.Sc., Physics, University of Guelph).

K. Fransham, *Evaluating the performance of a prototype TPC for use in the ND280m detector of the T2K experiment* (M.Sc., Physics and Astronomy, University of Victoria).

R.A. Pitcairn, *The search for tensor interactions in the β-decay of polarized ^{80}Rb* (M.Sc., Physics and Astronomy, University of British Columbia).

B. Rablah, *A coupled-circuit representation of IGBT module geometry for high di/dt switching applications* (M.App.Sc., Electr. Eng., University of British Columbia).

D. Schouten, *Jet energy calibration in ATLAS* (M.Sc., Physics, Simon Fraser University).

H.N. Bani-Salameh, *Muonium defect centers in aluminum nitride and silicon carbide* (Ph.D., Physics, Texas Tech University).

G.F. Grinyer, *High-precision half-life measurements for superallowed Fermi β decays* (Ph.D., Physics, University of Guelph).

C. Ouellet, *The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction using DRAGON* (Ph.D., Physics, McMaster University).

S. Sabik, *Top Quark Mass* (Ph.D., Physics, University of Toronto).

T. Spreitzer, *Top quark production cross section* (Ph.D., Physics, University of Toronto).

B. Stelzer, *Single top production* (Ph.D., Physics, University of Toronto).

T. Takami, *Physical properties of quasi-one dimensional cobalt oxides* (Ph.D., Physics, Nagoya University).

Theses – *2008*

S.H. Han, *ATLAS study of backgrounds to black hole events in the ATLAS detector* (M.Sc., Physics, University of Alberta).

E. Rezaie, *Commissioning of the ATLAS liquid argon calorimeters* (M.Sc., Physics, Simon Fraser University).

J. Wong, *Design study of DESCANT - DEuterated SCintillator Array for Neutron Tagging* (M.Sc., Physics, University of Guelph).

R.P. MacDonald, *A precision measurement of the muon decay parameters ρ and δ* (Ph.D., Physics, University of Alberta).

M.J. Smith, *A mass measurement of the short-lived halo nucleus ^{11}Li with the TITAN Penning trap spectrometer* (Ph.D., Physics and Astronomy, University of British Columbia).

M. Subramanian, *Lifetimes of states in ^{19}Ne above the $^{15}O + \alpha$ threshold* (Ph.D., Physics and Astronomy, University of British Columbia).

K. Vaughan, *Investigations in explosive hydrogen burning* (Ph.D., Physics, University of York).

Appendix B

Summary of Laboratory Statistics

Appendix B

Summary of Laboratory Statistics

Grants

The Natural Sciences and Engineering Research Council (NSERC) supports university research through the awarding of peer-reviewed grants. NSERC grants are designed and awarded to support scientific research and promote the advanced training of highly qualified people. There is clear evidence that research at TRIUMF is a priority for the federal government (through NSERC) and the Canadian university community.

Table 1 identifies the annual dollar value of the NSERC subatomic physics grant envelope (Grant Selection Committee 19) and the amount of the envelope awarded to grants with TRIUMF involvement. TRIUMF involvement means that either a TRIUMF paid scientist signed the grant application and/or the grant application was for research that used the TRIUMF facility (see Section 5.4 for a more complete discussion). The envelope funds both theoretical and experimental subatomic physics.

Year	NSERC Envelope $000	TRIUMF Award $000	Percent of Total
2003/2004	20,832	16,001	76%
2004/2005	22,352	16,451	73%
2005/2006	22,520	15,994	71%
2006/2007	22,433	16,660	74%
2007/2008	23.010	17,256	75%

Table 1: NSERC grants awarded for the years 2003–2007.

Memoranda of Understanding

TRIUMF has entered into collaboration agreements with various institutions, in Canada and abroad, for a variety of mutually beneficial reasons. Table B-2 lists universities, institutions, and other organizations, by country, with whom TRIUMF has entered into one or more collaboration agreements. These collective agreements allow TRIUMF scientists to work with other laboratories to enhance their research (see Figure B-1). International scientists often come to TRIUMF to share research and ideas.

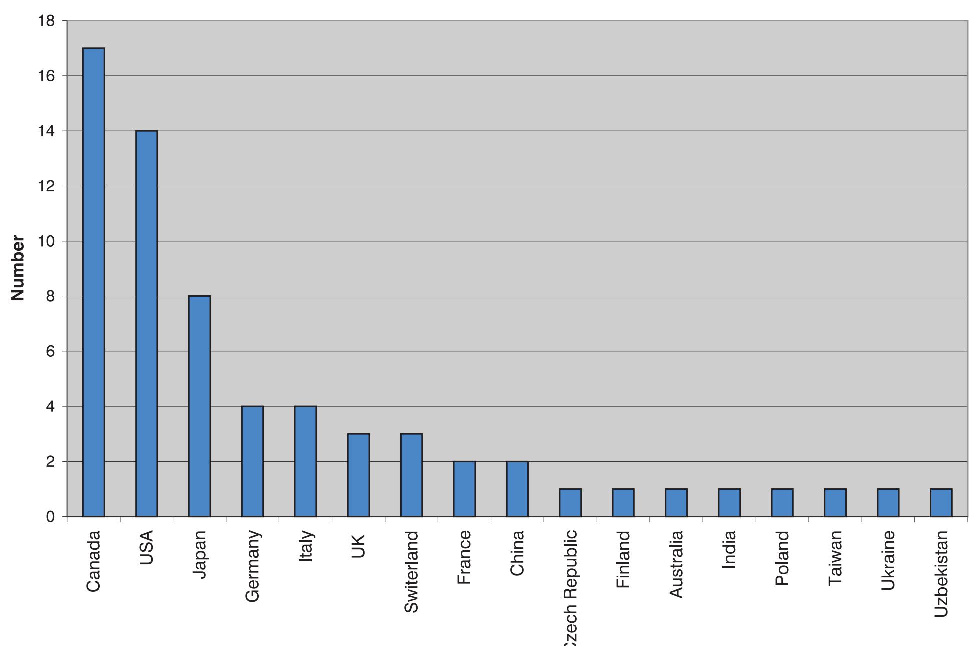


Figure 1: Histogram of TRIUMF's memoranda of understanding by country of partnering institution.

Country	Type of Institution	Name of Institution
Australia	Laboratory	University of Adelaide
Canada	Agency Laboratory Hospital	B.C. Cancer Agency CANARIE Ottawa Heart Institute
	Joint Venture Member Universities	Carleton University • l' Université de Montréal • Simon Fraser University • University of Alberta • University of British Columbia • University of Toronto • University of Victoria
	Joint Venture Associate Members	McMaster University • Queen's University • Saint Mary's University • University of Guelph • University of Manitoba • University of Regina
	Other	University of Sherbrooke PET Centre
China	University	China Institute of Atomic Energy
	Other	Chinese Tri-University Cluster
Czech Republic	Laboratory	Nuclear Physics Institute of the Czech Academy of Sciences
Finland	University	University of Jyvaskyla
France	Laboratory	GANIL • Laboratoire de Physique Subatomique et de Cosmologie de Grenoble • Laboratoire National Saturne (LNS) – Saclay
Germany	Laboratory	DESY • KfK • GSI • Max Plancke Institute
	University	University of Frankfurt • University of Giessen • University of Mainz
India	Laboratory	Variable Energy Cyclotron Centre (VECC)
Italy	Laboratory	INFN-LNL (Catania) • INFN-LNL (Frascati) • INFN-LNL (Legnaro) • INFN-LNL (Milano)
Japan	University	Osaka University
	Laboratory	Japan Atomic Energy Research Institute (JAERI) • Proton Accelerator Research Complex (J-PARC) • Japan Atomic Energy Agency • KEK • Osaka University Laboratory for Nuclear Studies • RIKEN • Toyota Central Labs • University of Tokyo Institute for Nuclear Study (INS)
Poland	University	Warsaw University
Russia	Laboratory	Budker Institute of Nuclear Physics • INR-Dubna • INR-Moscow • JINR-Dubna • Kurchatov Institute • Lebedev Physics Institute
	Other	Ministry of Science and Technology of the Russian Federation
Switzerland	Laboratory	CERN • CERN/PS • Paul Scherrer Institut (PSI)
Taiwan	Laboratory	INER
Ukraine	Laboratory	INR-Kiev
United Kingdom	Laboratory	Rutherford Appleton Laboratory
	University	University of Edinburgh • University of York
USA	University	University of California, Davis • University of Washington • Virginia State University
	Laboratory	Argonne National Laboratory (ANL) • Brookhaven National Laboratory (BNL) • Fermi Laboratory (FNAL) • Jefferson Laboratory (JLab) • Michigan State University • Lawrence Berkeley National Laboratory (LBNL) • Lawrence Livermore Laboratory (LLL) • Los Alamos National Laboratory (LANL) • National Superconducting Cyclotron • Oak Ridge National Laboratory (ORNL) • Stanford Linear Accelerator (SLAC) • TESLA
Uzbekistan	Laboratory	Uzbeskistan Academy of Sciences (INP)

Table 2: Memoranda of understanding with TRIUMF.

Patents

Table 3 lists the patents filed and issued by TRIUMF during the five-year period 2003–2007. Note the many instances of multiple foreign filings, which are normally executed after the Patent Cooperation Treaty (PCT) filing is granted.

