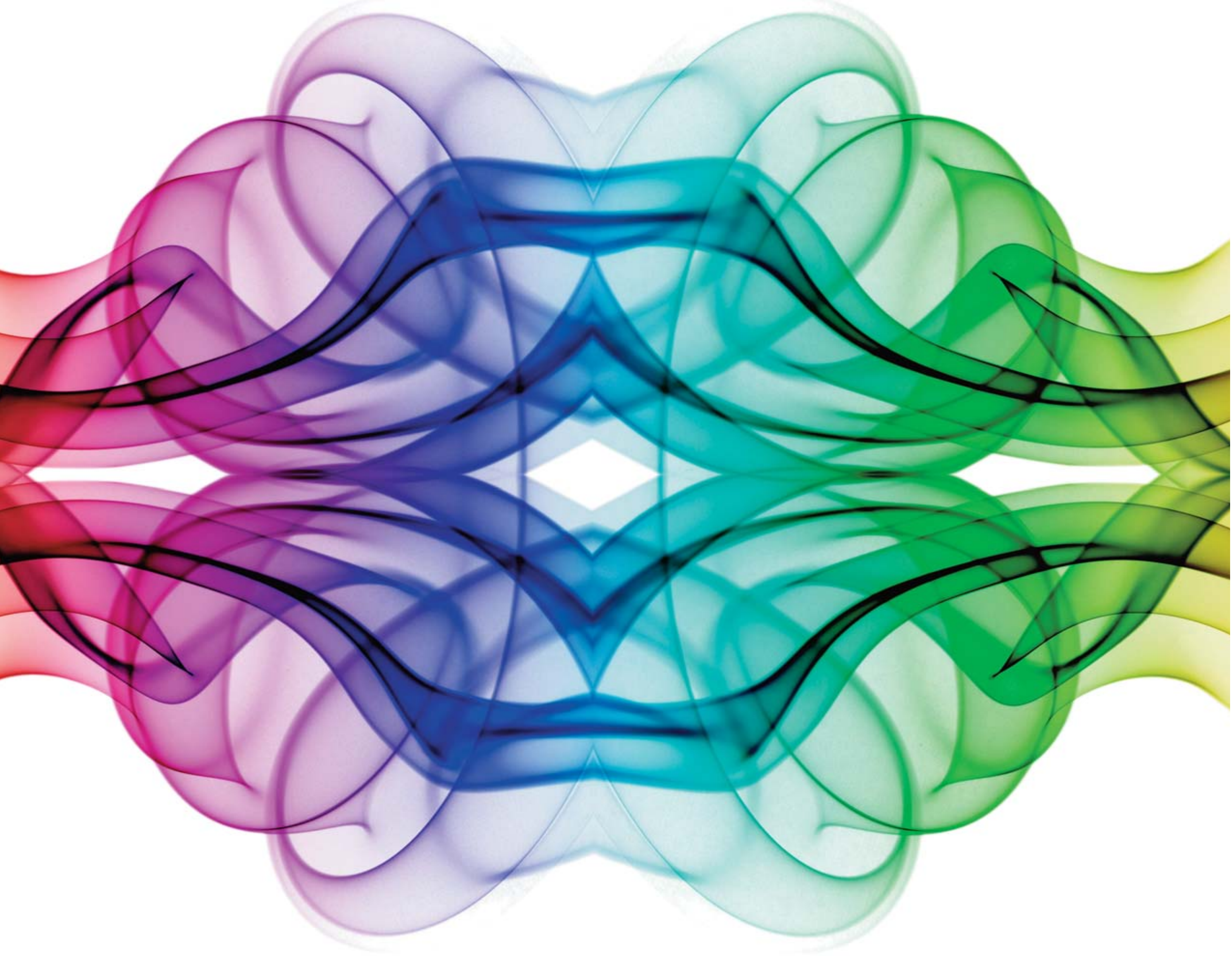
TRIUMF

Five-Year Plan
2015–2020

REALIZING THE VISION



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Five-Year Plan 2015–2020: Realizing the Vision

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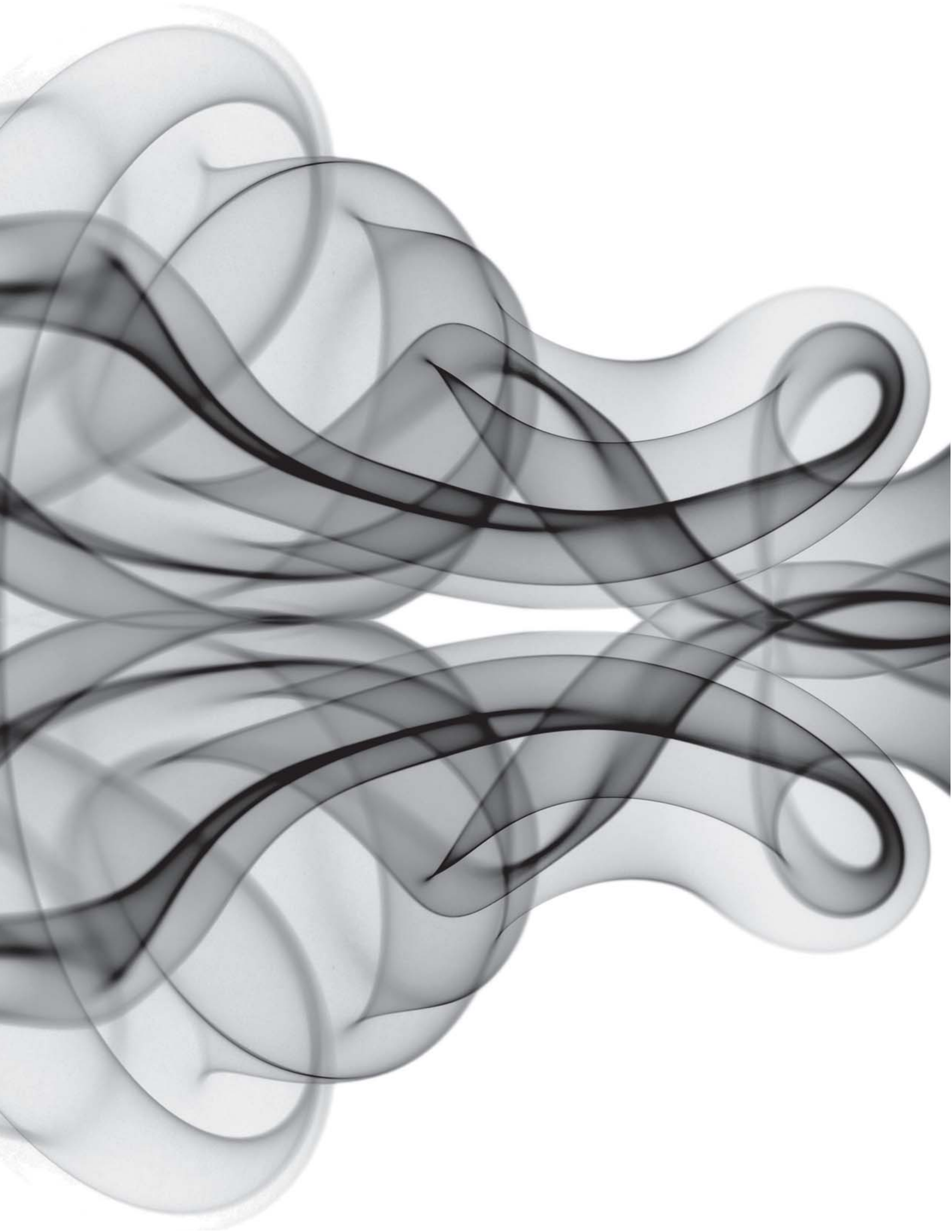

1 Executive Summary

Photographer: J. Gazzari

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1.1 TRIUMF: ACCELERATING SCIENCE FOR CANADA

TRIUMF is a publicly-funded, national laboratory with a basic research mission. Owned and operated as a joint venture by a consortium of Canadian universities, it provides a pool of talent, skills, and capabilities that no single university could maintain on its own.

The laboratory's activities are framed within its Mission and Vision with a strategic plan developed every five years and subject to review, approval, and funding by the Government of Canada and other agencies.

TRIUMF's many important achievements 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 future are enabled by new funding and by continuing to build on the foundation of the current resources. The present resources are a culmination of more than $1 billion of public investments over the past 40 years coupled with the wisdom and experience of a highly trained staff. Taken together, these resources represent a formidable asset that can be deployed in key areas of Canada's national agenda.

Advancing Knowledge

ACCELERATOR PHYSICS

MATERIALS SCIENCE

NUCLEAR MEDICINE

NUCLEAR PHYSICS

PARTICLE PHYSICS

1,300 scientific papers published

3,300 technical and engineering systems designed and fabricated

40,500 hours of isotope beams delivered for science

SOCIAL MEDIA NUMBERS

73,100 social-media impressions on facebook, flickr, twitter, vimeo, and youtube

1,739,000 website visits (since 2009)

OTHER NUMBERS

18 full and associate-member universities

350 staff members

12 acre site

44 years of safe, reliable operation

1,000 member scientific user community

Creating Leaders

370 undergraduate research experiences

30,000 informal science experiences for the public

195 graduate student researchers

Driving Growth

$941,000,000 total attributable GDP (decade)

11,700 person years of employment (decade)

5,000,000 patient doses of medical isotopes

6 new companies and products

CORE VALUES

The following core values reflect how TRIUMF operates as one of the leading physics laboratories in the world. These values are instilled in all those who work here, and guide how the laboratory approaches its goals.

excellence + impact

A commitment to excellence in achieving TRIUMF's mission and vision while making a real difference.

collaboration+ teamwork

Working together with others (individuals, groups, or institutions) for our mutual benefit.

honesty+ transparency

Being responsible and accountable for our actions and their consequences; respecting people, their ideas and diversity; working safely and sustainably with openness, authenticity, generosity, and equity.

innovation+ relevance

Approaching assignments, tasks, and problems in new and efficacious ways; creating novel ideas and techniques.

MISSION

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.

VISION

TRIUMF will:

LEAD IN SCIENCE

The world sees TRIUMF as Canada's leader in probing the structure and origins of matter and in advancing isotopes for science and medicine.

LEVERAGE UNIVERSITY RESEARCH

The Canadian university research community views TRIUMF as a way to strengthen and expand their research programs.

CONNECT CANADA TO THE WORLD

International subatomic physics laboratories look to TRIUMF when partnering with Canada and its research community.

CREATE SOCIAL AND ECONOMIC GROWTH

The global scientific community sees TRIUMF as a bridge between academia and the private sector and as a model for commercialization and social impact.

Member Universities University of Alberta | University of British Columbia | Carleton University | University of Guelph | University of Manitoba | Université de Montréal | Simon Fraser University | Queen's University | University of Toronto | University of Victoria | York University

Associate Members University of Calgary | McGill University | McMaster University | University of Northern British Columbia | University of Regina | Saint Mary's University | University of Winnipeg

1.2 FOREWORD

Five-Year Plan 2015–2020 represents a defining document for TRIUMF. Not only does it recap the performance of the past five years—2008–2012—it also presents an implementation plan for the second half of the decadal vision laid out in Five-Year Plan 2010–2015. That vision encompassed plans and goals for several different constituents: TRIUMF, scientists, and industry, as well as everyday Canadians. We have organized this report to appeal to a variety of audiences with a variety of needs and goals.

Chapter 1 presents an overview of the document that will appeal to senior executives and cabinet ministers with portfolios covering areas in which TRIUMF does research. Chapters 1, 2 and 3 will interest political staff, government policy makers, and intellectual leaders and experts. These chapters provide an overview of how TRIUMF plans to advance, even further, its work in service of the national agenda. Chapter 2 in particular places TRIUMF and its activities in the national context, while Chapter 3 discusses the key national and international partnerships that characterize TRIUMF's future commitments.

Chapters 4 to 6 will attract more technically advanced readers, theoretical and experimental physicists and academics, as well as those familiar with modern subatomic physics. These chapters provide the evidentiary basis for assessing TRIUMF's performance over the past five years and determining what comes next. Chapter 4 highlights TRIUMF's chief accomplishments 2008–2012 in terms of the three core benefits of science to society: new discoveries and knowledge, recruitment and training of talented individuals, and societal and economic growth. Chapter 5 summarizes what TRIUMF "brings to the table," that is, what physical and structural assets are already available to be deployed in service of the national agenda. Chapter 6 proposes the plan for 2015–2020 and includes an analysis of required resources and roles for TRIUMF's family of stakeholders and supporters. Finally, the concluding chapter provides supporting information as appendices.

The strategic-planning process cannot be done in isolation, and it is the most successful when the community plays an important and substantive role. Some individuals responded far beyond the ordinary call of duty to shoulder the thoughtful and soul-searching work to assemble this plan. They are: Nigel Lockyer, Reiner Kruecken, Byron Jennings, Jens Dilling, Hiro Tanaka, Isabel Trigger, Sampa Bhadra, Lia Merminga, Paul Schaffer, Colin Gay, Iain Mackenzie, Ken Ragan, Khashayar Ghandi, Carsten Krauss, and Paul Garrett. Finally, the entire manuscript here would never have made any sense without the efforts of Melva McLean, Melissa Baluk, and Jennifer Gagne, along with critical contributions from Gabriel Baron and Ariane Madden.

One of these acknowledgments needs to be expanded. On behalf of TRIUMF and the Five-Year Plan Steering Committee, I extend warm thanks and deep appreciation to outgoing laboratory director Nigel S. Lockyer. Without his ambition and guidance, TRIUMF's decadal vision of 2010–2020 would not have been possible. A man both bold and generous, Nigel assembled an impressive leadership team and brought electrons, (ultra-cold) neutrons, actinide targets, new international partners, and a spirit of entrepreneurialism to TRIUMF that has transformed and elevated the entire laboratory. Farewell, Nigel; we will miss you (and your shiny, red car). And we know that the U.S. Fermi National Accelerator Laboratory will continue to blossom under your leadership.

I wholeheartedly acknowledge everyone for their contributions and their incredible commitment to TRIUMF, the progress of science, and Canadian excellence. The future is bright.

T.I. Meyer
Head, Strategic Planning & Communication
TRIUMF

August 2013

1.3 PREFACE

TRIUMF, a joint venture of Canadian universities, is a premier subatomic-physics laboratory located in Vancouver. Canada has been recognized for above-average contributions in research excellence in subatomic science. TRIUMF, as the hub for Canadian subatomic research, brings together the network of international, industrial, and government partners to generate societal and economic growth from these strengths.

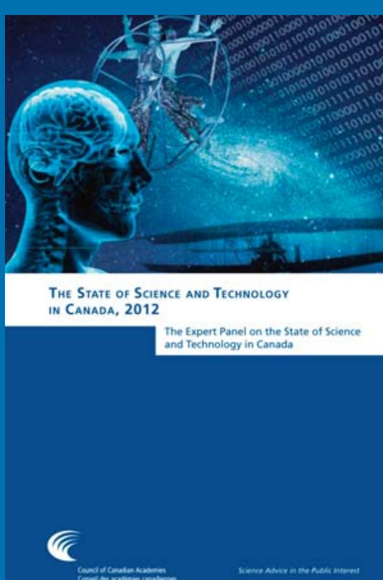
This document outlines a strategic plan for 2015–2020. We trust that you will find the future outlined within this report just as exciting as we do. We hope it inspires action to invest and to expand what TRIUMF can do for Canada.

With broad and sincere thanks and appreciation to everyone who has contributed to this vision, we remain,

Respectfully yours,

Nigel S. Lockyer
Outgoing Director, TRIUMF and,
Incoming Director, U.S. Fermi National Accelerator Laboratory

R. Paul Young
Chair, Board of Management, TRIUMF, and
Vice-President, Research and Innovation, University of Toronto



CANADA IS PHYSICS POWERHOUSE

27 September 2012

In a groundbreaking report released this morning by the Council of Canadian Academies, Canada's six world-leading fields of research were identified. Not only did "physics and astronomy" rank among the top six, but the subfield of "particle and nuclear physics" was also recognized as one of the key drivers for Canada's strength. About the report, the Council says it is, "An authoritative, evidence-based assessment of the state of science and technology in Canada and has found that Canadian science and technology is healthy and growing in both output and impact. "

The report found that the six research fields in which Canada excels are: clinical medicine, historical studies, information and communication technologies (ICT), physics and astronomy, psychology and cognitive sciences, and visual and performing arts. With less than 0.5% of the world's population, Canada produces 4.1% of the world's research papers and nearly 5% of the world's most frequently cited papers.

1.4 EXECUTIVE SUMMARY

TRIUMF is Canada's largest basic science enterprise probing the fundamental structure and origins of matter. In Canada, TRIUMF is synonymous with advancing isotopes for science and medicine. Internationally, TRIUMF is known for its leadership in rare isotope science and particle physics. In schools and among students, TRIUMF is an inspiration, a career path, and a resource for learning and sharing. In business circles, TRIUMF is recognized for its advanced-accelerator technologies and production of medical isotopes. In academia, TRIUMF is known as the regional hub for Canadian university researchers in particle and nuclear physics and the platform to work globally.

In the last five years, TRIUMF has lived up to this reputation. Building Canada's scientific prominence throughout the world of subatomic physics, TRIUMF has emerged on the international stage as a leader. TRIUMF along with Canadian physicists are known for their contribution to the discovery of the Higgs boson, a particle that captured the imagination of over one billion people during the announcement on BBC. TRIUMF scientists received international attention for trapping antimatter. The laboratory is known globally for pursuing an alternative, innovative solution for producing the world's most-popular medical isotope (Tc-99m) with existing accelerators. TRIUMF's rare isotope program is among the best in the world, attracting hundreds of users to Vancouver each year. Over the last five years, two small Canadian firms, building on TRIUMF's accelerator technologies, have more than doubled their number of employees and floor space and have expanded their business internationally. TRIUMF is partnering with India and Japan to further technology developments and open new markets for Canadian companies. TRIUMF's 35-year partner company, Nordion, continues to touch the lives of millions of people each year with medical isotopes produced on small TRIUMF-designed, Canadian-manufactured cyclotrons in Vancouver.

The core investment in TRIUMF by the Government of Canada through a contribution via the National Research Council drives these results and leverages the resources and talents of Canada's world-class research universities. Eighteen of those universities together form the consortium that owns and operates the laboratory.

In the next five years, TRIUMF will begin its march towards major scientific discoveries with ARIEL, the new facility for ultra-cold neutrons shared with Japan, and with crucial support for Canada's engagements on the international stage of particle physics. TRIUMF will commercialize new technologies, stimulate and train science and engineering students, challenge engineers and technicians with the latest accelerator-associated technologies, and impact up to 5% of Canadian citizens with the accelerator-produced medical isotope Tc-99m.

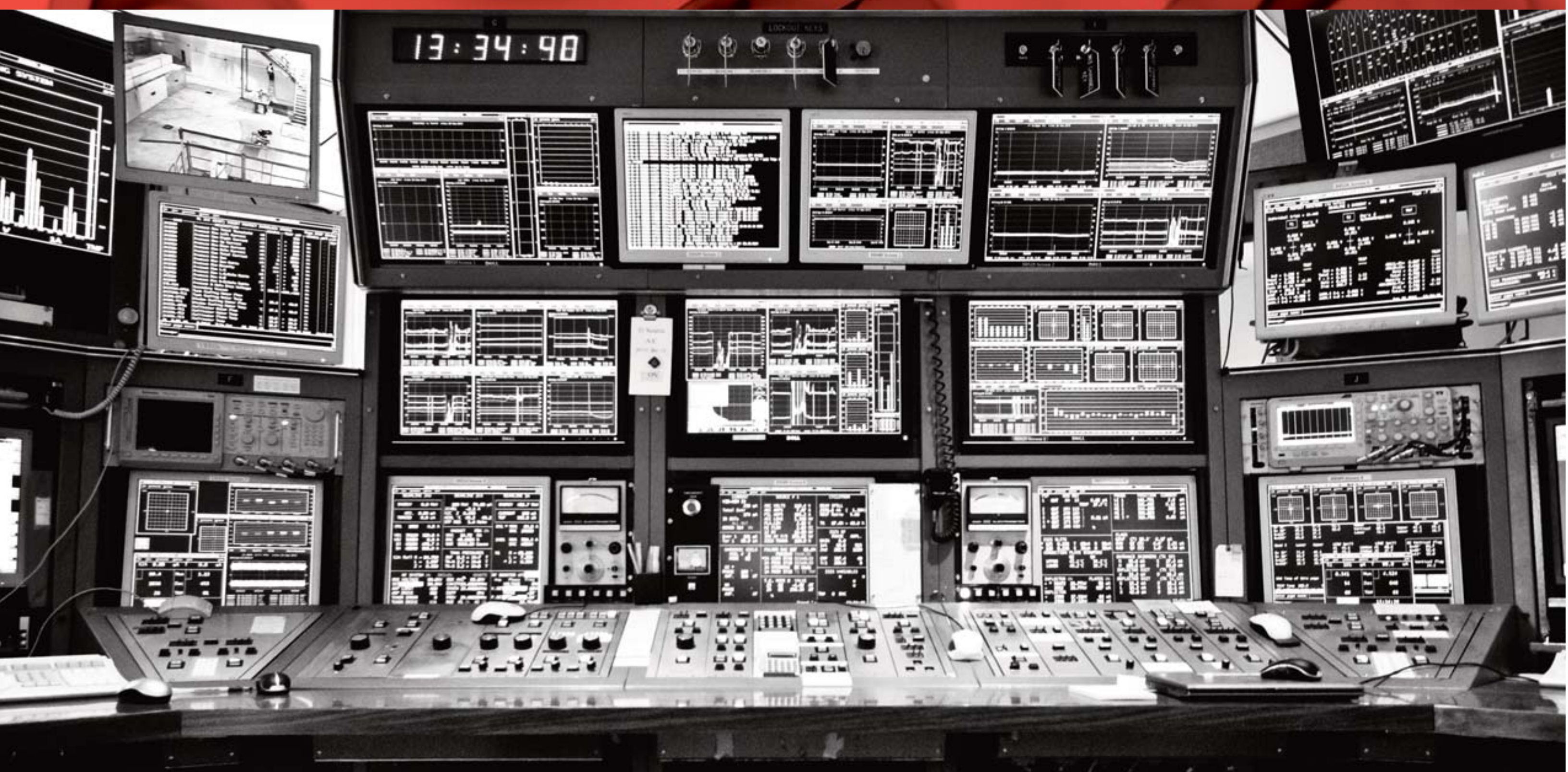
Five-Year Plan 2015–2020 seeks continued investment in TRIUMF and this vision. Optimal exploitation would require $290 million via the NRC Contribution Agreement combined with additional competitively-awarded funds. This request takes into account opportunities to complete the ARIEL laboratory, fully operate facilities, address deferred maintenance, and relieve pressures on ten-year-old buying power.

We have established that past investments generate significant dividends. TRIUMF is strong and continually advancing; a coordinated investment will allow Canada to make major strides forward in creating knowledge, developing technology, attracting and training talent, and contributing to economic growth.

2

The Vision

Accelerating Science for Canada 2015–2020



Photographer: J. Benjamin

CHAPTER 2 | THE VISION: ACCELERATING SCIENCE FOR CANADA, 2015–2020

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TRIUMF is Canada's national laboratory for particle and nuclear physics, renowned for its groundbreaking contributions to accelerator-based physics, nuclear medicine, and molecular and materials science research. Established in the late 1960s in Vancouver by three British Columbia universities, TRIUMF is now owned and operated by a consortium of 18 Canadian universities. It collaborates with numerous universities, research institutes, and companies around the world.

Five-Year Plan 2015–2020 proposes the realization of the decadal vision laid out in 2008 with the last five-year plan. This next step in TRIUMF's success story delivers on the promises made and gives Canada world-leading capabilities to make discoveries, attract and retain global talent, and enhance international competitiveness. In this vision, Canada capitalizes on historical strengths in basic research in subatomic physics. It couples this with applications to nuclear medicine and molecular and materials science. Leading universities and companies in the country are joining forces with TRIUMF to fuel the knowledge economy with science, technology, and innovation.

This chapter reports on TRIUMF's track record of excellence and key accomplishments under Five-Year Plan 2010–2015. These results position Five-Year Plan 2015–2020 as a natural extension to fulfill the decadal vision and to position TRIUMF for the next decade. This chapter also examines TRIUMF's alignment with Canada's objectives in science and technology and discusses the resource requirements to address the proposed 2015–2020 milestones.

2.1 EXPLORING FOREFRONT SCIENCE

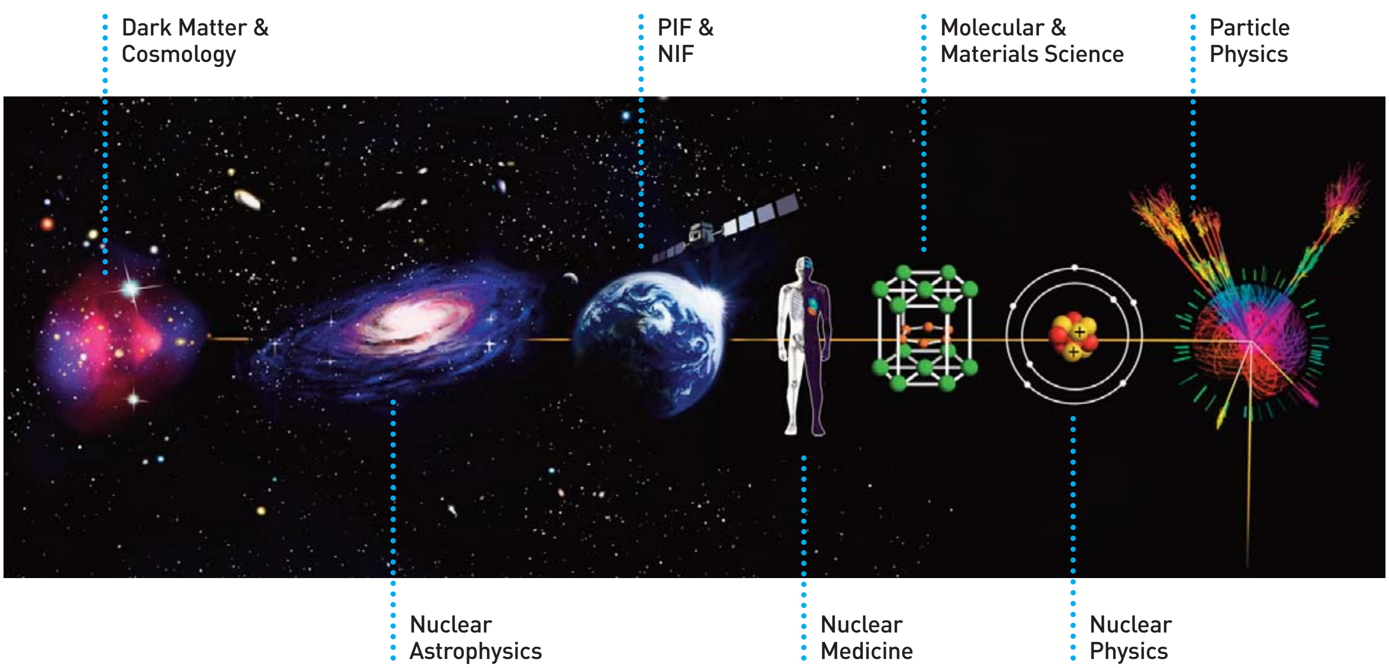
In the first moments after the Big Bang, matter and antimatter were formed from energy in equal amounts. In principle, all particles should have been annihilated with their antiparticles again, leaving nothing behind but energy. Obviously this didn't happen because we are left here to wonder what made one in a billion particles survive. Modern science tells us that the cause must lie in a small asymmetry in nature that led to the conversion of a tiny fraction of antiparticles to their partner particles, but what caused this asymmetry between matter and antimatter remains a mystery. Neutrinos, those elusive almost weightless particles streaming by the trillions through us every second, may hold the key to solving this puzzle.

But there is more to the question "How did it all start?" One of the most fundamental open challenges in science is to discover from whence the elementary particles get their mass and why their masses stretch over such an enormous range (neutrinos are nearly massless while the top quark is nearly 175 times heavier than a proton). The mechanism that gives these elementary particles their mass, the so-called Higgs mechanism, was predicted decades earlier and was recently confirmed by the observation of a Higgs boson at the Large Hadron Collider (LHC) at CERN, thus establishing the last missing piece in the Standard Model of particle physics. However, we still do not know why particles have such vastly different masses.

There is clear evidence from astronomical observations that there has to be yet another type of invisible matter besides the particles we know, the so-called "dark matter." We still do not know what these mysterious dark matter particles are and yet we think that our Milky Way Galaxy is embedded in a sphere of these particles. We know that they are all around us but just barely interact with our normal visible matter aside from gravitational attraction. Various theories beyond the Standard Model predict dark matter particles as well as a whole zoo of new particles in models named supersymmetry, composite Higgs, or technicolour. If confirmed, these models would essentially double the number of particle types that we know about. Together with university colleagues, Canadian scientists at the Perimeter Institute for Theoretical Physics and TRIUMF are working together on such theoretical models. Their predictions are being tested by experiments with large detectors deep underground at SNOLAB, and over the next five years these experiments will reach sensitivities that either allow for the discovery of dark matter particles or exclude a large fraction of theoretical models. Either way, something will change in our understanding of the universe. At the same time, the ATLAS experiment will try to detect the creation of dark matter particles produced in the collisions of the high-energy proton beams circulating in the 27 km circumference of the LHC.

Indirect hints for new particles may also become visible through high precision experiments that study properties of atomic nuclei or neutrons, looking for deviations of properties from those predicted in the Standard Model. TRIUMF is already carrying out the first high-precision experiments on atomic nuclei at its ISAC facility. The Advanced Rare IsotopE Laboratory (ARIEL) facility, when completed with two new isotope-production beam lines (one with electrons and one with protons), will drive multi-user capability and will provide the much larger amount of beam time needed to make ground-breaking discoveries possible. Likewise, the new Japanese-Canadian facility for ultra-cold neutrons (UCN) at TRIUMF will enable such studies on the neutron itself, a simpler system than complex atomic nuclei. The UCN facility will enable prize-worthy discoveries once it reaches its full capability.

As the universe expanded and cooled, protons and neutrons formed, followed by the first isotopes of the light elements hydrogen, helium, and lithium. This all happened in the first three minutes of the universe and it took about 400 million years until heavier elements from beryllium to iron were formed in the first stars. Stars continue to produce these elements to this very day, more than 13 billion years after the Big Bang. However, it remains unclear where in the universe the elements from iron to uranium were formed. This includes trace elements important for life (e.g., zinc, copper, selenium, iodine) and the majority of noble metals (e.g., silver, platinum, and gold). While we know that these elements have to be formed within a few seconds in cataclysmic events like supernova explosions of massive stars or mergers of



The spectrum of TRIUMF's research activities viewed through the lens of the size of the system being studied, well correlated with the evolution of the universe.

neutron stars, the models of such events don't reproduce our observations. A key to solving this mystery lies with the properties of very short-lived nuclei that are produced for brief moments in these explosive events. They are fittingly called rare isotopes. TRIUMF is already among the best facilities in the world to produce and study these rare isotopes and the electron linear accelerator (e-linac) at the heart of the ARIEL facility was conceived to solve this mystery.

TRIUMF's Five-Year Plan 2015–2020 presents a strategy that puts the laboratory at the scientific forefront, in a position to address—and even answer—these questions. This plan extends a vision for Canadian research that was launched in 2008. In this vision, Canada capitalizes on historical strengths in basic research in subatomic physics and couples these strengths with applications to nuclear medicine and molecular and materials science. This vision is becoming a reality: Canadian scientists are making their marks on the world stage with internationally recognized contributions to the discovery of the Higgs boson and crucial neutrino properties, to the trapping of antihydrogen, to advancing isotopes for science and medicine. They are developing and, successfully transferring advanced accelerator technology to the market. Canadian universities and research facilities are attracting talent from around the world.

2.2 ENJOYING A TRACK RECORD OF EXCELLENCE

Through a mixture of the curiosity-driven research of universities and the outcome-driven development of industry, TRIUMF has a track record for delivering high-quality results. Measured by progress on milestones in the five-year funding agreements, by meeting deadlines and expectations for Canadian participation in international projects, or by performance indicators that measure the outputs of scientific research, TRIUMF continues to be successful.

This section reports on TRIUMF's performance in two ways: (1) progress on achieving the five-year milestones identified in the 2010–2015 Contribution Agreement, and (2) performance indicators in each of the three areas of TRIUMF's impact—advancing knowledge, creating future leaders, and generating societal and economic growth.

2.2.1 PROGRESS REPORT ON MILESTONE DELIVERABLES FOR 2010–2015

The NRC Contribution Agreement for 2010–2015 defined a set of milestone deliverables for TRIUMF. Progress is reported at time of writing (September 2013). See Figure 1 for an overview of TRIUMF's research programs.

1) In Particle Physics, TRIUMF will support the Canadian community in alignment with the subatomic-physics Long Range Plan. In particular, TRIUMF will support extracting and analyzing the physics from the T2K experiment in Japan, the ATLAS and ALPHA experiments at CERN, and the PIENU experiment at TRIUMF.

TRIUMF has been effective in enabling the success of the Canadian particle physics community. For instance, the laboratory provided hardware, computing power, and intellectual leadership to Canada's participation in the Japan-based neutrino-physics experiment T2K. In July 2013, a TRIUMF post-doctoral researcher (Michael Wilking) was selected by the international collaboration to announce breakthrough

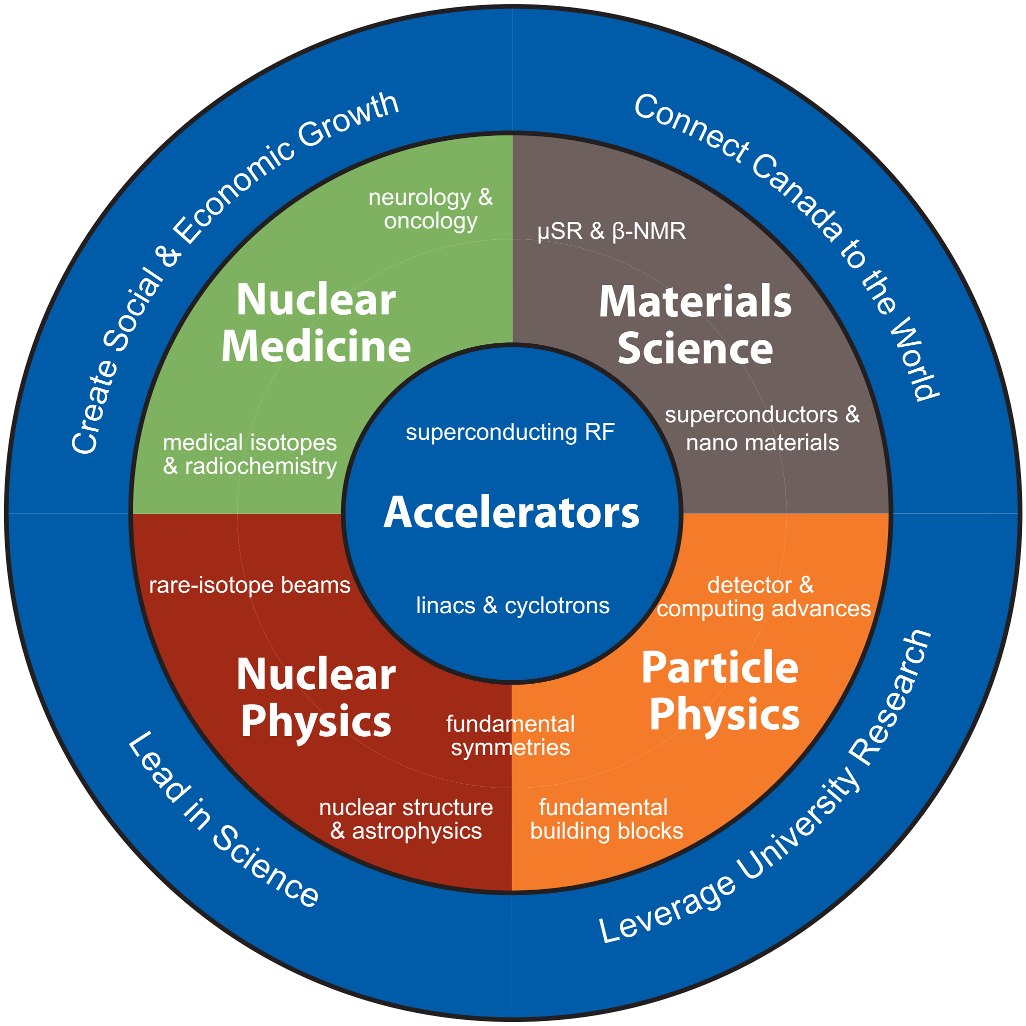


Figure 1: An overview of TRIUMF's research programs, driven by accelerators and delivering value for Canada.

scientific results at a physics conference in Stockholm, Sweden. Wilking reported T2K's unequivocal observation of the appearance of electron neutrinos in a beam of muon neutrinos created on the other side of Japan. This is the first observation of this phenomenon in such an experiment, and it opens the doors to the understanding of matter-antimatter asymmetry in the Universe.