Title of Patent	Country	Filing Date	Issue Date
Apparatus And Method For Generating ^{18}F-Fluoride By Ion Beams	US	December 2004	Pending
Automatic LN2 Distribution System For High-Purity Geranium Multi-Detector Facilities	Canada	April 2004	Pending
Automatic LN2 Distribution System For High-Purity Geranium Multi-Detector Facilities	Australia	April 2004	Pending
Automatic LN2 Distribution System For High-Purity Geranium Multi-Detector Facilities	World	April 004	Nationalized
Automatic LN2 Distribution System For High-Purity Geranium Multi-Detector Facilities	US	October 2003	September 2007
Composite Metal-Carbide/Graphic Target Foils	US	June 2005	Pending
Composite Metal-Carbide/Graphic Target Foils	World	June 2005	Nationalized
Composite Metal-Carbide/Graphic Target Foils	Canada	June 2005	Pending
Composite Metal-Carbide/Graphic Target Foils	Europe	June 2005	Pending
Composite Metal-Carbide/Graphic Target Foils	Japan	June 2005	Pending
Composite Metal-Carbide/Graphic Target Foils	US	June 2004	Expired
Forced Convection Target Assembly	US	June 2005	Pending
Forced Convection Target Assembly	World	June 2005	Nationalized
Forced Convection Target Assembly	Australia	June 2005	Pending
Forced Convection Target Assembly	Canada	June 2005	Pending
Forced Convection Target Assembly	Europe	June 2005	Pending
Forced Convection Target Assembly	Japan	June 2005	Pending
Forced Convection Target Assembly	S. Korea	June 2005	Pending
Forced Convection Target Assembly	Mexico	June 2005	Pending
Forced Convection Target Assembly	US	June 2004	Expired
Geological Tomography Using Cosmic Rays	US	November 2007	Pending
Geological Tomography Using Cosmic Rays	US	February 2006	Pending
Geological Tomography Using Cosmic Rays	World	February 2006	Nationalized

Table 3: Patents filed and issued by TRIUMF for the years 2003–2007.

Title of Patent	Country	Filing Date	Issue Date
Geological Tomography Using Cosmic Rays	Australia	February 2006	Pending
Geological Tomography Using Cosmic Rays	Canada	February 2006	Pending
Geological Tomography Using Cosmic Rays	Europe	February 2006	Pending
Geological Tomography Using Cosmic Rays	Japan	February 2006	Pending
Geological Tomography Using Cosmic Rays	S. Korea	February 2006	Pending
High Current Water Connection Coupling Block	Australia	May 2005	Abandoned
High Current Water Connection Coupling Block	Canada	May 2005	Abandoned
High Current Water Connection Coupling Block	Europe	May 2005	Pending
High Current Water Connection Coupling Block	Japan	May 2005	Abandoned
High Current Water Connection Coupling Block	S. Korea	May 2005	Abandoned
High Resolution 3-D Position Sensitive Detector For Gamma Rays	World	June 2003	Nationalized
High Resolution 3-D Position Sensitive Detector For Gamma Rays	Australia	June 2003	Pending
High Resolution 3-D Position Sensitive Detector For Gamma Rays	Canada	June 2003	Pending
High Resolution 3-D Position Sensitive Detector For Gamma Rays	Europe	June 2003	Pending
High Resolution 3-D Position Sensitive Detector For Gamma Rays	Japan	June 2003	Pending
High Resolution 3-D Position Sensitive Detector For Gamma Rays	US	November 2003	June 2005
Isotope Generator	World	May 2004	Abandoned
Isotope Generator	US	March 2004	April 2006
Method And Apparatus For Generating ^{186}Rhenium	US	March 2007	Pending
Method And Apparatus For Vetoing Random Coincidenced In Positron Emission Tomographs	World	March 2005	Nationalized
Method And Apparatus For Vetoing Random Coincidenced In Positron Emission Tomographs	Australia	March 2005	Pending
Method And Apparatus For Vetoing Random Coincidenced In Positron Emission Tomographs	Canada	March 2005	Pending
Method And Apparatus For Vetoing Random Coincidenced In Positron Emission Tomographs	Europe	March 2005	Pending
Method And Apparatus For Vetoing Random Coincidenced In Positron Emission Tomographs	Japan	March 2005	Pending

Title of Patent	Country	Filing Date	Issue Date
Method And Apparatus For Vetoing Random Coincidenced In Positron Emission Tomographs	US	March 2004	Expired
Method And Apparatus For Vetoing Random Coincidenced In Positron Emission Tomographs	US	March 2005	August 2007
Method For Calibrating Particle Beam Energy	US	August 2006	Pending
Method For Calibrating Particle Beam Energy	World	August 2006	Pending
Method For Calibrating Particle Beam Energy	US	March 2006	Expired
Method For Calibrating Particle Beam Energy	US	August 2005	Expired
Method for Penning Trap Mass Spectroscopy	US	May 2007	Pending
Method Of Synthesizing Compounds Having A Phosphorus-Fluorine-18 Bond	US	February 2005	Pending
Method Of Synthesizing Compounds Having A Phosphorus-Fluorine-18 Bond	World	February 2005	Nationalized
Method Of Synthesizing Compounds Having A Phosphorus-Fluorine-18 Bond	Canada	February 2005	Pending
Radioactive Ion	US	January 2005	Pending
Self-Supporting Multilayer Films Having A Diamond-like Carbon Layer	US	March 2007	Pending
Self-Supporting Multilayer Films Having A Diamond-like Carbon Layer	World	March 2007	Pending
Self-Supporting Multilayer Films Having A Diamond-like Carbon Layer	US	March 2006	Expired
Simplified Synthesis Of Desmethyl-FLB 457 In Two Steps	US	September 2003	Abandoned
Simplified Synthesis Of Desmethyl-FLB 457 In Two Steps	US	August 2003	Abandoned
Simplified Synthesis Of The 6-[F-18] Fluro-L-Dopa Precurser	US	August 2003	Abandoned
Synthesis Of Radiolabeled Sugar Metal Complexes	US	September 2005	Pending
Synthesis Of Radiolabeled Sugar Metal Complexes	World	September 2005	Nationalized
Synthesis Of Radiolabeled Sugar Metal Complexes	Australia	September 2005	Pending
Synthesis Of Radiolabeled Sugar Metal Complexes	Canada	September 2005	Pending
Synthesis Of Radiolabeled Sugar Metal Complexes	Europe	September 2005	Pending
Synthesis Of Radiolabeled Sugar Metal Complexes	Japan	September 2005	Pending
Synthesis Of Radiolabeled Sugar Metal Complexes	S. Korea	September 2005	Pending

Title of Patent	Country	Filing Date	Issue Date
Synthesis Of Radiolabeled Sugar Metal Complexes	US	September 2004	Expired
System For Selecting True Coincidence Events In Positron Emission Tomography	US	December 2005	Pending
System For Selecting True Coincidence Events In Positron Emission Tomography	World	December 2005	Nationalized
System For Selecting True Coincidence Events In Positron Emission Tomography	Australia	December 2005	Pending
System For Selecting True Coincidence Events In Positron Emission Tomography	Canada	December 2005	Pending
System For Selecting True Coincidence Events In Positron Emission Tomography	Europe	December 2005	Pending
System For Selecting True Coincidence Events In Positron Emission Tomography	Japan	December 2005	Pending
System For Selecting True Coincidence Events In Positron Emission Tomography	S. Korea	December 2005	Pending
System For Selecting True Coincidence Events In Positron Emission Tomography	US	December 2004	Expired
Unidimensional Array 3-D Position Sensitive Ionization Detector	US	March 2005	Pending
Unidimensional Array 3-D Position Sensitive Ionization Detector	World	March 2005	Nationalized
Unidimensional Array 3-D Position Sensitive Ionization Detector	Australia	March 2005	Pending
Unidimensional Array 3-D Position Sensitive Ionization Detector	Canada	March 2005	Pending
Unidimensional Array 3-D Position Sensitive Ionization Detector	Europe	March 2005	Pending
Unidimensional Array 3-D Position Sensitive Ionization Detector	Japan	March 2005	Pending
Unidimensional Array 3-D Position Sensitive Ionization Detector	US	March 2004	Expired

Students

Graduate Students

TRIUMF's research facilities are a resource Canadian universities can, and do, exploit on behalf of their graduate students in the fields of subatomic physics, materials science, accelerator technology, and life sciences. In addition to graduate students from Canadian universities, universities from Europe, Japan, and the United States use the TRIUMF facilities to educate their graduate students. In the years 2003–2007, 327 graduate students worked on theses based in whole, or in part, on research done using the TRIUMF facilities or under the supervision of TRIUMF staff. The breakdown by area of research and degree is shown in Table 4.

Topic	Ph.D.	M.Sc.
Subatomic Physics	65	126
Materials Sciences	32	69
Accelerator Technology	1	3
Life Sciences	6	25

Table 4: Graduate theses for the years 2003–2007.

Co-op and Summer Students

During the five years 2003–2007, TRIUMF hired 304 undergraduate students, an average of 60 students a year. The students were hired to fill four-month work terms, carrying out tasks as assigned by their TRIUMF supervisors. In addition, TRIUMF awarded 26 scholarships to exceptional undergraduate students, one from each of the five geographic areas of Canada. It is TRIUMF's practice to award five scholarships per year but, in 2006, an additional scholarship was awarded.

High-School Students

TRIUMF's connection with high-school students is made through the Saturday Morning Lecture Series, interactions with their teachers in the various programs offered for BC science teachers, and through videos, which are developed especially for high-school science students. In addition to these programs, TRIUMF's High-School Fellowship program awards each of two promising high-school students a scholarship and a six-week paid work term at TRIUMF each summer.

Scientific Visitors

Scientists from Canada and from abroad visit TRIUMF regularly to perform experiments and to collaborate with the TRIUMF scientific and engineering staff. Table B-5 identifies the number of scientific visitors to TRIUMF during the five years 2003 to 2007 and identifies the countries of their home institutions. Most of these scientific visitors visited TRIUMF on multiple occasions during the five-year period under review but have been identified only once for purposes of this table. TRIUMF Scientific visitors who have attended conference or workshops at TRIUMF are not included in this table.

Country	Visitors
Australia	1
Austria	2
Belgium	5
Brazil	1
Canada	122
China	10
France	41
Germany	35
India	2
Israel	6
Italy	11
Japan	92
Korea	1
Netherlands	1
Poland	1
Portugal	2
Russia	4
Spain	2
Sweden	1
Switzerland	13
United Kingdom	54
United States	142
Total	**549**

Table 5: Scientific visitors to TRIUMF for the years 2003–2007.

TRIUMF Tours

TRIUMF offers tours to a number of distinct groups as part of its Communications and Outreach Program.

General Public: TRIUMF offers tours to members of the general public twice a week from September to May and twice a day through the summer months of June to August.

Science: The lab conducts pre-arranged tours for university and college physics, chemistry or other science students as well as for scientists who are visiting TRIUMF to attend conferences or workshops.

Students: TRIUMF offers pre-arranged tours for older elementary students, high-school students, and university or college non-science students.

VIP: Senior management conducts specially arranged tours for VIPs, review or advisory committee members, and the media.

Table 6 lists the number of people in each of these groups, the number of tours, and the number of tour guides required to conduct them for the years 2003–2007. Tour groups of more than 15 people require multiple tour guides.

Category	2003	2004	2005	2006	2007
General Public					
# people	482	399	1342	428	471
# tours	126	109	111	99	138
# guides	126	111	139	100	138
Science					
# people	651	729	860	920	669
# tours	34	36	51	51	44
# guides	59	70	82	92	82
Students					
# people	626	440	831	586	806
# tours	38	23	33	24	43
# guides	50	35	66	48	77
VIP					
# people	260	95	98	133	160
# tours	63	26	30	42	42
# guides	71	26	31	42	50
Total					
# people	2,019	1,663	3,131	2.067	2106
# tours	261	194	225	216	267
# guides	306	242	318	282	347

Table 6: Breakdown of TRIUMF tour numbers by group for the years 2003–2007. Note that the 2005 general public numbers include a one-day tour for 950 delegates attending the Canadian Association of Physicists Congress 2005 (CAP05) Open House.

TRIUMF Users' Group

The TRIUMF Users' Group (TUG) consists of scientists and engineers with a special interest in the use of the TRIUMF subatomic physics facilities. This group does not include experimenters and other users of the TRIUMF facility who have not specifically joined the TRIUMF Users' Group

Year	Number of Users	Number of Countries
2003	310	10
2004	316	9
2005	325	12
2006	332	13
2007	339	13

Table 7a: The TRIUMF Users' Group membership for the years 2003–2007.

In addition to TUG, there is a TRIUMF Condensed Matter and Materials Science (CMMS) User Group. For the five years ending 2007, 286 members of this group used the TRIUMF CMMS facilities at least once a year.

Country	Number of Users
Canada	100
USA	12
Japan	114
Europe	55
South America	5
Total	**286**

Table 7b: The TRIUMF Users' Group membership for the years 2003–2007 by country of affiliation.

Seminars

TRIUMF provides regular seminars to educate and update our staff, the staff of nearby universities, TRIUMF students, students of nearby universities and the general public on a broad range of science topics generally, but not always, related to physics. In addition to TRIUMF's regular weekly seminar schedule, which features invited speakers from institutions in Canada and from abroad, the lab holds seminars on ISAC-specific topics, technical subjects and subjects targeted at students. Figure 2 shows the total number of seminars each year,

In 2005, the TRIUMF Communications and Outreach Program developed the Saturday Morning Lecture Series. This lecture series, which is specifically designed for the general public, has proved to be extremely popular, and attendance is often "standing room only."

Seminar Type	2003	2004	2005	2006	2007
Scientific Seminars	55	78	83	86	114
Lunchtime Seminars	8	5	2	15	1
Technical Seminars	2	5	9	10	9
ISAC Seminars	7	10	11	10	8
Student Seminars	-	-	18	16	11
Saturday Morning Lecture Series	-	-	2	10	17
Total	**72**	**98**	**125**	**147**	**160**

Table 8: TRIUMF seminars for years 2003–2007.

Conferences

TRIUMF helps organize workshops and conferences, which are important in the scientific community to disseminate information and establish contacts among scientists. Table B-9 is a list of conferences, workshops, and institutes that TRIUMF has either organized or co-organized. TRIUMF's "convening power" is growing; over the past 5 years, the number of participant-days for conferences organized by TRIUMF has increased by over 40%. This means that more people are coming to more conferences at TRIUMF then ever before.

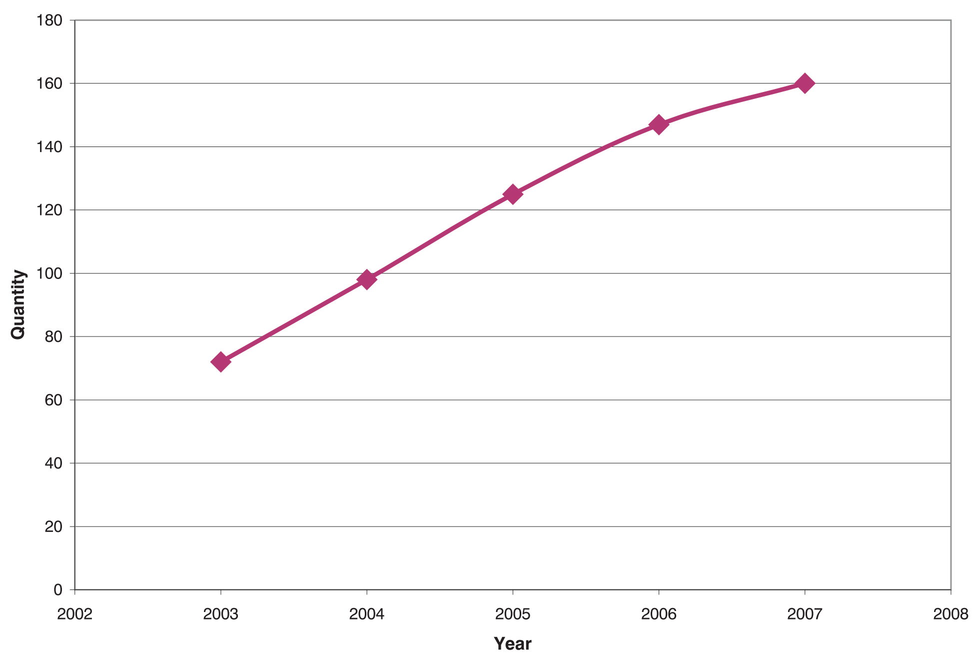


Figure 2: Trend in annual number of seminars over the past few years.

DATE	ACRONYM	NAME OF CONFERENCE	No. of DELEGATES	No. of PERSON DAYS
2008-02-15	WNPPC-08	Winter Nuclear and Particle Physics Conference	45	135
2007-10-27	RDW-07	Radiotracer Development Workshop	42	42
2007-09-13	UCN-07	International Workshop: Ultracold Neutron Sources and Experiments	45	90
2007-09-02	CHEP-2007	International Conference on Computing in High Energy and Nuclear Physics	470	2,820
2007-08-01	TOWNMTG07	TRIUMF Town Meeting: Opportunities for Innovation and Research	55	165
2007-07-30	PACSPIN-07	6th Circum-Pan-Pacific Symposium on High Energy Spin Physics	38	152
2007-07-09	TSI-2007	TRIUMF Summer Institute 2007	33	396
2007-03-12	Workshop	Three-Nucleon Interactions from Few-to Many-Body Systems	32	160
2007-02-16	WNPPC-07	Winter Nuclear and Particle Physics Conference	48	144
2006-09-03	TCP06	Trapped Charged Particles Conference	106	424
2006-07-19	VLCW06	Vancouver Linear Collider Workshop	317	1,268
2006-07-10	TSI2006	TRIUMF Summer Institute 2006	34	408
2006-07-10	SRA-RM101	SRA Research Manager 101	155	310
2006-04-27	WATD-2006	TRIUMF 1st Workshop on Actinide Target Development	41	123
2006-04-09	FPCP2006	Flavor Physics & CP Violation	106	424
2006-02-17	WNPPC-06	Winter Nuclear and Particle Physics Conference	44	132
2005-08-29	T2K-2005	TRIUMF T2K 280m Near Detector Meeting	57	171
2005-07-11	TSI2005	TRIUMF Summer Institute	35	420
2005-06-10	TITAN-2005	TITAN Collaboration meeting and workshop	45	90

Table 9: TRIUMF seminars for years 2003–2007.

DATE	ACRONYM	NAME OF CONFERENCE	No. of DELEGATES	No. of PERSON DAYS
2005-06-05	CAP/ACP-2005	2005 CAP Congress UBC/TRIUMF	608	3,040
2005-02-18	WRNPPC-05	42nd Western Regional Nuclear and Particle Physics Conference	47	141
2004-09-11	5ISR	Fifth International Symposium on Radiohalogens	76	380
2004-07-19	NIC VIII	Eighth International Symposium on Nuclei in the Cosmos	300	1,500
2004-07-05	TSI2004	TRIUMF Summer Institute 2004	35	420
2004-04-15	FFAG2004	Fixed Field Alternating Gradient Workshop	23	161
2004-02-13	WRNPPC2004	Western Regional Nuclear & Particle Physics Conference 2004	45	135
2003-10-20	HEPiXNT2003	HEPix/HEPNT Fall/2003	76	228
2003-09-02	GEANT4-2003	GEANT4 2003 Workshop	54	270
2003-07-21	TSI2003	TRIUMF Summer Institute 2003	35	420
		Total	**3,047**	**14,569**

Appendix C

Media Coverage of TRIUMF

Appendix C

Media Coverage of TRIUMF

Although TRIUMF does not subscribe to a news-clipping service, informal tallies of press coverage are kept. In the past two years, over 90 articles about TRIUMF were printed in approximately 45 different publications in Canada, the US, and on the World Wide Web. These articles range from a discussion of TRIUMF's in-house cloud chamber to the announcement of TRIUMF as one of the recipients of the National Centres of Excellence for Commercialization and Research award. Features covered TRIUMF's activity in the field of nuclear medicine, its standing as a national laboratory, and its effect on the community.