For ALPHA, TRIUMF provided key intellectual and engineering leadership for the experiment's success in trapping antihydrogen, a result ranked as the top physics breakthrough of 2010 by Physics World magazine. The experiment seeks to establish if this antimatter behaves exactly like normal matter hydrogen; the Canadian team is led by TRIUMF scientist Makoto Fujiwara. Furthermore, TRIUMF spearheaded the subsequent measurement of the "chemistry" of antihydrogen atoms (i.e. the spectroscopy of electron energy levels) in mid-2012, and provided critical engineering support in late 2012 to complete a complex contribution of hardware for the next-generation of the experiment.

For the ATLAS experiment at CERN's LHC, TRIUMF played and continues to play a key role in Canada's involvement. CERN has become a global laboratory for particle physics with close to 10,000 scientists and students participating from more than 600 institutions in 113 countries around the world.

Not only has TRIUMF spearheaded Canadian participation since 1995 (with contributions to the accelerator, detector, and worldwide computing grid), but TRIUMF scientists have also led key physics analysis working groups within the collaboration of 3,000 scientists (and TRIUMF/SFU researcher Michel Vetterli now chairs the overall publications board of the entire collaboration and a TRIUMF/UofT researcher Pierre Savard will be convener of the ATLAS Higgs physics group starting in October 2013). The result was the confirmed discovery of a brand-new particle in July 2012, now identified as a Higgs boson (thanks in part to ground-breaking research by TRIUMF post-doctoral researcher Doug Schouten). The ATLAS Tier-1 Data Centre (operated by a consortium of universities led by SFU and hosted at TRUMF) provided critically needed computing resources in the final months before the announcement. The Tier-1 Centre is one of only ten such centres in the world. These centres are the foundation of the LHC Worldwide Computing Grid that supply data for the Tier-2 and Tier-3 centres at universities around the world.

2) In Nuclear Physics, TRIUMF will support the Canadian and international community in alignment with the subatomic-physics Long Range Plan. In particular, TRIUMF will develop rare-isotope beams from actinide targets required for the ISAC experimental program. TRIUMF will complete the installation and commissioning of EMMA and IRIS by 2013.

TRIUMF provides rare-isotope beams to the global nuclear physics community. Since April 1, 2010, TRIUMF has delivered close to 8,000 hours of isotopes for nuclear physics including several running periods each year using exotic heavy isotopes derived from actinide targets. A number of high-profile results were achieved. TITAN has been very productive with 13 publications since 2010, including internationally highly recognized mass measurements of very neutron-rich calcium isotopes demonstrating the relevance of three-nucleon forces in heavy nuclei. The installation and commissioning of IRIS was completed in 2012, and first experiments with the halo-nucleus lithium-11 were carried out. Experiments with TUDA and DRAGON capitalized on the high-intensity fluorine-18 beams to study the nuclear reactions in Nova explosions. TITAN, the 8π spectrometer and laser spectroscopy were used in a concerted effort for precision studies of super-allowed beta-decays to test fundamental symmetries of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix. First trapping and laser spectroscopy were performed on francium isotopes, critical for precision experiments searching for physics beyond the Standard Model. The magnets and high-voltage electric dipoles required for the EMMA experiment have been delayed by the European vendor. TRIUMF has recently received the last components and will finish the assembly and commissioning of the experiment in 2014.

TRIUMF STUDENT IS RUNNER-UP FOR "CANADA'S SMARTEST PERSON"

17 March 2012

In March, TRIUMF research assistant Laura Suen competed and placed runner-up in the CBC television special "Canada's Smartest Person" next to CFL defensive linebacker Peter Dyakowski. Laura was compelled to try her hand at the competition given her incredible breadth of experience: at 23, she holds separate Bachelors degrees in journalism, physics and cellular biology, as well as minors in economics and mathematics.

At TRIUMF, Suen works with the ALPHA-Canada collaboration adding a laser spectroscopy system to the ALPHA experiment at CERN for the study of antihydrogen. "TRIUMF is one of my favourites, of all the places I've worked in because of the flexibility and the environment," she said. "It's amazing how they always encourage you to learn. I love the encouraging, positive atmosphere that truly differentiates TRIUMF as a research institute in Canada."

3) In Nuclear Medicine, TRIUMF will support the development of Canadian leadership in nuclear medicine and molecular imaging. In particular, TRIUMF will complete development of the localized Good Manufacturing Practice laboratory. TRIUMF will produce medical isotopes for the Pacific Parkinson's Research Program and will develop and deliver medical isotopes for research with the British Columbia Cancer Agency (BCCA).

TRIUMF's role in the physics and chemistry of radioisotopes for nuclear medicine has blossomed. With support from Western Economic Diversification Canada, TRIUMF completed upgrades of its infrastructure to create laboratory space operating consistently with Good Manufacturing Practices guidelines in summer 2011. TRIUMF also joined forces with industrial partner Nordion, Inc., via an NSERC Cooperative Research & Development award, to complete refurbishment and commissioning of a new radiochemistry lab in the MHESA area.

Since 2008, TRIUMF has provided 3,900 runs of medical isotopes for the Pacific Parkinson's Research Program and 1,200 runs for the BC Cancer Agency (BCCA). TRIUMF has also provided proton irradiation therapy for 40 patients with ocular melanoma.

TRIUMF has galvanized a Canadian team of four institutions to develop a modern-day, accelerator-based alternative production technology for the world's most popular medical isotope (technetium-99m) that avoids the use of nuclear reactors and highly-enriched, weapons-grade uranium. The technology is now being deployed and packaged for commercialization in the private sector.

4) In Materials and Molecular Science, TRIUMF will support the scientific community and, in particular, will complete the construction and commissioning of the M9A and M20 muon beam lines in 2012.

The M20 muon beam line upgrade was supported by a Canada Foundation for Innovation (CFI) project led by Simon Fraser University. The project was successfully completed and commissioned in 2012. Already 15 experiments have been carried out since October 2012, predominantly focusing on materials science and chemistry but also including first tests of muon-irradiation of electronics components for industry. All the components of the M9A muon beam line have been installed in the Meson Hall in 2012. However, ageing components of the main proton beam line for the Meson Hall have hampered efforts to operate the M9 meson-channel and thus off-line commissioning has been postponed to 2013, while efforts are underway to restore operation to this important and unique meson channel.

5) For the Advanced Rare IsotopE Laboratory supported by multiple agencies and partners, TRIUMF will meet the following milestones:

a) Fabrication and assembly of the first Injector Cryomodule and a 30 kW beam test will be completed by March 31, 2012.

b) Civil construction of the ARIEL facility will be nominally complete by March 31, 2013.

c) Installed in the Proton Hall, the e-linac will deliver low-current beams at 25 MeV by March 31, 2014.

d) Electron beams at 25 MeV, 100 kW will be delivered by March 31, 2015.

ARIEL is Canada's flagship in advancing isotopes for science and medicine, funded by the CFI to a university consortium led by the University of Victoria and a substantial investment by the Government of British Columbia. The facility will ultimately nearly triple TRIUMF's capacity for generating isotopes. The present phase of the project was not fully funded until July 2010, after the Contribution Agreement deliverables were negotiated. Civil construction of the ARIEL facility started in 2011 with excavation starting November 1, 2011. The buildings were substantially completed and transitioned into commissioning and nominal operations in August 2013.

Based on a revised opportunity analysis in late 2010, the University of Victoria and CFI agreed to a revised intermediate schedule for design, assembly, and commissioning of the e-linac. Essentially, TRIUMF was able to pursue a higher-power electron source and set of radio frequency power elements that impacted the first 18 months of schedule but will lead to substantial cost savings in the completion of the e-linac. The injector cyromodule installation and 100 kW beams will now be ready in September 2014.

2.2.2 PERFORMANCE INDICATORS FOR FIVE YEARS 2008-2012

The enterprise of scientific research produces a triple impact by advancing knowledge, creating future leaders, and generating societal and economic growth. Taken together, these outcomes motivate public investment. Public policy researchers have sought to build a predictive, quantitative model that connects inputs (e.g., investments, scientific and technical staff, or infrastructure) to outputs (e.g., publications, trained students, or industrial partnerships) and longer-term outcomes such as standards of living and economic competitiveness. Common sense suggests that some key performance indicators that measure outputs are positively correlated with longer-term outcomes.

Indicators that measure TRIUMF's productivity over the past five years (April 2008–March 2013, inclusive) are presented in the discussion below. One limitation of this approach is the challenge of attribution—that is, identifying which publications, students, or companies were directly and uniquely impacted by TRIUMF's activities.

Advancing Knowledge

In 2008–2012, TRIUMF delivered more than 12,500 hours of isotope beams for nuclear physics and 28,000 hours for materials science research to about 3,000 scientists and students who visited TRIUMF to conduct their research.

During the 2008–2012 period, TRIUMF expanded its scientific publication output from about 900 in 2003–2007 to more than 1,300 for the current period (see Figure 1). Of these papers, more than 50 have been already cited more than 50 times. By 2013, the 2008–2012 publications had been cited more than 13,000 times while in 2008 the 2003–2007 publications received just above 7,000 citations. An independent study (see Appendix 7.6) reported that TRIUMF is one of Canada's top three most productive publishers of high impact papers in particle and nuclear physics and is, in general, among the top five of a set of a dozen international comparators in terms of citation impact.

> “Given the increasing internationalization of science, it is worthy of note that Canadian researchers are very active in collaborating with their global counterparts, as evidenced through their participation in international co-publications.”
>
> Science, Technology and Innovation Council: Aspiring to Global Leadership 2012 report.

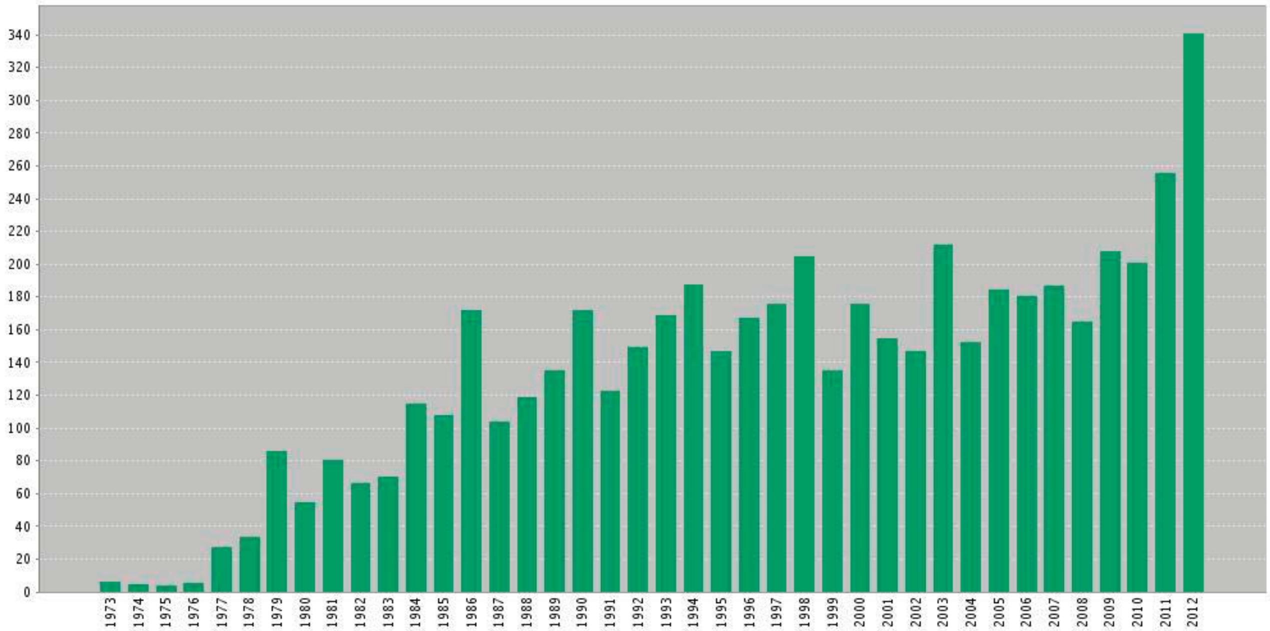
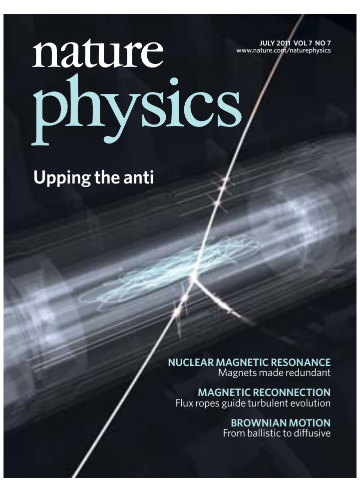
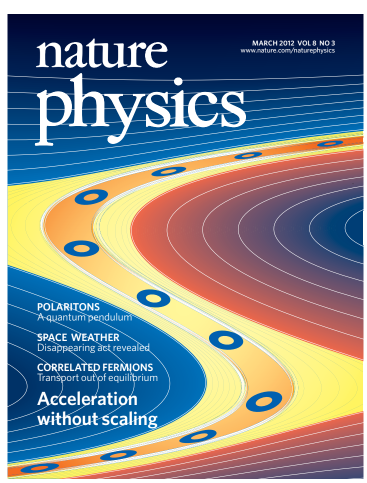


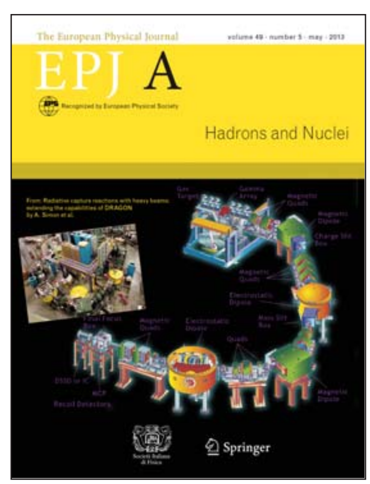
Figure 1: Time series of the annual number of scientific publications with an acknowledged TRIUMF co-author for the past 40 years based on a query from Web of Knowledge databases.

TRIUMF enabled Canadian leadership in a number of key scientific pursuits:

- Discovering and confirming the existence of a Higgs boson via ATLAS at CERN while also searching for new phenomena beyond the Standard Model of particle physics;
- Trapping and probing the "chemistry" of antihydrogen via ALPHA at CERN;
- Unequivocally confirming neutrino appearance after flavour changing via T2K in Japan;
- Being among the world leaders in precision mass-measurements of short-lived rare isotopes;
- Confirming the role of three-body forces within the atomic nucleus using rare calcium isotopes;







- Making highest precision measurements of superallowed beta-decays on several nuclei;
- Conducting critical measurements of the properties of exotic halo nuclei; and
- Measuring critical nuclear reaction rates for hydrogen and helium burning in stars and stellar explosions.

Creating Future Leaders

TRIUMF provides direct research experiences for high-school, undergraduate, and graduate students and manages a portfolio of informal science education programs. During the 2008–2012 period, these activities resulted in the following outputs.

- 12 high-school students, 370 undergraduate students and 195 graduate students conducted research projects at TRIUMF leading to more than 85 M.Sc. and Ph.D. theses; in addition 45-50 post-doctoral fellows were resident at TRIUMF each year;
- 350 undergraduate and high-school students participated in Virtual Researcher on Call, Scientists in the Schools, ATLAS Master Classes, and Let's Talk Science programs involving TRIUMF scientists;
- 225 high-school physics teachers participated in three TRIUMF-led professional development days (2008, 2010, 2012) in coordination with the BC Association of Physics Teachers;
- 2,500 people attended public science lectures as part of programs at Science World British Columbia, Global Civic Society's Public Salon, Saturday Morning Physics Lectures, and TEDxStanleyPark; and
- 2,800 people toured TRIUMF as part of its public tours program each year; 25,000 people interacted with TRIUMF booths and activities at events such as the University Neighbourhoods' Association Annual Barn Raising, Wesbrook Village Festival, Telus World of Science Community Science Days, BC Year of Science exhibitions, and the American Association for the Advancement of Science Family Science Days.

Cover stories of prestigious science journals that feature TRIUMF-enabled research.

Cover 1: Reprinted by permission from Macmillan Publishers Ltd: Nature Physics, © 2011.

Cover 2: Reprinted by permission from Macmillan Publishers Ltd: Nature Physics, © 2012.

Cover 3: European Physical Journal A, Volume 49, Issue 5, May 2013, cover page, © 2013. With kind permission of the European Physical Journal (EPJ).

Cover 4: Copyright © 2010 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

The American Association for the Advancements of Science (AAAS) held its annual meeting in Vancouver in February 2012, returning to Canada for the first time in 30 years. As a member of the Canadian steering committee and chair of the local organizing committee, TRIUMF helped set a conference record for attendance. TRIUMF facilitated the participation of the Governor General of Canada and partnered with the BC Innovation Council to organize and support the participation of 200 BC high-school students in the conference.

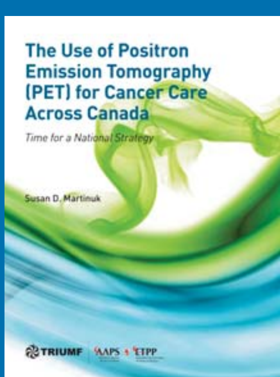
Generating Societal and Economic Growth

The third public benefit of basic research is the fuel for innovation that drives societal and economic growth. TRIUMF generates societal growth through its programs that impact healthcare and quality of life. TRIUMF generates economic activity not only through its science and technology programs that use public funds to challenge, stretch, and expand the private sector's capabilities but also through collaborative research agreements and technology transfers.

In 2008, TRIUMF was awarded $14.95 million by the Networks of Centres of Excellence program to launch a Centre of Excellence for Commercialization and Research called Advanced Applied Physics Solutions, Inc. (AAPS). By bringing together a board of experienced business leaders and a small staff of trained business professionals, AAPS has significantly expanded TRIUMF's ability to connect and impact Canada's industrial sector.

During the 2008–2012 period, TRIUMF and AAPS achieved the following results.

- Treated 40 patients successfully for ocular melanoma;
- Provided more than 5,200 production runs of medical isotopes for the Pacific Parkinsons' Research Program and the BC Cancer Agency;
- Launched 4 spin-off companies (IKOMED Technologies, Inc.; Micromatter, Inc.; CRM Geotomography Technologies, Inc.; and ARTMS, Inc.);
- Entered into two technology-transfer agreements with Canadian industry for development of new product lines (Advanced Cyclotron Systems, Inc.; PAVAC Industries, Inc.) and developed one technology (cyclotron-based production of technetium-99m) for commercialization;



TRIUMF & AAPS JOINTLY RELEASE REPORT ON STATUS OF PET IMAGING FOR CANCER ACROSS CANADA

14 Feb 2012

TRIUMF, together with Advanced Applied Physics Solutions Inc. (AAPS Inc.) released a report entitled: "The Use of Positron Emission Tomography (PET) for Cancer Care Across Canada: Time for a National Strategy". The report, prepared for the organizations by independent medical-research consultant and well-known writer Susan Martinuk, outlines fundamental differences in the availability and uptake of Positron Emission Tomography (PET) in cancer care across Canada.

According to Martinuk, "PET is revolutionizing clinical cancer care in the United States and Europe, yet many Canadian doctors and policy officials continue to see PET as experimental and unproven technology. Cancer patients can suffer because of this reluctance." She reports that she was surprised at the variability among provinces in the utilization of, and access to, this key diagnostic technology.

Martinuk added, "This report is not the last word; it's the start of something. Our intention is to move the conversation forward by engaging the provincial health authorities, the practitioners, and the patients."

CANADIAN SOLUTION TO MEDICAL ISOTOPE CRISIS DEMONSTRATES THAT CITIES COULD PRODUCE THEIR OWN MEDICAL ISOTOPES

09 June 2013

With Canadian-developed tools and technology, a national team led by TRIUMF has reached a crucial milestone in developing and deploying alternatives for supplying the key medical isotope technetium-99m (Tc-99m). The team used a medical cyclotron that was designed and manufactured by Advanced Cyclotron Systems, Inc. (ACSI) of Richmond, BC, and successfully achieved large-scale production of Tc-99m, sufficient for an urban area the size of Vancouver. With a half-life of six hours, the isotope could also be shipped to more remote locations. This achievement eliminates the need for nuclear reactors to produce isotopes, which use weapons-grade uranium.

Paul Schaffer, head of TRIUMF's Nuclear Medicine Division and principal investigator for the project, said, "This achievement is a crucial step on the road to meeting Canada's isotope needs after the NRU ceases production in 2016." In addition to TRIUMF, the team includes experts at the BC Cancer Agency, the Centre for Probe Development and Commercialization (CPDC), and the Lawson Health Research Institute.

- Generated $9.0M of commercial revenue largely from royalty agreements for production of medical isotopes, and industry fees for irradiation of aerospace and high-performance computing components;
- Achieved direct GDP impact of $424.9 million and a total GDP attributable to TRIUMF and AAPS of $941.1 million over the past decade; and
- Generated more than 11,700 person years of employment over the past decade.

One example of this impact is the growth of technology-transfer recipient PAVAC Industries, Inc., based in Richmond, BC. After working with TRIUMF to learn how to manufacture superconducting radio-frequency (SRF) accelerator cavities, the company has doubled in size in two years to 50 employees. In addition to winning the only non-Chinese contract for the manufacture of spoke SRF cavities for a Beijing project with the technical and engineering backing of TRIUMF, Ralf Edinger, president and CEO, has a goal of growing the business to more than $100 million revenues by 2017 and employing over 200 staff by adopting TRIUMF's cryomodule technology.

> "In 2010, physics-based industries generated 3.8 trillion Euro of turnover (revenue), representing over 15% of total turnover within Europe's business economy. Turnover per person employed in the physics-based sector substantially outperforms the construction and retail sectors. The physics-based sector can therefore be viewed as a highly productive part of the European economy."
>
> European Physical Society, "The importance of physics to the economies of Europe," 2013.

2.3 ALIGNING WITH CANADA'S PRIORITIES, 2015–2020

TRIUMF's proposed program is well aligned with Canada's priorities outlined in the report *Mobilizing Science and Technology to Canada's Advantage*, released in 2007. 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. The following discusses how TRIUMF's Five-Year Plan 2015–2020 will adhere to these four principles and act on all three advantages.

> "Scientific discovery, technological breakthroughs, and innovation are the primary engines for expanding the frontiers of human knowledge and are vital for responding to the challenges and opportunities of the 21st century."
>
> "Science and Technology Priorities for the FY 2014 Budget," Memorandum from the U.S. Office of Management and Budget Director, Sylvia Burwell.

2.3.1 PRINCIPLE: PROMOTING WORLD-CLASS EXCELLENCE

TRIUMF inspires and helps Canadians perform at world-class levels of scientific and technological excellence. TRIUMF's technical and engineering skills and capabilities are unique in Canada and were critical to Canada's participation and success in discovering the Higgs boson at CERN in Switzerland via the ATLAS experiment, making the breakthrough observation of neutrino "appearance" in Japan via the T2K experiment, trapping antihydrogen at CERN via the ALPHA experiment and pursuing the

OLIVER STELZER-CHILTON ELECTED TO IPP COUNCIL

06 July 2012

Oliver Stelzer-Chilton, TRIUMF Research Scientist and a member of the ATLAS experiment at CERN—which played an integral role in the discovery of the Higgs-like particle that was announced in early July—was recently elected as a member of the Institute of Particle Physics (IPP) council.

IPP is a Canadian organization that serves to maximize the impact of Canadian particle physics through an exceptional group of IPP research scientists that play key roles in the organization's high priority projects and long-term planning goals. Dr. Stelzer-Chilton is one of eight exceptional research scientists from across Canada that serves as a council member of the IPP.

Dr. Stelzer-Chilton also plays a large role in the ATLAS experiment at CERN. He plays a part in the management in the Exotics Group and, together with a local team from TRIUMF and Simon Fraser University, as a researcher in the Higgs Group. In October 2011, he was appointed the Convener of the Exotics subgroup that focuses on exotic decays with leptons.

three-body forces that underpin the glue that holds nuclei together in the centre of atoms via the TITAN experiment at TRIUMF's ISAC facility.

The engine of TRIUMF is the main cyclotron, the world's largest such device, which has been operating steadily since 1974. The cyclotron was recognized as one of eleven Canadian IEEE Engineering Milestone Awards in 2010 and was decorated again in 2012 with one of six awards from the Engineering Institute of Canada on the occasion of that institute's 125th anniversary.

Scientists and students working at TRIUMF have received national and international awards including Vanier Canada Graduate Scholarships, American Physical Society fellowships, Japan's Bunka Korosha prize, the CAP-TRIUMF Vogt Medal and CAP Brockhouse Medal, and Radio Canada's "Scientist of the Year" award—to name just a few. Moreover, TRIUMF promotes Canada's reputation by organizing and hosting prestigious global scientific conferences. In addition to the AAAS meeting mentioned above, TRIUMF brought the International Nuclear Physics Conference (2010), Low Energy Antiproton Physics Conference (2011), Physics at the Large Hadron Collider Conference (2012), and International Conference on Cyclotrons and their Applications (2013) to Canada.

Finally, TRIUMF's contribution to Canadian scientific prowess has been recognized by an independent advanced bibliometric study that found TRIUMF to be the third-most productive publisher in Canada in its fields of expertise and consistently among the top six among international comparators in terms of citation impact and prestigious-journal publication patterns.

2.3.2 PRINCIPLE: FOCUSING ON PRIORITIES

The recent report of the Council of Canadian Academies *The State of Science and Technology in Canada, 2012* identified six areas of Canadian research strength that rival the best in the world. The field of physics and astronomy was identified as one of the fields in which Canada excels; moreover, the sub-field of particle and nuclear physics was identified as one of the key drivers of this performance.

As Canada's national laboratory for particle and nuclear physics, TRIUMF seeks to connect the established research excellence in particle and nuclear physics to business relevance, directly attacking the innovation gap in Canada. TRIUMF leverages Canada's existing strengths to seize new opportunities, from using particle-physics detector technology to improving mineral exploration procedures and airport security to using high-power accelerators to address energy production technologies. The Government of Canada has announced its intention to cease producing medical isotopes with a subsidized nuclear reactor in Chalk River using highly enriched, weapons-grade uranium imported from the U.S. TRIUMF has been at the head of a national effort to develop modern alternatives for Canadians which can be licensed elsewhere around the world.

By focusing on these priorities, TRIUMF's proposed Five-Year Plan 2015–2020 will enhance Canada's competitive advantage.

2.3.3 PRINCIPLE: ENCOURAGING PARTNERSHIPS

TRIUMF operates with a network of academic, government, and industry partners across Canada and around the world (see Chapter 3). The strategic value of these connections is immeasurable. Within Canada, TRIUMF brings together the research capabilities of 18 different universities in a seamless enterprise that builds on the strengths of nearly a dozen different public agencies.

Canada is home to three complementary institutes that drive leadership in subatomic physics with different approaches: the Perimeter Institute for Theoretical Physics with analytic and computational models and predictions, SNOLAB for deep-underground science, and TRIUMF for accelerator-based experiments, science, and technology. While bilateral activities already existed (TRIUMF works with Perimeter on LHC-related theory and is involved in several SNOLAB detector projects), these three have taken the partnership to the next level by inaugurating a yearly international summer school for particle physics, named TRISEP, to inspire the next-generation of Canadian students and create the future leaders of the field. The new program was inaugurated in summer 2013.

Internationally, TRIUMF attracts foreign investment for its programs. Japan is contributing $4 million to a University of Winnipeg project at TRIUMF that is co-supported by the Canada Foundation for Innovation, Japan's KEK laboratory is planning to install its first international office at TRIUMF, and agencies from the U.S., Germany, U.K., and Japan have invested $3.75 million in experimental facilities at ISAC. TRIUMF also builds relationships in global markets for Canadian businesses. For example, with the assistance of TRIUMF, partner company PAVAC Industries, Inc., in Richmond, BC, was the only non-Chinese company selected to supply an advanced-technology accelerator component to a major Beijing-based accelerator project. TRIUMF has teamed up with the Kavli Institute for the Mathematics and Physics of the Universe to create an international joint position, a first for Canada and Japan, to strengthen the collaboration in neutrino physics. (The incumbent is an American researcher who will eventually have the choice to stay in Japan or return to Canada as a TRIUMF researcher. The competition is on.) TRIUMF's network includes 75 universities, research institutes, global laboratories, and companies around the world.

2.3.4 PRINCIPLE: ENHANCING ACCOUNTABILITY

TRIUMF is federally regulated by the Canadian Nuclear Safety Commission. Based on a strong record, the laboratory was awarded a ten-year operating license in 2012 instead of the usual five-year term. TRIUMF's Board of Management undertook a governance review and now operates an Executive Committee that convenes between Board meetings to enhance agility and response time. TRIUMF has implemented formal project management methods across its entire operation in order to more effectively manage project resources. During tough economic times and constrained investments, TRIUMF controlled costs, improved efficiencies, and delivered a larger program than ever before.

A healthy scientific enterprise offers three distinct advantages: advancing knowledge, creating future leaders, and generating societal and economic growth. Five-Year Plan 2015–2020 promises to distinctly elevate Canada in all of these areas.

YAMAZAKI AWARDED BUNKA KOROSHA PRIZE

24 March 2010

Established in 1951, the Government of Japan annually recognizes a "Person of Cultural Merit" with the Bunka Korosha Award, one of Japan's highest honours. Earlier this year, a former TRIUMF researcher Toshimitsu Yamazaki was distinguished for his unique contributions in the promotion and advancement of contemporary physics.

During the celebrations, Professor Yamazaki continually praised the value of Canada-Japan collaboration in science throughout his career; the celebratory reception was held at the Canadian Embassy in Tokyo. His association with the Canadian research community can be traced back to the late '60s when he established the techniques of using muon beams for studying a wide variety of processes involving magnetism, spin physics, and materials science. At TRIUMF, Yamazaki developed such a facility and planted the seed for what is now a very successful program in muon spin resonance. This is one of only four such facilities around the world, which attracts more than 100 foreign researchers to Canada every year.

2.3.5 KNOWLEDGE ADVANTAGE: ADVANCING GLOBAL EXCELLENCE IN RESEARCH

TRIUMF's proposed Five-Year Plan 2015–2020 will place Canada at the front of the pack of nations pursuing isotopes for science and medicine. The flagship ARIEL project is globally unique and will give Canada the advantage in understanding the creation of the chemical elements in neutron-star mergers and discovering cracks in seemingly fundamental laws governing the universe. Based on an analysis of competing capabilities being developed at other facilities, Canada will have a distinct opportunity to exploit its head start with ARIEL to make breakthrough discoveries.

TRIUMF's support will also continue to drive Canadian leadership in international scientific collaborations such as ATLAS at the LHC, the antihydrogen ALPHA experiment, and the Japan-based neutrino T2K collaboration.

The primary public benefit of basic research is the advancement of knowledge through discovery and synthesis. TRIUMF monitors its impact on Canadian leadership in advancing knowledge using a quantitative set of advanced bibliometric indicators, performance measures of delivered beams to users, and a qualitative set of indicators (awards, journal cover stories, prestigious lectures, and so on) measuring of Canadian leadership in emerging science topics.

2.3.6 PEOPLE ADVANTAGE: CREATING FUTURE LEADERS

Nothing happens without people, and nothing improves without the dedication and focus of talented people. Through programs that offered direct research experiences to high-school students, undergraduates, and graduate students and informal science-education activities, TRIUMF's talented researchers touched the lives of thousands over the last five years (see Section 4.3 for a full report). Young researchers at TRIUMF work in an international, multi-disciplinary competitive environment supported by mentorship and supervision. Post-doctoral fellows at TRIUMF have become some of Canada's leading researchers (e.g., Malcolm Butler, Peter Blunden, Randy Lewis, Shelley Page, Ritu Kanungo).

Five-Year Plan 2015–2020 will continue to utilize TRIUMF's existing pool of talent to not only secure a competitive position in relevant areas of science and technology, but also inspire and attract the next-generation of leaders. With a new partnership that connects the laboratory and its international network of scientific leaders to the science education and outreach prowess of Telus World of Science in British

152ND NOBEL SYMPOSIUM INVITES JENS DILLING

11 October 2012

On June 13, 2012, TRIUMF researcher Jens Dilling attended the 152nd Nobel Symposium in Gothenburg, Sweden. The Nobel Symposia is a program that brings together world experts to discuss breakthroughs and progress in areas of science. Participation is by invitation only. The focus of this year's symposium was Physics with Radioactive Beams. The Nobel Community for Physics was in attendance to gauge and evaluate the field. Dr. Dilling shared his research on Probing the Nuclear Interaction through Precision Mass Measurements. Another Canadian and TRIUMF collaborator, Dr. Ritu Kanungo of Saint Mary's, also participated in the symposia.

The 152nd Nobel Symposia manifested the increasing international interest and investment in nuclear physics. According to Dr. Dilling, radioactive beams are in high demand because of their threefold benefit: intellectual gain, development of nuclear medicine, and advancement in materials science.

Columbia, TRIUMF will share the process of research and innovation with thousands of students and families over the next five years. A new online, recorded-seminar archive will make these events and other lectures at TRIUMF available to Canadians across the country.

With university-based colleagues, TRIUMF is leading the preparation for an international graduate school program at UBC in the framework of an NSERC CREATE program, called ISOSIM that will provide multi-disciplinary and multi-sector research and learning experiences to graduate students around the theme of advancing isotopes for science and medicine. The program includes an exchange program for the students with several institutions of the German Helmholtz Association and Siemens Foundation.

TRIUMF maintains a vigorous visiting-scientist program, hosting not only hundreds of scientists and students coming each year to TRIUMF to conduct experimental research but also researchers visiting for longer periods to share their knowledge and learn new skills. As Canada's scientific and technology workforce becomes more globally integrated (both personally and digitally), the importance of workforce mobility will be replaced by workforce "global access," meaning that leading organizations will be distinguished by their connections and networking across the globe on strategic topics. Capitalizing on Canada's strength in subatomic physics, TRIUMF will engage world-leading scientists and students in its research program, enabling Canadian students to establish and develop the key relationships that will elevate their careers.