The titles of a few selected articles from 2008, with brief summaries are below:

- "Chance structure makes carbon dating possible" *physicsworld.com,* January 31, 2008. TRIUMF studies nuclear structure and effects of Brown-Rho scaling with scientists from the University of Idaho.
- Morton, Brian. "Vancouver lands $60m for research centres," *Vancouver Sun*, February 14, 2008. In an announcement by Jim Prentice, Minister of Industry, TRIUMF receives $15 million of funding to establish a new company Advanced Applied Physics Solution, Inc., as part of a $163 million national program to establish 11 new Centres of Excellence for Commercialization and Research.
- Mercurio, Antoinette. "Undergraduate student gets up close and personal with physics." *Ryerson University*. February 21, 2008. Award-winning

undergraduate medical-physics student receives TRIUMF's Summer 2008 Research Award.

- Munro, Margaret. "Massive project to re-enact Big Bang." *Vancouver Sun,* March 1, 2008. TRIUMF scientists involved with ATLAS project at CERN announce a milestone as the big project comes together.
- Savory, Eve. "Erich and the KAON Factory." *CBC News*, May 2, 2008. Celebrating Erich Vogt, a former TRIUMF director, at a symposium held at UBC.
- Sinoski, Kelly. "Students find thrills in physics." *Vancouver Sun.* May 2, 2008. Two B.C. high-school physics students win B.C. Innovation Council fellowship awards to participate in summer research projects at TRIUMF.
- Cherewayko, Curt. "TRIUMF taps Richmond company's superconductor welding technology," *Business in Vancouver.* Issue 967. May 6-12, 2008. TRIUMF's working partnership with Richmond-based PAVAC Industries, Inc., a specialist in electron beam welding, achieves a major milestone.
- Spears, Tom. "A Carleton University team has spent years slowly, carefully, ingeniously crafting pieces needed for a project that aims to solve the biggest mystery of the universe." *The Ottawa Citizen.* May 20, 2008. Rob McPherson, a University of Victoria physicist who works at TRIUMF, explains the purpose of the Large Hadron Collider at CERN and what it expects to achieve.
- UBC Faculty of Science. "Accelerating the Next Generation of Medical Isotopes." *UBC Science Connect.* Issue 2, 2008. TRIUMF and UBC are working toward a national network to bring together expertise on the production and application of accelerator-produced medical isotopes.

Appendix D

Committees Providing Input to the Five-Year Plan

Appendix D

Committees Providing Input to the Five-Year Plan

TRIUMF has a number of planning, advisory, and oversight committees. In preparing the Five-Year Plan report, TRIUMF has had, as outlined in Section 6.6, extensive formal consultations with the Canadian and international community through these committees. The committees formally consulted are: the Advisory Committee on TRIUMF (ACOT), the Board of Management (BOM), the Policy and Planning Advisory Committee (PPAC), the Kitchen Cabinet Advisory Committee, a special Subatomic Physics Experiments Evaluation Committee, the TRIUMF Users Executive Committee (TUEC), the Accelerator Advisory Committee (AAC), and the Life Sciences Projects Evaluation Committee (LSPEC). The memberships of these committees are listed below and where appropriate, the dates and agendas of meetings that were dedicated to the five-year plan process are provided.

In addition to these standing committees, TRIUMF instituted a Five-Year Planning Steering Committee to oversee the preparation of the plan. Its membership is also given below. To prepare the case for Five-Year Plan, a dedicated workshop on halo nuclei was organized. Information on the workshop is also included below.

Policy and Planning Advisory Committee (PPAC)

The TRIUMF Policy and Planning Advisory Committee (PPAC) is composed of scientists from Canadian universities and reports to the TRIUMF Director and the Board of Management. It advises TRIUMF on scientific policy and planning and facilitates two-way communication with the research communities at Canadian universities.

MEMBERS

Chair: Colin Gay, U. of British Columbia
Mauricio Barbi, U. of Regina
Sampa Bhadra, York U.
Mark Boulay, Queen's U.
Stephen Godfrey, Carleton U.
Aksel Hallin, U. of Alberta
Michael Hayden, Simon Fraser U.
Ritu Kanungo, Saint Mary's U.
Rob Kiefl, U. of British Columbia
Graeme Luke, McMaster U.
Shelley Page, U. of Manitoba
Maxim Pospelov, U. of Victoria
Michael Roney, U. of Victoria
Pierre Savard, U. of Toronto
Vesna Sossi, U. of British Columbia
Carl Svensson, U. of Guelph
Brigitte Vachon, McGill U.
Michael Vetterli, Simon Fraser U.
Viktor Zacek, U. de Montréal

MEETING

March 14, 2008
Presenter: Nigel Lockyer

MEETING

March 15, 2008
Presenter: Colin Gay

Review materials and presentations for March 14 and 15, 2008 may be found at http://admin.triumf.ca/facility/5yp/PPAC/ppac.php

Kitchen Cabinet Advisory Committee

The TRIUMF Kitchen Cabinet Advisory Committee is composed of TRIUMF scientists. It acts as an advisory committee to the TRIUMF Director. It also promotes two-way communication within the laboratory.

MEMBERS

Chair: Nigel Lockyer
Mike Adam
Fred Bach
Ewart Blackmore
Lothar Buchmann
Iouri Bylinskii
Paul Delheij
John Drozdof
Makoto Fujiwara
Phil Gardner
Greg Hackman
Bassam Hitti
Phil Jones
Rolf Keitel
Shane Koscielniak
Andy Miller
A.C. (Colin) Morton
John Ng
Chris Oram
Matt Pearson
Jean-Michel Poutissou
Chris Ruiz
Paul Schmor
Achim Schwenk
Igor Sekachev
Reda Tafirout
Stan Yen

MEETING

February 11, 2008

MEETING

March 17, 2008

The Committee's feedback and first written report, which was published on March 20, 2008 may be found at http://admin.triumf.ca/facility/5yp/kcac.php.

Special Subatomic Physics Experiments Evaluation Committee

The Experiments Evaluation Committee (EEC) provides advice to the TRIUMF Director on which experiments should be run and assigns priorities to those experimental proposals that are independently peer-approved for beam time. A special meeting of the EEC was held to review the physics motivation of the new beam lines and the ultra cold neutron sources. The Committee was augmented for this special meeting on March 25 and 26, 2008, with three additional members. Names marked with * are members of the regular EEC.

MEMBERS

Chair: Robert Tribble, Texas A&M U.*
Peter Butler, U. of Liverpool*
Stuart Freedman, U. of California at Berkeley
Paul Garrett, U. of Guelph*
Chuck Horowitz, Indiana U.*
Christian Iliadis, U. of North Carolina*
Byron Jennings, TRIUMF, Scientific Secretary
Achim Richter, TU-Darmstadt
Carl Wieman, U. of British Columbia

MEETING

Tuesday, March 25, 2008

08:30 Vision document and mandate (N. Lockyer)
09:00 E-linac session
- 09:00 E-linac project overview (D. Karlen)
- 09:15 E-linac technical proposal (S. Koscielniak)
- 09:35 E-linac yields (P. Bricault)
- 09:55 Physics case (B. Davids, J. Dilling, A. Schwenk)

10:55 Break
11:10 Open discussion
12:00 Working lunch (Boardroom)
13:30 Second proton beam line session:
- 13:30 Overview (J.-M. Poutissou)
- 13:45 Yields (M. Dombsky)
- 14:00 Physics case (G. Gwinner, T. Chupp)

15:15 Break
15:30 Physics case (R. Kanungo)
15:45 ISAC beam delivery strategy (R. Laxdal)
16:05 Open discussion
17:15 EEC *in camera*

MEETING

Wednesday, March 26, 2008

08:30 UCN source session:
- 08:30 Physics case (J. Martin, Masuda-san)
- 09:30 Facility proposal (D. Ramsay)

10:10 Break
10:30 Issues / discussion
12:00 Working lunch (Boardroom)
14:00 EEC *in camera* report writing (B. Jennings)
16:30 Close-out with Director (*in camera*)
17:00 Close-out with users

The presentations, review materials, and Terms of Reference may be found at http://admin.triumf.ca/facility/5yp/seec.php.

Halo Nuclei Workshop

A workshop on halo nuclei was held at TRIUMF on March 27 and 28, 2008. The workshop was co-organized by Saint Mary's University and TRIUMF to review progress in understanding halo nuclei and to determine how to proceed in the future. The workshop also highlighted TRIUMF's contributions to this research topic.

MEMBERS

Organizing Committee:

Chair: Rituparna Kanungo, Saint Mary's U.
Workshop Coordinator: Sandi Miller, TRIUMF
Jens Dilling, TRIUMF
Byron Jennings, TRIUMF
Dave Lunney, U. de Paris Sud
Jean-Michel Poutissou, TRIUMF
Achim Schwenk, TRIUMF

MEMBERS

International Expert Committee:

G. Drake, U. of Windsor
H. Geissel, GSI/U, Giessen
W. Mittig, NSCL/ MSU
A. Richter, TU Darmstadt
I. Tanihata, RCNP, Osaka

MEETING

March 27, 2008

08:30	Registration desk open
08:50	Welcome (J.-M. Poutissou)
09:00	Nuclear halos — Past, present, and future (A. Richter, I. Tanihata)
10:00	Break
10:20	The binding energy of halo nuclides: TRIUMF's new role in the global mass market (A. Richter, D. Lunney)
10:45	Mass measurements of halo nuclei with the TITAN Penning trap spectrometer (M. Smith)
11:00	Laser shed new light on halos - Nuclear charge radii of ^{11}Li and ^{11}Be (W. Nörtershäuser)
11:25	Laser trapping and probing of exotic helium isotopes (P. Mueller)
11:50	Lunch
13:00	ISAC Tour
14:00	Structure of exotic nuclei probed by spin-polarized radioactive beams (G.C. Ball, T. Shimoda)
14:25	Deuteron emission from ^{11}Li: decay of the halo (R. Raabe)
14:50	Beta-decay experiments at TRIUMF: present and future (F. Sarazin)
15:15	Break
15:35	Transfer reactions with two-neutron halo nuclei (G.C. Ball, I. Thompson)

16:00 Exploring Efimov physics in ultracold atomic and molecular quantum gases (M. Mark)
16:25 Discussion session (H. Geissel)

MEETING

March 28, 2008

08:35 Calculated isotope shifts for halo nuclei: A progress report (A. Schwenk, G. Drake)
09:00 *Ab-Initio* Coupled Cluster Theory for weakly bound and unbound nuclear states (G. Hagen)
09:25 The role of pions on nuclei and observable characters based on the relativistic chiral mean field model (Y. Ogawa)
09:50 Role of the explicit tensor correlation in neutron halo nuclei (T. Myo)
10:15 Break
10:35 Fusion reactions with exotic nuclei (W. Loveland)
11:00 Halo physics at GANIL *Chair:* T. Nakamura (H. Savajols)
11:25 Halo nuclei at (REX)-ISOLDE (H. B. Jeppesen)
11:50 Transfer reactions with exotic beams at ATLAS current status and future prospects (A. Wousmaa)
12:15 Lunch
13:30 Present and future opportunities for the study of skin- and halo nuclei at GSI and FAIR (J. Dilling, C. Scheidenberger)
13:55 Study of halo structure in neutron-rich nuclei via intermediate-energy direct reactions of RI beams (S. Shimoura)
14:20 Low-lying excited states of halo nuclei (T. Nakamura)
14:45 Low-lying level structure of light neutron-rich nuclei beyond the drip line: ^{7,9}He and ^{10}Li (N.A. Orr)
15:10 Investigation of the radial shape of halo nuclei by elastic proton scattering in inverse kinematics (P. Egelhof)
15:35 Break
15:55 Discussion session (Coordinator: W. Mittig)
16:55 Workshop summary (W. Mittig)

Presentation materials may be found at
http://www.triumf.info/hosted/HALO/index.html.

TRIUMF Users Executive Committee (TUEC)

Then TRIUMF Users Group (TUG) is the formal organization for TRIUMF users. It has an elected executive (TUEC), which represents the users in interactions with TRIUMF administration and where appropriate with other bodies. TUEC devoted several of its meetings to assisting with preparation of the Five-Year Plan in addition to convening two special meetings of the full user group to provide input to the process.

MEMBERS

Chair: David Kulp, Georgia Institute of Technology
Kim Chow, U. Alberta, Chair Elect
Martin Comyn, TRIUMF, Liaison Officer
Barry Davids, TRIUMF
Uwe Greife, Colorado School of Mines, Past Chair
Byron Jennings, TRIUMF
Rituparna Kanungo, Saint Mary's U.
Isabel Trigger, TRIUMF

MEETING

December 17, 2007

09:00 Welcome and introductory remarks (U. Greife)
09:05 Status of the Laboratory (N. Lockyer)
10:00 ISAC-II status and developments (B. Laxdal)
10:30 Break
10:45 ISAC ion sources and targets (P. Bricault)
11:15 Future directions of detector development (F. Retiere)
11:45 TRIUMF science report (J.-M. Poutissou)
12:15 Lunch
13:15 Highlights of ISAC science (G. Ball)
14:00 TUEC business — Your committee in 2008 (U. Greife, and D. Kulp)
14:05 Connections to the rest of the world (T. I. Meyer)
14:35 Status report for TRIUMF 5-Year Plan (B. Jennings)
14:45 Comparison of ISOL (ISAC) to in-flight RIB production (D. Kulp)
15:15 New target module and 2nd beam line design (P. Bricault)
15:30 Break
15:45 Physics case for the photo fission machine (B. Davids)
16:15 e-linac (S. Koscielniak)
16:30 Life Sciences (T. Ruth)

MEETING

December 18, 2007

09:00 Computing services at TRIUMF (S. McDonald, K. Raywood, and R. Poutissou)
09:30 Particle physics (R. McPherson)
10:00 SNOLAB (W. Trischuk)

10:30 Break
10:45 Materials science (A. MacFarlane)
11:15 The anticipated social and economic impacts from TRIUMF's knowledge transfer 2010–2015 (A. Fong)
11:45 JLab, UCN and non-ISAC nuclear physics (M. Gericke)

Presentations for the Annual General Meetings held on December 17 and 18, 2007 may be found here https://indico.triumf.ca/conferenceDisplay.py?confId=672

Accelerator Advisory Committee (AAC)

The Accelerator Advisory Committee is an external body of experts who advise TRIUMF on accelerator research and development. At its inaugural meeting, the AAC reviewed the technical and engineering aspects of the proposed Five-Year Plan.

MEMBERS

Chair: Mark de Jong, Canadian Light Source
Mats Lindroos, CERN
Sergei Nagaitsev, Fermi National Accelerator Laboratory
Hasan Padamsee, Cornell U.
Marco Schippers, Paul Scherrer Institute
Charles Sinclair, Thomas Jefferson National Accelerator Facility (retired)
Yasushige Yano, RIKEN

MEETING

April 3, 2008

08:30 Executive session, Chair: M. De Jong
Information session (P. Schmor)
09:00 Welcome, AAC charge (N. Lockyer)
09:05 TRIUMF accelerators overview (P. Schmor)
09:20 Cyclotron high intensity upgrade and beam lines (R. Baartman)
09:40 Cyclotron refurbishing (Y. Bylinsky)
10:00 ISAC actinide targets (P. Bricault)
10:20 Break
10:40 ISAC-III: new front end (R. Laxdal)
11:00 E-linac: ISAC new photo-fission driver (S. Koscielniak)
11:20 SRF (R. Laxdal)
11:40 Accelerator operations (R. Ruegg)
12:00 Lunch
12:45 TRIUMF tour
13:30 Parallel breakout sessions:
Cyclotron, Chair: R. Baartman (M. Schippers, Y. Yano, H. Padamsee)
ISAC front end (R. Laxdal. De Jong, M. Lindroos, C. Sinclair, S. Nagaitsev)
15:15 Break

15:30 ISAC targets (P. Bricault, M. Lindroos, M. Schippers, Y. Yano)
15:30 E-linac & SCRF (S. Koscielniak, S. Nagaitsev, H. Padamsee, C. Sinclair, M. De Jong)
17:00 Executive session (M. De Jong)

MEETING

April 4, 2008

08:30 Executive session and report writing (M. De Jong)
10:15 Break
11:00 Presentation of Committee Draft Report to TRIUMF
12:00 Close and lunch

Presentations, Terms of Reference and first report may be found at http://admin.triumf.ca/facility/5yp/aac.php

Life Sciences Projects Evaluation Committee (LSPEC)

The Life Sciences Projects Evaluation Committee advises TRIUMF on matters related to the Life Sciences Program. Its role is similar to the EEC in subatomic physics. At its April 2008 meeting, LSPEC convened several special sessions to discuss the proposed nuclear-medicine initiative in TRIUMF's Five-Year Plan. LSPEC also invited key partners of TRIUMF to present their views.

MEMBERS

Chair: Roger Lecomte, U. de Sherbrooke
Chaitanya R. Divgi, U. of Pennsylvania Radiology
Dave A. Hutcheon, TRIUMF, Secretary
Robert H. Mach, Washington U. School of Medicine
Wayne Martin, U. Guelph
Jean-Michel Poutissou, TRIUMF, Ex-Officio
Frank S. Prato, Lawson Health Research Institute
Lyle P. Robertson, U. of Victoria, Secretary
John F. Valliant, McMaster U.

MEETING

April 3, 2008

07:30 *In camera* meeting with breakfast in the boardroom
08:30 TR13 Report (K.R. Buckley)
09:00 Radiotracers for the physical and biological sciences (T.J. Ruth)
TR13 targets for PET radioisotope production (T.J. Ruth)
09:20 PET facilities (K.R. Buckley)
09:35 Synthesis of radiopharmaceuticals for Positron Emission Tomography (J. Greene)
09:50 Production and evaluation of high specific activity ^{186}Re (D. Becker)
10:05 Break

10:20 Synthesis of ^{99m}Tc and $^{186,188}Re$ sugar derivatives (M.J. Adam)
Synthesis of radiolabelled nucleotides and oligonucleotides (M.J. Adam/D. Perrin)
Imaging and therapy of lysosomal storage diseases (S. Withers/M.J. Adam)
Ferrocene Conjugates as Potential Antimalarial Agents (M.J. Adam)
11:05 Physiological role of copper in marine phytoplankton (M.T. Maldonado)
11:20 Evaluation of novel bifunctional chelates for antibodyimaging with Cu-64 (C. Ferreira)
11:40 Report on Pacific Parkinson's Research Centre (J. Stoessl)
12:10 UBC plans in the Life Sciences (D. Brooks)
12:25 Lunch in the Boardroom
13:15 Imaging of Pancreatic Islets Following Transplantation Using PET (S-J. Kim)
13:30 Improvement of the Resolution and Quantitative Accuracy of the HRRT (V. Sossi)
In Vivo Studies… Dopamine Turnover… Rat Model (V. Sossi)
Analysis and Interpretation of Dopaminergic Tracer PET Imaging in Rodents (V. Sossi)
Investigation of treatment-related compulsive mehaviours and impulse control disorders in Parkinson's Disease (V. Sossi)
14:30 Frontotemporal dementia with ubiquitinated inclusions: Clinical, Genetic and pathological characterization (N. Kandiah)
Alzheimer's Disease Neuroimaging Initiative (ADNI) (N. Kandiah)
14:55 Break
15:15 Methionine-PET for the prediction of treatment outcome in radiation-treated acoustic Neuromas (S.A. Reinsberg)
15:30 Development of PET imaging agents for measuring tissue hypoxia (J. Laskin)
Assessment of tumour microenvironment with MicroPET and MRI (D. Yapp)
15:50 Studies of Nitrate Uptake in Plants and Fungi (T. Glass)
16:05 Development of Liquid Xenon Detectors for PET (L. Kurchaninov)
16:20 *In camera* meeting in the boardroom

MEETING

April 4, 2008

07:30 *In camera* presentations on the future plans for the life sciences
10:15 Report on the BC Cancer Agency functional imaging, clinical and research programs (F. Benard, D. Wilson)
10:45 Life sciences in the TRIUMF 5-Year Plan and CFI proposal (T. Ruth)
11:15 *In camera* meeting with lunch in the boardroom

Description of the committee may be found at
https://www.triumf.info/facility/experimenters/expdb/public.php?schedule=all

Board of Management (BOM)

The Board of Management is the formal Board responsible for the operation, supervision, and control of TRIUMF. It consists of two voting members from each university that is a member of the consortium and one non-voting member from each associate member of the consortium. The Board meets about three times per year.