> “[T]hese realities imply that Canada's prosperity will depend, more than ever, on an innovative economy. Innovation drives our ability to create more economic value from an hour of work.”
>
> Innovation Canada: A Call to Action, Expert Panel Report of the Review of Federal Support to Research and Development, 2011.

2.3.7 ENTREPRENEURIAL ADVANTAGE: GENERATING SOCIETAL BENEFIT AND ECONOMIC GROWTH

TRIUMF has a long history and unique expertise in the accelerator-based production of isotopes used for nuclear imaging and tumour treatment. The year 2013 marks 35 years of cooperation with Nordion, Inc., in the technology-partnership framework that produces 15% of the isotopes exported from Canada. Where does this happen? At TRIUMF, with the lab's expert staff at the tiller and guiding Nordion's production to reliable and reproducible success. This core expertise in accelerator production of isotopes has recently been employed by TRIUMF in service of Canadian national objectives to develop alternative technologies for the production of technetium-99m, an isotope that presently requires nuclear reactors and highly enriched, weapons-grade uranium to manufacture.

Other technologies spinning out of the TRIUMF enterprise involve the use of cosmic-ray muons to enhance mineral explorations below ground, improve airport security, and reduce radiation exposure to patients during routine fluoroscopy and medical-stent procedures.

Together with its commercialization partner Advanced Applied Physics Solutions, Inc. (AAPS), TRIUMF proposes to double its commercial revenues by leveraging relationships with existing industrial partners by 2020. AAPS will focus on developing platform technologies in the areas of accelerators and beams and radiation detection and control. Applications presently being explored in the natural resources and healthcare sectors will mature. Five-Year Plan 2015–2020 proposes to deploy TRIUMF's network of universities and international labs so that opportunities for development, commercialization, and marketing are seized. AAPS will manage a formidable intellectual property portfolio with a dozen industrial partners invested in key opportunities.

> "Accelerators began to generate wealth for industry – and rewards for society – 60 years ago. Worldwide, around 20,000 accelerators now produce, sterilise or examine 400 billion Euro worth of goods each year. And that doesn't include the 10,000 accelerators made for medical use in the world's hospitals."
>
> Statement prepared by the European Strategy Group for Particle Physics for the special European Strategy Session of Council in Brussels on 30 May 2013.

2.4 REALIZING THE VISION

TRIUMF's Five-Year Plan 2015–2020 lays out a vision that will extend Canada's premiere position in particle and nuclear physics and bring its efforts in nuclear medicine and molecular and materials science to the next level of national impact and relevance.

The three major themes remain the drivers for the laboratory into the next decade:

Advancing isotopes for science and medicine;

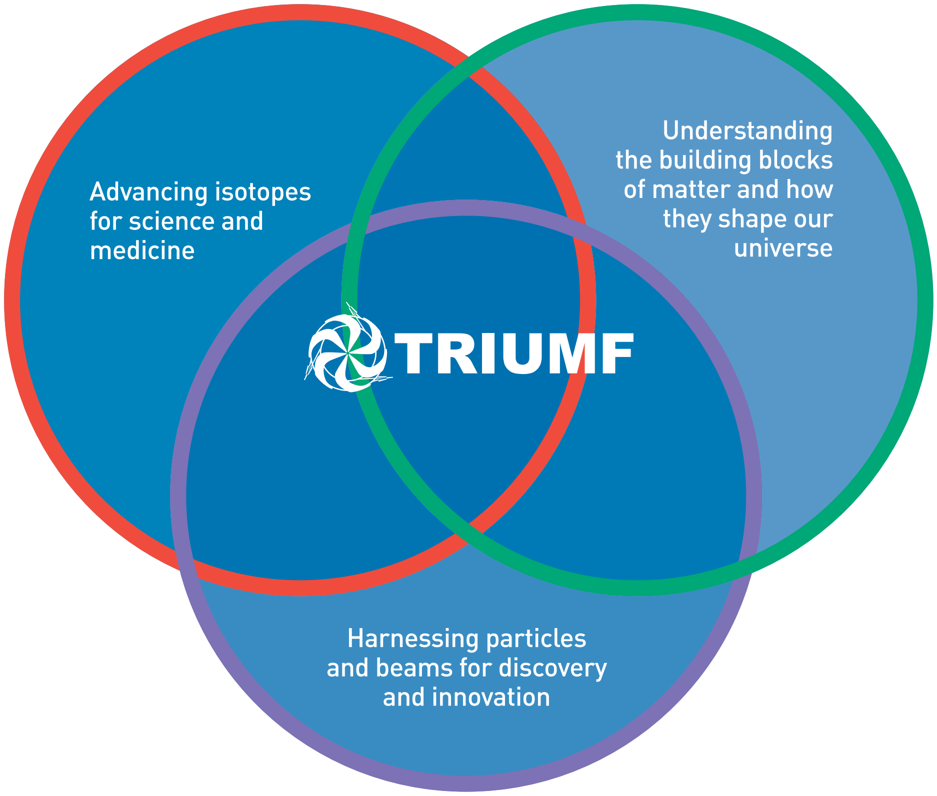
Understanding the building blocks of matter and how they shape our universe; and

Harnessing particles and beams to drive discovery and innovation.

Five-Year Plan 2015–2020 will transition TRIUMF from a major era of construction to one of exploitation and operation with discovery science being performed in all scientific areas.

With ample beam from the e-linac, the β-NMR facility will exploits its full potential as a user facility for molecular and materials science. The rare-isotope beam program will start, supported by a strong effort in theory, to exploit multi-user operation and explore nuclei along the astrophysical r-process. The UCN facility will begin its search for the neutron electric dipole moment.

On the international front, the period 2010–2015 has been one of exploitation of the investments made in the past with ATLAS and T2K firmly in their data-taking and discovery phase, guided by the local theory efforts. The period 2015–2020 will see further exploitation but also preparations for the next big steps in the worldwide efforts to unravel the most foundational principles of the universe. ATLAS and T2K will undergo upgrades in which TRIUMF will again play a significant role, and new major initiatives like LHC upgrades, the linear collider (LC), and the Hyper-Kamiokande are being discussed for construction in the next decade. TRIUMF is poised to be a relevant partner for these endeavours.



TRIUMF will build on its successes in developing new technologies for accelerator-based medical isotope production and elevate Canada and its isotope related industry into leading positions. With the much-expanded capabilities for materials characterization, Canada will be able to instantly follow up on the development of new materials, impacting progress in a broad range of fields including quantum computing, microelectronics, and energy storage.

Building on the completion of the ARIEL facility and its e-linac, TRIUMF will investigate the next steps in facility development that will keep it at the forefront of accelerator-based research and technology, and ahead of its competitors.

Through all of these activities, TRIUMF will continue to advance knowledge on the highest level; to create the next-generation of leaders in science, industry, and health; and to generate societal and economic impact for the betterment of Canada.

2.5 IMPLEMENTING THE PLAN

TRIUMF's strategic plan for the 2015–2020 period fulfills the decadal vision launched in 2010. This ambitious plan will have optimal impact in the three major themes and will maximize the return on the investments made by both Canadian taxpayers as well as several international partners, including Germany, India, Japan, CERN, U.K., and U.S. These investments have led to a Canadian leadership position in physics and astronomy and, in particular, particle and nuclear physics. To convert this intellectual leadership into full value for the Canadian economy, continued investment is necessary. We must seize the advantage while it is available.

> **In particular, the (U.S.) nation benefits from government funding for basic and applied research in areas in which the private sector does not have the economic incentive to invest.**
>
> Science and Technology Priorities for the FY 2014 Budget,"
> Memorandum from the U.S. Office of Management and Budget, Director Sylvia Burwell.

The highest priority for TRIUMF in the next five-year period is the completion of the ARIEL facility and the launch of experiments exploiting its new scientific capabilities. At the same time TRIUMF must capitalize on past Canadian investments in three areas: (1) high-profile international efforts in particle physics, in particular, ATLAS, T2K, ALPHA, and SNOLAB (2) the rare-isotope experiments at ISAC, and (3) the user Centre for Molecular and Materials Science. The laboratory will also leverage international investments in Canada with the Japanese-Canadian facility for ultra-cold neutrons. At the same time, TRIUMF will continue to be an essential partner for Canadian universities to connect to the world in particle and nuclear physics and will facilitate these universities' ambitions to play visible roles in large international detector projects.

TRIUMF's Five-Year Plan 2015–2020 also calls for the staff and funds to operate its facility at maximum capacity while completing ARIEL. This will allow for investments in refurbishments or replacements of aged infrastructure needed to continue carrying out an already excellent scientific program as well as to make modest investments in a few strategic program enhancements. Operating at full capacity will enable the lab to keep up its scientific competitiveness around the world as well as substantially increase the social and economic benefits it brings to Canada.

Canada's scientific competitiveness will be enhanced even more through an expansion of the Canadian ATLAS Tier-1 Data Centre (for which TRIUMF will provide infrastructure as well as staff and funds for operation) and an upgrade of the liquid helium and beam line infrastructure for the new facility for ultra-cold neutrons. A targeted handful of joint faculty positions with member universities will strategically strengthen Canadian research. For instance, consider the following: the leader of the Tier-1 Data Centre is Michel Vetterli, jointly appointed to TRIUMF and SFU's Department of Physics; Canada's involvement in the Japan-based T2K experiment is driven by Dean Karlen, jointly appointed to TRIUMF and University of Victoria's Department of Physics and Astronomy; Paul Garrett, who transitioned from a joint position to a full faculty position at the University of Guelph's Department of Physics leads the DESCANT project at TRIUMF adds critical neutron-detection capabilities to experiments at the TIGRESS facility.

Canada's leadership in the production and beneficial use of medical isotopes will be fortified by the creation of an Institute for Accelerator-Based Medical Isotopes (IAMI), with a new medical cyclotron for which TRIUMF will provide staff for operation and isotope processing. Intensifying industrial partnership activities to allow TRIUMF-developed technologies to get to the market will further increase TRIUMF's economic impact. Finally, TRIUMF will address key deferred maintenance issues to ensure reliability and competitiveness including refurbishment of existing space.

The outcomes of Five-Year Plan 2015–2020 are, simply put, enhanced excellence: enabling Canadian scientific research that leads the world in terms of journal publications and impact; inspiring, attracting, and training the next-generation of leaders at a new level; and substantially progressing on connecting research excellence to business relevance in accelerator-based science. With full investment, the new Plan will:

- Enhance productivity from 1,300 scientific publications to 1,500 such papers with experiments at CERN running full steam along with expanded capacity and capability at ARIEL and ISAC;

- Expand networking and collaboration in the Canadian subatomic physics community to move from 15% contributing authorship to 20%;

- Engage 675 students in direct research experiences, 100 more than 2010–2015;

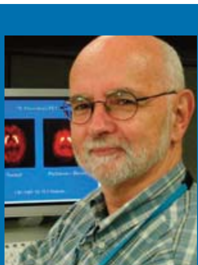
- Excite 35,000 people through informal science education activities including laboratory tours, public science lectures, and community events; and

- Enlarge economic impact by $50 million per year, adding a $500 million impact within Canada over the next decade.

Realizing the vision for ARIEL and for Canada's success in connecting research excellence with business relevance will require coordinated investments by the Government of Canada (via the NRC Contribution Agreement, Canada Foundation for Innovation, Natural Sciences and Engineering Research Council, Western Economic Diversification Canada, and Natural Resources Canada) and the provincial governments.

To realize the full potential of Five-Year Plan 2015–2020, an investment of $290M in 2015–2020 by the Government of Canada via the NRC Contribution Agreement is requested. In concert, the University of Victoria will lead a consortium of TRIUMF member and associate member universities to seek funding from the Canada Foundation for Innovation (CFI) for the capital needed for the completion of the ARIEL facility (about $32M). TRIUMF, along with regional collaborators will pursue capital funding ($2M-$3M) from Western Economic Diversification Canada, the Government of British Columbia, and the private sector for a new TR-24 cyclotron as part of a regional centre of excellence called the Institute for Accelerator-based Medical Isotopes. CFI funding will also be sought by the respective Canadian collaborations for ATLAS detector upgrades and Tier-1 expansion, T2K and ALPHA upgrades, the neutron EDM experiment at the UCN facility, as well as a number of smaller initiatives.

This request for NRC-contributed funds may appear as a substantial increase compared to the $222.3M of the 2010–2015 period; however, it should be noted that the NRC contribution to TRIUMF's core operations has been flat-flat for 10 years (i.e., constant in nominal terms). TRIUMF has not been able to keep pace with utility prices and other cost-of-business increases and has little capacity to maintain competitive salaries. To set the scale, ordinary economic progress (inflationary adjustments at less than



TOM RUTH APPOINTED TO UN IAEA BOARD

06 June 2013

Recognized internationally as an expert on nuclear medicine and medical isotopes, TRIUMF's Dr. Thomas J. Ruth has been appointed to serve from 2013 to 2015 as the Canadian representative member of the United Nations International Atomic Energy Agency's (IAEA) Standing Advisory Group for Nuclear Applications (SAGNA).

Dr. Ruth has been an integral part of operating the TRIUMF medical isotope cyclotron for routine production of clinical research isotopes for the Pacific Parkinson's Research Centre as well as the BC Cancer Agency. Dr. Ruth's work has helped to advance Canada's profile on the international stage as a key contributor to the development of alternative production methods of medical isotopes such as Technetium-99m and Molybdenum-99 that are used in early detection and diagnosis of disease and cancer.

As the sole Canadian representative on the 20 member advisory committee, Dr. Ruth is looking forward to learning more about how others are advancing radioisotope applications, and sharing his experiences and expertise in turn.

2.0% per year) would have moved TRIUMF's annual core operating budget from $44.5M in FY2005 to $53.1M in FY2015, meaning that the buying power of FY2005 would be worth $282M for Five-Year Plan 2015–2020.

TRIUMF has been able to carry out a successful program in the current 2010–2015 period through substantial funding beyond the NRC Contribution Agreement, in particular from CFI for the first phase of ARIEL and Natural Resources Canada (NRCan) for the accelerator-based production of technecium-99m. Just as other institutions did in response to the global economic downturn, TRIUMF deferred certain maintenance items and sought new efficiencies in order to operate with reduced staff levels and reduced buying power while driving enhanced scientific productivity, relevance, and impact.

While the TRIUMF research program is broad, the NRC contributed funds are used for the core program of operating the accelerator complex, maintaining the laboratory infrastructure, and supporting a lean management and administration. In Five-Year Plan 2010–2015, a major activity has been the labour to design and construct ARIEL as an in-kind contribution to the CFI-supported project. Figure 1 shows the deployment of the workforce supported by the NRC funds for FY2012 and projected for FY2017. Although the nuclear-medicine and materials-science programs are crucial drivers of the laboratory's output, most of their manpower funding comes from outside the NRC Contribution Agreement. The proposed contribution for particle physics increases because of the inclusion of the ATLAS Tier-1 Data Centre staff in the 2015-2020 Contribution Agreement.

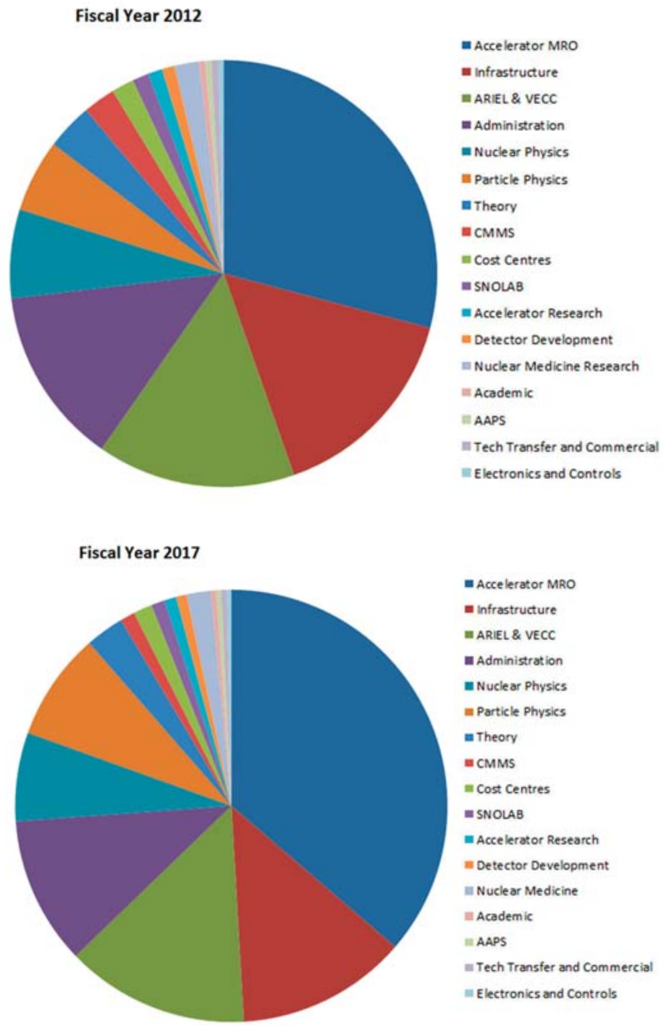


Figure 1: Allocation of TRIUMF's work force supported through NRC funds by major program area; FY2012 actuals (upper) and FY2017 projections (lower). Five-Year Plan 2015–2020 proposes to add about 35 FTEs (presently supported by temporary funds from other sources) onto the NRC salary budget. Note: MRO = maintenance, repair, and operations.

A principal aspect of the proposed Five-Year Plan 2015–2020 is baseline budget support for additional key staff (~35 FTEs) that are presently funded through temporary CFI-IOF funds (for ARIEL and the ATLAS Tier-1 Data Centre) and NRCan. These existing resources will be depleted by the end of FY2014. With new facilities like ARIEL and UCN becoming operational, the need to support the operating staff for the ATLAS Tier-1 Data Centre, and the opportunity to generate long-term benefits for Canada through an increased effort in nuclear medicine via a partnered Institute for Accelerator-based Medical Isotopes (IAMI), these highly skilled staff members should be transitioned onto TRIUMF's core operating budget funded through the NRC Contribution Agreement. Section 6.4.2 offers an array of three budget scenarios and discusses the impact on realizing this vision. A continuation of the past decade of flat-flat core operating funding (i.e., without any adjustments for inflation) compromises many of the objectives presented above.

2.6 LOOKING A DECADE AHEAD

An investment in science is an investment in the future. But what will the future hold? Where will Canada and TRIUMF be a decade from now, when this Five-Year Plan is complete, and the next one is already in full swing? This section sketches the future a decade from now.

TRIUMF will drive significant progress for Canada in three areas: understanding the basic building blocks that shape our universe, advancing isotopes for science and medicine, and harnessing particles and beams for science and innovation.

Over the next ten years, TRIUMF will continue to advance Canada's impact in particle and nuclear physics and build upon its already significant worldwide reputation for top-level science and innovation. The ARIEL facility will produce beams for advanced materials research, nuclear-structure physics, nuclear astrophysics, fundamental symmetries, and the medical isotopes of tomorrow. These outcomes will launch a suite of advanced programs that will train the future scientists, engineers, technicians and students that Canada will require to face the challenges of the future. In the process of completing the ARIEL project, TRIUMF will co-develop with industry several advanced technologies that will become globally significant. Furthermore, the ARIEL project will position Canada with some of the most advanced accelerator technologies in the world, allowing our industries to stretch the Canadian footprint in particle and nuclear physics even farther. In nuclear medicine, TRIUMF will have commercialized new technologies for producing today's medical isotopes and will have uncovered designer isotopes that hold the promise for effective therapies.

As noted in the 2012 Council of Canadian Academies report, Canada excels globally in particle and nuclear physics research. Over the next decade, TRIUMF in Vancouver, along with the Perimeter Institute for Theoretical Physics in Waterloo, and SNOLAB in Sudbury, will provide Canada with a unique combination of facilities to unravel the leading questions in subatomic physics.

From the discovery of the Higgs boson to trapping of antimatter, CERN will continue to be at the forefront of particle physics. Canada will continue to contribute and benefit by its association with CERN via TRIUMF and its collaborating universities because it provides a superb training ground for science and engineering students. A decade from now, Canada will be involved in upgrades for the LHC and the ATLAS detector as the international research teams take advantage of expanded capabilities at the accelerators and detectors. TRIUMF will have coordinated industrial involvement and demonstrated Canadian excellence in technical and engineering capabilities.

New detectors presently coming online or being designed will be working full steam in SNOLAB, searching for dark matter particles and teasing out the nature of the neutrino. A decade from now, these experiments may have breakthrough discoveries and the next generation of investigations will be underway. In Japan, neutrinos will have been fully characterized and a massive new detector called Hyper-Kamiokande could be coming online.

The ultra-cold neutron facility, a new collaborative effort between Japan and Canada, addresses fundamental questions about the basic laws of our universe. A decade from now, TRIUMF will have set new constraints on or possibly even measured the electric dipole moments of the electron, neutron, and atom radon. Together with various other precision experiments at TRIUMF and abroad, these efforts will place Canada in a unique and powerful position to search for physics beyond the Standard Model.

The three physics thrusts of rare-isotope science are fundamental symmetries, nuclear astrophysics, and nuclear structure. ARIEL will enable TRIUMF to provide multiple rare-isotope beams simultaneously, some generated from the electron accelerator and some from the main proton cyclotron. These multiple beams will allow Canadian and international researchers to pursue experiments that will probe the details of what happens in stellar super-explosions that created the heavy chemical elements (heavier than iron) that make up our Solar System and that will test the fundamental symmetries of our basic physical laws. One of the “holy grails” of isotope research is to develop a complete and accurate mathematical description of any nucleus; new and more beams will move this vision within reach.

As the ARIEL facility matures over the next decade, plans to design the next logical phase will be fleshed out. The ideas are simple. ARIEL will be producing some of the most intense beams of rare isotopes in the world. Other labs use storage rings of rare isotopes to increase the effective intensities to drive new sets of higher-energy experiments for nuclear astrophysics. Stored beams of rare isotopes and counter-rotating electrons can be used to probe the structure of isotopes with exquisite details. At ARIEL it will become possible to pass these beams through a thin target and produce even more exotic beams than are talked about today. These ideas are already being proposed in China (CIAE), India (VECC), and Korea (RISP), as these countries try to proceed directly to the next-generation isotope accelerators. TRIUMF’s goal is for Canada to play a recognized role in this future pursuit.

In the decade beyond, one possible expanded direction for the ARIEL e-linac would be to pursue a free-electron laser (FEL). A FEL is a tool to explore the inner workings of atoms and molecules in regions where tabletop lasers cannot probe. This potential avenue would require a modest addition to the accelerator and several state-of-the-art instrument suites to trap the molecules for study. TRIUMF already has significant atom-trapping capabilities (both neutral and charged ion traps are in use). The FEL facility with atom trapping would be unique in North America and would drive new directions in biological, atomic and molecular physics and nanoscale research. A number of Canadian and U.S. researchers have already expressed an interest in an FEL at TRIUMF.

Nuclear medicine at TRIUMF will continue to grow as we strengthen the bonds between TRIUMF, the BC Cancer Agency, the Pacific Parkinson’s Research Centre, and local businesses. In other areas, such as developing new targets for advanced isotopes, TRIUMF will continue to leverage its work with private-sector partners, thus becoming the “Silicon Valley” of isotopes, or “Isotope Valley”. Having achieved commercial success for accelerator-produced Tc-99m by 2016, TRIUMF will have turned its attention to global markets and the development of new medical isotopes that serve specialized purposes in diagnostic imaging and even therapy. A decade from now, at least one therapeutic isotope will be produced at TRIUMF for experimental testing with partners. TRIUMF will be addressing at least one new biological question for degenerative brain diseases that will require a number of new “designer molecules” presently not in our chemistry kit, expanding from the current work in the dopamine system to full mastery of the serotonin system. In oncology, TRIUMF will have driven the development of a new oxidative stress tracer.

TRIUMF has established an international reputation for technology transfer, especially its 35 year partnership with Nordion for producing medical isotopes. TRIUMF is also strongly associated with the small medical cyclotrons manufactured in Canada by ACSI. A decade from now, TRIUMF will have been involved in several technology transfer activities involving both new ion sources and enhanced diamond-like carbon foils for small medical cyclotrons. Formed five years ago, AAPS, Inc. will be self-sufficient and will routinely make investments in TRIUMF technologies in partnership with industrial partners to bring new products to market. These products will be rooted in TRIUMF’s expertise in accelerators, isotopes, and radiation detection and control.

By the end of the next decade, TRIUMF's partnerships will have transformed into a "science leading to business" model similar to one that is working now in India. These new partnerships will expand to include the research collaborations with China, Japan, and Korea. The existing strong partnership with Japan in neutrino science, accelerator physics, and fundamental symmetries will lead to several programs that will be jointly managed and coordinated. Japan's leading high-energy physics lab KEK will establish a field office at TRIUMF, the first of its kind. Similarly, TRIUMF's role in driving university-campus-based research will expand.

The Linear Collider (LC) project, a next generation 30-km long electron-positron particle collider, will be a truly international laboratory (possibly hosted by Japan) to answer a simple physics question: What are the properties of the new Higgs boson and what does it tell us about the rest of the universe? TRIUMF is being invited to play a role in the initial project, largely following from the highly successful accelerator contributions to the LHC at CERN and building on the recent accomplishments here in Canada for ARIEL's electron accelerator. The LC project will open up new and exciting opportunities for Canadian researchers and students as well as for the Canadian high-tech industry. Construction on the LC will start once international agreements have been reached (~3 to 4 years), and the facility will take ten years to build but Canada, via TRIUMF, will be there when it is.

The outlook for TRIUMF for the next ten years and beyond is remarkably rich in opportunity. The particle physics program, driven by our advanced accelerator and detector technologies, is in demand all over the world. The science and technology opportunities at CERN with the LHC and in Japan with the LC are truly exciting and unparalleled. The ARIEL project is certain to meet its potential as a leading facility in isotopes for science and medicine as is its advanced-materials program. The flexible nature of the facility allows for the expansions in the next-generations of isotope science and in photon science with a free electron laser. Nuclear medicine will continue to impact the lives of Canadians. Most importantly, TRIUMF will be a premier platform upon which young Canadian scientists and engineers will be trained in a research arena where they work with, and compete with, the best researchers in the world using the latest technologies. Their future discoveries and skills will surely prepare us well for the challenges of the 21st century.

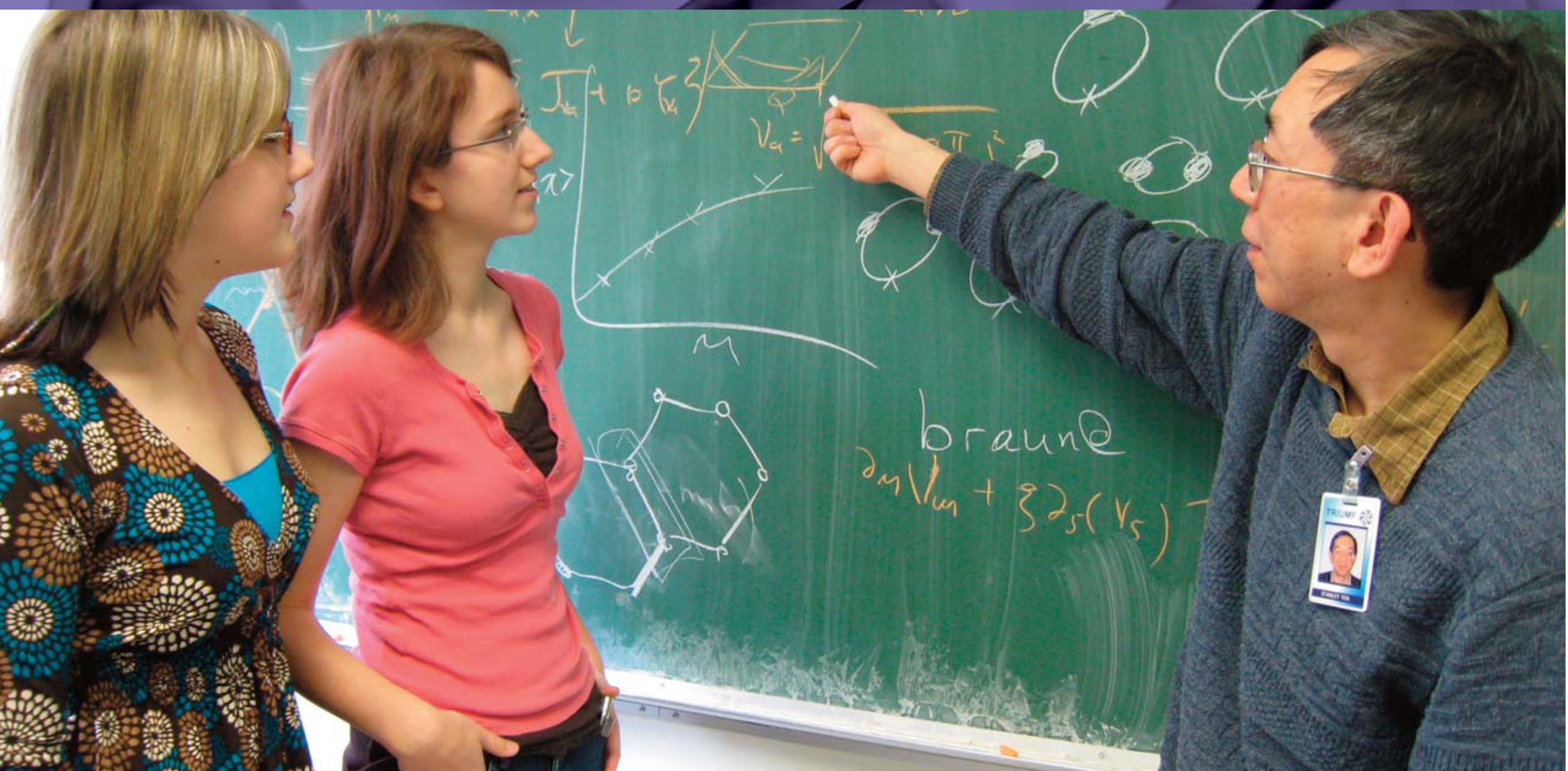
2.7 SUMMARY

Five-Year Plan 2015–2020 lays out a vision that is well aligned with Canada's priorities for science and technology and builds on TRIUMF's track record for excellence. It is a forward-looking strategy that will strengthen Canada's leadership in nuclear and particle physics while further elevating its relevance in the applications of isotopes for nuclear medicine and materials science. TRIUMF exemplifies the role of national and international partnerships in science and technology for the benefit of society and the economy. Five-Year Plan 2015–2020 represents an opportunity to invest into Canada's future leaders and to maximize the return on investments made in the advancement of knowledge, the development of high technology, and its transfer to industrial partners.

3

Partnerships

From Global Excellence to Local Impact



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OWNED AND OPERATED BY A CONSORTIUM OF UNIVERSITIES, TRIUMF'S VERY EXISTENCE DEPENDS ON PARTNERSHIPS DRIVEN BY COMMON COMMITMENTS AND SHARED RESOURCES. THIS SECTION DISCUSSES THE NATURE OF TRIUMF'S COLLABORATIONS AND CONNECTIONS WITH CANADIAN UNIVERSITIES AND RESEARCH INSTITUTIONS, INTERNATIONAL UNIVERSITIES AND LABORATORIES, AS WELL AS INDUSTRY. THE WHOLE IS GREATER THAN THE SUM OF ITS PARTS: **TRIUMF'S ACCOMPLISHMENTS ARE ONLY POSSIBLE THROUGH THE HEALTHY STEWARDSHIP OF THESE RELATIONSHIPS**.

3.1 INTRODUCTION

Several efforts have been made to diagram the Canadian science, technology, and innovation environment. One feature is immediately apparent: no single performer, patron, or benefactor of basic research has value without the seemingly complex web of interconnections to other institutions and organizations. TRIUMF is no different. The laboratory maintains a unique collection of accelerators and detectors; it employs hundreds of highly talented scientists, technicians, and engineers; and it maintains a system of controls, checks, and balances in order to conduct its research and development activities on time and on budget. But the full value of TRIUMF is realized through its set of partnerships and agreements, which are driven by common commitments and shared resources, those which are (1) "upstream"—some TRIUMF activities require resources and/or guidance from outside the laboratory to achieve its goals and (2) "downstream"—sometimes TRIUMF provides the ingredients or resources for its partners to generate successes.

> "Best 10 Research Facilities in Canada:
> #8 – TRIUMF, a Vancouver-based lab specializing in particle and nuclear physics."
>
> Backbone.com, "Backbone 200: The best of everything in Canadian tech," 25 Feb 2013.

3.2 PARTNERSHIP STRATEGY

TRIUMF was founded to provide the centralized resources, tools, and expertise for scientific research that no single Canadian institution could afford to build or maintain. Through international partnerships, TRIUMF endeavours to connect Canada to the global science and technology community. Additionally, as a bridge between the academic sector and the private sector, TRIUMF is resolved to drive Canada's innovation engine through collaborative and joint projects. Partnerships do not just happen. TRIUMF actively sought, and continues to seek, two-way partnerships that benefit both the lab and the larger community.

3.2.1 CANADIAN UNIVERSITIES AND RESEARCH INSTITUTIONS

At its core, TRIUMF is a partnership among leading Canadian research universities. It is owned and operated as a joint venture by a consortium of 18 Canadian universities, from Halifax to Victoria, in an inherently close relationship that keeps TRIUMF relevant and connected to Canada's science, technology, and innovation ecosystem. As such, it is globally unique, although through its practical exercise of governance, TRIUMF shares many characteristics and best practices with other publicly supported laboratories around the world.

Universities are either full members or associate members of the TRIUMF consortium. Full members share equally in the liability of the laboratory (including both operations and decommissioning) and enjoy two positions on the governing Board of Management. Associate members have one position on the Board and do not vote, although they listen and contribute to the overall strategic direction of the laboratory and the deployment of its resources. For a university to join the consortium, it must already have a campus-based research program that intersects with and connects with TRIUMF activities. Full members are expected to have three or more distinct research activities that will be strengthened and benefit from full participation in TRIUMF. Membership in TRIUMF works both ways. TRIUMF expands the on-campus footprint of particle and nuclear physics in Canada and some universities will expand their research to better fit with and work with TRIUMF.

The TRIUMF consortium presently comprises eleven full members and seven associate members. This represents substantial expansion over the past five years; in 2008, the consortium was seven full members and six associate members.

Staff researchers at TRIUMF often get involved in Canadian universities, ranging from seasonal instructors and adjunct appointments for supervising students to full investiture as grant-tenured faculty in an academic department. Managed by the Board of Management's Personnel Committee, staff researchers can be designated Board Appointed Employees, which grants them eligibility for competitively peer-reviewed NSERC research funds.

TRIUMF does not itself grant degrees but all graduate students at TRIUMF are associated with a university and work either with a TRIUMF staff researcher or a visiting university researcher as their supervisor. In many instances, students at TRIUMF have co-supervisors from both TRIUMF and a university.

Since 2009, TRIUMF has also expanded its training programs to include select opportunities for non-science graduate students. Working with faculty at nearby Emily Carr University of Art + Design, TRIUMF has participated in offering training opportunities for arts students. And, at the present time, we are exploring similar arrangements with several business schools.

For universities, the process of membership begins with informal conversations with TRIUMF to assess the benefits of joining. These benefits include:

- Enhancing the university's reputation;
- Leveraging TRIUMF resources and opportunities to augment "campus" research efforts, including boosting international access and reputation;
- Enhanced student and faculty research or training opportunities (including recruitment); and
- Stewardship role for the types of resources and capabilities that TRIUMF provides.

Universities support and drive the TRIUMF agenda in another way: by securing and steering other grants and funds to the laboratory. For instance, TRIUMF is not directly eligible for awards from the Canada Foundation for Innovation (CFI). Canadian universities and colleges are eligible and can apply for funds to co-develop and place leading-edge infrastructure at TRIUMF. This practice is very effective from several considerations: **(1)** By requiring a university and its community to support the application, infrastructure placed at TRIUMF through CFI will automatically connect a university-based user community with the laboratory; **(2)** Universities have the opportunity to co-locate their relevant infrastructure with other tools and facilities at TRIUMF to obtain the best leveraging; and **(3)** TRIUMF's multi-university structure facilitates the cooperation and coordination of university proposals to CFI in its primary research areas. For instance, the University of Victoria led a national consortium of 13 Canadian institutions to secure nearly $18M from CFI for the superconducting electron accelerator (e-linac), which forms the heart of ARIEL at TRIUMF.

In addition to academic institutions, TRIUMF partners with the two other major subatomic-physics institutes in Canada: SNOLAB and the Perimeter Institute of Theoretical Physics. More details are given below.

> "With the coming of the new regional Cancer Centre to Prince George, additional research into generation, transport, and novel application of medical isotopes in smaller-scale urban and rural communities is in the works. 'We are delighted to strengthen our connections with TRIUMF and look forward to a new level of research excellence with national and international impact,' said UNBC vice president of research Gail Fondahl. UNBC has been involved in TRIUMF since the university began operations nearly 20 years ago."
>
> Prince George Citizen, "UNBC Joins TRIUMF," 06 Jan 2011.

3.2.2 INTERNATIONAL ORGANIZATIONS

TRIUMF's purposeful international outlook began in the 1980s with Director Erich W. Vogt. Today, TRIUMF attracts experts from around the world, stimulating a give-and-take sharing of knowledge and innovation.

Over recent years, the laboratory has redefined its strategy for international engagement to focus the attention of TRIUMF leadership, to guide communications efforts for promoting and enhancing TRIUMF, and to develop an approach for implementing the third element of the lab's vision statement: "Connect Canada to the World." Actively following this vision keeps Canada right at the forefront of breakthroughs and technologies that can be quickly deployed for Canada's benefit. Moreover, Canadians can experience the excitement of scientific discoveries that happen on home soil or are driven by researchers in their own backyard.

When considering international opportunities and/or invitations TRIUMF uses five evaluation criteria:

- Does it enable Canadian university scientists and students to work at the best facilities and with the top scientists in the world?
- Does it afford access to scientific or technological facilities not already available in Canada?
- Will a significant benefit accrue to TRIUMF and Canada either in technology or infrastructure?
- Does government policy encourage such a collaboration? and
- Does TRIUMF have a critical mass in the activity and will the activity significantly advance the TRIUMF mission?

The application of these criteria allow TRIUMF to focus on delivering value to Canada for each international engagement by seeking those opportunities that address Canadian objectives and add to the country's global reputation for integrity and excellence. For example, TRIUMF's work with the VECC laboratory in Kolkata, India, not only directly advances the ARIEL project, but it also engages a partner designated both provincially and federally as one of high priority. In a related example, TRIUMF is monitoring development of discussions in Japan with the help of Canadian diplomatic channels regarding the International Linear Collider. If Japan makes a forward move, TRIUMF would provide scientific, technical, and engineering leadership for many aspects of Canadian involvement.

Canada has an unwritten policy for engaging in foreign megaprojects in subatomic physics that TRIUMF supports and implements. For substantive involvement that returns the best value on investment, the research team will seek to become involved in the accelerator or core infrastructure (e.g., the LHC at CERN), to become involved in the scientific apparatus or detector (e.g., the ATLAS detector), and to compete for leading roles in the physics analysis and results (e.g., leadership in the analysis working groups and participation in the ATLAS Collaboration Board). TRIUMF underpins this triple involvement to ensure triple impact: participation in the core infrastructure broadens the chance for Canadian industry to participate and provides unique learning experiences for students; participation in the detector again can engage Canadian industry and gives Canadian researchers recognized "ownership" of part of the science project; in turn, these contributions give Canadians stature in the collaboration and encourage talented scientists and students to be on the front lines of the research.

VOYAGE OF DISCOVERY SIGHTS WHAT COULD BE THE HIGGS

04 July 2012

Early this morning, the ATLAS and CMS particle-physics experiments at the LHC accelerator at CERN presented their latest results in the hunt for the Higgs boson with thousands of viewers from around the world at a global press conference in Geneva, Switzerland. Both experiments observe a new particle in the mass region around 125-126 GeV consistent with the Higgs. Across Canada, hundreds have played critical roles in this breakthrough and are now celebrating.

More than a 150 Canadian scientists and students are involved in the global ATLAS experiment at CERN. TRIUMF has been a focal point for much of the Canadian involvement that has ranged from assisting with the construction of the LHC accelerator to building key elements of the ATLAS detector and hosting one of the ten global Tier-1 Data Centres that stores and processes the physics data for the team of thousands.

"The discovery of a particle consistent with the Higgs boson opens the way to more detailed studies, requiring larger statistics, which will pin down the new particle's properties, and is likely to shed light on other mysteries of our universe," said CERN Director-General Rolf Heuer.

TRIUMF's approach to international engagement can be roughly organized into three categories with broad overlaps.

Scientific/Intellectual. Most international collaborations start with individual researchers identifying common work of mutual interest and benefit. Once their one-on-one experiences prove successful, the relationship is usually formalized through a laboratory-to-laboratory Memorandum of Understanding (MOU). Although the MOU is not legally binding, it provides a framework of specific scope and extent that will greatly assist with student and staff exchange. At this stage, collaboration typically involves exchange and sharing of just personnel and equipment.

Diplomatic. When scientific collaboration is working well, TRIUMF seeks to brief the Canadian embassy in the foreign country about the activities and highlight the role of both partners. TRIUMF would then also connect with the foreign consulate in Vancouver to brief the host nation. The objective is to have embassies and diplomatic staff support the future of the partnership and guide future initiatives; at times, international visitors would be encouraged to visit the foreign effort in Vancouver or the Canadian effort in the foreign country. This type of promotion is especially key to stimulating the next phase of interaction.

Business. Once regular scientific and diplomatic relations are established, the goal is to connect Canadian suppliers or industrial partners with counterparts and customers in the foreign country. TRIUMF will make introductions and provide informal recommendations as appropriate. At times, TRIUMF will take the "first customer" role to validate and endorse a Canadian supplier developing a new product. (See Section 4.4 for further examples.)

TRIUMF does not have a formal list of priority countries and scientific collaborations are openly encouraged between individuals and small groups. Institutionally, the lab does pursue a more focused strategy with partners in China, Germany, India, Israel, Italy, Japan, the U.K., and the U.S. The laboratory also seeks institutional relationships with the major laboratories in subatomic physics, the most significant of these being CERN as a true multi-national laboratory.

Through this strategy, TRIUMF aims to achieve the following objectives:

- Work with the best in the highest-priority fields, no matter where they are;
- Attract international talent and investment to TRIUMF and Canada;
- Work with countries that the public (government) prioritize as important;
- Open new international markets for Canadian companies;
- Enhance TRIUMF's image as a conduit for international science and collaboration; and
- Generate global interest in and support for TRIUMF and its programs.

A list of TRIUMF's international collaborations and partnerships is included in Section 5.10. About 50 active international entities are involved in a collection of 600 inter-institutional agreements.

From a public policy perspective, international networking and collaboration are crucial to competitiveness.

- As science becomes more complex and sophisticated, the combined talents and resources of multiple nations are required to make true progress. These partnerships have to be designed to be of mutual advantage to work in the long term.

- In a globalized world, exploiting scientific breakthroughs to economic or social benefit depends on swift action and complete understanding of the science. To do this, Canada needs to be at the table and alongside the pioneers, otherwise we will read about the science in the newspaper and be obliged to buy the new technology from an overseas company a few months later.
- For Canadians to be globally competitive, they have to train with and compete with the best. International access and exposure is critical to developing our best talent.
- Canada cannot borrow from other countries forever; there is a *quid pro quo* principle in play. Other countries sharing access to their facilities with Canada expect that over the course of a decade, Canada will develop and share access to leading-edge facilities on its own soil with them. To the point, other countries will expect Canada to build and maintain leading-edge facilities with a global-access policy.
- Major science initiatives attract, retain, and develop the best talent. If Canada wants to compete globally, it needs some crown jewels on home soil to bring talent to or through Canada.

As a final comment, TRIUMF is modifying its international engagement strategies to reflect the modern theme of "brain circulation" as opposed to the conventional theme of "brain gain." As human talent becomes increasingly mobile, what matters most is not where people are located in the long term, but what level of access and familiarity they have with working with the best and the brightest.

> "On November 7, 2011, KEK hosted the third KEK-TRIUMF Scientific Symposium with the theme, 'From Collaboration to Partnership: Accelerator-Based Science at KEK and TRIUMF.' This symposium was attended by about 70 researchers from Canada and Japan. Commemorating the 80th anniversary of diplomatic relations between Japan and Canada, and in keeping with the theme of Innovation, the Canadian Embassy in Tokyo hosted the inaugural Canada-Japan Particle Accelerator Science Symposium in 2009."
>
> KEK website, "From Collaboration to Partnership:
> KEK –TRIUMF Scientific Symposium held at KEK," 17 Nov 2011.

3.2.3 CANADIAN INDUSTRY

One of the three primary outcomes of basic research, in addition to knowledge and highly trained personnel, is economic growth, which is driven either (a) by the direct application of scientific breakthroughs to develop new products and services or (b) by the demands that scientific research places on technology causing it to "stretch," thereby improving performance or generating new applications and markets. The third element of TRIUMF's mission mandates attention to these types of opportunities by "transferring knowledge" and "commercializing research" for the benefit of all Canadians.

TRIUMF's approach to working with industry is collaborative as opposed to transactional. The laboratory is committed to fostering innovation and building long-term, mutually beneficial relationships with partners. Moving a technology out the door is no longer sufficient; in some instances, that might be just the beginning of a valuable long-term relationship. And that relationship holds greater value than any one new product.

> **Because the pathway from laboratory bench to commercial product is complex, involving numerous and sometimes difficult steps, the process can derail at any point and products may not always reach, or find success in, the marketplace.**
>
> U.S. Government Accountability Office report on U.S. DOE Technology Transfer (GAO-09-548), 2009.

As a national laboratory, TRIUMF must bring together the talents and resources of Canada to advance the country's innovation objectives. With a solid connection to Canada's world-class university-research system and long-time experience in delivering complex programs and projects on time and on budget, TRIUMF provides a unique platform for innovation, collaboration, and commercialization. Although breakthroughs and inventions are not individually predictable, a firm commitment to innovation from the leadership and staff of a laboratory makes a critical difference.

The Jenkins report, "Innovation Canada: A Call to Action," identified four complementary inputs to innovation when R&D is a key driver: ideas and knowledge; talented, educated, and entrepreneurial people; networks, collaborations, and linkages; and capital and financing. Through its partnerships with Canadian universities, TRIUMF develops and accesses the ideas and knowledge. Through industrial partners and AAPS, Inc. TRIUMF accesses and develop the talented personnel. Through its collaborations domestically and overseas with researchers, laboratories, and business, TRIUMF develops the networks and linkages. Access to capital and financing is almost always a bottleneck, but the creation of AAPS, Inc. is a powerful step forward: AAPS has its own limited capital as well as access to the broader community of business investors.

The Board of Management has developed a policy statement to control the amount of "contract research" that TRIUMF undertakes. With limited resources and a basic-research mandate, the laboratory uses the following considerations for evaluating involvement in externally proposed projects for innovation and industrial partnerships. This policy is a combination of what the laboratory is prepared to do and what it is not:

- TRIUMF does not generically undertake "work for others" (i.e., work for hire). Exceptions are not prohibited.
- TRIUMF does have a mandate to drive and develop new technology.
- Any project with a private-sector partner should be formalized and agreed to using the TRIUMF project management framework if it is above threshold for resource usage.
- A project with a private-sector partner should advance the TRIUMF research program. Licensing the technology would be a natural follow-up, and intellectual property is not generally given away.

In this context and beyond the conventional model of simply patenting an invention and launching a start-up company to sell the product, TRIUMF's partnerships drive business development and commercialization through three primary channels:

- TRIUMF's expertise is in demand by companies who are looking to enhance their revenue-generating activities. By making this expertise available on a selected basis, either through licenses or by contracting out employees, TRIUMF not only helps these companies, it increases its own expertise and capabilities. (Example: Nordion, Inc.)

MDS NORDION & TRIUMF TO COLLABORATE ON URANIUM-FREE ISOTOPE PRODUCTION

28 April 2009

TRIUMF and MDS Nordion, a leading global provider of medical isotopes and radiopharmaceuticals used in molecular medicine, announced on Tuesday, April 28, 2009, that they have signed an agreement to study the feasibility of producing a viable and reliable supply of photo-fission-produced molybdenum-99 (Mo-99) used globally for diagnostic medical imaging. MDS Nordion and TRIUMF will also provide their respective expertise and resources to collaboratively develop a commercialization plan, which will include an operations plan, business model, and time lines.

Medical isotopes produced using photo-fission employ the use of a linear accelerator rather than nuclear reactors. As such, the need to ship and handle highly enriched uranium is eliminated in favour of naturally occurring uranium. The photo-fission technology is based on superconducting radiofrequency cavities to achieve the high levels of beam power required to produce the isotope.

"With the superior level of the science at TRIUMF, combined with Nordion's market and technical expertise, we seek to provide a flexible, reliable and responsive medical isotope solution to potentially strengthen the global supply chain," said MDS Nordion President Steve West.

- TRIUMF trains people in specialized areas of expertise, and these people, in turn, take their expertise to existing companies or to start new companies. (Example: D-Pace, Inc.)
- 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 increases their bottom line. TRIUMF may also help the company develop access to new markets. (Example: PAVAC Industries, Inc.)

Fueled by the Centres of Excellence for Commercialization and Research (CECR) program of the federal Networks of Centres of Excellence virtual agency, TRIUMF has added a fourth mechanism for industrial interactions with the formation of Advanced Applied Physics Solutions, Inc. This non-profit company, AAPS Inc., has a primary mission to develop the most commercially viable technologies arising from TRIUMF and to exploit new ideas that arise through interactions with TRIUMF's university owners and corporate partners. In this way, AAPS expands TRIUMF's capability and capacity for commercial impact.

When promising inventions and innovations arise at TRIUMF, AAPS will assemble a collaborative team to evaluate and develop the commercialization potential, and then launch a new spin-off company using the intellectual property. Not only has AAPS supplied direct expertise on projects where TRIUMF is developing new technology for industrial use (such as the production of the medical isotope technetium-99m using existing commercial cyclotrons), but AAPS has also challenged TRIUMF's leadership and its staff to recognize and bring forward potentially relevant technologies for commercialization (such as geotomography using cosmic rays).

AAPS enhances a distinct class of TRIUMF-industry interactions by providing expertise in contract management, IP control and technology licensing, product development, business planning, market analysis, fund-raising, and corporate governance. AAPS operates in the sphere of commercializing technologies by connecting TRIUMF intellectual property with either real-world investors (e.g., creating a start-up such as IKOMED) or real-world industrial partners (e.g., ACSI, Inc., for the high-resolution magnetic separator device). TRIUMF scientific and engineering staff need the expertise and guidance of AAPS to navigate, survive, and ultimately succeed "out there."

TRIUMF's industrial partnership and business-development activities are organized around four main business lines. In each of the areas, TRIUMF has specialized expertise and equipment that attract industrial partners.

- Irradiation Services. TRIUMF's accelerators provide beams of particles that can be used to probe materials to reveal their structure or bombard systems to examine their performance in elevated radiation environments. The space industry and segments of the high-performance electronics sector are steady customers.
- Isotope Production and Chemistry. TRIUMF's research program in nuclear medicine has developed core competencies in the production of isotopes using a variety of cyclotron and target technologies. TRIUMF also has expertise in the purification, processing, and chemical synthesis that attaches the isotopes to biologically relevant molecules for medical imaging or treatment. These capabilities are regularly in demand by the private sector.
- Technical Consulting. TRIUMF's capabilities in physics, engineering, and design are often tapped in the form of short-term technical consulting arrangements. TRIUMF staff might contribute to trouble-shooting a private company's product line or provide advice in developing needed high-tech infrastructure. TRIUMF's contributions to the success of AAPS, Inc. projects fall into this category.
- Professional Training. Last but extremely important, TRIUMF provides training experiences for highly skilled workers ranging from apprentices and journeymen in the technical trades to professional development of scientists and engineers through courses, workshops, and conferences.

With each industrial partnership, TRIUMF develops Canadian business in several ways. TRIUMF might provide direct technical assistance to the company on a product line or a platform for product development. Or it might be involved with a vendor to enhance an existing product to meet an application needed for TRIUMF's research program. Finally, TRIUMF might also collaborate with a company to investigate and develop a new technology, market, or service offering. One example of an industrial partnership is with Nordion, Inc, a relationship that won a NSERC Synergy award in 2004.

The business partnership between TRIUMF and Nordion Inc. is a well-known and successful example of technology transfer involving isotope-production technologies, and it certainly is the lab's largest model of success. The mixing of the laboratory's academic culture (TRIUMF is, after all, owned by universities), and the business culture has taken time and effort to develop, but it is by all measures a smooth and profitable partnership. During a period when federal and provincial governments are seeking to enhance Canada's competitiveness with the best economies in the world, it is certainly the time to develop new success stories.

> "Norsat International Inc. ("Norsat") (TSX: NII and OTC BB: NSATF), a leading provider of broadband communications solutions, announced today that one of its Ka-Band BUCs was recently used in an antimatter study called the ALPHA (Antihydrogen Laser Physics Apparatus) experiment at the CERN Laboratory located near Geneva, Switzerland."
>
> Business Wire, "Norsat Ka-Band BUC Unit Used in CERN Laboratory in Antimatter Research," 22 Dec 2010.

3.3 SELECTED EXAMPLES

3.3.1 ARIEL

The ARIEL project, from its inception, through the funding application, to the project execution, is a prime example of how TRIUMF works with its partners in Canadian universities, various international laboratories, and Canadian industry to the benefit of Canadian science, students, and the economy.

The CFI (Canada Foundation for Innovation) proposal for the ARIEL project was enabled through a broad consortium of TRIUMF member universities under the leadership of University of Victoria with Dean Karlen, joint TRIUMF/UVic appointment, as principal investigator. The UVic group is also making major contributions to the e-linac front end, including the development of diagnostics elements to characterize the high-intensity electron beam. The technical development of the e-linac is ideally suited for the education of graduate students in accelerator science; as such, TRIUMF has initiated Canada's only graduate program in accelerator science with graduate lectures at UVic and UBC. Several graduate students from Canadian universities are carrying out their Ph.D. projects in this program and working directly on the e-linac.

The electron gun and the injector cryomodule (ICM) of the e-linac have been developed in close cooperation with the VECC laboratory in Kolkata, India, under the auspices of a cooperative MOU signed in 2008. Using substantial investments by VECC, two electron sources and ICMs are being constructed: one for the ARIEL e-linac and one for the corresponding ANURIB project in India. The VECC MOU also enabled the implementation of a test stand that expedited validation of the front-end design including beam parameters and beam optics that fed into the final choices for the Electron Hall and ARIEL building.

NORDION, TRIUMF, AND THE UNIVERSITY OF BRITISH COLUMBIA ANNOUNCE PARTNERSHIP TO DEVELOP NEW DIAGNOSTIC IMAGING AGENTS

May 4, 2009

Nordion, TRIUMF, and the University of British Columbia announced that they have entered into a three-year research and development partnership to pursue the development of new diagnostic imaging agents—medical isotope products using technology based on radiometals and chelates.

Radiometals are a class of medical isotopes that has been the backbone of nuclear medicine for decades and are currently used in 80% of nuclear medicine procedures. Scientists will combine select radiometals with newly developed chelates—substances that bind to radiometals and protect them as they are carried through the body—with the goal to provide new agents for the diagnoses and treatment of cancer and heart disease.

"This strategic partnership with TRIUMF and UBC is expected to accelerate innovation, which could provide the opportunity to commercialize new molecular medicine products," said Nordion President Steve West. "Our combined capabilities and technical expertise will create a dynamic setting in which to develop new tools for physicians to detect disease earlier and more precisely, and to offer breakthrough treatments for patients."

International collaborations also facilitated other technical developments for the e-linac, including a cooperation with the Helmholtz-Centre Berlin, Germany, on the klystron providing RF power to the ICM; DESY Hamburg, Germany, on physical and chemical processing of the accelerating cavities; MPIK Heidelberg on the ARIEL electron beam ion-source (EBIS) charge breeder; and the U.S. Fermi National Accelerator Laboratory for the e-linac's cryogenic system. In each case, TRIUMF was able to tap into established international expertise and experience to more effectively advance its objectives.

ARIEL is also an excellent example of TRIUMF's cooperation with Canadian industry and efforts to bring high-technology solutions developed for Canadian science to the global market.

The chief technical element of the e-linac is the superconducting radio-frequency (SRF) cavity that performs the acceleration of the beam of electrons. Only four companies in the world had the ability to fabricate these components and none of them were in Canada. Recognizing the emergence of SRF as the technology of choice for modern accelerators, TRIUMF elected to develop and transfer its expertise to a local company, PAVAC Industries in Richmond, BC. PAVAC started as an electron-beam welding company, a vendor to provide one of the key assembly services required to make an SRF cavity. TRIUMF worked with PAVAC to master the entire fabrication and assembly process. Through the VECC MOU, TRIUMF made introductions to their Indian counterparts for PAVAC and the company promptly sold several multi-million dollar e-beam welder products to India. Furthermore, PAVAC has now been selected as the vendor of choice for the five SRF cavities needed for ARIEL and will also be contracted by India to make the SRF cavities for their ANURIB project.

The technology used for these cavities is also the technology of choice for the prospective international linear collider (ILC), which Japan has recently indicated an interest in hosting. The ILC would need on the order of 16,000 cavities for this next-generation particle-physics accelerator, and PAVAC is now well positioned to secure substantial contracts for this project, enabling a visible Canadian contribution to this world project. PAVAC's work with TRIUMF has also generated SRF contracts for the company in China, Japan, Korea, and the U.S.

The construction of the high-resolution mass separator, a set of precision magnets, for the ARIEL front-end will be carried out in cooperation with local industry with the aim to commercialize this technology. TRIUMF, AAPS, and ACSI—a leader in the production of the TR-series of medical cyclotrons based on a TRIUMF design—have teamed up to develop these very demanding precision magnets. They are of interest to numerous other laboratories in the world for projects that are either under construction or in the planning stage. This mass-separator project is part of a broader effort led by Saint Mary's University with the support of CFI via the "CANREB" initiative that also engages funding from the provinces of Nova Scotia, Manitoba, and British Columbia.

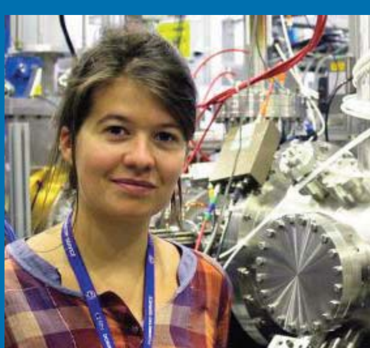
3.3.2 CYCLOTRON-PRODUCED TECHNETIUM MEDICAL ISOTOPES

Technetium-99m (Tc-99m) is the most widely-used radionuclide in diagnostic nuclear-medicine studies around the world. This radioisotope is used in 20 to 40 million diagnostic procedures worldwide annually, for purposes ranging from detecting bone metastases to detecting coronary artery disease. The conventional approach for the parent isotope molybdenum-99 or Mo-99 production involves the fission of weapons-grade uranium in a small number of aging reactors around the world. Alternative, safe, non-reactor and non-uranium based production methods of Tc-99m are known.

Based on evidence presented in a 1971 report from the University of Miami School of Medicine, Dr. François Bénard (BC Cancer Agency, UBC) with Thomas J. Ruth of TRIUMF spearheaded a joint proposal to produce and validate using Tc-99m from medical cyclotrons in 2009. The proposal engaged TRIUMF, the BC Cancer Agency, UBC, Lawson Health Research Institute (London, Ont.), the University of Sherbrook, Advanced Cyclotron Systems Inc. (ACSI), and was funded by NSERC/CIHR.

The effort was successful and established the feasibility of producing Tc-99m using particle accelerators already installed at major hospitals around the country. This research led to a second and third round of funding, this time from Natural Resources Canada (NRCan). The second round collaborators were TRIUMF, the BC Cancer Agency, Lawson Health Research Institute, the Centre for Probe Development and Commercialization (CPDC) (Hamilton, Ont.), UBC, and Advanced Applied Physics Solutions Inc. (AAPS). For the third round of funding, the collaborators were the same with AAPS taking a facilitating role for the development of the BC market. With a total investment of over $13M across these three efforts, the consortium has now successfully developed, and is in the process of commercializing, the competitive cyclotron-based production of Tc-99m.

The initial development work was funded by NSERC/CIHR, who support academic research, but as the project progressed to a more commercial focus the funding shifted to NRCan who were interested in alleviating shortages of Tc-99m (notably when Canada's NRU reactor ceases isotope production in 2016). The mix of collaborators is also relevant: it includes two research institutes (TRIUMF and Lawson), a provincial health-care agency (BC Cancer), a private company (ACSI), three universities (UBC, Alberta, and Sherbrooke) and two Centre of Excellence for Commercialization and Research (CECR) award recipients (AAPS and CPDC). While this may seem complicated, it reflects the collaborative nature of research with the different stake holders each playing an important role and the roles changing as the project progresses. The end result of all this collaboration will be a commercial product that saves lives, secures isotopes for Canadian patients, and generates economic benefit to the country.



TRIUMF STUDENT AWARDED CERN FELLOWSHIP

18 July 2013

UBC physics doctoral graduate and former TRIUMF researcher, Chloé Malbrunot was recently awarded a Senior Research Fellowship at CERN, effective this October in Geneva. As a member of the ASACUSA (Atomic Spectroscopy And Collisions Using Slow Anti-protons) Collaboration, Dr. Malbrunot studies the properties of antihydrogen and anti-matter.

Dr. Malbrunot was on hand from the early stages of TRIUMF's PIENU experiment through to its recent completion, which measured rare pion decays. Dr. Malbrunot credits this experience within the team to her successful application for the CERN fellowship this year:

"I learned a lot from the scientists, technicians, and different experts within the collaborative environment at TRIUMF, and am thankful to those from whom I learned for their contribution to this fellowship!"

As a Senior Research Fellow at CERN, Malbrunot will continue developing the spectroscopy apparatus needed to do precise studies of the properties of antihydrogen. The lack of precise and wide-ranging details about antihydrogen stands as a great challenge within physics today.

> **So far, the cost of using the process on a commercial scale is not known, though Bénard expects it would be cheaper than using a reactor. Bénard says another benefit of using medical cyclotrons instead of nuclear reactors is that a cyclotron produces no radioactive waste.**
>
> Vancouver Sun, "Team of BC scientists makes breakthrough in producing isotope for medical imaging," 09 Jun 2013.

3.3.3 CERN

Over the past five decades, experimental particle physics has coalesced into an increasingly collaborative global enterprise. The founders of TRIUMF had the foresight to appreciate that university physics departments with a small cyclotron or Van de Graaff generator in the basement could not hope to explore the energy frontier alone: they needed a joint venture. Those original efforts, which created TRIUMF and built the world's largest cyclotron, allowed Canadian universities to develop, own, and operate a facility big enough to nurture the engineering and technological skills required to remain relevant in a field that was rapidly transforming from regional to global.

CERN, born out of post-war Europe's need for collaboration not only among universities but also nations, has been a natural inspiration from the start. With improvements in communication shrinking the world, and the growth of high-energy physics collaborations from tens to thousands of participants, CERN has increasingly become not just a model but a home to experiments assembled in labs and universities around the globe.

TRIUMF has helped Canadian university researchers to design and build experiments destined for CERN since the early 1980s, when scientists from TRIUMF, UBC, and UVic participated in the ASTERIX experiment. More formal involvement began in the early 1990s when TRIUMF, Victoria, and the Université de Montréal collaborated on the silicon-strip microvertex detector of the OPAL detector at the Large Electron Positron Collider (LEP).

It was in the 1995–2000 Five-Year Plan that TRIUMF was given the mandate to act as Canada's main conduit for interactions with CERN and to develop and construct components for the Large Hadron Collider (LHC). Although Canada was not a member of CERN, universities across Canada wanted to be part of the world's only viable energy-frontier project. A mechanism for Canadian participation in the LHC through in-kind contributions made by TRIUMF provided the means. The agreement between TRIUMF and CERN involved a $30M contribution made up of $19M in equipment and $11M in TRIUMF labour. Initially, TRIUMF was asked to work on the conversion of the Proton Synchrotron (PS) and its Booster, to upgrade them for use in the LHC injector system. The LHC required proton beams with twice the brightness, more strictly controlled emittance, and different bunch spacing for LHC operation, a task well matched to TRIUMF's in-house expertise. The Canadian contribution included high-voltage power supplies for the PS Booster, all the magnets and power supplies for the upgraded transfer line between Booster and PS, new transformers for the Booster main magnet supply, and various related projects. Specialized beam instrumentation and electronics for the upgrade were developed at TRIUMF; in addition, the beam-dynamics group assisted in beam simulation studies towards higher

JAPANESE APPROVE FUNDING FOR UCN PROJECT AT TRIUMF

03 June 2009

The Japan Society for the Promotion of Science (JSPS) recently announced that it has approved the grant application to fund a new international user facility for Ultra-Cold Neutrons at TRIUMF. The project is a collaborative effort among over a dozen Japanese, Canadian, and U.S. institutions led by Professor Jeff Martin at the University of Winnipeg.

Ultra Cold Neutrons (UCN) are free neutrons that move very slowly (typically less than 30km/h), due to their low energies, allowing scientists to study their properties like never before. When completed, the UCN source at TRIUMF will provide the highest density of UCN in the world. It will enable a new generation of experiments on the fundamental interactions of neutrons to be conducted with higher precision than ever before.

As a result of this funding announcement, the Japanese component of the project has already begun to move forward with activities for explicitly siting the project at TRIUMF. These developments will take place over the next two years, with efforts in Canada having started as soon as Canadian funding was later secured.

currents in the Booster. By 2000 TRIUMF had completed all of the tasks included in the PS conversion. By the end of that year, the nominal LHC beam with the required protons/bunch in an emittance below the allowed limit—and with 25 ns bunch spacing—was produced in the PS.

In 1998, TRIUMF had initiated prototype developments on two large projects for the LHC itself. The first involved development of a resonant charging power supply for the LHC injection kickers as an in-house project and the second, working with industry, the fabrication of a prototype twin-aperture quadrupole magnet for the focusing elements of the beam-cleaning insertions of the LHC. In 2002, TRIUMF and CERN signed an extension to Canada's agreement that involved substantial Canadian industrial partnerships in the design and fabrication of components. The largest and most important item in this extended contribution was a series of 52 twin-aperture warm quadrupoles for LHC beam cleaning. These magnets had to be assembled with much higher precision than is common for normal quadrupole magnets due to the small aperture required to get the necessary high field gradient. Series production began at ALSTOM Canada in Tracy, Quebec in 1999. This work required ALSTOM Canada to meet much higher assembly tolerances than their previous experience in fabricating generators for the power industry and to set up improved quality assurance procedures for this type of work.

Funding at a level of $11.5M for the completion of this ambitious project, which also included the production of the components for four LHC injection kicker systems, was part of TRIUMF's Five-Year Plan 2000–2005. The power supplies, pulse-forming networks and switch tanks for the kickers were completed and shipped to CERN where they were installed between 2005 and 2006.

All of the Canadian contributions to the LHC were selected based on the technical expertise that existed or could be developed at TRIUMF as well as the availability of Canadian industry to supply a high fraction of the components. Approximately 90% of the total contribution was spent in Canada. There were a number of spin-offs from this activity. The companies I.E. Power, Inverpower, and Digital Predictive Systems in Ontario were awarded $3.7M in contracts for high current power supply design and fabrication for the PS conversion project, and the expertise gained in developing high-precision pulse mode power supplies subsequently allowed them to compete favourably in the international market.

They went on to receive contracts in excess of $10M from Brookhaven, Los Alamos, SLAC, Argonne, and the Canadian Light Source. Likewise, ALSTOM took the quality assurance procedures they created during magnet construction and used them elsewhere in the plant. The company and its subcontractor for the coil fabrication were asked to bid on other magnet projects.

Today, these major in-kind contributions to the CERN accelerator complex have made it possible for TRIUMF and the Canadian university community to participate in the ATLAS experiment at the LHC, as well as several other parts of the CERN program. The University of Calgary became a member of TRIUMF through its participation in the ALPHA antihydrogen experiment at CERN. McGill University, which has recently joined TRIUMF, has collaborated for years on nuclear physics experiments both at TRIUMF's ISAC and at CERN's ISOLDE.

The results from experiments conducted at CERN are revolutionizing our understanding of matter, energy, space, and time. LHC operations are currently supported by CERN member states to the benefit of all participating countries. This model—requiring member states to commit to sustaining the laboratory on a long-term basis, while allowing countries like Canada to participate in specific projects by means of in-kind contributions—is being stretched and will likely give way to a more equitable, "pay-to-play" model within the next 5-10 years.

Over 300 Canadian researchers, graduate students and technical staff are currently involved in the CERN program. Of the nearly 100 graduate students working at CERN with Canadian universities, a third have scholarships and a quarter were recruited from outside of Canada. TRIUMF's involvement in CERN puts Canadian universities and industries on the world stage.

3.3.4 ULTRA-COLD NEUTRONS

TRIUMF is in the process of installing a new beam line and spallation target in its Meson Hall. This new infrastructure will form the basis for the Ultra-Cold Neutron (UCN) facility that seeks to discover an electric dipole moment (EDM) of the neutron. The project is only possible through the close collaboration of TRIUMF with a number of university partners in Canada and in Japan as well as in Canadian industry.

The project is funded in its initial stage through a CFI grant along with matching funds contributed by the two major Japanese laboratories: KEK near Tsukuba and RCNP in Osaka. In addition, the Manitoba company Acsion Industries is contributing its nuclear-engineering expertise for the design of the neutron moderator.

On the Canadian side, the collaboration includes researchers from University of Winnipeg, University of Manitoba, University of British Columbia, University of Northern British Columbia, Simon Fraser University, and TRIUMF. TRIUMF is responsible for the implementation of the beam line and spallation target, and the Canadian collaboration is expanding its involvement with various aspects of the source and EDM experiment itself. The Japanese collaborators provide beam line magnets, the UCN source itself, as well as a first version of the EDM experiment, and contribute to the procurement of the liquid helium recovery and liquefaction plant, the first stage of which is currently being installed.

The design of the kicker magnet, which will kick bunches of the proton beam away from BL1A into the new beam line, was carried out with strong input from CERN, which had recently completed the design of a similar magnet for the hadron therapy facility, MedAustron, in Austria.

Japan will invest around $2M in this project in addition to $2M of in-kind contribution for the experiment itself. In addition, the project will benefit from a soon-to-be-launched KEK office at TRIUMF, a first of its kind outside Japan that will provide support for Japanese researchers at TRIUMF, not just the UCN project, but also users of the ISAC and materials-science facilities.