MEMBERS

Voting Members:

Chair: Feridun Hamdullahpur, Carleton U.
John Beamish, U. of Alberta
Donald Brooks, U. of British Columbia
Howard Brunt, U. of Victoria
Andy Greenshaw, U. of Alberta
Norbert Haunerland, Simon Fraser U.
Patricia Kalyniak, Carleton U.
Richard K. Keeler, U. of Victoria
Claude Leroy, U. de Montréal
Robert S. Orr, U. of Toronto
Michael Plischke, Simon Fraser U.
Pekka Sinervo, U. of Toronto
Jeff Young, U. of British Columbia

Non-Voting Members:

Robert Brooks, U. of Guelph
Malcom N. Butler, Saint Mary's U.
George J. Lolos, U. of Regina
Anthony J. Noble, Queen's U.
Edward. Odishaw, Private Sector Representative
Willem T. Van Oers, U. of Manitoba
David Venus, McMaster U.

Ex-Officio Members:

Walter Davidson, NRC Liaison Officer
Mr. James D. Hanlon, Secretary
Robert V. Janssens, Chair, ACOT
Nigel S. Lockyer, Director, TRIUMF
Jean-Michel Poutissou, Associate Director, TRIUMF

MEETING

April 11, 2008

Description of the committee may be found at
http://www.triumf.info/public/about/bom.php?omid=327

Five-Year Plan Steering Committee

The Five-Year Plan Steering Committee was appointed by the TRIUMF Director in 2007 to oversee the process for preparing the 2010–2015 Five-Year Plan. The Committee included experts from a variety of scientific fields and individuals both inside and outside of TRIUMF. The Committee was responsible for engaging the broader community, coordinating the multitude of reviews, working with experts to generate the technical content of the report, and acting as managing editors of the entire report.

MEMBERS

Chair: Timothy Meyer
Vice Chair: Byron Jennings
Vice Chair: Rob McPherson
Nigel Lockyer
Jean-Michel Poutissou
Yuri Bylinski
Barry Davids
Jens Dilling
Ann Fong
Gerald Gwinner
Garth Huber
Shane Koscielniak
W. David Kulp
Andrew Macfarlane
Shirley Reeve
Tom Ruth
Paul Schmor
Achim Schwenk
William Trischuk
Vijay Verma

Advisory Committee on TRIUMF (ACOT)

The Advisory Committee on TRIUMF advises the National Research Council on all aspects of the TRIUMF program insofar as they relate to the determination and administration of the federal contribution to TRIUMF.

MEMBERS

Chair: Robert V. Janssens, U. of Notre Dame
Baha A. Balantekin, U. Wisconsin-Madison
Samir Boughaba, *Ex-Officio*, Representing NSERC
Henri Buijs, ABB
Walter Davidson, NRC Liaison Officer, Secretary
Jonathan Dorfan, SLAC
Elisabetta Gallo, DESY
Bruce D. Gaulin, McMaster U.
Feridun Hamdullahpur, *Ex-Officio*, Representing TRIUMF Board of Management
Sylvain Houle, U. of Toronto
Karol Lang, *Ex-Officio*, Representing NSERC GSC
Dieter Proch, DESY
William Trischuk, *Ex-Officio*, Representing Institute of Particle Physics
Michael Wiescher, U. of Notre Dame

MEETING

May 9, 2008

08:00 Committee *in camera* session
08:30 Committee discussions
09:00 Highlights of recent results and progress
09:00 Success in science (J. Dilling)
09:20 Success in technology and broader impacts
SRF cavity (R. Laxdal)
International partnerships
Educational video (M. Pavan)
09:45 Discussion
10:00 Five-Year Plan: Overview
A vision for the next decade (N. Lockyer)
10:30 Discussion
10:40 Break
10:50 Five-Year Plan: Major initiatives:
The next fecade of ISAC science:
Rare isotope physics: Nuclear structure (W.D. Kulp)
Rare isotope physics: Nuclear astro (B. Davids)
Rare isotope physics: Fundamental symmetries (C. Svensson)
11:20 The proposed set of tools:
Actinide targets (P. Bricault)
E-linac (S. Koscielniak)
New beam line and cyclotron upgrade (Y. Bylinski)

12:20 Discussion
12:30 Lunch
13:30 Leading the revolution in nuclear medicine (T. Ruth)
13:50 Discussion
14:00 Five-Year Plan: Highly leveraged initiatives
AAPS (P. Gardner)
14:15 Knowledge transfer (P. Gardner, A. Fong)
14:30 Discussion
14:45 Molecular and materials science (A. Macfarlane)
15:05 Particle physics (R. McPherson)
15:25 SNOLAB (A. Hallin)
15:50 Discussion
16:00 Break
16:15 Ultracold neutrons (J. Martin)
16:35 Discussion
16:45 Report from TUEC (W.D. Kulp)
17:05 Discussion
17:15 Adjourn

MEETING

May 10, 2008

Closed Session
Description of the committee may be found at
http://www.triumf.info/public/about/com.php?which=3

Appendix E

Sample Stories of TRIUMF Alumni

Appendix E

Sample Stories of TRIUMF Alumni

A significant fraction of the Canadian physical-science research community has passed through TRIUMF's doors at one point or another. The following list samples the career progress of some of the most recent graduate students and post-doctoral fellows (PDF) after they moved beyond TRIUMF.

- Dan Melconian (Ph.D. SFU 2005, TRINAT) – assistant professor, Texas A&M University
- Sihong Gu (PDF 2000-2003 , TRINAT) – research scientist, Shanghai Institute of Optics
- Jacques Chakhalian (Ph.D. UBC 2002, μSR) – U of Arkansas. His paper on oxide interfaces was selected in the Dec 2007 issue of *Science* as one of the 10 breakthroughs of 2007.
- Shaomin Chen (PDF 2005, Kaon decays) – Professor at Tsinghua University, China
- Jinliang Hu (PDF 2006, TWIST, Kaon decays) – Atomic Energy of Canada
- Ken Garrow (PDF 2005, HERMES) – Bubble Technologies Inc.
- Paul Bergbusch (Ph.D. UBC, 2001 Kaon decays) – Worked at McDonald Detweiller, then FINCAD to do financial derivatives modeling; presently working for a hedge fund in London, UK

- Joss Ives (Ph.D. 2008, Kaon decays) – Science Teaching and Learning Fellow, UBC
- Ermias Gete (Ph.D. 2000, UBC, Nuclear Astrophysics) – Physicist, BC Cancer Agency
- Alison Laird (PDF 2002-2003, Nuclear Astrophysics) – Lecturer, York University
- Chris Iliadis (PDF 1993-1996, Nuclear Astrophysics) – Professor, North Carolina State University
- Alexander Zyuzin (PDF 2003, Nuclear Astrophysics) – ACS Industries, Richmond BC
- Don Hunter (PDF 2002, Nuclear Astrophysics) – Physics instructor, Langara College, Vancouver BC
- Andrei Gaponenko (Ph.D. Alberta 2005, TWIST experiment) – Recipient of Owen Chamberlain fellowship at UCLA, working on ATLAS experiment
- Jim. Musser (Ph.D. 2006 Texas A&M, TWIST experiment) – Assistant Professor at Arkansas Tech
- Cara Ferriera (Ph.D. UBC 2006, PET group) – researcher at MDS Nordion, Vancouver
- Simon Bayly (PDF 2004, PET group) – head chemist of PET group, Oxford.
- Neil Lim (PDF 2006, PET group) – senior chemist with AVID Pharmaceuticals
- Richard Ting (Ph.D. UBC 2007, PET group) – PDF at UC San Diego
- Suzy Lapi (Ph.D. SFU 2007, PET group) – PDF at UC San Diego
- Barry Pointon (Ph.D. UBC 2007, PET group) – Instructor in nuclear medicine, BCIT
- Guillaume Belanger (M.Sc. Carleton 2002, ATLAS) – European Space Agency
- Arther Moraes (PDF 2007, ATLAS) – Professor at University of Glasgow
- Monika Wielers (PDF 2003, ATLAS) – Researcher at Rutherford Appleton Lab, UK
- Rituparna Kanungo (PDF 2007, ISAC) – Professor at Saint Mary’s University
- Juergen Wendland (Ph.D. 2004 SFU, Hermes Experiment, and PDF 2006 T2K) – at FINCAD for financial modeling software
- Roland Horn (PDF 2003, TRILIS) – R&D manager of quartz glass, Haereus (Germany).
- Tobias Achtzehn (Ph.D. 2007, TRILIS) – Bubble Technologies Inc.

- Gail McLaughlin (PDF 2000 TRIUMF theory group) – Professor a North Carolina State U
- W.F. Chang (PDF 2004 TRIUMF theory group) – Professor at National Tsing Hua U, Taiwan
- Laura Sinclair (PDF 2005, Carleton) – Radioactivity mapping and imaging, Geological Survey of Canada
- David Waller (PDF 2006, Carleton) – Defence Scientist, Department of National Defence.
- Khashayer Ghandi (PDF 2005, TRIUMF μSR) – Professor at Mount Allison University

For a sense of the continued performance of TRIUMF scientists and staff, individuals from before 2003 are profiled in the next section. Again, the list is not exhaustive, but only a representative sampling to show the impact that TRIUMF has had in Canada and abroad.