3.3.5 COMBINED STRENGTH IN SUBATOMIC PHYSICS: PERIMETER INSTITUTE, SNOLAB, AND TRIUMF

In Canada, there are three institutions with a common interest in subatomic physics: The Perimeter Institute for Theoretical Physics (PI) in Waterloo; SNOLAB, with laboratory space situated two kilometers below the surface in the Vale Creighton Mine located near Sudbury; and TRIUMF in Vancouver. Each institution has a distinct niche in the Canadian scientific ecosystem. The PI's raison d'être is theoretical studies of fundamental physics; SNOLAB is dedicated to low-background experiments primarily relating to neutrinos or dark matter, and TRIUMF is a more broadly-based facility with both theoretical and experimental physics capabilities and technical, computing, and engineering facilities. There are multiple points of contact between TRIUMF and the theorists at PI in terms of defining research avenues, evaluating and interpreting physics results, and synthesizing the larger picture. To support these interactions, TRIUMF and PI have signed a formal MOU that outlines a framework of regular personnel exchanges, joint meetings (especially the theory/ATLAS experimentalist joint meetings), and coordination of student opportunities. TRIUMF and PI also participate in a national award recognizing the top high-school physics teachers in each province.

TRIUMF was involved in the original SNO experiment through two TRIUMF scientists and an engineer working on the project. In addition, SNO used TRIUMF's technical facilities in the development and testing of components for their detector. A joint appointment between TRIUMF and Carleton University became the principal investigator of the SNOLAB proposal and its facility development director. Since then, TRIUMF has been involved in a number of SNOLAB experiments: SNO+, HALO, Super-CDMS, and DEAP3600. The partnership is two-way. SNOLAB capitalizes on the accumulated technical expertise, including a TRIUMF engineer residing at Carleton University, and capabilities at TRIUMF, and TRIUMF scientists participate in some of the world's most competitive low-background, underground experiments at SNOLAB. SNO+ has used the expertise of the TRIUMF Design Office and Machine Shop to design and construct the Universal Interface (UI), and TRIUMF is involved in DEAP3600 with a research scientist leading the effort to design and construct the readout electronics and oversee the machining of the light guides in the scintillator shop of TRIUMF's detector facility. A TRIUMF scientist is also involved with the HALO experiment, which studies neutrinos from supernovae.

In addition to the purely technical collaborations, the three institutes have teamed up to run an annual summer school for graduate students, the Tri-Institute Summer School on Elementary Particles (TRISEP). Its location rotates between the three institutes. The first one was held in July 2013 and was well attended. The next one will be at SNOLAB in 2014, followed by PI in 2015, and a return to TRIUMF in 2016.

3.4 SUMMARY

By nature, TRIUMF works with partners in the government, university, and industrial sectors—and these partners extend outside of Canada to international locations. By applying specific criteria that focus on advancing TRIUMF's mission, these partnerships ultimately add value to the investments made by the Canadian taxpayer.

GLOBAL SCIENCE AS GLOBAL ENTERPRISE

The European Centre for Nuclear Research (CERN), based in Geneva, Switzerland, is often cited as one of the most important scientific legacies of the aftermath of World War II and is credited with forging intellectual and cultural connections among a broad, multi-national scientific community—CERN's Large Hadron Collider (LHC) is the largest global science project ever built.

But what actually makes a science project global? Essentially just three ingredients: mutual scientific interest, pooled resources and/or investment, and opportunities for shared impact.

Mutual Scientific Interest

Humans are curious by nature, always asking "Why this?" or "Why that?" and even sometimes "Why me?" The practice of science fulfills our quest to understand the world around us. But not everyone is interested in the same science. Biologists are fascinated by the mechanisms of life, physicists love to reduce observed phenomena to basic principles, and chemists look at the principles that govern our daily experience of the world. Some science questions are global. How old is the universe? How did life evolve? What is inside a proton? These questions excite many minds across the planet and anthropology shows that mankind has been fascinated with these questions for thousands of years. Global science, therefore, is science that many, many people are curious about.

Pooled Resources and Investment

Global science is often called "big science" or even "megascience" (although these days, perhaps we need an upgrade from mega to peta or exa). The manned mission to the Moon was almost global science; one nation, roughly on its own, completed this feat. Global science requires the combined resources and talents of multiple countries to design, build, and operate its major tools. Astronomy is in this category with the growing family of telescopes and telescope arrays populating the Chilean desert. Aspects of particle physics are in this category, too, namely the "energy frontier"– dealing with questions about the origins of mass or whether dark matter is really a particle that springs from modifications to our beloved Standard Model.

CERN's LHC fits exactly in this category; depending on how you do the accounting, the project cost more than $6 billion and took advantage of significant existing infrastructure at CERN. Such an amount actually exceeds many national budgets for total annual investment in basic research. A number of global scientific disciplines now pool resources to assemble the capital investment required to design and construct a megascience facility. This model is being stretched in the present day as annual operating costs (typically 10% of the total capital investment) are themselves becoming large enough to be shared or distributed among multiple countries.

Opportunities for Shared Impact

The third ingredient for global science is perhaps the most critical because it is the glue of the global effort: globally realized and relevant returns. Sure, particle physics is intrinsically interesting and inspires young minds to pursue training in science, technology, engineering, or mathematics. But is that generalized bonus sufficient to justify dozens of countries spending a billion dollars per year to probe the energy frontier?

No. The LHC is not just a globally coordinated extra-large Shakespeare Festival. The pursuit of the science at the LHC actually provides real technological and intellectual value to every participating country. Certain technologies may be invented in the design and construction of the LHC and these technologies are likely to have an impact all around the world. The most direct way to be involved in the development, distribution, and deployment of these technologies is to be directly involved in the project.

This, then, forms the two-way give-and-take relationship of global science. Countries with common scientific interests pool resources to develop the next scientific instrument needed to attack the frontiers of knowledge. The world at large will, ultimately, enjoy the benefit of any discoveries. The participating countries have an extra benefit: not only are they involved in the creation and engineering of new technologies, but they are "at the table" of anything that is developed. Consider the global science project called ITER, the International Thermonuclear Experimental Reactor. This device is the next step on the research and development path of harnessing nuclear fusion for energy. The participating countries are certainly intellectually interested in the detailed properties of confined, high-temperature plasmas, but they are also extremely motivated to have a share of the eventual technology, either to replicate and fuel their own domestic energy needs, or, better yet, to commercialize and sell it to other countries.

Working Together

The LHC is a global science project. There will be future global science projects, and CERN is well positioned to offer the organizing framework. It no longer makes sense to restrict CERN to facilitating ongoing cooperation among just European nations. It is time to consistently and regularly coordinate global science activities.

As CERN picks up the discussion of expanding its membership base to include countries outside Europe, it is a validation of the natural evolution of our global connectedness or our "flattened" world. It is a statement that our mutually shared scientific appetite can be satiated through coordinated investments that bring positive benefits to everyone, and in a world where time-to-market dictates the winner, those benefits go first to the primary participants.

These are the types of considerations that each country will be weighing and judging as they consider a more formal partnership with CERN, perhaps as an associate member. Canada, which has contributed nearly $150M over 15 years to the LHC and the ATLAS detector, is certainly mulling it over. A commitment to an international science venture with CERN is an invaluable opportunity and one that requires careful analysis. If the program shifts too much to CERN, what scientists and students will remain in Canada to reap the benefits of participating in the world's best particle-physics laboratory?

The Government of Canada has identified that future economic growth will come from a knowledge-based economy, one that expands beyond natural resources and added manufacturing value. Formal strategic international partnerships are one vehicle to accelerate (no pun intended) that approach.

There is a distinct advantage for Canada when its scientists connect with the best in the world, and vice versa. Canada contributes unique value to the global enterprise (the cleaning-insertion magnets, which transfer the LHC beam into the final ring, were designed and built in Canada). Working with the best keeps the home team competitive, plugged-in, and up-to-date. These are the downstream, long-term benefits that make it all worthwhile.

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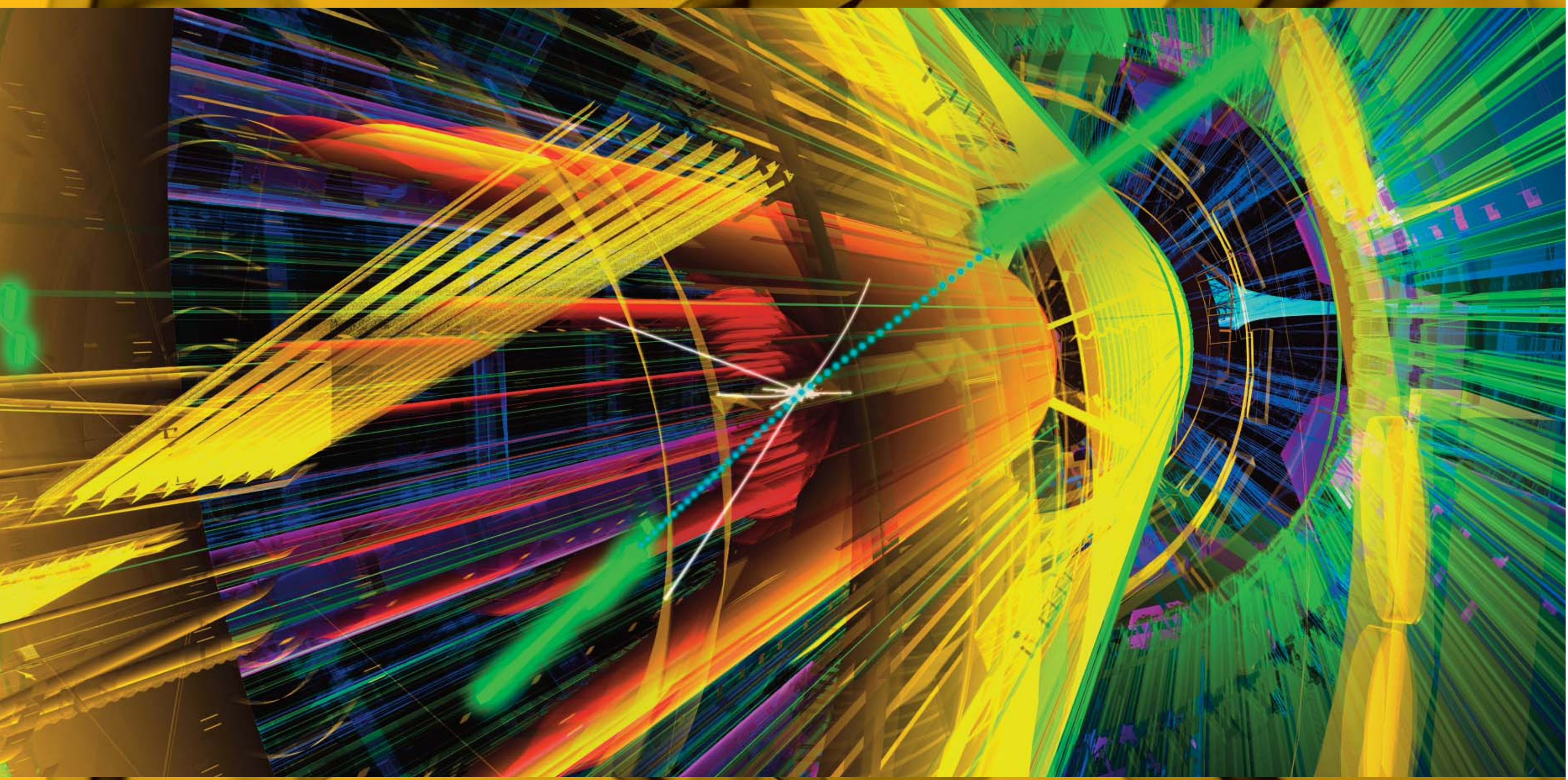
Successes

Highlights from 2008–2012

4



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4.1 INTRODUCTION

The scientific enterprise drives three basic benefits for society: advancing knowledge, creating future leaders, and generating direct societal benefit and economic growth. This chapter is organized to show how TRIUMF has contributed to each of these three areas. The recent successes enjoyed by TRIUMF in all three areas have been noteworthy. This is evidenced by the quantity and quality of publications, by the positive attention received from the press, by the number of invitations TRIUMF scientists receive to speak at conferences, by prestigious awards, and by the success of companies TRUIMF has helped foster.

TRIUMF is working to advance knowledge on many fronts: fundamental constituents of matter and their interactions, strongly interacting systems, from nuclei to stellar explosions, nuclear medicine, molecular and materials science, and accelerator science (please see Figure 1 in Section 2.2. for an overview).

The first three of these fronts can be combined under the rubric: subatomic physics. The study of subatomic physics is the study of the entire spectrum, from nuclear to ever-decreasing sub-nuclear scales. TRIUMF scientists are not only involved in but are leaders at both extremes of the scales, and this is an impressive feat. Understanding the nature and origin of elementary particles and the forces that are responsible for their interaction is a key area of research at TRIUMF. The parameters of the Standard Model of particle physics have been tested to extreme precision and so far attempts to disprove any aspect of it have failed. But while physicists have established with great precision the overall validity of the Standard Model to describe the bulk of matter, the ongoing task is to obtain a deeper understanding of its applicability to a wider range of phenomena. Strong evidence for the Higgs particle, a key component of the Standard Model, has come about recently through the ATLAS experiment, and its properties are being investigated. Canada and TRIUMF have played a well-recognized leadership role within the international collaboration.

Our quest has shifted from testing the Standard Model to looking for chinks in the armour, and this can be done through searches for new particles. These searches involve very high precision measurements of Standard Model observables, or of phenomena forbidden or suppressed in the Standard Model. Indeed, these "indirect" signatures of new physics can probe very large energy scales, i.e., scales that are not accessible in the laboratory. The lightest new particle may be a candidate as dark matter particle and searches are ongoing. Nuclear physics measurements of the electric dipole moment can also probe very large energy scales and provide complementarity, and experiments conducted at TRIUMF are poised to lead the way in this field. Other high-precision tests are being carried out with antihydrogen or by using the atomic nucleus as a laboratory.

Properties of the elusive neutrino have been extensively studied by TRIUMF scientists at experiments based at accelerators (T2K) and deep underground (SNO). The TRIUMF-conceived "off-axis" method for long baseline neutrino measurements is now used worldwide. Massive neutrinos and neutrino oscillations have challenged the Standard Model, and with recent confirmation (T2K) of one type of neutrino transmutation that allows sensitivity to CP violation, this will open the path towards a better understanding of the origin of matter-antimatter asymmetry in the universe from neutrinos.

The theory of strong interactions (QCD) is relevant for a large part of the TRIUMF subatomic program, from ISAC to the Large Hadron Collider at CERN. QCD, through a low-energy effective theory, is the basis for understanding the interactions that bind nuclei. It is used to explain the structure of hadrons, and also to form the theoretical foundation for nuclear physics studies, providing a useful meeting ground between theory and experiment.

Primordial nucleosynthesis is the formation of nuclei that occurred during the cooling immediately following the Big Bang, producing H, He, and Li. All other chemical elements in the universe were produced as a result of nuclear reactions occurring in stars, during supernovae explosions, novae, neutron-star mergers, etc. It is a central goal in physics to explain the origin of matter in the universe, and nuclear astrophysics addresses the many fundamental questions involving nuclear physics.

Studying matter under extreme conditions, such as very high densities and temperatures and/or extreme proton-to-neutron ratios is undertaken at the unique facilities provided by ISAC. Under such conditions, very short-lived exotic nuclei are produced that do not exist under "regular" everyday conditions but that play decisive roles in the understanding of key processes. This latter field has benefited enormously from the ISAC radioactive-beam facility that allows for the measurement of nuclear reactions involving nuclei of relevance to astrophysics. These include measurements of the various nuclear capture processes and the determination of masses, half-lives, and structures of rare nuclei that occur in cataclysmic stellar environments such as novae or supernovae explosions. The TITAN experiment measures the mass of short-lived isotopes with high precision, but also demonstrates the reach of such an experiment to astrophysics, fundamental symmetries, nuclear isomers, and laser and X-ray spectroscopy. Jens Dilling (the leader of TITAN) and Ritu Kanungo (a leading TRIUMF collaborator from Saint Mary's University) were among the select invitees of the 152nd Nobel Symposium in Gothenburg, Sweden, on *Physics with Radioactive Beams*.

As a multi-program laboratory, TRIUMF also supports interdisciplinary projects that cut across the traditional academic disciplines. 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 were developed at TRIUMF and a cryostat was built with TRIUMF expertise.

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. 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.

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 quadrupole resonance). The CMMS program now encompasses these techniques. To date, β-NM(Q)R 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 mono-layers. β-NQR can also be used to measure the ground state quadrupole moment of a nucleus.

The nuclear medicine program at TRIUMF is supported by the strength and expertise of the accelerator scientists who provide isotopes and radiopharmaceuticals for biological and imaging studies. The power of accelerators and beams for the production of isotopes is particularly noteworthy in this Five-Year Plan because a solution was found to the Tc-99m crisis. Through TRIUMF's leadership, three institutions in Canada are now capable of producing Tc-99m using cyclotrons, paving the way for a safe, secure supply of this critical isotope for years to come. Many cardiac and cancer patients will continue to receive life-saving medical scans after the cessation of isotope production from Chalk River in 2016.

Training future leaders is an important part of TRIUMF's mandate. It provides direct research experiences and informal science education for thousands of people, helping them to thrive in the increasingly technology driven world. The training of highly qualified personnel is evident, not only for graduate and postdoctoral students—many of whom have moved on to prestigious positions—but also for technicians, engineers, etc.

The co-op program has been very successful, and the graduate student summer institutes have proven to be popular. The open houses and outreach events at TRIUMF and Science World BC at Telus World of Science, and in the local university communities, are popular and provide a vital link to the community.

Science is supported because it is perceived to be useful and indeed it is. TRIUMF puts great emphasis on not just learning about how the universe works, but on putting that knowledge, and the techniques used to acquire that knowledge, to practical use. One avenue is the medical program, which treats ocular melanoma and provides rare isotopes for medical studies.

A second avenue is the commercialization of TRIUMF's technical knowledge. In 2008, TRIUMF was awarded funds by the Networks of Centres of Excellence Program to launch a Centre of Excellence for Commercialization and Research called Advanced Applied Physics Solutions, Inc., (AAPS). In addition TRIUMF beams are used for a number of applications, including the irradiation of electronics components used in the space and aeronautics industry.

This chapter of the report expands on all these avenues, detailing the results and progress enjoyed over the past five years and sets the stage for the future. In the following chapter (Chapter 5) where the facilities are described, the role of TRIUMF in each of these activities is given along with a list of the national and international partners with whom TRIUMF has teamed up for each topic.

4.2 ADVANCING KNOWLEDGE

TRIUMF is predominantly a basic science laboratory that addresses fundamental questions in nuclear and particle physics, develops next-generation accelerator technology, and advances knowledge in nuclear medicine as well as molecular and material science. As described in this chapter, TRIUMF has made major contributions to this wide range of topics, resulting in numerous new and interesting discoveries and breakthroughs. In this report, the topics have been arranged by science theme, not by device or location. For example, the TITAN mass measurement apparatus produces results that have application in both nuclear structure and nuclear astrophysics. Hence the results from TITAN are discussed in different sections. Similarly the work of the Theory Group is discussed under the relevant science topic not as separate section with all the theory in one place.

4.2.1 FUNDAMENTAL CONSTITUENTS OF MATTER AND THEIR INTERACTIONS

Particle physics is dominated by the Standard Model. This model has been phenomenally successful in passing all experimental tests thrown at it, from the fine structure of the hydrogen atom to the recently discovered Higgs boson. But we know that it is not a complete description of even the known forces, as it does not include gravity. It also has a number of features that are not aesthetically pleasing, like its large number of parameters or the fine-tuning needed for the parameters. So we proceed on two fronts: First, we want to determine the parameters of the Standard Model and secondly, we want to find shortcomings that would drive a revolution in our understanding of the basic properties of nature.

There are two broad experimental approaches to attacking these problems. One is denoted as the energy frontier and the other the precision frontier. The first relies on producing ever more energetic beams of particles and the second on doing ever more precise experiments. The energy frontier produces results that are easier to interpret; the direct production of a particle leaves little doubt of its existence. The precision experiments, on the other hand, allow one to probe energy scales inaccessible even with the highest energy facilities available. But they leave room for doubt on the interpretation. Previous experiments had ruled out Higgs bosons over a variety of mass ranges. Fits to precision data constrained a Standard Model Higgs boson to a window of about a hundred GeV around the mass where it was eventually found. Although no viable theory existed to explain electroweak symmetry breaking without a Higgs mechanism, it was only by direct observation of a Higgs boson that the mechanism was finally confirmed.

TRIUMF is involved in both of these complimentary approaches to exploring the Standard Model and its extensions; the high-energy approach at CERN and the high precision approach at a number of sites including the TRIUMF laboratory itself. TRIUMF is also actively involved in the theoretical aspects of the problem.

4.2.1.1 DIRECT PARTICLE PRODUCTION SEARCHES

Particle physics is the study of the most fundamental building blocks of the universe. Some are ubiquitous: photons, electrons, the up and down quarks that form the protons and neutrons that make up the bulk of the visible universe, and the ghostly neutrinos that pass almost imperceptibly through it. These particles are effectively stable—a photon emitted in a distant galaxy can travel for billions of years before being absorbed in a human eye. There are other particles, however, which are no less fundamental (or "elementary") but are not stable: their lifetimes range from attoseconds to microseconds. To study their properties, we must first produce them.

An elementary particle is produced in the decay or annihilation of other elementary particles; in order to produce a child particle more massive than its parents, the original particles must be accelerated so that they have enough kinetic energy to convert into the required mass, $E=mc^2$. There also needs to be a force that couples the parent particle to the one being produced. These two characteristics—the mass and the couplings—determine the kind of accelerator required to search for a given particle. While the existence of particles too massive to be produced at an accelerator may be inferred indirectly in experiments at lower energies, their nature and properties can only be confirmed by producing them directly. The Large Hadron Collider (LHC) collides protons at energies of 7 to 8 TeV (1 trillion electron volts = 1 TeV), to be increased within two years to 13 TeV [1]. The ATLAS detector records the results of these collisions [2]. The following sections describe a number of searches (and one, now-famous discovery) (see Section 5.5.5.2).

The Standard Model (SM) of particle physics was developed about forty years ago to accommodate and explain all the elementary particles then known. It predicted the existence of a number of additional particles, which were subsequently produced and discovered at accelerators. The last of the particles predicted by the Standard Model to remain undiscovered was the Higgs boson. Without postulating the existence of an otherwise unobservable scalar field, of which the Higgs boson would be an observable quantum, it is impossible to construct a consistent (gauge invariant and renormalizable) theory with massive elementary particles. If such a scalar field exists, it can generate masses for the weak vector bosons (the W and Z), and its remaining degrees of freedom manifest themselves as massive scalar particles: the Higgs bosons. In the simplest case, the SM, there is only one of these. Higgs bosons interact through the electroweak force, and couple to fermions in proportion to their masses, as well as to the massive weak vector bosons. In order to produce Higgs bosons, it was necessary to build an accelerator that could produce large numbers of massive, weakly interacting particles that could decay to Higgs bosons.

The LEP (Large Electron-Positron) experiments established that the Higgs boson mass had to be greater than 114 GeV/c^2, and unitarity bounds suggest it should be less than about 1 TeV/c^2. Protons are strongly interacting particles, so most collisions at the LHC produce jets of strongly interacting particles: quarks and gluons. Only a tiny fraction of collisions can produce Higgs bosons; however, the total rate of collisions is so high that substantial numbers will be detected: the advantage of the LHC is in its very high collision rate (luminosity) and in its coverage of the entire mass-range of interest. The strongly interacting massive particles that are produced so copiously at the LHC also interact weakly, and thus sometimes decay to Higgs bosons, either directly or through intermediate decays to W and Z bosons, which can radiate Higgs bosons.

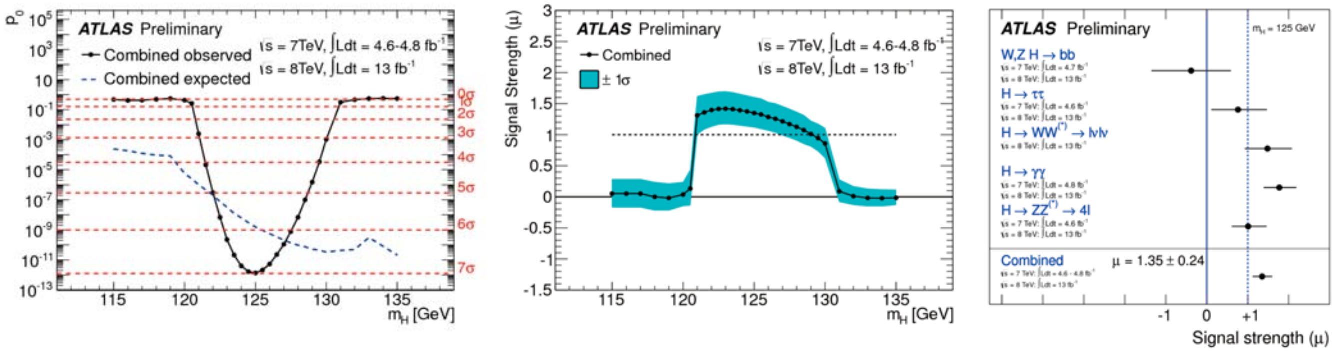

Figure 1: Left-hand plot shows consistency of data with background-only model (no Higgs boson); the middle plot shows the signal strength as a function of assumed Higgs boson mass. A strength of 1 corresponds to the signal strength expected for a Standard Model Higgs boson of the mass indicated on the abscissa—thus, a value near one indicates consistency with a Higgs boson of the corresponding mass, while a value near zero indicates consistency with the background-only hypothesis; the right-hand plot shows the signal strength for each decay channel, as well as for the combination.

Higgs bosons can decay in many different ways, depending on their mass, which is not predicted by the Standard Model. After analyzing 4.8 fb^{-1} of ATLAS data from 7 TeV collisions, and 13 fb^{-1} from 8 TeV collisions, significant excesses of events were observed with two photons in the final state, or with particles consistent with the decays of pairs of W and Z bosons. The numbers of events observed were significantly discrepant with numbers expected from decays of previously known particles, the combined discrepancy being at the level of more than five standard deviations, the gold standard for a discovery [3]. In all cases these excesses were consistent with the decay of a scalar boson with a mass around 125 GeV/c^2. Similar excesses were observed by the CMS experiment, also at the LHC, and the two experiments announced their results simultaneously on July 4, 2012. Since then, each experiment has published their results [4,5] and subsequently accumulated additional data [6], confirming the discovery (see Figure 1, Figure 2). Critical to these results was the superb performance of the ATLAS detector, including the hadronic endcap and forward calorimeters, designed and built at Canadian ATLAS Tier-1 Data Centre at TRIUM and by TRIUMF personnel at Canadian universities. The timely addition of extra resources at the Canadian Tier-1 computing centre at TRIUMF was essential for the prompt reconstruction and analysis of the data. Canadian researchers, including a number of TRIUMF research scientists and university-based faculty, as well as the post-doctoral researchers and students they supervised, played leading roles in the analysis, review, and production of these results.

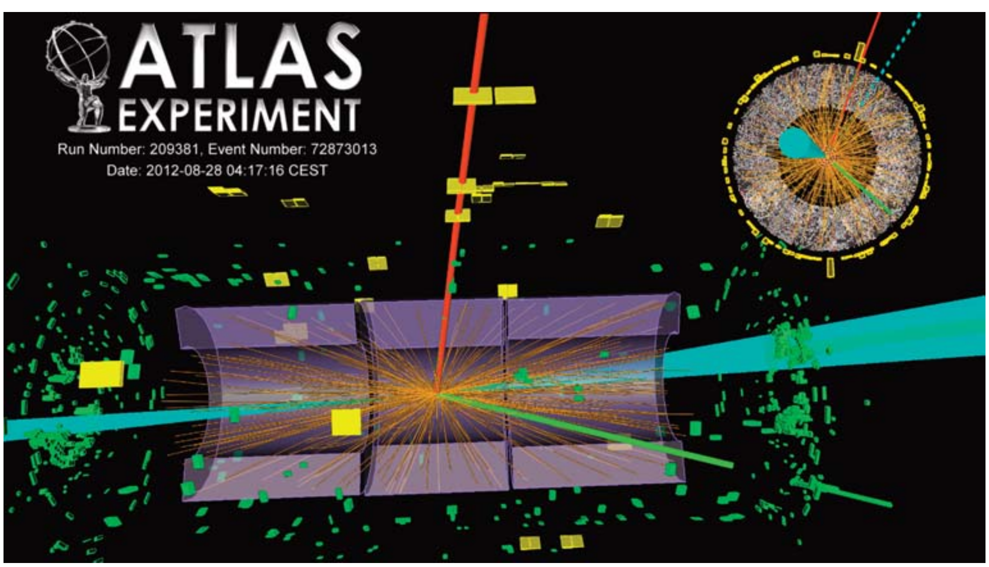

Figure 2: Candidate Higgs event from vector boson fusion, decaying to tau leptons (green and red narrow cones). The forward jets (cyan) in the hadronic end-cap (left) and forward (right) calorimeters are essential to identify vector boson fusion events.

Now that this Higgs boson has been observed it is important to establish its properties with precision. Higgs bosons with a mass in this range are expected to decay to a large number of different final states, with the fraction of each final state predicted by the Standard Model. The highest priority is therefore to search for all the final states predicted and confirm whether they are produced in the proportions expected. So far, the observed properties of the new particle are consistent with the predicted properties of a 125 GeV/c^2 Higgs boson. The new particle decays to pairs of photons, Z bosons, and W bosons; however, the ATLAS experiment has not yet reported a significant observation of decays to pairs of tau leptons or b-quarks. The observed results in the tau and b-quark channels are thus consistent both with the hypothesis of a Standard Model Higgs boson and with a background-only hypothesis. Other final states, such as Higgs decays to a photon and a Z boson, are so rare that there is as yet no sensitivity. It is also essential to confirm that Higgs bosons are produced in all of the expected processes, at the expected rates, which may be done by looking for Higgs boson production in association with other particles: ttH, ZH, WH.

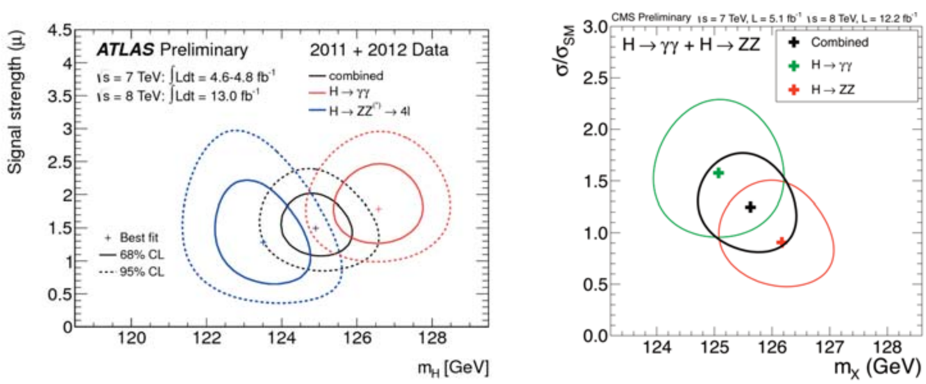

Figure 3: (Left) Mass of Higgs boson from the two high-mass-resolution decay channels; in the preliminary ATLAS results, these are compatible within 2.7 standard deviation; (Right) the CMS preliminary results show the 68% confidence level contours.

Another priority is determining with precision the mass of the new particle (see Figure 3), as this is an important input in fits of existing experimental results to the Standard Model and to other models that can be used to infer the existence of particles too massive to have been observed yet.

It is also possible to distinguish Higgs production through vector boson fusion (see Figure 2 again) from the more common gluon fusion, as the former often produces distinctive event topologies with jets in the detector endcaps (including the Canadian-built hadronic endcap and forward calorimeters), and the decay products of the Higgs boson in the central part of the detector. Canadian groups, including several TRIUMF group members, have been active participants in many of the Higgs boson search analyses, notably the W^+W^- final state, but also ZZ and two-photon signatures, and final states with tau leptons, particularly in the vector boson fusion topology.

While the analysis of the full ATLAS dataset of ~25 fb^{-1} has already confirmed that the newly discovered particle is indeed a Higgs boson, it remains to be seen if it is in fact *the* Standard Model Higgs boson or the first of a host of particles (including a SM Higgs) not predicted by the Standard Model. It is particularly interesting to study the kinematics of the final-state particles to determine the spin of the new particle, and confirm that it is indeed a scalar (spin 0). This work is in progress for the ZZ and W^+W^- final states [7]. The 0^+ state is found to be favoured over the 0^-, 2^+ and 2^- states with 0^- excluded by 2.7 standard deviations [8] compared to 0^+. The full data set should be sufficient to find evidence for Higgs boson decays to tau pairs and b-quark pairs (see Figure 1 again), confirming that the new particle does indeed decay to fermions as well as bosons.

The Higgs boson was the last particle predicted by the Standard Model to be discovered, but the Standard Model is a low-energy effective model that leaves too many open questions to be a complete theory. If there are other strongly interacting particles, so far unknown, and if they are not too massive, these should be produced in very large numbers at the LHC. Several extensions to the Standard Model predict such new particles: supersymmetry predicts that each quark has a scalar counterpart, a *squark*, which would be strongly produced. The LHC was designed not only to find the Higgs boson and complete the Standard Model but to be sensitive to the broadest possible range of models of new physics, including supersymmetry, models with extra spatial dimensions, and a variety of extensions of the Standard Model with additional gauge bosons or additional quark or lepton families. There are also models where particles currently thought to be elementary are found to have excited states, implying that they are in fact composite particles made up of more fundamental constituents. There are also various effective field theories designed to remedy some of the immediate problems of the TeV scale. In some of these, the role of the Higgs is played by composite particles; such models include Technicolor. Many of these models predict vector boson resonances and new vector-like fermions.

Searches have been made for excesses of events over Standard Model predictions in a wide variety of final states including leptons, jets from quark and gluon production, missing transverse energy consistent with the undetected escape of electrically neutral weakly interacting particles. These searches have increased the previous limits on a broad range of models, in many cases by orders of magnitude, but so far no evidence has been found for particles not predicted in the Standard Model. Only a selection of these searches can be described here.

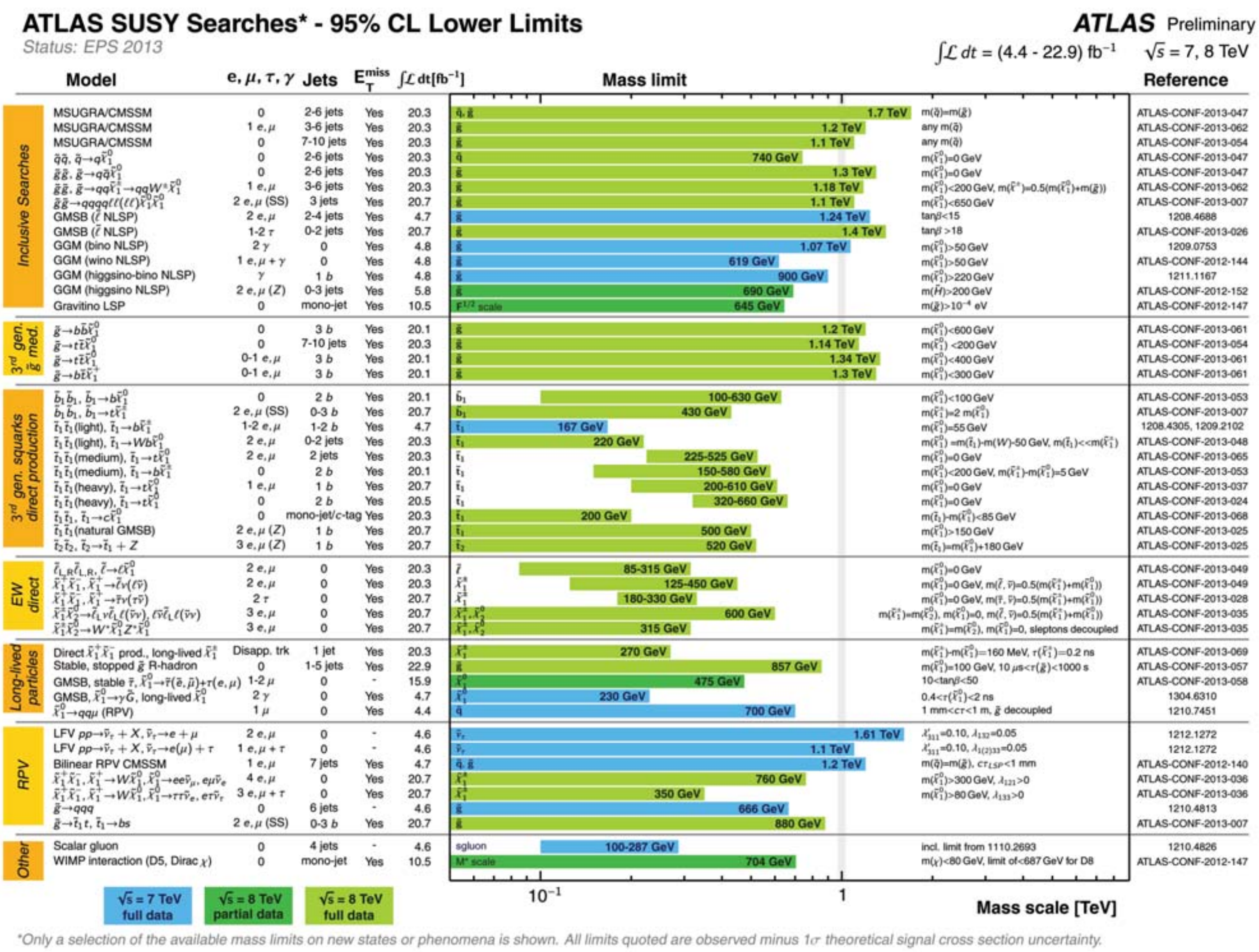

Figure 4: A selection of limits from ATLAS searches for supersymmetry (as of December 2012). The ATLAS-CONF note numbers on the coloured bars can be used to find the documents describing these results in detail.

Supersymmetry

Supersymmetry is an elegant theory which extends the Standard Model by postulating the existence of a scalar bosonic partner for each of the Standard Model fermions, and a fermion for each of its gauge and scalar field components, thus doubling the number of fundamental particles with the hypothetical "superpartners". Searches for evidence of supersymmetry fall into several broad categories, described in the following paragraphs. Figure 4 shows a selection of limits set by the ATLAS experiment on masses of supersymmetric particles; all of these have some model dependence, but most are now in the 100 GeV – 1 TeV range.

The LHC collides protons, which are made of strongly interacting particles called quarks and gluons. It is thus an ideal place to look for the supersymmetric particles that carry strong-force charges because we expect them to be copiously produced. There are therefore many generic searches for strong production of supersymmetric particles [9]. It is typically assumed that there is a conserved quantity ("R-parity") corresponding to the supersymmetric particles, and that the lightest supersymmetric particle (LSP) must therefore be stable. If the LSP carries no electric or strong force charge, and interacts only weakly, it is an ideal candidate for dark matter (see Section 4.2.1.2). ATLAS would not directly detect a particle that interacts only weakly, but is designed to be hermetic so that the escape of such a particle would leave a signature of unbalanced momentum in the plane perpendicular to the incident beams (also referred to as "missing transverse energy"); this is the key feature of most searches for R-parity-conserving supersymmetry. These searches for strong production of supersymmetric particles tend to set the strongest limits (see Figure 5) on generic supersymmetry models but are model-dependent and must be treated cautiously.

If supersymmetry were an unbroken symmetry, then the superpartners would have the same masses as the corresponding Standard Model particles. If this were exactly the case, then the divergences in the Higgs mass predicted at high energies due to loop contributions from the massive fermions, especially the top quark, would be cancelled by corresponding contributions from superpartner loops. While it is clear that supersymmetry is broken, because we have not observed scalar partners of the electron, muon, and other light fermions, this cancellation would still be possible if the masses of the top and its scalar partner (*stop*) were close enough. In so-called "natural" supersymmetry [10] considerations such as these imply that supersymmetric partners of the Higgs boson, top, and bottom quarks should not be too far above the weak scale. The rest of the spectrum, including the squarks of the first two generations, can be heavier and beyond the current LHC reach.

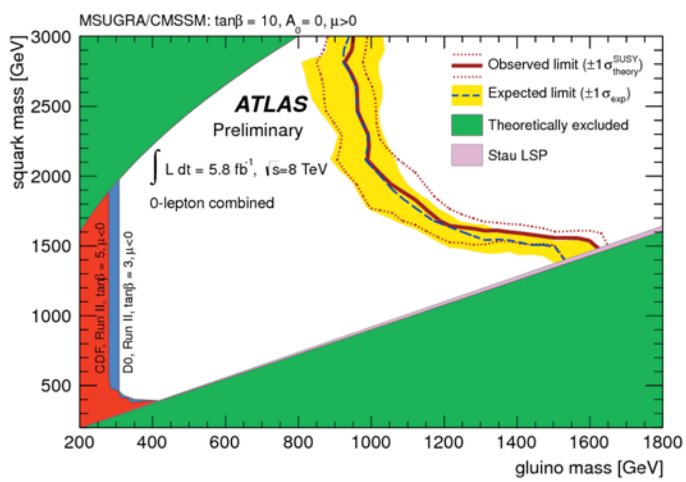

Figure 5: Limits on squark and gluino mass in the classic benchmark MSUGRA model, for the given parameter settings [19].

The second class of supersymmetry searches look for the direct production of the supersymmetric partners of the gauge and Higgs bosons. These fermions, which can mix with the partners of the Higgs bosons, are collectively referred to as "electroweakinos." Electroweakinos are produced in weak interactions, with much smaller cross-sections than the strong production referred to previously; however, with the large dataset now collected, we are able to look for these as well. The limits on weak gaugino production show that the LHC is already sensitive to the mass range relevant for demonstrating whether or not supersymmetry can

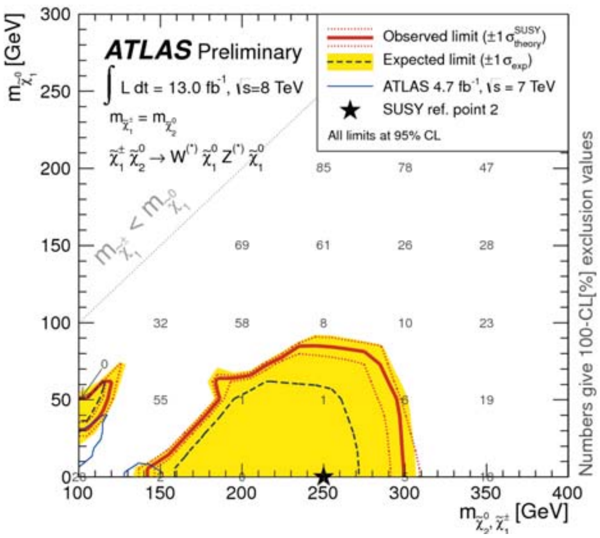

Figure 6: Limits on gaugino production in a simplified model assuming all gauginos decay to Standard Model gauge bosons and the lightest neutralino, which is the LSP.

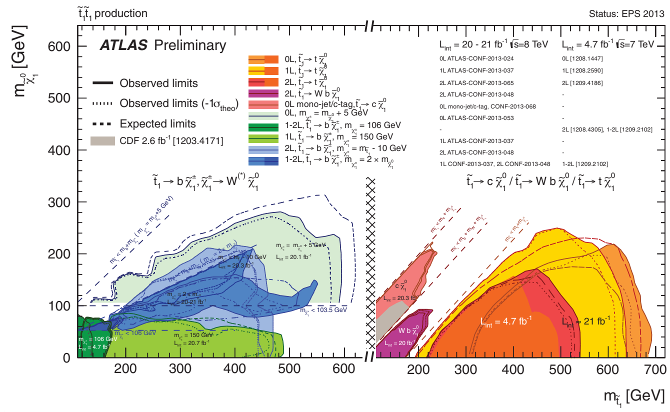

Figure 7: Current status of searches for the supersymmetric partner of the top quark at ATLAS, with several different assumptions about the stop and LSP masses indicated by the different colours. The "natural" preference is for a stop mass not too far from the top quark mass (which is 175 GeV) to cancel divergences in the Higgs mass from top quark loops. The legend refers to the ATLAS-CONF notes documenting these preliminary results.

(if it exists) actually furnish all the solutions to problems of the Standard Model that make it such an attractive theory. Good sensitivity is achieved for the models considered (see Figure 6), although the "interesting" mass region is by no means excluded for all possible models.

Because of the implications of "naturalness" for the partners of the top quark, a third class of searches looks specifically for the scalar partner of the top quark with masses relatively close to the top quark mass (that is, below about 1 TeV). How the stop decays depends chiefly on its mass, so several searches need to be combined; however, it can be seen from Figure 7 that much of the allowed parameter space is excluded for stop masses below about 500 GeV.

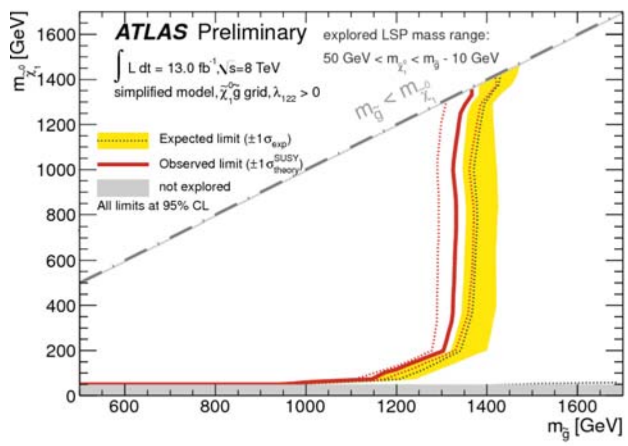

Figure 8: Limits on R-parity violating supersymmetry in a particular simplified model, where the gluino is strongly produced and decays to a final state with four leptons (electrons or muons).

A fourth class of supersymmetry searches abandons the assumption of R-parity conservation and includes a number of final states without missing transverse momentum, typically marked by pairs of leptons of the same flavour and charge, arising from the Majorana nature of the scalar partners of the leptons. While R-parity violating (RPV) supersymmetry lacks the stable LSP dark matter candidate that is such an appealing feature of other supersymmetric scenarios, and requires numerous constraints to avoid allowing flavour-changing neutral currents in Standard Model processes where they are already excluded, it is essential to consider that R-parity is simply an *ad hoc* addition to the model and cannot be assumed. Removing the assumption that supersymmetry signatures should include significant missing transverse energy opens up a host of possibilities (see Figure 8 for a particular simplified model). The LHC is able to probe well into the interesting region where supersymmetry could solve the Standard Model hierarchy problem, but the limits are very model-dependent and RPV supersymmetry is by no means excluded.

While supersymmetry is perhaps the most appealing theory for extending the Standard Model to higher energies and greater symmetry, it is by no means the only possibility. Other classes of models for "beyond Standard Model" physics can be roughly grouped according to whether they require compositeness of particles currently thought to be elementary, extra dimensions, additional gauge interactions, "hidden" sectors with new interactions that can communicate with the Standard Model particles either through "messenger sectors" or decays tunneling through from "hidden valleys".

Alternatively, models can be grouped by signature: for example, searches for two oppositely charged leptons and a photon can be interpreted as compositeness searches (for excited leptons), as Technicolor searches (invoking a new strong interaction at high energies), as Higgs boson searches (with the Higgs decaying to a Z boson and a photon), or as generic searches for new components of the electroweak interaction (triple-gauge-coupling measurements). The groups of signatures considered in ATLAS searches include: final states with leptons, final states with jets, final states corresponding to pairs of gauge bosons, final states including top quarks, and final states including long-lived particles (that is, particles which travel at least some measurable distance from the interaction point, and possibly right through the detector, before they can decay into Standard Model particles).

Perhaps the most striking of the lepton final-state signatures is the search for new, very massive neutral particles or narrow resonances (additional gauge bosons, Kaluza-Klein gluons, for example) decaying into oppositely charged pairs of electrons or muons (see Figure 9). Such resonances can be excluded up to masses of over 2 TeV (where the precise exclusion is model-dependent and a function of the couplings of the hypothetical particle to electrons and muons).

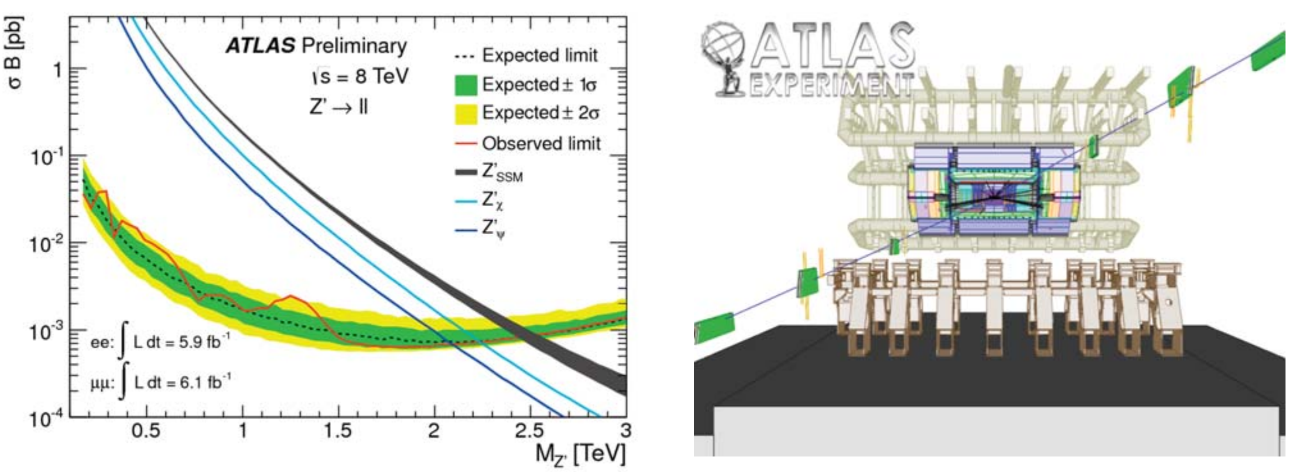

Figure 9: Limits on neutral gauge boson production in various models from searches for resonances in electron- and muon-pair production. The right-hand plot is an event display of a muon pair with an invariant mass of 1.2 TeV.

A closely related search, which includes an energetic photon as well as two oppositely charged electrons or muons in the final state, looks for hints of compositeness by searching for excited leptons emitting a photon as they return to their ground state. Limits are set on the excited lepton mass as a function of the compositeness scale. In the special case where these are equal, both excited electron and excited muon masses below 2.2 TeV are excluded at 95% CL [11].

The simplest possible final state with jets is a single jet (a "monojet") with nothing else. A monojet is necessarily unbalanced, so there is substantial "missing" momentum in such an event. Searches for this final state set some of the tightest constraints on dark matter candidates and also on the existence of extra dimensions which could dilute TeV-scale gravity, with a strength comparable to the electroweak and strong forces, down to the ultra-weak force that holds our planet in orbit and keeps our feet on the ground without pulling apart the atoms that make up our bodies. An example of the constraints ATLAS data [12] place on the mass of a weakly interacting massive particle (WIMP) in the context of other spin-independent WIMP searches is shown in Figure 10.

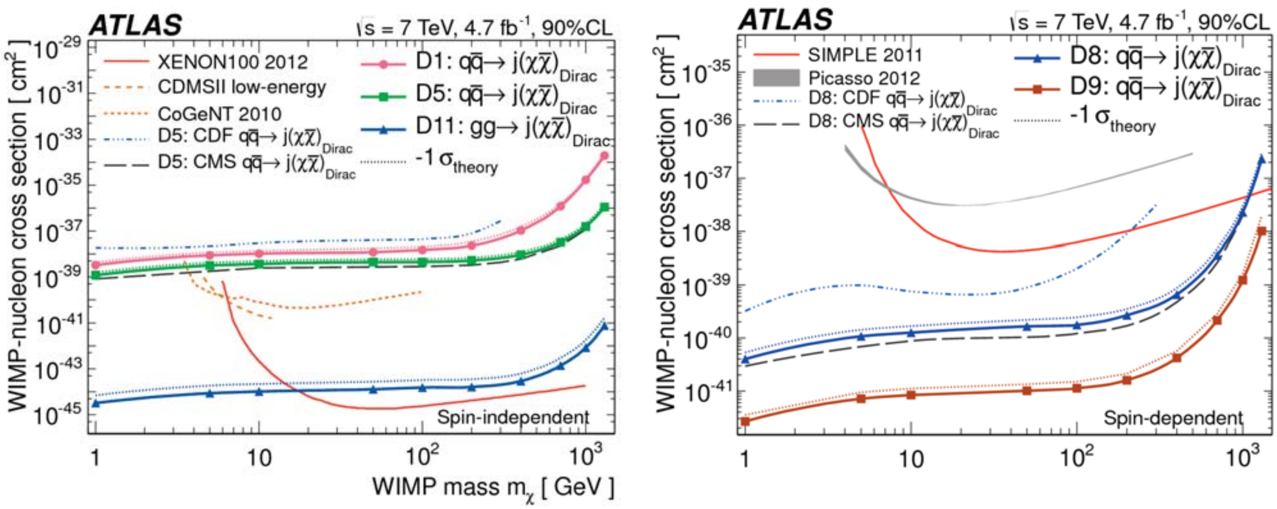

Figure 10: ATLAS 90% confidence-level inferred cross-section limits as a function of WIMP mass for (left) spin-independent and (right) spin-dependent WIMP-nucleon scattering. Cross-sections are shown versus WIMP mass m_chi. In all cases, the thick solid lines are the observed limits excluding theoretical uncertainties; the observed limits are shown as thin dotted lines. The latter limits are conservative because they also include theoretical uncertainties. The ATLAS limits for operators involving quarks are for the four light flavours assuming equal coupling strengths for all quark flavours to the WIMPs.

ATLAS has produced a rich set of analyses of final states consisting of two gauge bosons (WW, WZ, ZZ, Zg, Wg, gg), which are also discussed briefly in Section 4.2.1.4. These can be interpreted in searches for new resonances, including those predicted by models with new strong interactions such as Technicolor [13], or in Higgs boson searches.

Since the top quark is the only quark whose mass is close to those of the W and Z bosons, corresponding to the scale at which the strengths of the electromagnetic and weak interactions become comparable, it does not seem unreasonable to expect it to play a special role, perhaps as the gatekeeper to physics beyond the Standard Model. Searches for resonances in the spectrum of top-anti-top-quark pair production exclude the existence of such resonances up to masses of around a TeV (again, the precise limits are model-dependent).

Searches for long-lived exotic particles make up the final component of “exotic” searches. The methods used in these searches depend on the mass, speed, lifetime, and charge of the particle being sought. If the particle decays inside the beam pipe, these are searches for displaced interaction vertices. If the particle decays inside the ATLAS inner detector, it will produce a kinked, disappearing or non-pointing track. Decays in the calorimeters may produce jets or photons that do not point back to the primary interaction point. Particles that traverse the Inner Tracker or the outer Muon Spectrometer can be identified if they are heavy enough to produce unusual ionization tracks (or if they are multiply charged, which can lead to similar results). Special searches are made for very slow “muon-like” particles [14] and the transition radiation tracker of the inner detector is used to identify long-lived, highly ionizing, penetrating particles with electric charges from twice to six times the electron charge [15]. These are ruled out for masses between 50 GeV/c^2 and 420-490 GeV/c^2 (depending on the charge).

Direct Searches and the TRIUMF Theory Group

Direct experimental searches by the ATLAS group are complemented by theoretical investigations by TRIUMF's Theory Group. The Theory Group interprets ATLAS results in the context of the Standard Model and beyond, and connects these findings to other direct-search experiments, lower-energy precision experiments, and astrophysical observations. The Theory Group also develops and studies extensions of the Standard Model that address the many puzzles this model presents [16], and investigates how best to search for new particles and forces in future experiments.

A key research topic of the Theory Group is the Higgs boson. A broad range of extensions of the minimal Higgs sector of the Standard Model have been developed, and their implications for experimental searches for the Higgs boson have been predicted [17]. The Group has also studied the recent discovery of a new Higgs-like particle at the LHC on extensions of the Standard Model. Under the assumption that this particle is indeed the Higgs boson, the Group has studied the implications of the data on the structure of the electroweak phase transition in the early Universe [18], and has used the data to constrain additional scalar particles [19].

The Theory Group also studies new particles and forces beyond the Standard Model that could be discovered in direct experimental searches. The scalar partners of the top quark predicted by supersymmetry were investigated [20]. Existing LHC searches for other types of new physics were found to be sensitive to light stop particles and provide new limits on their masses. A new mechanism was developed to explain both the missing dark matter and the asymmetry of matter over antimatter [21]. The sensitivity of LHC monojet searches to the new particles and interactions required by this mechanism were studied and related to searches for dark matter and nucleon decay [5]. Other topics, which include extended supersymmetric theories [22], attempts to explain the top asymmetry seen at the Tevatron [23], and new light particles and forces that could be discovered in lower-energy high-intensity experiments [24].

CANADIAN RESEARCHERS ON HAND FOR IMPORTANT JAPANESE NEUTRINO OBSERVATION

19 July 2013

At the prestigious European Physical Society meeting in Stockholm, Sweden, TRIUMF's Michael Wilking announced a new breakthrough in understanding neutrinos, nature's most elusive particles. Together with Canadian, Japanese, and other international colleagues as part of the T2K collaboration, Dr. Wilking confirmed the definitive observation of a new type of neutrino oscillation, in which muon neutrinos transform to electron neutrinos. It has been known that neutrinos transform from one kind into another, but this particular transition had never before been conclusively observed.

Scott Oser, UBC professor of physics and astronomy and spokesperson for the Canadian team known as T2K-Canada, commented, "Canada has been an international leader in neutrino research since the success of the Sudbury Neutrino Observatory (SNO). T2K was the logical next step after SNO in our quest to understand neutrino oscillations, and Canada was in fact the first international partner to join T2K. These new results are the culmination of a decade of work, and open the door to future studies of how both neutrinos and antineutrinos oscillate."

ATLAS has reaped an extraordinary harvest of physics analyses from the unprecedented energy-frontier dataset furnished by the LHC in its first three years of running. In addition to the discovery of a Higgs boson, ATLAS data have been used to explore vast regions of the parameter space of a wide range of extensions to the Standard Model, including supersymmetry, extra dimensions, compositeness, and new gauge interactions. Substantial room remains for discoveries in the dataset already collected, and collaboration between experimenters and theorists allows many fruitful discussions to take place and new directions to be explored. After the 2013–2014 long shutdown, the LHC will turn on again at its design energy, allowing searches for more new particles and push even farther into the unexplored regions.

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4.2.1.2. NEUTRINO AND DARK MATTER PHYSICS

Neutrinos are ghostly particles that feel only the weak nuclear force and can therefore pass through the entire earth with almost no probability of a collision. Due to this elusive nature, some fundamental properties of neutrinos, particularly their tiny but non-zero mass, have only recently been established. Current research is focused on understanding fully the nature of this mass, and the property of "mixing" which, together with the non-zero masses, allows the neutrino to transmute between three "flavours", i.e. ν_e, ν_μ, and ν_τ, through a process called neutrino oscillations.

Unlike the photon, whose masslessness is dictated by gauge symmetry, there is no *a priori* reason to expect that the neutrino should be massless (as was long believed) or to have such tiny masses—nearly one million times smaller than the next lightest particle, the electron—as we now know. However, neutrino masses do not fit into the Standard Model of particle physics because the normal mechanisms by which fermions acquire mass require coupling right- and left-handed partner states, whereas neutrinos are found in only one of these states in the Standard Model.

Unlike its charged cousins, the quarks and the charged leptons, a neutrino can acquire mass by coupling to its antineutrino state; if this is observed to happen, it implies that the neutrino and antineutrino are the same particle. This form of mass is known as "Majorana," while the quarks and charged leptons have "Dirac" masses, which necessarily distinguish a particle from its antiparticle.

If neutrinos possess some combination of Majorana and Dirac mass terms, the states will naturally split into two sets of Majorana-neutrinos with observed masses in inverse proportion. This "see-saw" mechanism potentially explains the tiny neutrino masses that we observe. If true, it implies that neutrino mass is of a fundamentally different origin from other forms of mass, and that the neutrino has ultra-heavy siblings with mass $O(10^{15}$ eV). Establishing that the neutrino is its own antiparticle is an essential element of this hypothesis. If this is in fact the case, a process known as "neutrinoless double beta decay" should occur, in which a nucleus undergoes two beta decays simultaneously, with the two neutrinos usually emitted from the process annihilating each other.

The mixing properties of neutrinos, in which the three flavours of neutrinos are combinations of states with definite masses (m_1, m_2, m_3), is governed by three "angles" (θ_{12}, θ_{13}, θ_{23}) which parameterize how much of each mass state is present in each flavour state. These angles determine the amplitude of neutrino oscillations, while the mass-squared differences ($\Delta m_{ij}^2=m_i^2-m_j^2$) determine the wavelength of the oscillations. We now know that the mixing pattern of neutrinos, where the mixing is very large, is strikingly different from that of quarks, where the mass states nearly align with the flavour states. As with the quarks, the mixing also allows the presence of an irreducible complex phase δ that induces CP violation, giving rise to different oscillation properties for neutrinos and anti-neutrinos. Current neutrino oscillation experiments seek to make precise measurements of the mixing parameters, which may provide some clues to whether there is any underlying pattern or relation between the mixing parameters. Planned experiments such as Hyper-Kamiokande and LBNE will search for the CP violation expected from the δ parameter.

The possible Majorana nature of the neutrino mass, the associated see-saw mechanism and potential CP violation in neutrino oscillations come together in the theory of leptogenesis to explain the matter/antimatter asymmetry of the universe. Leptogenesis posits that the matter domination of the universe originated in the CP-violating decay of the heavy Majorana partner of the neutrino. While no rigorous relationship is known between the mixing parameters of the light neutrinos we observe and these heavy Majorana particles, confirmation of the Majorana nature of the neutrino through neutrinoless double beta decay and the observation of CP violation in neutrino oscillations would establish the key elements of this conjecture. Thus in addition to probing fundamental properties of the neutrino, in particular whether its mass is of a profoundly different nature from other elementary particles, and whether the roots of mixing of flavour and mass states in the Standard Model can be understood at a deeper level to enlighten us about the mysterious observed pattern, the physics of neutrinos is intimately connected to astrophysics and cosmology. The coming decade will see continued rapid progress in neutrino oscillations and double beta decay experiments, as results from current experiments such as EXO, SNO+ and T2K are reaped and new experiments with high sensitivity start operation.

Neutrino Oscillations

Conclusive evidence for neutrino oscillations came from the observation of the solar neutrino flux with the SNO detector [1,2], in which TRIUMF was involved. Results from all phases of the SNO experiment combined [3,4,5] with results from all other solar experiments and the KamLAND reactor experiment led to best-fit values of the mixing parameters of

$\Delta m^2_{21} = 7.59^{+0.19}_{-0.21} \times 10^{-5}\ eV^2$ and $\theta_{12} = 34.4^{+1.3}_{-.12}$ degrees

A three-flavour analysis found a best fit value of $\sin^2\theta_{13}$ to be $2.5^{+1.8}_{-1.5} \times 10^{-2}$, implying an upper bound of $\sin^2\theta_{13} < 0.053$ (95 % C.L.) [6].

Results from measurements of the through-going muon flux at the SNO observatory were also recently published [7]. For zenith angles $0.4 < \theta_{zenith} < 1$, for which the muons originate mainly from pion and kaon decays in the atmosphere, the flux was 3.31 ± 0.01 (stat) ± 0.09 (sys) x 10^{-10} muons/s/cm^2. The zenith angle distribution was measured for zenith angles $-1 < \theta_{zenith} < 0.4$, for which the muons originate from atmospheric neutrino-induced interactions in the materials surrounding the detector. This distribution was interpreted [7] in terms of neutrino oscillations with best-fit oscillation parameters of maximal mixing and $\Delta m^2 = 2.6 \times 10^{-3}\ eV^2$, consistent with parameters measured previously in other experiments. An interesting aspect of this latter measurement is that it is the first to observe atmospheric neutrino-induced events from above the horizon, a result of SNO's greater depth than other observatories, for which the neutrinos are not expected to undergo oscillations.

Long baseline neutrino experiments like T2K in Japan [8], in which TRIUMF scientists play a leading role, aim at precisely determining the mixing angles θ_{13} and $\theta_{23,}$ and the mass difference Δm^2_{32} that are not measured by solar neutrino experiments. In particular, T2K studies the $\nu_\mu \rightarrow \nu_e$ oscillation that is expected from non-vanishing θ_{13} and makes precision measurements of θ_{23} and Δm^2_{32}. For the former, there was no evidence until recently for non-zero θ_{13}, and thus establishing this mode of oscillation would constitute the observation of a new form of neutrino oscillations. In the latter case, current measurements point to the peculiar possibility that $\theta_{23} = 45°$, indicating the maximal mixing between the flavour and mass eigenstates. If precise measurements uphold this situation, or if $\theta_{23} > 45°$, this may provide some hints on whether there are any underlying symmetries or patterns in the mixing. As mentioned above, the mixing matrix also contains a CP-violating phase δ, which, if non-vanishing, can be explored by T2K and measured in the next-generation long-baseline experiment Hyper-Kamiokande (HK) in Japan.

T2K uses an intense muon neutrino beam produced at the J-PARC proton accelerator in Tokai, Japan to search for neutrino oscillations, especially for the previously unobserved oscillation of muon neutrinos into electron neutrinos. T2K uses a magnetized near detector, with key components built at TRIUMF [9, 10], and the existing Super-Kamiokande detector, located 295 km west of Tokai, as its far detector. T2K began taking its first data early in 2010.

Unfortunately, data-taking was interrupted by the large earthquake of March 11, 2011. By this point T2K had collected 1.4 x 10^{20} protons on target, corresponding to about 1/50th of T2K's planned data set, and had achieved beam powers in excess of 150 kW. The 2011 earthquake resulted in no injuries to T2K members and no significant damage to the beam line or detectors. Recovery efforts throughout the year re-established beam operations in December 2011, and neutrino data taking resumed in March 2012. An extended period of operations between October 2012 and July 2013 saw the experiment achieve its highest beam power yet of 220 kW.

In June 2011, T2K released the first oscillation results from the 2010–2011 data, reporting the observation of six candidate ν_e events in the data collected before March 2011, with an expected background of 1.5±0.3 for θ_{13}=0. [11] This 2.5σ excess suggested that θ_{13} might be large, at or just below the limit established previously by the CHOOZ experiment [12]. This indication was confirmed by the Daya Bay and RENO reactor neutrino experiments, which in early 2012 reported high-significance evidence for the disappearance of reactor antineutrinos at short baselines at rates consistent with T2K's favoured value of θ_{13}.

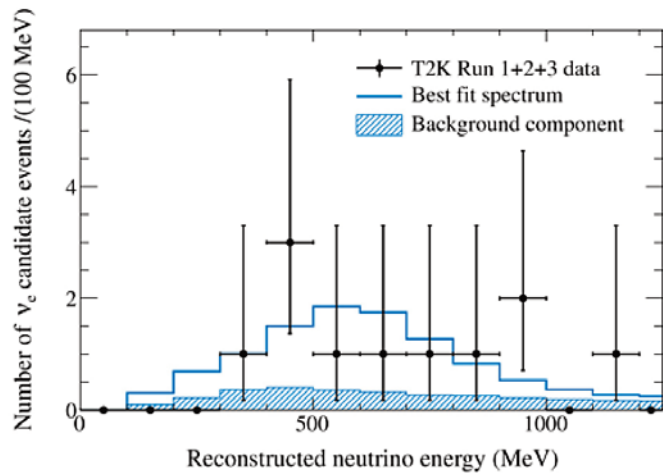

Figure 1: Energy spectrum of candidate electron neutrino events in T2K data taken through summer 2012.

In summer 2012, T2K presented an upgraded analysis, using full spectral information from its near detector and including more than twice as much data as its 2011 analysis. At the ICHEP 2012 conference T2K reported seeing 11 candidate ν_e events on a background of 3.2±0.4 for θ_{13}=0 (see Figure 1). With a statistical significance of 3.2σ, this is the strongest evidence for the oscillation of muon neutrinos into electron neutrinos in a long-baseline experiment seen to date. TRIUMF-based scientists led the development of improved constraints from T2K's near detector, which greatly decreased the fractional uncertainty on the background rate. Further improvements are expected as analysis developments permit the measurement of critical neutrino cross-sections. Unlike reactor neutrino experiments, which are sensitive to only θ_{13}, electron neutrino appearance at T2K also depends on the CP-violating phase δ_{CP} of the mixing matrix and on the sign of the neutrino mass hierarchy. Further improvements in T2K's electron neutrino appearance measurement, in combination with other experiments, may provide the first hint for CP violation in the neutrino sector.

Measuring the disappearance of muon neutrinos probes different neutrino mixing parameters, especially θ_{23} and Δm^2_{32}. In a 2012 paper T2K analyzed its data for muon neutrino disappearance, clearly confirming neutrino oscillation seen in previous experiments [13]. With just 1/50th of its ultimately anticipated data set, this measurement was already competitive for both mixing parameters, thanks to the off-axis neutrino beam tuned at the oscillation maximum. In February 2013, with twice as much data accumulated, T2K announced the world's best measurement of θ_{23}, which is consistent with maximal mixing. There is considerable theoretical interest surrounding the value of $\theta_{23,}$ which appears close to maximal mixing and possibly indicates a flavour symmetry protecting its value.

T2K continues to collect more data, with data taken through summer 2013 expected to give >5 σ sensitivity to electron neutrino appearance. In August 2013, J-PARC will shut down for a LINAC energy upgrade that will enable a significant increase in the beam power. T2K's goals for the next several years are to improve the precision for all neutrino mixing parameters, especially θ_{13} and θ_{23}, measure several important neutrino interaction cross-sections, and lay the groundwork for a next-generation upgrade to definitively measure CP violation in the neutrino sector. This will involve the construction of a new megatonne-scale water Cherenkov detector, called Hyper-Kamiokande, near the site of the Super-Kamiokande. Such an upgrade will be proposed in the next few years and, if funded, will not only give sensitivity to CP violation, but will extend sensitivity to proton decay by one order of magnitude.