- Alan Fry (Ph.D. UBC 1985) – recently sold his software company Dataphile that wrote code for trading on the Vancouver Stock Exchange; his 100-person company had its roots in the software engineering work that he did at TRIUMF.
- Alan Chen (PDF 2002) – a professor at McMaster University
- Morgan Dehnel (Ph.D. UBC 1995) – founder of D-PACE, provider of products and services to the international accelerator community.
- Andrew Feltham (Ph.D. UBC 1992) – senior software engineer, Broadcom Canada Ltd.
- Reena Meijer-Drees (Ph.D. UBC 1991) – Principal Research Scientist, Honeywell.
- Manuella Vincter (PDF 1998) – professor at Carleton University
- Ralf Kaiser (Ph.D. SFU 1997) – professor at University of Glasgow
- Munasinghe Punyasena (Ph.D. Alberta 1997) – professor at University of Kelaniya, Sri Lanka
- Clarence Virtue (Ph.D. UBC 1987) – head of Physics Department at Laurentian University
- Sehwan Park (Ph.D. 2002) – Korea Atomic Energy Authority
- Zerah Lurie (M.Sc. UBC 2002) – Science journalist, CBC Vancouver.
- Fraser Duncan (Ph.D. UBC 1993) – Associate Director of SNOLAB
- Allena Opper (PDF Alberta 1996) – Professor at George Washington U.
- Grant O'Rielly (PDF 2001) – Professor at U of Massachusetts Dartmouth.
- Dieter Frekers (PDF 1992) – Professor at Universitat Muenster, Germany
- Ken Hicks (PDF 1988) – Professor at Ohio University.

- Ami Altman (Ph.D. U of Tel Aviv 1983; UBC PDF to 1986) – Scientific Director, Tomography Systems, Philips Healthcare, Haifa, Israel.
- Randy Sobie (Ph.D. Toronto 1984) – IPP research scientist at U of Victoria
- Ted Mathie (Ph.D. UBC 1979) – Professor at University of Regina
- George Lolos (PDF UBC 1983) – Professor at University of Regina
- Garth Huber (Ph.D. Regina 1988) – Professor at University of Regina
- Jacques Dubeau (PDF 2001) – President of DETEC, a Franco-Canadian company providing expertise in radiation detection technology
- Zisis Papandreou (Ph.D. Regina 1989) – Professor at University of Regina
- Anna Celler (PDF 1991) – Medical physicist with BC Cancer Agency
- Vesna Sossi (Ph.D. UBC 1991) – Professor of medical physics, UBC.
- David Armstrong (Ph.D. UBC 1988) – Professor at College of William and Mary
- Brian McParland (Ph.D. UBC 1985) – Imaging Research and Development, Amersham Laboratories, UK
- Derek Leinweber (PDF 1995, TRIUMF theory group) – Professor at University of Adelaide
- Cornelius Bennhold (PDF 1992) – Head of Physics at George Washington U.
- Tony Thomas (Staff, 1976-1984) – Head of Theory Group at Jefferson Lab
- Angels Ramos (PDF 1992) – Professor at University of Barcelona
- Pat Kalyniak (Ph.D. UBC 1982; PDF 1983) – Professor at Carleton University
- Steve Godfrey (PDF 1988) – Professor at Carleton University
- Peter Blunden (PDF 1988) – Head of Physics Dept., U of Manitoba
- Randy Lewis (PDF 1997) – Professor at York University
- Howard Trottier (PDF 1992) – Professor at Simon Fraser University
- Malcolm Butler (PDF 1989) – Dean of Science, Saint Mary’s University
- Michel Gingras (PDF 1996) – Professor at U of Waterloo, awarded Herzberg Medal in 2001
- Nader Mobed (PDF 1988) – Professor at University of Regina
- David London (PDF 1987) – Professor at Université de Montréal
- Dale Harshman (Ph.D. UBC 1986) – Executive Vice-President of Physikon Research Corporation, Lynden, WA

- Richard Keeler (Ph.D. UBC 1981) – Associate VP of Research, U of Victoria
- Michael Landry (Ph.D. Manitoba 2000,) – Research Scientist at LIGO interferometer
- Kim Chow (Ph.D. UBC 1995; PDF 2000-2001) – professor at U of Alberta.
- Bruce Milton (Staff 1987-99) – Director of Engineering, OMNEX Trusted Wireless.
- Yasutomo Uemura (Ph.D. Tokyo 1982) – Professor at Columbia University and winner of the International Society of Materials Science Yamazaki Award for his work on spin glasses.
- Graeme Luke (Ph.D. UBC 1988) – Professor at McMaster University

Appendix F

Selected Commentary on Global Medical Isotope Production

Appendix F

Selected Commentary on Global Medical Isotope Production

Summary: "US weighs entering radioisotope market"

Physics Today, May 2008[1]

Radioisotope molybdenum-99 (^{99}Mo) is used in its decayed state, known as technetium-99m (^{99m}Tc), for cancer detection medical imaging. Presently, the major production facilities are in Canada, Belgium, the Netherlands, and South Africa. By its geographical location, Canada naturally captures the North American market share. Currently, the USA does not have adequate

1 This summary is prepared from the article, David Kramer, "US weighs entering isotope market," *Physics Today*, Volume 61, Issue 5, May 2008, p. 22-24.

facilities to produce ^{99}Mo and purchases the vast majority of these isotopes from Canada. Now, the US is poised to construct one or two facilities to domestically produce ^{99}Mo. The research reactor at the University of Missouri-Columbia (MURR) and Babcock and Wilcox (B&W), an energy technology company, are working on plans to build ^{99}Mo production facilities within a decade. Currently, Canada has the lead in the North American market, but demand for Canadian produced ^{99}Mo may decline if the plans for these facilities proceed.

> "The US accounts for about half the world's ^{99m}Tc use, and the world market is projected to grow by 7-10% a year for the next decade or so," writes David Kramer in the *Physics Today* article.

Reasons for Building USA Production Facilities

- **Security** — There is concern over moving large amounts of high-enriched uranium (HEU) because it can be used for nuclear weaponry and because it is relatively easy to handle, chances of it being stolen en route are heightened. Thus, there is a movement to use low-enriched uranium (LEU) instead to reduce security issues. LEU is considered less of a threat because nuclear weapons use HEU, not LEU.
- **Cost** — Primarily because of security, the International Atomic Energy Agency and others are pushing for a general global movement to convert HEU facilities to LEU facilities. It's argued that building new LEU facilities is more economical than converting old HEU ones.
- **Availability** — the Canadian radioisotope producer at Chalk River experienced a production disruption in 2007. This disruption increased the USA's awareness of its external dependency on Canada for its medical radioisotope supply. Since ^{99}Mo cannot be stockpiled (the half-life is 66 hours), delivery has to be fast and consistent in order to treat cancer patients. Therefore, the US is seeking to secure a domestic source of radioisotopes.

Two Development Plans

1. *MURR (Missouri)*. If MURR is built, it plans to supply 50% of the US's demand for ^{99}Mo. Production is set to begin by 2012 if the funding is secured and plans finalized. The funding will most likely come from a combination of private and public donors. The estimated cost is around C$35 million.

2. *B&W (Virginia)*. Plans for this non-traditional type of reactor markets itself as a fail-safe nuclear reactor. This aqueous homogeneous, or

solution, reactor uses uranium salt dissolved in an acid and water mixture. It will use less uranium and is planning to meet 20% of the US's ^{99}Mo demand. The estimated cost is around $70 million for 200kW.

Summary: "Report of Meeting Held to Discuss Existing and Future Radionuclide Requirements for the National Cancer Institute"

National Cancer Institute, April 30, 2008[2]

The panel's report acknowledges there is a current shortage of radionuclides produced in the US. Specifically, there is an immediate need for ^{211}Astatine, ^{225}Actinium, ^{213}Bismuth, ^{223}Radium, and access to ^{67}Copper. Studies show radioisotopes can effectively treat cancers, and continued clinical research on radionuclides is necessary for further development of treatments. The radionuclide shortage continues to stall American research and clinical trials for radiopharmaceuticals. Since clinical trials depend on readily available quantities of radioisotopes, approved National Cancer Institute (NCI) research grants have been discontinued due to the lack of supply. Consequently, it is now a high priority to increase the availability of radionuclides. Radionuclide supply is lagging behind increasing demand; the NCI panel is investigating domestic solutions to increase supply, such as exploring the idea of constructing a new multi-particle cyclotron.

Current Status of Facilities

- The National Institutes of Health (NIH) Clinical Center has a CS-30 cyclotron and a cGMP hot cell (a heavily protected room for manipulating radioactive material). Both are reportedly underemployed and, if managed efficiently, may be a valuable facility. The panel's short-term goal is to improve accessibility to the NIH cyclotron.
- The Duke University Radiology Department (North Carolina) produces isotopes for PET imaging. However, the Department has not been able to support additional users. This situation could be reversed if additional support and funding is offered.
- The University of Pennsylvania cyclotron is unable to produce ^{211}Astatine because it is over-subscribed.
- The University of Washington cyclotron currently produces ^{211}Astatine for research programs.
- Trace Life Sciences (Texas) produces ^{67}Copper at suboptimal energy parameters.

2 This summary is prepared from the article, Timothy Harris, Joseph Kalen, Jennifer Hall, "Report of Meeting Held to Discuss Existing and Future Radionuclide Requirements for the National Cancer Institute," National Cancer Institute, April 2008.

- All cyclotrons producing ^{211}Astatine lack cGMP hot cells, are older designs, and cannot effectively support training programs.
- There is a current shortage of trained staff in all positions of nuclear medicine. In order to properly staff facilities with increased usage or new facilities, a new training centre must be build to provide staff for these locations.