Neutrinoless Double Beta Decay

While much progress has been made on the mixing angles and squares of mass differences through neutrino oscillations, the exact arrangement of the mass's differences and the absolute values of the neutrino masses have not been determined so far. As mentioned above, there is a natural explanation for small neutrino masses if neutrinos have Majorana mass that result in it being its own antiparticle. Proof that neutrinos have Majorana mass would be found if the neutrinoless double beta-decay process could be observed. In addition, it would demonstrate for the first time a violation of total lepton number. Such observations would help in our understanding of the creation of matter in the Big Bang. If such a decay is indeed observed, e.g., by the EXO or the SNO+ experiments, in which TRIUMF is involved, it would mean that neutrinos are their own antiparticles, the so-called Majorana particles, and the decay rate is sensitive to the neutrino masses. A controversial claim of evidence for this process was made in 2001 by some members of the Heidelberg-Moscow experiment with subsequent experiments aiming to confirm or refute this claim.

The EXO experiment is a search for neutrinoless double beta decay in xenon. The work is in two parts. A 200 kg liquid xenon TPC is taking data in the Waste Isolation Pilot Plant (WIPP) facility in New Mexico while R&D for a ton-scale detector is progressing mainly in Canada.

In 2011, EXO published the first observation of the two-neutrino decay mode of Xe-136 [14]. This observation was significant for two reasons. First, it indicated that there is nothing anomalous about the nuclear structure of the decay (as might have been inferred from earlier limit). Secondly, it showed that the care in reducing the backgrounds has been successful as the signal to background through most of the spectrum is better than 10:1. In contrast, the Heidelberg-Moscow group has a signal to background of 1:2 for the equivalent measurement in germanium. The detector is now taking data as one of the world's most sensitive detectors for double beta decay.

In 2012, EXO published the results of its first search for neutrinoless double beta decay in Xe-136 [15]. No evidence for this decay mode was found, and the limit placed on the rate established a new world record for sensitivity. For the first time in over a decade, a serious challenge to the Heidelberg-Moscow claim was produced. The claimed observation is ruled out at 90% confidence for almost all published nuclear matrix elements. There is substantial variation in the nuclear matrix elements calculated for neutrinoless double beta decay and nuclear physics experiments like TITAN-EC at TRIUMF are needed to constrain the nuclear theory calculating these matrix elements.

With the excellent performance of the EXO 200, work is in progress to design the next-generation detector that is envisioned as a five-ton liquid xenon TPC. The preferred location for this detector is at SNOLAB and negotiations have begun with the SNOLAB management to allow a full proposal to go forward. To fully exploit the increase in mass, it will be necessary to either reduce further the radioactivity of the materials of construction or to extract and identify the daughter Ba-136 ion by laser fluorescence [16]. Canadian groups are working on both aspects of this development. If successful, this detector would achieve the next milestone in the field—to explore the inverted mass hierarchy of neutrinos. At the same time, the SNO+ experiment to search for neutrinoless double beta decay of Te-130 is nearing completion at SNOLAB, and is due to start data taking in 2014.

Results and Progress: Neutrinos as Astrophysical Messengers

Neutrinos also play an important role in many astrophysical environments from stellar burning to stellar explosions. The flux of neutrinos resulting from the nuclear burning at the centre of our sun is a sensitive probe of the environment in terms of density, temperature, and chemical composition. The Sudbury Neutrino Observatory (SNO) experiment was unique in that, by using heavy water as the detection medium, it could detect both the ν_e component of the solar neutrino flux via the charged current (CC) reaction $\nu_e\, d \rightarrow p\, p\, e^-$, and all neutrino flavours via the neutral current (NC) reaction $\nu\, d \rightarrow \nu\, p\, n$. In addition, the electron scattering (ES) reaction $\nu\; e^- \rightarrow \nu\, e^-$ is sensitive mainly to ν_e. In 2001, the SNO experiment solved the long-standing problem of the missing ν_e's from the sun by showing that the solar flux contains a non-ν_e component. At TRIUMF, nuclear astrophysics experiments at the ISAC facility for rare-isotope beams have been addressing uncertainties in the production rates of B-8 neutrinos in the sun.

The second and third phases of the SNO experiment incorporated salt and He-3 neutron detectors in the heavy water for additional sensitivity to the neutrons liberated by the ν_μ, and ν_τ. Results from the third phase of SNO were published in the present reporting period. In the first phase of the experiment neutrons from the neutral current break-up of deuterium were detected by observing the gammas from subsequent (n,γ) reactions on deuterium, while in the second phase detection of these neutrons was enhanced by observing gammas from (n,γ) reactions on Cl-35 following the introduction of 2 kt of NaCl into the heavy water. In the third phase the neutrons were predominantly detected by an array of He-3 proportional counters arranged throughout the detector volume. This independent technique reduced the correlations among CC, NC and ES fluxes extracted in the previous two phases [6].

The equivalent neutrino fluxes derived from the fitted CC, NC, and ES events in the third phase were found to be

$\varphi_{CC} = 1.67^{+0.05}_{-0.04}$ (stat) $^{+0.07}_{-0.08}$ (syst) x 10^{-6} cm^{-2} s^{-1},
$\varphi_{ES} = 1.77^{+0.24}_{-0.21}$ (stat) $^{+0.09}_{-0.10}$ (syst) x 10^{-6} cm^{-2} s^{-1},
$\varphi_{NC} = 5.54^{+0.33}_{-0.31}$ (stat) $^{+0.36}_{-0.34}$ (syst) x 10^{-6} cm^{-2} s^{-1}.

A paper describing a joint analysis of the data from the first two phases of SNO was also published [3]. A significant development for this analysis was the lowering of the analysis threshold to 3.5 MeV, the lowest yet achieved with a water Cherenkov detector. This was accomplished by including late-arriving scattered and reflected light in the energy estimation, by developing a suite of event-quality cuts based on PMT charge and time information, and by removing known periods of high radon infiltration that occurred during early SNO running. Inclusion of the late-arriving light resulting improved the energy resolution by ~ 6%; this in turn reduced the contamination by low-energy background by ~ 60%.

The total flux of active-flavour neutrinos from B-8 decay in the Sun measured with SNO's neutral current reaction of neutrinos on deuterons was found to be

$\varphi_{NC} = 5.14^{+0.160}_{-0.158}$ (stat) $^{+0.132}_{-0.117}$ (syst) x 10^{-6} cm^{-2} s^{-1}.

The uncertainties are more than a factor of two smaller than previously published results. A fit to the data in which the free parameters directly describe the total B-8 neutrino flux gave

$\varphi_{^8B} = 5.046^{+0.159}_{-0.152}$ (stat) $^{+0.107}_{-0.123}$ (syst) x 10^{-6} cm^{-2} s^{-1}.

Another publication was based on a search for periodicities in the B-8 solar neutrino flux [2]. SNO has previously reported on searches for periods from 10 years down to 1 day. The present work concentrated on periods from 1 day down to 10 minutes. These high-frequency searches were partly motivated by recent expectations for helioseismological variations on scales of an hour or less, in particular solar "gravity modes." Three searches were carried out, the first looking for any significant peak in the frequency range 1-144 day^{-1}, the second looking for gravity modes in a more restricted frequency range, and the third looking for any extra power across the entire frequency band. No statistically significant signal was detected in any of these searches.

Results from a low-multiplicity neutrino burst search were also published. Such bursts could indicate the detection of a nearby core-collapse supernova explosion. The data were taken from the first two phases of the experiment. A number of combinations of event multiplicity and resolving times were utilized to maximize the chance of observing a burst from various different supernova mechanisms while at the same time minimizing the chance of a false burst within the given time window. Simulations were used to estimate the backgrounds expected in each window, and less than 0.11 background events were expected in all cases. No evidence for low-multiplicity bursts was observed [4].

Neutrinos also play an important role in the explosions of massive stars, so called core-collapse supernova explosions (CCSN). In this context the TRIUMF Theory Group is studying the neutrino-nucleus interaction, which is an important input for an improved modelling of CCSN.

CCSN are also favourite candidates for the astrophysical site of the so-called r-process that is responsible for the production of about half of the heavy chemical elements. Reactions of neutrinos with nuclei will play a role in this as well. The HALO supernova neutrino detector experiment at SNOLAB, which has just started data taking, is almost unique in that it is primarily sensitive to ν_e rather than anti-ν_e. As a part of the Supernova Early Warning System (SNEWS), HALO will help detect galactic supernovae by their neutrino burst allowing time to notify astronomers.

Searching for Dark Matter

Evidence from large-scale structure formation in the universe and the structure of the cosmic microwave background indicates that non-luminous "dark matter" (DM) not corresponding to any known form of matter is about five times as abundant as regular baryonic matter from which our environment is built. DM exerts a gravitational force but feels neither the electromagnetic nor the strong nuclear force. One conjecture is that DM consists of a vast swarm of weakly interacting massive particles (WIMPs) surrounding each galaxy. If so, they could be observed via collisions with detectors here on earth (e.g., DEAP currently under construction in SNOLAB or SuperCDMS), or they could be produced in very high-energy collisions (e.g., ATLAS at the Large Hadron Collider). Determining the nature of DM is one of the most pressing issues in particle physics today.

The TRIUMF Theory Group investigates and proposes candidates for DM by making use of data from direct, indirect, and collider searches. It also works to develop new methods to discover and measure the properties of DM, to conduct direct searches for DM and opens new experimental directions.

Most direct experimental searches for DM focus on the simplest possibility of a single DM particle scattering elastically with target nuclei. Recent proposals for DM candidates by the Theory Group show that much richer interactions are possible, such as contributions to the scattering from multiple stable dark matter species [16] and inelastic processes [17].

The observed density of DM is also significantly close to the cosmological density of baryons, suggesting a common origin for both. Recently a new mechanism was developed in which the DM consists of hidden exotic antibaryons [18, 19]. The DM candidates in this mechanism can contribute to elastic scattering in direct detection searches, but they can also undergo inelastic collisions with nucleons, producing anti-DM and a meson. This latter process leads to novel signals from DM scattering in searches for nucleon decay, and opens up a new channel for DM discovery.

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4.2.1.3 FUNDAMENTAL SYMMETRIES

Symmetries play a central role in particle physics and our understanding of the basic building blocks of the universe. In addition to space-time symmetries that give rise to fundamental laws like the conservation of energy and gauge symmetries which produce the fundamental interactions, there are the discrete symmetries of charge-conjugation (C), which exchange particles and antiparticles, parity (P), the reversal of spatial coordinates, and time-reversal (T).

The foundations of physics were shaken to its core in 1957 with the discovery of the violation parity symmetry of violation in beta decay, which has since been incorporated into the Standard Model of weak interactions. The combined charge-parity symmetry (CP) was also found in 1964 and has since been explained by the presence of a complex phase in the mixing of quarks. The combination of all three discrete symmetries (CPT) is an intrinsic outcome of the quantum field theories that are the foundation of the Standard Model of particle physics. An observation of CPT violation would require radical reworking of our understanding of particles and interactions.

The question of CPT violation remains a crucial question, as the known sources of CP violation in the Standard Model, an essential ingredient in generating a matter-dominated universe, are insufficient to create the observed asymmetry in our universe. Further sources of CPT violation can be studied by comparing matter/antimatter counterparts of the same system, or through T violation, which is related to CP violation through CPT symmetry.

MAKOTO FUJIWARA WINS JOHN DAWSON AWARD

04 April 2012

TRIUMF scientist and ALPHA-Canada spokesperson, Makoto Fujiwara, was awarded the 2011 John Dawson Award by the American Physical Society. Dr. Fujiwara was recognized for his role in the introduction and use of innovative plasma techniques which produced the first demonstration of the trapping of antihydrogen inside the ALPHA experiment at CERN. The award is bestowed upon scientists that make breakthroughs in the field of plasma physics. Dr. Fujiwara was the sole recipient from TRIUMF and the only Canadian to win the award in 2011.

This award was specifically given for the trapping of antihydrogen, which took place in November 2010. Since that time, there have been a number of important breakthroughs involving ALPHA. In the middle of 2011 Dr. Fujiwara was the lead author of a paper that appeared in Nature Physics, which revealed that the ALPHA team had trapped antimatter atoms for 16 minutes. In March 2012, another paper was published in Nature, revealing that ALPHA, with leadership from Canadian researchers, had measured for the first time an intrinsic property of antimatter atoms.

Probing Matter/Antimatter Asymmetry with ALPHA

Atomic hydrogen is one of the best-studied systems in all of physics and has played a central role in establishing quantum physics from the Bohr model to the theory of quantum electrodynamics. A comparison of properties of hydrogen and its antimatter counter-part antihydrogen addresses the validity of a fundamental symmetry, CPT, which occurs in quantum field theories that are relativistic, local, and unitary.

CPT symmetry violation is a possible explanation for how our universe comes to be composed almost entirely of matter. The ALPHA (Antihydrogen Laser Physics Apparatus) at CERN has achieved trapping of antihydrogen in 2010 [1]. In 2011, ALPHA reported confinement of antihydrogen for nearly 1,000 seconds [2], an increase by a factor more than 5,000 from the initial result. Most recently in 2012, ALPHA performed the first spectroscopic measurement on antihydrogen atoms by driving its hyperfine transitions with microwaves, an initiative led by Canadian scientists on the experiment [3]. Canadian physicists were the principal authors of two [2, 3] of the three papers published in Nature journals.

Between 2008 and 2010, ALPHA developed techniques to prepare and measure the plasmas needed to enable trapping of antihydrogen. A novel diagnosis for antiproton plasma radial profile using annihilation detection was reported [4]. Rotating RF fields were used to compress multi-component charged plasmas to the required densities [5]. A new mode of particle transport in a Penning trap was observed [6]. Formation dynamics of antihydrogen were studied in detail in a multipolar neutral antiatom trap [7]. Evaporative cooling, a common method for cooling neutral atoms, was applied for the first time to cold plasmas, achieving antiproton temperatures as low as 10 K [8]. Autoresonant injection of the antiprotons into the positron plasmas enabled the mixing of these plasmas with minimal heating [9]. Direct observation of centrifugal separation allowed detailed studies of equilibration dynamics in electron-antiproton plasmas [10]. These developments involving innovative plasma techniques were made possible by the use of antiproton annihilation detection, together with plasma imaging with multi-channel plates [11]. Microwave probing and manipulations of trapped charged plasmas provided useful information about their properties and allowed a precise measurement of the magnetic field in the trap centre. Its position-sensitive annihilation detection capability distinguishes ALPHA from its competition.

In 2009 ALPHA achieved plasma conditions that produced very cold antihydrogen atoms and reached detection sensitivity which allowed detection of trapped antihydrogen. The first six candidate events for trapped antihydrogen were observed that year, with a statistical significance sufficient to reject the dominant cosmic background [12]; however, it was not possible to experimentally rule out a background process from annihilations of magnetically trapped bare antiprotons. In 2010, new techniques were proposed and developed to experimentally eliminate the possibility for bare antiproton background [13]. This led to a definitive proof of trapping [1]. Subsequently, ALPHA increased the trapping yields, and by introducing a delay between the time when the antihydrogen atoms are synthesized and their release time from the trap, the collaboration ascertained that antihydrogen remained trapped for at least 1,000 seconds [2] (see Figure 1), which was sufficient to enable spectroscopic studies on single antiatoms. This was the major milestone required to proceed with spectroscopy.

Techniques to irradiate plasmas in the ALPHA trap with microwaves have been developed at the University of British Columbia and Simon Fraser University since 2005, and in 2011 the first experiments with high-power microwaves were performed. Irradiating the

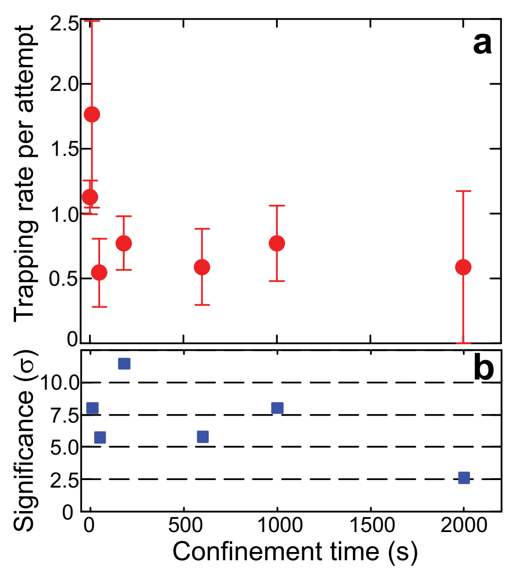

Figure 1: Antihydrogen trapping rate as function of confinement time. From Ref. [2].

antihydrogen atoms at the resonant frequency of the positron spin resonance transitions at 28 GHz drives the transition from a trappable to a non-trappable state, expelling it from the trap. An excess of annihilation events during the irradiation (see Figure 2) and a strong decrease of these events when the trap was subsequently emptied were seen, setting bounds on the antihydrogen resonances within 100 MHz of the corresponding hydrogen resonances [3]. Highly sensitive annihilation detection capability was a key to both of these measurements.

Following the success in initial microwave spectroscopy, the collaboration has taken on a major upgrade project, ALPHA-2, to enable laser spectroscopy of trapped antihydrogen, and to provide improved and more flexible magnetic field configuration for microwave spectroscopy and anti-atom manipulations (see Figure 3). Recent theoretical simulations suggest that such an extension would allow laser cooling of antihydrogen to temperatures as low as 20 mK [14].

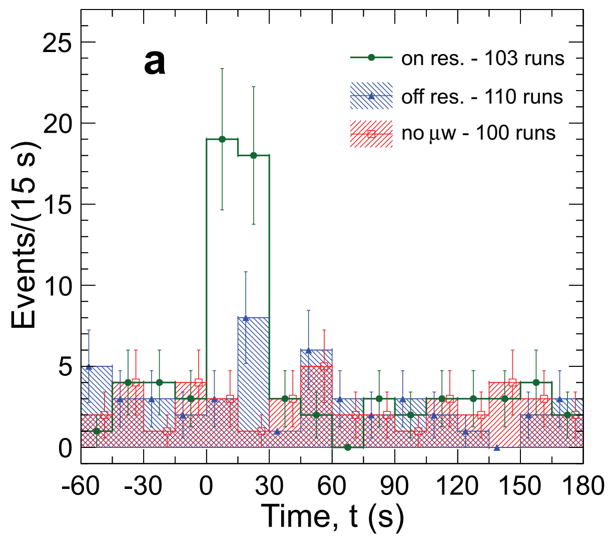

Figure 2: Antihydrogen annihilation time distribution as a function of time, for microwave on resonance, off resonance and no microwave dataset. Microwaves are applied at time 0, and the annihilation peak at that time indicates the induce spin flip of antihydrogen. From Ref. [3].

Electric Dipole Moments

An electric dipole moment (EDM) of a system is the projection of its charge distribution along the total angular momentum vector J. Thus D=*d*J. Under parity transformations (P), D changes sign, but J does not, and under time reversal (T), J changes sign, but D does not. Thus *d* must be odd under both P and T transformations. We can think of the EDM as arising from an electrical polarization of the system that is induced by elementary particle interactions that violate P and T, and, assuming CPT invariance, must violate CP.

Among the most interesting contemporary motivations for the measurement of EDMs is the connection to baryogenesis laid out in the Sakharov criteria requiring (1) baryon number violation, (2) CP violation, and (3) non-equilibrium expansion. Standard Model sources are not sufficient to generate even the observed baryon asymmetry of the universe; thus new forms of beyond-Standard-Model physics CP violation are expected. Most significant extensions of the Standard Model introduce additional phases that could produce the baryon asymmetry and lead to an EDM many orders of magnitude larger than those through quark mixing in the Standard Model [5]. For example, supersymmetric models introduce phases that could produce the baryon asymmetry at the electroweak scale and produce EDMs of atoms or the neutron close to the current limits of sensitivity. CP violation is also a valuable observable for probing physics beyond the

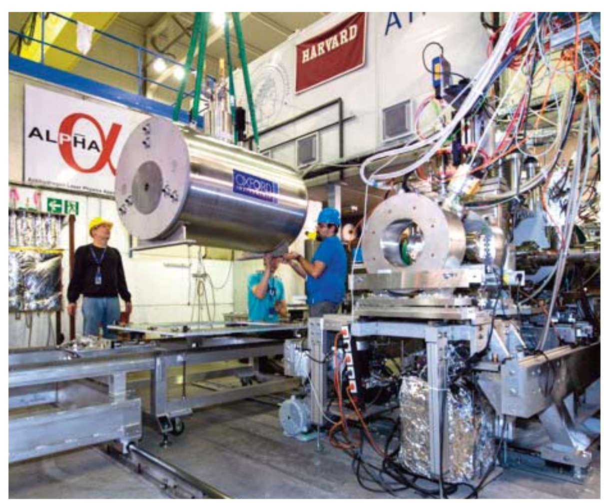

Figure 3: The ALPHA-2 apparatus is the major upgrade project currently in progress. The most recent addition has been the atom-trap cryostat built at TRIUMF. Together with the new superconducting solenoid (built by Oxford Instruments in the UK and financed by the Danish Carlsberg Foundation), they join the catching trap and the existing positron accumulator from ALPHA to make up the complete chain of apparatus. Photo © 2012 CERN

Standard Model more generally, i.e. CP violation can be used to reveal a weaker interaction in the presence of the dominant strong and electroweak interactions of the Standard Model.

There have been a number of measurements of EDMs in systems that have strong sensitivity to the electron EDM (paramagnetic systems) and EDM in hadronic systems (diamagnetic atoms, the neutron and future storage-ring experiments with nuclei). There are also several ways in which beyond-standard-model physics can contribute to the EDM of a system: θ_{QCD}, electron EDM, intrinsic quark EDMs, and EDMs induced by hadronic currents (chromoEDMs-$d_{u/d}$), 4-quark interactions, and 3-gluon interactions. In fact, there are three dominant contributions in paramagnetic systems and at least ten independent parameters in hadronic systems. This means that it will be crucial to push ahead with EDM measurements in a number of systems, particularly hadronic systems.

Neutron EDM

Measurements of the neutron electric dipole moment (nEDM) d_n are sensitive probes of quark EDMs, or quark chromo-EDMs. New physics scenarios seeking to describe the baryon asymmetry often generate nEDMs of O(10^{-27}) e-cm, just beyond the current experimental limit of $d_n < 2.9 \times 10^{-26}$ e cm. The nEDM tends to be more sensitive to the EDMs of the constituents (quarks and gluons) than the atomic and molecular systems because there is no electron cloud in the system to screen the EDMs.

The next generation of nEDM experiments worldwide aims to constrain the d_n O(10^{-27}-10^{-28}) e cm. The goal of the first experiment at the TRIUMF Ultra-Cold Neutron (UCN) Source is to reach a precision corresponding to $d_n < 1 \times 10^{-27}$ e cm by 2017. Further improvements to the apparatus, and to the UCN facility itself, are planned for after 2018, with the eventual goal of achieving $d_n < 1 \times 10^{-28}$ e cm. A basic overview of the physics behind our nEDM concept is presented in Ref. [17]

The basic design of the TRIUMF nEDM experiment calls for a room temperature EDM experiment to be filled with ultra-cold neutrons (UCN) by our cryogenic UCN source, which is based on the design successfully deployed by our Japanese collaborators, led by Y. Masuda [17,18]. Neutrons are moderated, and then converted into UCNs by down-scattering in superfluid helium (see Section 5.5.3.2). The EDM experimental apparatus to be used at TRIUMF has several unique features and improvements with respect to other EDM experiments. The cell size is reduced, anticipating the gains in UCN density. Both the active and the passive magnetic shielding are improved, as are the control and characterization of the magnetic field, and a new Xe-129 comagnetometer technology is used.

The UCN source and a prototype EDM experiment will be developed and operated at the Research Center for Nuclear Physics (RCNP, Osaka) at low luminosity until 2014. Relevant apparatus for the eventual experiment at TRIUMF will be moved in 2015 for integration with subsystems now being developed in Canada, with first operations in 2016.

Further experiments on the neutron lifetime in a magnetic trap, and on quantized energy levels of neutrons confined above a mirror by Earth's gravitational field are considered, among others, as candidates for the long-term physics program.

Canadian involvement in the nEDM experiment has now expanded to include research and development on key components, and construction of new equipment. The main components are the comagnetometer and the UCN detector. The University of British Columbia (UBC) and the University of Winnipeg are completing new systems to develop the xenon comagnetometer concept. At UBC, a system to study direct two-photon optical pumping of xenon has produced its first results. At the University of Winnipeg, a xenon polarizer system has been developed based on spin-exchange optical pumping with rubidium. They are also investigating a new UCN detector concept for sensing the high count rate expected in the EDM experiment, based on lithium-loaded glass scintillator and possible pulse-shape discrimination to reject gamma-ray backgrounds. Figure 4 displays some detector prototyping and fabrication process steps at the Nanosystem Fabrication Laboratory at the University of Manitoba.

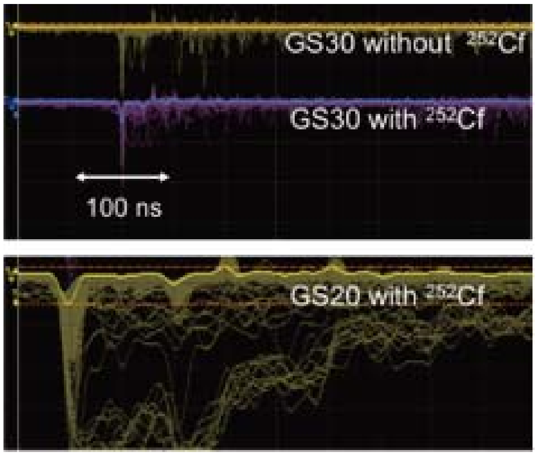

Figure 4: Left: Oscilloscope traces of PMT outputs showing neutron captures on GS20 (Li-6 enriched) and GS30 (Li-6 depleted) glass scintillator.
Right: Cutting glass scintillator at UM

TRIUMF is developing a new high-voltage system to study EDM cell geometries and leakage currents in xenon and other gas environments, and the University of Winnipeg group is developing a prototype magnetic shield for the nEDM experiment. Both will eventually come together at TRIUMF to combine shielding, the Xe comagnetometer, and high voltage into one apparatus before the first experiments with ultra-cold neutrons. Figure 5 displays a test apparatus at the University of Winnipeg for active magnetic compensation of environmental fields in the laboratory, using a fluxgate magnetometer within a box coil. The group is also conducting detailed Monte Carlo studies of cold neutron moderators, and spin evolution in the EDM experiment due to magnetic field inhomogeneities (resulting in a variety of systematic effects). These studies include estimates of thermal transport in the UCN source, in particular, heat transport through the superfluid helium.

Active research and development on most of these topics is in progress at this time. The xenon work has produced some first results on spectroscopy of the relevant levels and magnetic sublevel effects.

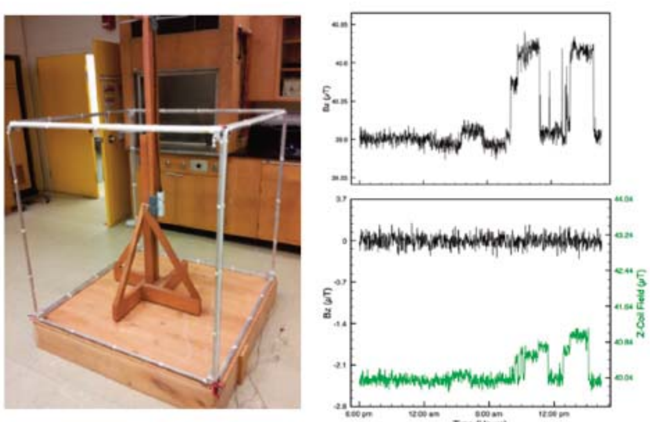

Figure 5: UW test apparatus (left) with three-axis fluxgate magnetometer on wooden stand at centre of x-, y-, and z-compensation coils. Results showing the ~ 1 μT field perturbation (top right) that occurs during working hours due to opening/closing of shipping bay doors one floor below; the same time period on a different day with active compensation running (bottom right), the compensating field is shown in green.

Atomic EDM using Radon

In octupole-deformed nuclei, collective effects produce higher order vibrations and deformations that can lead to a large intrinsic dipole moment, and a T-violating interaction can align this moment with the nuclear spin. The result is an expected enhancement of the Schiff moment (effectively the RMS of the dipole moment distribution) by factors of several hundred to a thousand with respect to Hg-199. Two different systems provide experimental opportunities to extend the sensitivity to T violation: laser cooled Ra-225 in an optical trap and spin-exchange polarized Rn-223 in a cell, both of which are investigated by TRIUMF experiment S929. For Ra-225, calculations combined with well-established spectroscopy of nuclear levels provide confidence that the enhancement relative to Hg-199 is a factor of several hundred; however, the nuclear structure information on radon isotopes is meager, and establishing a confident estimate of the octupole enhancement requires nuclear structure measurements as input to theoretical calculations. We have therefore set the primary initial goals of the RadonEDM program as technical developments essential to the EDM measurement, with nuclear structure measurements as the secondary goal.

The radon nuclei will be polarized by spin exchange with laser-polarized rubidium in cells with N_2 buffer gas. The technical developments for the RadonEDM experiment, which are detailed in Section 5.5.1.9, include measurements of the rubidium polarization [19] and developments of the EDM measurement cell.

The RadonEDM apparatus was moved to TRIUMF from Stony Brook and set up in dedicated space on the floor of ISAC-I. [20] The beam line was extended to a new, dedicated end station and beam optics were developed to deliver beam to the foil and transfer apparatus. A test run in July 2008 had the following goals: (1) to use short-lived (i.e. about a 20-minute half-life) noble gas isotopes to perfect the online transfer techniques; (2) to set up the laser optical pumping apparatus that satisfy lab safety requirements; (3) to observe gamma-anisotropies in noble gas isotopes with a nuclear spin greater than 1/2; and (4) to measure rubidium polarization online. The experiment was successful, to some degree, in all four goals.

During a 2004 run, the technique was sufficiently developed to efficiently transfer noble gas atoms into a cell using a buffer gas. The half-life of Xe-120 was also measured. The transfer technique was about 50% efficient, so a goal was set to improve this significantly. M. Hayden of Simon Fraser University developed a cold finger (that could be rapidly heated and cooled), as well as efficient gas transfer geometry. The efficiency was tested with Xe-123 (I = 1/2), which could be produced in quantities sufficient for accurate efficiency measurements. Transferring a known amount of xenon from the measurement cell to the cold finger and back to the measurement cell provided a self-calibrated measurement, showing that the transfer efficiency is consistent with 100%. The process of heating and cooling takes about 5 minutes, or 1/6 of a half-life, leading to minimal loss of activity due to decay.

We also measured gamma ray anisotropies for transitions populated by the decay of polarized Xe-121. Unfortunately the production rate of Xe-121 was very low due to ion source problems, and the count rates were correspondingly low.

Currently there are essentially no data on excited states of the radon isotopes of interest. Study of nuclear structure of Rn-221 and Rn-223 is essential, and the group at TRIUMF has established an attack on several fronts. The current focus of the group is to make measurements that will establish energy levels, spins and parities of excited states through astatine decay; in contrast, at ISOLDE, radon isotopes are excited by Coulomb exchange on medium-mass targets and gamma-ray angular distributions are used to establish spins and parities, while at Michigan State University's National Superconducting Cyclotron Laboratory, gamma ray spectroscopy is used in coincidence with particle identification for fragments of a U-238 beam to identify gammas and excited states in a number of neutron-rich heavy isotopes.

The scheme at ISAC is to study astatine β-decay with a uranium carbide target operating at 2 μA of proton current. Beam time in December 2010 led to a new and efficient three-step laser ionization process for identifying astatine isotopes by the TRILIS group at ISAC using the α decay of At-199 detected in the PACES Si(Li) detectors of the 8π spectrometer as the optimization signal. Moving to neutron-rich astatine beams, isotopes up to At-219 were delivered to, and identified with, the 8π spectrometer. This was possible because of the limited beam contamination from the surface-ionized francium and actinium isobars due to their short α-decay half-lives (e.g., 20 ms for Fr-219 and 12 μs for Ac-219). However, for the isotopes of specific interest to the RadonEDM program, the much longer francium and actinium half-lives (4.8 minutes and 22 minutes for Fr and 52 ms and 2.1 minutes for Ac) led to a large surface-ionized contamination of the beam that completely masked any potential signal from the much less intense laser-ionized At isobars. A major effort has since been made to suppress surface-ionized beam contamination by combining the TRILIS ion source with a new RFQ system, which will be tested online at ISAC in early 2013. Based on the current conservative estimate of a roughly 1% efficiency associated with the RFQ, the predicted rates of beams delivered to the 8π spectrometer for 10 μA of protons on a uranium carbide production target are 10 pps and 0.1 pps for At-221 and At-223, respectively, with negligible isobaric surface-ionized contamination. While the expected At-223 intensity is below the useful threshold for coincidence spectroscopy and will require further development through, for example, implementation of thorium carbide targets at ISAC concentrating on the higher yield At-221, it will provide sufficient coincidence data to elucidate the structure of the low-lying levels of the essentially unknown Rn-221, daughter nucleus. This will also complement work at ISOLDE and NSCL described below.

At ISOLDE a Coulomb excitation experiment, led by P. Butler of the University of Liverpool, was carried out to measure octupole collectivity in Ra and Rn isotopes [21]. The initial goal has been study of the neighbouring even-even Rn and Ra isotopes with radioactive beams of Rn-220 and Ra-224 accelerated to ~ 2.8 MeV/u. Gamma decays following Coulomb excitation in Ni, Cd, and Sn targets were detected in the MINIBALL array and analyzed using the GOSIA code to determine octupole collectivity. The conclusion is that Rn-221 is most consistent with an octupole vibrator, while Ra-224 is consistent with permanent deformation. The trends in these two species suggest that Rn-221 is not permanently deformed, but may have comparable octupole moments to Ra isotopes. If this is the case and the splitting of parity-coupled states is ~ 400 keV in Ra-221 compared to ~ 40 keV in Ra, the EDM enhancement may be a factor of ten less for radon. A paper has been recently submitted. In 2012, an attempt was made to continue these studies with Rn-221. A low-current beam was eventually used to observe gamma rays associated with Rn-221 decay. However it was not possible to further identify these levels.

Recently a successful experiment was carried out at NSCL in which a 80 MeV/u U-238 beam was incident on an active diamond target. Gamma rays detected with GRETINA are correlated with fragments detected in the S800 magnetic spectrometer. The systems worked as designed and analysis is underway with the goal of identifying gammas and thus levels in the isotopes of interest along with the very large number of neutron-rich isotopes in the mass range near A = 238.

Electron EDM Experiment Using a Fountain of Francium

An experiment to discover or rule out an electric dipole moment (EDM) of the electron, as small as a factor of 100 below the present limits, is being developed. Francium has the highest sensitivity to an electron EDM of any atom studied and Fr-211 is the least sensitive to systematic effects. The experiment is done on atoms in free space and free fall, with no confining lasers, gasses or walls, and with no applied magnetic fields.

Discovering an electron EDM would prove the existence of a new source of CP violation, new TeV-scale physics, and undiscovered particles. Finding no EDM would, for example, constrain supersymmetric models by raising the minimum superpartner masses and lowering the maximum CP-violating phases, making supersymmetry a less plausible solution to the hierarchy problem (please see Section 4.2.1.1). Electron EDM experiments, sensitive to lepton-sector CP violation, are complementary to neutron EDM experiments, which are sensitive to new sources of quark sector CP violation and to the strong CP phase, θ_{QCD}.

A proof-of-principle, laser-cooled cesium atom electron EDM experiment was conducted in 2007, and identified areas needing further development [22]. They were: preventing loss of atoms, reducing magnetic field noise, and further understanding and controlling systematic effects. The TRIUMF experiment will look for an electric dipole moment in the valence electron of the francium atom by comparing the interaction energy (phase advance) of the francium atoms with their spin aligned and anti-aligned with an applied electric field.