> "There is an immediate and acute need for alpha-emitting therapeutic radionuclides… [and] additional beta-emitters are needed…. The NCI has a specific and unique interest in these radionuclides," says the Report of Meeting Held to Discuss Existing and Future Radionuclide Requirements for the National Cancer Institute

Proposed Solutions

1. Implement a Production and Distribution Network for Existing Facilities
2. The beam time for existing cyclotrons is considerably underused at only about 15 – 20% of total capacity because of a variety of issues, such as funding mechanisms and limited access to cGMP hot cells. To implement an efficient production and distribution network, these conditions must be resolved.
3. Construct a New NCI Cyclotron Radionuclide/Radiochemistry Facility.
4. It remains undecided whether the new cyclotron would be 30 MeV or 70 MeV. Consensus among the panel decided it would be best to pursue a 30 MeV (proton)/30 MeV (alpha) beam cyclotron as opposed to constructing a 70 MeV cyclotron. A 30 MeV cyclotron is able to produce 90% of all radionuclides used in nuclear medicine studies. It is estimated that a new 70 MeV cyclotron with associated production facilities will cost over US$50 million. The savings for building a 30 MeV cyclotron is not presently known, but it would presumably cost less. A partnership between the US Department of Energy (DOE) and NCI would be beneficial, but some DOE funding restrictions may hinder progress; therefore, the panel encourages consideration of all interested parties, public or private, for a partnership.

Appendix G

Selected Letters of Support

Appendix G

Selected Letters of Support

The following pages contain copies of selected letters of support from the Canadian and international community for the TRIUMF Five-Year Plan. The first letter is from the Board of Management representing the ownership of TRIUMF; the second is from the Canadian university-user community; the third one reflects TRIUMF's international partnerships with the specific example of collaboration with the CERN Accelerator Division on the Large Hadron Collider in Geneva, Switzerland.

TRIUMF

CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada

Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada

01 June 2008

Dr. Pierre Coulombe
President
National Research Council
1200 Montreal Road, Bldg. M-58
Ottawa, Ontario
Canada K1A 0R6

Dear Pierre:

On behalf of all university members of TRIUMF, it is with pleasure that I write to you fully endorsing the TRIUMF Five-Year Plan detailed in this comprehensive report.

The TRIUMF plan for 2010-2015 has been prepared with extensive consultation of the broad Canadian community as well as TRIUMF's international collaborators. The TRIUMF Users' Group and the Policy and Planning Advisory Committee played key roles in identifying the most important opportunities for TRIUMF to pursue. Multiple international expert review panels then examined the leading elements of the plan and provided comments and guidance. The resulting Five-Year Plan is both ambitious and inspiring—and well within the reach of TRIUMF's scientific and technical expertise. It will build on TRIUMF's fantastic successes over the past 40 years with world-class discoveries and innovative technologies delivered to the marketplace.

At the present moment, TRIUMF is poised for a significant transformation—a transformation that would dramatically expand its impact and value for Canada. In this report you will note three major initiatives. (1) TRIUMF will seize the opportunity for international excellence in several trend-setting areas of nuclear physics to position Canada for global recognition with breakthrough discoveries. (2) TRIUMF proposes to lead a national effort to develop and market the next generation of medical isotopes, thereby solidifying Canada's global lead in this market. (3) In the area of information and communications technology, TRIUMF will assume full stewardship of the international ATLAS Tier-1 Data Centre launched with support from the Canada Foundation for Innovation. The balance of the plan is directed at a portfolio of high-leverage research projects in subatomic physics.

I would also like to thank you for the unflagging support and wise stewardship of TRIUMF from NRC. The entire Canadian community is very excited about this Five-Year Plan and we are looking forward to working closely with you for its successful approval and funding.

Sincerely,

/s/

Feridun Hamdullahpur, Chair
Board of Management

THE UNIVERSITY OF BRITISH COLUMBIA

Department of Physics and Astronomy
6224 Agricultural Rd
Vancouver, B.C. Canada V6T 1Z1

Tel: 604-822-3853
Fax: 604-822-5324

June 4, 2008

National Research Council of Canada
1200 Montreal Road, Bldg. M-58
Ottawa, Ontario
Canada K1A 0R6

Dear NRC Council Members,

I write to you in support of the 2010-2015 TRIUMF Five-year Plan in my capacity as Chair of the TRIUMF Policy and Planning Advisory Committee (PPAC). This committee was convened by the TRIUMF Board of Management to advise the Director on scientific policy and to facilitate two-way communications with the research communities at the member universities. PPAC consists of 19 highly-qualified scientists drawn from the TRIUMF member and associate member Universities, with expertise covering the wide range of science initiatives in the TRIUMF program.

During early 2008, I was asked by TRIUMF director Nigel Lockyer to work with PPAC to perform a prioritization exercise with the list of more than 100 different potential activities proposed for TRIUMF's 2010-2015 plan. With so many interesting scientific and technical directions for TRIUMF to pursue, a basic framework outlining both the general research directions and specific priorities for the next five years at the lab was required. PPAC, with its extremely broad representation of physics disciplines, was charged with generating this framework of prioritized tasks.

For each project, we considered several factors in our ranking -- the potential scientific impact, which was required to be of the highest order, the support within the wider Canadian research community, the potential societal impacts from the direct research or spinoff technologies, and the projected effectiveness and necessity of TRIUMF's involvement. We also considered the proposals in the context of the wider international community, comparing the TRIUMF proposals to competing efforts in other leading labs around the world, and identified key areas in which TRIUMF is particularly well-placed to impact the field. Our final report was issued publicly on March 15, 2008. We articulated a vision for TRIUMF that called for a transformation of its activities and held out the promise of global excellence in several pivotal areas of science and technology.

After our initial report, TRIUMF embarked on a series of detailed workshops and reviews that served to define the detailed resource needs, as well as technical and scientific challenges faced in turning a scientific vision into a final plan. The Five-Year Plan articulated in this report, which details a set of implementation strategies that realize this vision, is as ambitious as it is impressive. It is a program that holds promise to significantly increase the scientific output of the lab by capitalizing on TRIUMF's strengths in rare-isotope beams, nuclear medicine, and globally networked computing as well as expanding in several key areas that present timely opportunities for broad and far-reaching economic and social impacts for Canadian society. On behalf of the entire committee, I offer it my full support.

Sincerely,

/s/

Colin Gay
Chair, TRIUMF Policy and Planning Advisory Committee
and
Professor of Physics, University of British Columbia

CERN

GENEVE, SUISSE
GENEVA, SWITZERLAND

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics

Mail address: Dr Lyndon Evans
LHC Project Leader
CERN
CH-1211 GENEVE 23
Switzerland

Téléfax/fax : +41 22 767 6595
Téléphone/Telephone : + 41 22 767 4823
Secretariat: +41 22 767 4321
Central/Exchange : +41 22 767 6111
E-mail : <Lyn.Evans@cern.ch>

Professor Nigel S. Lockyer, Director
TRIUMF
4004 Wesbrook Mall
Vancouver, BC, V6T 2A3
Canada

Notre référence/Our reference: LHC/LE/cn/2008-021

Geneva, 23rd June 2008

Dear Professor Lockyer,

As you know, the Large Hadron Collider is now in the final stage of commissioning. If all goes well, operation of the machine for physics will start in autumn this year.

I would like to thank you and your staff for the very important contributions that TRIUMF has made to the construction of the machine and to the upgrade of its injectors. I would particularly like to mention three areas where Canada has made essential and unique contributions.

The beam instrumentation systems rely entirely on a digital acquisition board designed at TRIUMF. This board is the standard interface to the digital acquisition from all beam instrumentation and required extensive development before series production could be launched.

TRIUMF has long been acknowledged as world leaders in the technology of fast pulsed magnets and the associated high-voltage equipment. For the LHC, this expertise has been put to good use in the design and construction of the generators for the injection kickers with the associated resonant charging power supplies, pulse-forming networks and high-voltage switches. All this equipment is now in routine operation in the LHC.

Finally, I would like to mention the two of the eight long straight sections of the LHC where the Canadian flag is particularly dominant. This concerns the very important collimation insertions whose purpose is to protect the machine from unwanted beam loss and to control the backgrounds in the detectors. They require very advanced two-in-one quadrupole magnets designed at TRIUMF and constructed in Canadian industry under the supervision of TRIUMF.

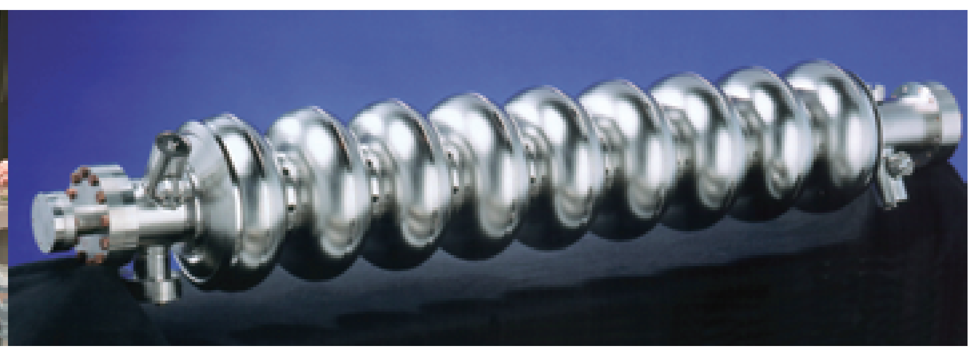
We have always appreciated the high level of competence and the spirit of collaboration of the TRIUMF staff. We look forward to continuing this collaboration in future years in order to exploit the full potential of the LHC and to prepare our field for a long and fruitful future.

Please transmit my sincere thanks to all TRIUMF staff who have participated in this great adventure in scientific collaboration.

Yours faithfully,

Dr Lyndon Evans





TRIUMF