Atoms in a francium fountain (a cloud of cold atoms launched upward by laser beams, similar to an atomic clock) will enter an electric field produced by parallel conducting plates 1 cm apart at about ±50 kV. Under the influence of gravity, the atoms, which enter at about 3 m/s, slow, turn around, and fall out of the electric field plates, having spent about 0.7 s in the electric field. The atomic state is prepared by laser light before entering the electric field and is analyzed after leaving the electric field. The measurement is thus done in free space and free fall, with no confining lasers, gasses, or walls.

The slow-moving neutral atoms, however, will experience forces in an inhomogeneous field region as they enter and exit the electric field, which will cause them to defocus. Without some form of focusing, almost all of the atoms would be lost. To avoid magnetic fields, the required focusing is provided by a pair of electrostatic triplet lenses upstream of the electric field plates. The shape of each triplet lens provides a combination dipole and sextupole electric field that acts as a transverse defocusing-focusing-defocusing lens combination, resulting in net focusing of the atoms in both transverse directions.

A linear optics solution has been completed for the transport of the francium atoms through the fountain. In addition, the optimum shape for the entrance field has been modeled [23]. With the current design, most of the atoms launched into the fountain will return and be detected.

To reach the required experimental sensitivity, magnetic noise between the state preparation and analysis needs to be 5 ft or less. Electron EDM experiments are sensitive to magnetic noise (principally along the electric field direction) through the interaction of the magnetic moment of the valence electron with the changing magnetic field. Magnetic noise was measured at a possible experimental site on the TRIUMF ISAC facility experimental floor during machine operation on May 25, 2011. To reduce the fluctuations to below 5 ft, a shielding factor of about 6.6×10^6 is needed along the quantization axis. Both time varying magnetic fields, and the Earth's static magnetic field can in principle be shielded with mu-metal although a shielding factor of such a large magnitude must be demonstrated.

Figure 6: The magnetic shielding test stand with Ben Feinberg. The shields are inside the central cylinder and are positioned vertically as in a fountain. Magnetic fields in both transverse directions are produced by long rectangular coils wound on the wood forms seen prominently in the photograph. Axial fields are produced by solenoid coils wound on a fiberboard cylinder.

To test shielding calculations, design, and assembly, a half-scale prototype magnetic shield was constructed consisting of four layers of 3.17 mm-thick Carpenter HyMu 80 alloy. It was constructed at LBNL and tested in a three-axis vertical test stand designed and constructed at TRIUMF (see Figure 6). A known external field was applied and the field inside the shields was measured to determine the transfer function. Three layers provided a radial shielding factor in excess of 10^7, in agreement with calculations. Because the shielding factor decreases with size, the full-size shield will have four layers.

The most complete calculations of EDM-mimicking effects in any system have recently been completed for francium and cesium [24]. Control of systematic effects is the main obstacle to improving the electron EDM limit. The use of electric field quantization, in which the ratio of electric field splitting of levels of different $|m_F|$ to the Zeeman splitting is about 100, suppresses the EDM-mimicking effects of motional magnetic fields seen by the atoms moving through the electric field. The calculation expands the complete time evolution operator in inverse powers of this ratio. For a specific set of coherent states, potential systematic errors enter only as even powers of the ratio, making the expansion rapidly convergent. The use of Fr-211, which has large electric field splittings, and the nulling of remnant magnetic fields, can keep false EDMs below the experimental goal.

MTV: Test of Time Reversal Symmetry Using Polarized Unstable Nuclei

The MTV (Mott polarimetry for T-Violation) experiment searches for violation of time reversal symmetry in a nuclear beta-decay using a new type of particle position detection device. A test experiment in 2008 at KEK in Japan confirmed 10% precision [25] by precisely measuring the polarization of electrons emitted in the beta decay of polarized Li-8. A demonstration of the existence of electron polarization perpendicular to the electron momentum direction would signal the violation of time reversal symmetry. The world's highest precision of 0.1% can be achieved at TRIUMF, thanks to the large intensity and high polarization of the Li-8 beam produced at ISAC.

A first test experiment in 2009 demonstrated that 0.1% statistical precision can be achieved to 10^7 polarized Li-8 particles per second from ISAC, at around 80% polarization, a marked improvement over the 10^5 particles per second and 8% polarization at KEK. A physics run in 2010 accumulated sufficient statistics for a 0.1% result [26,27]. Further improvements of the sensitivity can be achieved with a new Cylindrical Drift Chamber (CDC) that was developed in Japan, and successfully tested at ISAC in November 2012. The physics datataking with the new CDC setup will start in 2013. The Standard Model of particle physics predicts negligible signals for the MTV experiment, thus any evidence of a T-violating effect in MTV would constitute evidence for new physics beyond the Standard Model. MTV expects to eventually achieve 0.01% precision to T-violating effects.

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4.2.1.4 WEAK INTERACTION STUDIES

Of the three fundamental forces described by the Standard Model (SM) of particle physics, the weak interaction is the least well understood. The relative weakness of the weak force at low energies, compared to electromagnetism or the strong force, makes it more challenging to study experimentally. The weak force is also very different in its structure from the other known forces in that it violates the parity (P), charge conjugation (C), and flavour symmetries. Precision studies of the weak force at TRIUMF seek to improve our understanding of the weak interaction, and to investigate the origin of P-, CP-, and flavour-symmetry breaking.

Fundamental forces in the SM are induced by the exchange of vector boson particles. The electromagnetic force is mediated by the massless photon and the strong force is mediated by the massless gluon. In contrast, the weak force arises in the SM from the exchange of massive $W^{+/-}$ and Z^0 vector bosons. The large masses of these mediators compared to the proton ($m_p = 0.938$ GeV/c^2), $m_w = 80.4$ GeV/c^2 and $m_z = 91.2$ GeV/c^2, are the reason why the weak force is so weak at low energies. At higher energies, approaching m_w, the SM describes how the weak force grows to be of comparable strength to the other forces and unifies with the electromagnetic force to form a single electroweak force. The splitting of the weak and electromagnetic components is called electroweak symmetry breaking, and is caused by the Higgs field in the SM. Studies of the weak force at high energy seek to test this unification and to probe the underlying cause of electroweak breaking.

In addition to testing the SM, precision measurements of the weak force at both low and high energies also offer the exciting prospect of discovering new particles and forces beyond the SM.

The many possibilities for this new physics can be classified according to the mass scale Λ of the new particles. Energies larger than Λ are needed to create the new particles directly; however, the effects of exotic particles can also make themselves felt at much lower energies by inducing new interactions among SM particles suppressed by the large mass Λ (in direct analogy to how the weak force operates at energies below m_w). By looking for deviations from the SM in weak-interaction processes, lower-energy experiments with high precision can detect indirectly the existence of new physics. Low- and high-energy tests of the weak force therefore play a complementary role in the search for new particles and forces, and TRIUMF has been and continues to be involved in a number of world-leading efforts through its in-house program (TWIST, PIENU, TRINAT, 8π, FrPNC) as well as through external efforts with ATLAS (please see Section 5.5.5.2 (LHC/CERN), and Qweak (JLAB).

The simplest and best-studied weak interaction process is the decay of the muon into an electron and a pair of neutrinos, $\mu \rightarrow e\nu_e\nu_\mu$. This decay is induced by the exchange of a W vector boson.

The TRIUMF Weak Interaction Symmetry Test (TWIST) made a detailed study of the decays of positively charged spin-polarized muons. By measuring the angle and momentum distributions of the positrons (e+) emitted in these decays, the experiment obtained the most precise determination ever of the muon decay parameters ρ, δ, and $P_\mu\xi$, as shown in Figure 1.

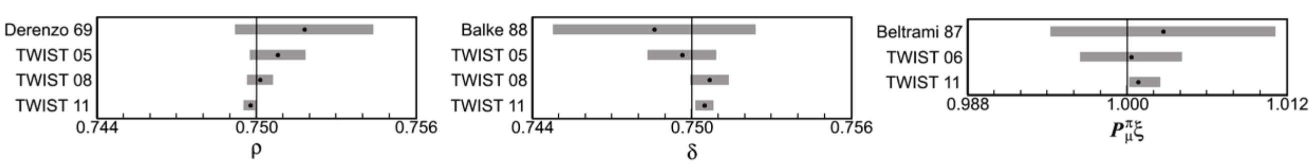

Figure 1: TWIST measurements of the muon decay parameters ρ, δ, and $P\mu\xi$ relative to previous determinations. In each plot, the vertical line shows the Standard Model prediction and the grey bars show the total uncertainty.

The TWIST measurement relied on an intense high-quality TRIUMF muon beam and used a high-precision positron tracking spectrometer to measure the decay products, together with the extensive computational resources of WestGrid Canada for data analysis. A first intermediate result was published in 2008 [1] demonstrating an understanding and control over the dominant systematic uncertainties. Some data were also obtained for negative muon decay in orbit around a nucleus, with a precision that required the inclusion of radiative corrections for the first time in that system [2]. The summary of the final results from a blind analysis of billions of muon decays was released in early 2011 [3]. As with most precision experiments, the final uncertainties were dominated by systematic effects whose magnitudes had to be assessed and verified carefully [4,5].

The final TWIST result improved the measurement of the muon decay parameters ρ, δ, and $P_\mu\xi$ by approximately one order of magnitude compared to the previous Particle Data Group world-average. These results are consistent with the predictions of the SM, and they place a strong limit on many types of new physics. For example, in the case of left-right symmetric models, the masses of exotic charged scalars or vectors coupling to leptons are constrained to be larger than thousands of GeV in some cases. These limits are comparable to those obtained by direct high-energy searches (such as the LHC) if the new particles also couple to quarks, and much stronger if they do not [3].

The PIENU experiment at TRIUMF is studying this decay channel with the primary goal of measuring the decay rate of charged pions to electrons relative to the much more common decay to muons, $R_{e/\mu} = \Gamma(\pi\rightarrow e\nu(\gamma))/\Gamma(\pi\rightarrow\mu\nu(\gamma))$, to a precision better than 0.1%. This measurement will provide the best test of electron-muon universality in weak interactions and test the Standard Model (SM) prediction of $R_{e/\mu} = 1.2353(1) \times 10^{-4}$.

The branching ratio $R_{e/\mu}$ is obtained comparing the positron yield from the $\pi^+ \rightarrow e^+\nu$ decay (E_e = 69.8 MeV) to the yield from the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain, where $\pi^+ \rightarrow \mu^+\nu$ is followed by the decay $\mu^+ \rightarrow e^+\nu\nu$ (E_e = 0.5 - 52.8 MeV). To reduce positron contamination in the pion beam, the M13 channel was upgraded [6] and the detector system was installed in 2008 for an engineering run. After many improvements in the detector and data acquisition system in 2009, smooth data taking started in 2010. Although the sample size was ultimately limited by short beam periods, a few million clean $\pi^+ \rightarrow e^+\nu$ events were accumulated by the end of 2012, and this reduced the statistical uncertainty to below 0.1%. Extensive Monte Carlo simulation and data studies are expected to reduce the systematic uncertainties significantly below this level as well.

A measurement of $R_{e/\mu}$ to a precision of 0.1% will represent an improvement by a factor of four relative to the current world-average. At this level, deviations from the SM due to new pseudoscalar particles with masses up to 1,000 TeV can be probed, as can charged Higgs bosons with masses up to 500 GeV [7]. Data from PIENU can also be used to search for exotic massive neutrinos N emitted in $\pi^+ \rightarrow e^+N$, as these would modify the energy spectrum of the emitted positron. An analysis of preliminary data has been used to improve the limit on massive neutrinos in the mass region m_ν = 65-130 MeV, where the limit on mixing with SM neutrinos $|U_{ei}|^2$ has been constrained to a level of ten parts in a billion [8,9].

Weak interactions also play an important role in atomic nuclei. The best-known example is beta decay where a neutron decays to a proton, an electron, and a neutrino through the exchange of a W boson, $n \rightarrow pe\nu_e$. Precision measurements of beta decays have been made at TRIUMF by the 8π, GPS, TITAN, and TRINAT experiments.

The TRIUMF 8π experiment has measured the half-life of Fermi-type beta decays in Ga-62, K-38m [10], and Al-26m [11,12], obtaining world-leading precision branching ratios in each case. Also half-life measurements with GPS and 8π on O-14 [13], Ne-18 [14], Ne-19 [15] achieved world leading precision. These results have been combined with other experiments to obtain a world-best determination of V_{ud}, the first element of the Cabbibo-Kobayashi-Maskawa matrix that describes the coupling of the W boson to quarks and a fundamental constant of the SM. The result for V_{ud}, together with the world averages of V_{us}

and V_{ub} provide the most stringent test of the unitarity of the CKM matrix. Detailed measurements of the energy released in these decays also give the best existing limits on new scalars that couple to normal-chirality leptons. Measurements in Al-26m give a sensitive test of isospin mixing, a vital input needed to determine the potential accuracy of future isospin-mixing calculations. Related measurements of the beta decay, mass, and structure of Rb-74 have been made by GPS, 8π, collinear laser spectroscopy, and TITAN [16,17].

Beta and Nuclear-Recoil Asymmetries

Beta decays provide another access to weak-interaction physics. The TRINAT collaboration studied Rb-80 and K-37 using a neutral atom trap. The recoil asymmetry with respect to the spin in the decay of Rb-80 improves the bounds on non-standard four-fermion couplings to exotic neutrinos [18]. These measurements are limited by the 1% systematic theory uncertainty on the corrections from nuclear structure effects. To improve this, TRINAT has begun to study K-37 decays to its isobaric analog Ar-37, which has much smaller corrections that can also be calculated more accurately. Measurements of K-37 were made in an upgraded apparatus in December 2012, reaching a statistical error below 2%. Eventual goals are to reach 0.1%, a level at which several types of new physics, such as supersymmetry, can potentially produce observable effects.

The weak processes discussed so far have all been induced by the charged W boson. Significant effects can also be generated by the neutral Z boson. An example studied at TRIUMF is the violation of parity in atoms, where the exchange of Z bosons between orbital electrons and the nucleus allows atomic states with different parities to mix with one another and induces transitions that would otherwise be forbidden. The goal of the Francium Parity Non-Conservation (FrPNC) experiment [19] is to measure these effects in francium (Fr) atoms. As the heaviest alkali, francium is particularly well suited to this type of study; the single valence electron implies the atom is simple enough in structure to be understood theoretically, while its large mass produces a strong overlap of the electron wave-function with the nucleus, enhancing the effects of the short-ranged weak interaction. While francium has no stable isotopes, it has now been produced at rates of $5x10^8$/s from ISAC, making precision measurements possible.

In fall 2012, the FrPNC collaboration measured the atomic hyperfine splitting in francium atoms using collinear and in-trap laser spectroscopy, and detected the next higher magnetic moment beyond the nuclear dipole in Fr-207 and Fr-213. These isotopes show similar behaviour to that previously measured in Fr-208-212, suggesting regular single-particle behaviour for the valence nucleons. Such measurements will be essential for interpreting future atomic parity violation experiments at TRIUMF, which will be sensitive to the spatial distribution of neutrons in the nucleus.

DNP THESIS PRIZE AWARDED TO ROB MACDONALD

27 January 2010

Rob MacDonald of the University of Alberta was this year's winner of the 2008-2009 Division of Nuclear Physics (DNP) Thesis Prize. This prize is given in Experimental or Theoretical Nuclear Physics to a student who is obtaining his/her Ph.D. degree from a Canadian University. MacDonald's thesis "A Precision Measurement of the Muon Decay Parameters Rho and Delta" was based on doctoral research performed at TRIUMF with TWIST, under the supervision of Art Olin.

MacDonald's thesis reported intermediate results for the TWIST experiment. It was the quality of his analysis and dissertation that brought attention to his work. The thesis was not only useful for committee members, but also served as a useful reference document for the TWIST group as the experiment continued.

MacDonald commented, "Good science and good communication are very important to me. The last stages of my thesis work were devoted to checking every corner of our analysis and turning over every rock, looking for potential problems and making sure we accounted for every possible source of error." The result was a measurement Rob was confident he could support and defend.

The ultimate goal of the FrPNC experiment is to measure the weak charge, the effective coupling of the nucleus to the Z boson, of several Francium isotopes to better than 0.1%. A determination at this level will be sensitive to new vector bosons with masses up to several TeV, comparable to the sensitivity of direct searches at the LHC. These measurements will also be sensitive to the hypothetical exchange of much lighter bosons that violate parity and couple only very feebly to the Standard Model.

Parity violation can also be induced in scattering processes by the exchange of Z bosons. The Qweak experiment is studying this effect in the scattering of polarized electrons on a liquid hydrogen target by measuring the change in the scattering rate when the electron spin is reversed. The Qweak experiment is based at JLab (Jefferson Laboratory), but many of the key components including the electron detector and the electronics for the data acquisition system were built at TRIUMF. Installation of the experiment in Hall C began in December 2009 and was completed in May 2010, and commissioning took place from October 2010 until February 2011. During this commissioning phase, some 4% of the anticipated total data were obtained in 2,500 hours. Further data are being taken and considerable progress has been made analyzing them. It is anticipated that when the full data set is analyzed in 2013 and 2014, a statistical error close to the design goal of 6×10^{-9} will be achieved.

The SM prediction for the scattering asymmetry is approximately -250×10^{-9}, while the goal of the Qweak experiment is a precision of 6×10^{-9} (combined systematic and statistical) [20]. A measurement of this accuracy would determine to 0.3% the weak mixing angle $\sin^2\theta_W$ at low momentum transfer, which describes the relative strength of the weak and electromagnetic forces. The precision of this result relative to measurements of the weak mixing angle at other energies is shown in Figure 2. This level of precision also makes the Qweak experiment sensitive to many types of new physics with masses up to the TeV scale, such as an extra neutral vector boson or supersymmetry.

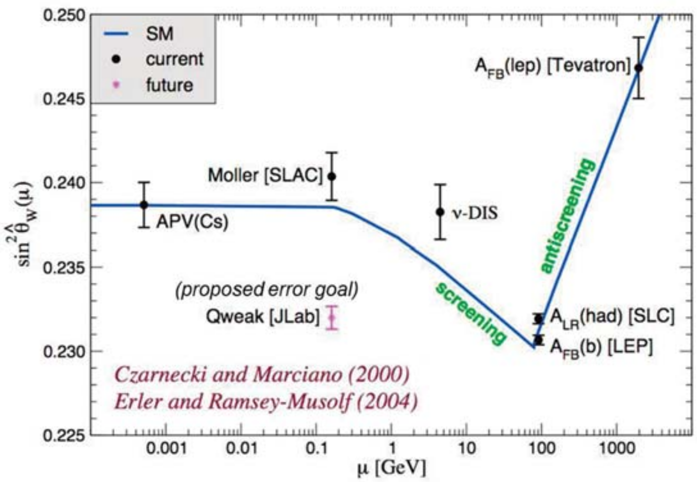

Figure 2: Estimated precision of the Qweak determination of the weak mixing angle $\sin^2\theta_W$ relative to other measurements at different energies.

A sensitive test of both the W and Z contributions to the weak force and of new physics is the anomalous magnetic moment of the muon $(g\text{-}2)_\mu$. The Brookhaven E821 experiment has already measured $(g\text{-}2)_\mu$ very precisely, and the value they obtain differs by more than three standard deviations from the theoretical prediction of the Standard Model. To confirm this result, TRIUMF is involved in a program at J-PARC (Japan Proton Accelerator Research Complex) to measure $(g\text{-}2)_\mu$ with a different approach, with independent systematic uncertainties, using the acceleration of muons following the laser ionization of muonium in vacuum [21].

In collaboration with KEK and RIKEN, a TRIUMF group has measured and characterized the emission of muonium (μ^+e^-) into vacuum following muon thermalization in silica aerogel. This is an important step in developing the high-intensity muon beam needed for the J-PARC $(g\text{-}2)_\mu$ measurement. Following an initial μSR experiment at M20 to identify promising materials, silica aerogel samples were studied further via imaging of muon decay positrons from vacuum near the aerogel surface. Two experimental periods at the M15 muon channel allowed the characterization of muonium emission from several types of aerogel. This input was crucial to the J-PARC evaluation process that resulted in the $(g-2)_\mu$ project receiving Phase 1 approval in early 2012.

Higher-Energy Probes

Studies of the weak force at higher energies, near or above m_w, seek to probe directly the W and Z bosons that mediate this interaction. The Collider Detector at Fermilab (CDF) experiment at the Tevatron measured the mass of the W boson to a very high precision by studying proton-antiproton collisions at 1.96 TeV in which a W boson was created. In the subset of these events, where the W boson decayed to an electron or a muon and a neutrino, the particle momenta were measured and combined to form a quantity called the transverse mass m_T. The W boson mass was extracted by fitting the predicted shape of the distribution of m_T values to the data.

Applying these methods to 2.2 fb^{-1} of collision data, the W boson mass was measured to a precision of 19 MeV [22]. This single experimental measurement improves significantly on previous Tevatron and LEP combinations, which had precisions of 31 MeV and 33 MeV respectively, and dominates the new world-average W boson mass, m_W=80385±15 MeV. This improvement in the measurement in the W mass is significant because its value is sensitive to the mass of the Higgs boson and any other new particles that might be present. Applying the measured W mass to the global fit to electroweak observables gives a prediction for the Higgs boson mass of $m_h=94^{+29}_{-24}$ GeV, consistent with the mass of the Higgs boson discovered at the LHC [23].

The ATLAS experiment at the CERN Large Hadron Collider (LHC) has studied the collisions of protons at centre-of-mass energies of 7 and 8 TeV (please see Section 5.5.5.2). With this much energy, ATLAS is able to probe both the W and Z bosons that mediate the weak force as well as the underlying structure of electroweak symmetry breaking. With the 25 fb^{-1} of proton collision data obtained so far and the exquisite sensitivity of the ATLAS detector, these studies may be done to a very high precision.

The large collision energy of the LHC means that it is a veritable factory for the W and Z weak bosons, and for top quarks (which decay by the weak interaction without first hadronizing). New results from studies of W and Z boson production include: W and Z cross-section measurements [24,25,26,27] and transverse momentum distributions [28,29]; WW [30,31,32], WZ [33,34], ZZ [35,36], Wγ and Zγ [34,37,38] cross-section measurements; triple-gauge-boson coupling measurements for all combinations of W and Z bosons and photons; and measurements of W polarization [39] and W charge asymmetry [40] in proton collisions. There are also many new results from top quark studies, including measurements of W boson polarization in top decays [41], and measurement of the t-channel single top-quark electroweak production cross-section [42] as well as evidence for the associated production of a W boson and a top quark [43]. Many of these results are shown in Figure 3, 4, 5.

This diverse range of studies provides a strong test of the underlying electroweak structure of the weak force predicted by the SM, and so far the measurements made by ATLAS are consistent with the SM. The SM description of electroweak symmetry has also received further experimental support from the discovery of a new bosonic particle at the LHC whose properties agree with those of the SM Higgs [43]. ATLAS searches for new physics constrain the direct production of additional new particles with masses up to several TeV. These direct limits are complementary to those obtained by lower-energy precision tests. A more detailed description of these studies can be found in Section 4.2.1.1.

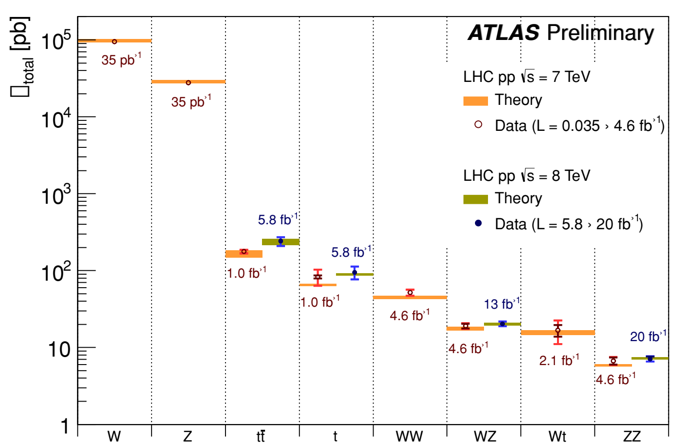

Figure 3: Measurements of weak boson production cross-sections by the ATLAS experiment.

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4.2.2 STRONGLY INTERACTING SYSTEMS: FROM NUCLEI TO STELLAR EXPLOSIONS

The strong interaction is one of the four known fundamental interactions of nature. It is responsible for a broad range of bound states between quarks and gluons. Protons and neutrons, the basic building blocks of atomic nuclei, are most commonly known representatives of strongly bound systems, jointly referred to as nucleons. Nuclei are the core of atoms and account for essentially all the mass of the matter known in the universe. The interactions between nucleons inside atomic nuclei determine the properties of atomic nuclei, for example if a nucleus is stable or is transformed through radioactive decay into another nucleus. Reactions between atomic nuclei govern the energy production in stars and the synthesis of heavier elements from the primordial fuel of stellar burning, hydrogen and helium. The elements from carbon to iron, with 26 protons, are predominantly produced in stellar interiors while we know that about half of the elements heavier than iron, up to uranium with 92 protons, are created in cataclysmic events in the universe.

Thus the study of nuclear physics connects the building blocks of life on Earth with the life and death of stars and history of the early universe back to first few minutes when the first helium and lithium were created.

The strong interaction is remarkably complex at the low energies (1 GeV) and long distance scales (1 fm = 1 millionth of a billionth of a meter) relevant for the binding of quarks into nucleons. The force between nucleons can be studied through scattering experiments with high precision. However, it remains impossible to derive the interaction between two and more nucleons in an analytical way from the underlying interaction of quarks through the exchange of gluons, the force carriers of the strong interaction. Effectively the nucleon-nucleon interaction can be viewed as a kind of Van-der-Waals interaction that leaks out of the nucleons, similar to the molecular binding of neutral molecules.

The study of the atomic nucleus has undergone a major re-orientation in the last decades and has seen the emergence of new frontiers. In particular the availability of energetic beams of short-lived (radioactive) nuclei, in the following referred to as rare isotope beams or beams of exotic nuclei, has opened the way for the exploration of the structure and dynamics of complex nuclei in regions far away from stability, where very limited information is available. Among the exciting new topics emerging from this research are, for example, the appearance of single- and double-nucleon (Borromean) halo nuclei, the increasing ability to describe nuclear properties from first principle using ever more realistic forces, as well as the breakdown of the magic numbers, the long-standing benchmark for structural evolution, and the emergence of simple patterns in the complex nuclear many-body system.

TRIUMF is at the forefront of this quest with world-leading expertise both in the theoretical and experimental investigations. The TRIUMF Theory Group is carrying out leading edge research on the properties of heavy bound mesons using lattice QCD and the application of *ab initio* theories to describe light nuclei and their reactions using realistic forces, based on chiral effective field theory. The TRIUMF rare isotope facility ISAC is using the isotope separation online (ISOL) method to produce and deliver intense rare isotope beams to a suite of world-class experiments that study the properties of ground states and excited states of nuclei, and study nuclear reactions with the aim to map out nuclear properties and determine reaction rates relevant for the understanding of nuclear burning stars and star explosions. ISOL RIB facilities like ISAC at TRIUMF, which is the ISOL facility with the highest power in the world, enable not only the precision study of nuclear properties but are also able to deliver sufficiently intense beams of species that allow the direct measurement of the very low reaction rates of nuclear reactions occurring in various astrophysical environments.

During the past five years the ISAC facility has further developed its spectrum of available beams, in particular taking advantage of laser ionization, as well as its operational reliability, enabling the new and existing experimental facilities, some of which recently expanded their capabilities, to carry out forefront research on the structure and dynamics of exotic nuclei and their role in the universe.

4.2.2.1 FROM QCD TO NUCLEAR FORCES

Quantum Chromodynamics (QCD) is a microscopic theory of strong interactions, formulated at the level of the quark substructure of matter; it specifies how the six fundamental quarks interact by exchanging gluons, the force carriers of the strong interaction. This theory can in principle explain a diverse range of phenomena, from the nature and distributions of new particles produced in the highest energy collisions at the Large Hadron Collider (LHC), to the properties and structure of known particles, stable and unstable atomic nuclei as studied at ISAC. Indeed, the development of QCD and the confirmation of its role as a microscopic description of strongly interacting matter has been a major success of the Standard Model.

Progress is advancing on a number of fronts, and TRIUMF scientists have had key roles, with seminal contributions. On the theoretical side, a method known as lattice field theory allows for a non-perturbative calculation of properties of strongly interacting quark and gluon systems. In this method, space-time is represented as a discrete lattice in a numerical procedure that can be controlled systematically. This allows for a computation of the quantum field theory equations and the prediction of a wide range of phenomena. Lattice QCD has been a long-standing research topic in the TRIUMF Theory Group, and some recent results are presented here. On the experimental side, predictions of lattice QCD, and of QCD-inspired effective field theories, can be tested by comparison with data. Precise measurements using polarized beams to study the spin structure of the proton and neutron are powerful tools to advance our progress in this challenging field. TRIUMF's contributions here have been focused on the G0 experiment at the Thomas Jefferson National Accelerator Facility (JLab) in Newport News, VA, USA. The G0 experiment probed the strange quark contributions to the nucleon electric and magnetic moments via scattering of spin polarized high-energy electron beams (see Figure 1).

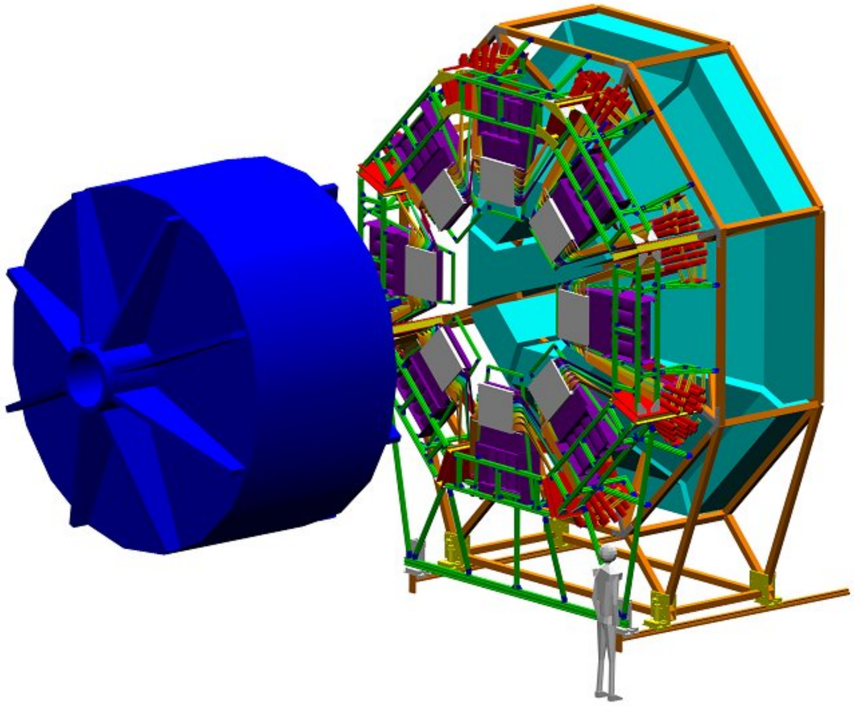

Figure 1: Detectors fabricated and tested at TRIUMF for the G0 backward angle measurements at JLab. The 8-fold symmetry of the detector system is matched to that of the superconducting magnetic spectrometer. Visible are the supports for the scintillation detector arrays (white), in front of the aerogel Cherenkov detectors, whose magnetically shielded photomultiplier tubes are visible in yellow.

The theory of QCD is studied at TRIUMF by means of numerical simulations using the techniques of lattice field theory. Understanding the strong force among quarks and gluons is a very difficult problem. The strong force bears some resemblance to the electromagnetic force between a proton and an electron, which produces the hydrogen atom with its large number of possible energy levels, but the strong force presents additional unique challenges. First the underlying theory of low-energy QCD has no small parameter in which to make an expansion, so theorists have developed a computer simulation method called lattice QCD. Secondly, there are several flavours of quarks in nature (u,d,s,c,b,t), and their range of masses (a few MeV/c^2 to 170 GeV/c^2) exceeds the ability of present-day computers for computation unless specific lattice QCD methods are developed and tuned to each quark flavour. Recent lattice QCD research from the TRIUMF group has produced valuable progress in the theoretical understanding of physics involving two of the heavier quarks: the charm quark and the bottom quark. A few major research highlights, where TRIUMF personnel played a primary role, are presented in this plan.

The bound state of one quark and one antiquark is called a meson. Because additional quark-antiquark pairs can appear and disappear at any time in nature, a lattice QCD study will find that two-meson states can mix with single-meson states. To deal with this significant complication, an advanced lattice algorithm called distillation has become available recently. This has been applied to the calculation of the mass and decay rate of the ρ meson (made of u, d light quarks), a benchmark problem that provides a good test of the simulation methods.

A novel application of distillation has been the ongoing study by TRIUMF scientists of mesons containing a charm quark. The goal of this work is a unified description of the energy levels within the whole family of charmed mesons, whether the second quark is up, down, strange or charm. Mesons with and without angular momentum (S and P waves) have already been studied successfully [1] and state-of-the-art lattice methods, including a large set of basis operators and the variational analysis method, were invaluable in achieving these results.

A subsequent study examined two charmed mesons, the D_0^* and D_1 mesons, in particular detail [2]. These two mesons are experimentally broad (i.e. they decay rapidly) and thus are particularly affected by nearby two-meson states. This lattice study used the distillation technique to include the coupling of D_0^* with its two-meson state ($D\pi$) and the coupling of D_1 with its two-meson state ($D^*\pi$). The calculation was done on a rather small lattice and with up and down quarks somewhat heavier than their true masses so it should be considered an exploratory study, but it stands as the first time that the D_0^* and D_1 mesons were calculated as resonances in lattice QCD. Overall, this study gave a good description of the charmed meson spectrum, including some excited states that are compatible with recent results from the BABAR experiment.

Work is ongoing to implement an even more powerful method, called stochastic distillation, which should allow simulations to be done on lattices of larger volume with lighter up and down quark masses. A goal is to extend the inclusion of two-meson operators to the charm-antistrange meson (D_{s0}^*), which still represents a puzzle for the physics community.

Lattice QCD simulations of bottom-antibottom mesons were also carried out. In familiar quantum language, one would expect to see energy levels that can be categorized as radial excitations and orbital excitations. This study observed orbital excitations (S, P, D, F and G waves) beyond the reach of any previous lattice results [3]. Radiative transitions from a radially-excited S-wave state to a lower state (by photon emission) were also observed for the first time in any lattice study of bottom-antibottom mesons [4].

A major effort was undertaken to calculate the masses of b-quark baryons (i.e. three-quark objects) using lattice gauge field configurations to contain the effects of quark vacuum polarization due to up, down, and strange quarks (provided by Japanese collaborators) [5]. In a separate effort, the bottom quark was described by a nonrelativistic expansion in the lattice simulation and tested by applying it to the bottomonium and B mesons [6].

After using known meson masses to determine all required parameter values, the baryon masses emerged as predictions from the lattice QCD simulation. When this study was published, only four of the baryons had already been seen experimentally (Λ_b, Σ_b,Σ^*, and Ξ_b) and there was an experimental prediction for the $_\Omega$b that differed significantly from the lattice QCD prediction. As Figure 2 indicates, a subsequent experimental measurement produced a new value for Ω_b that is very close to the lattice QCD prediction, and another experiment published a measurement of the Ξ^*_b mass in perfect agreement with the lattice QCD prediction.

The other two baryons in the figure remain as lattice QCD predictions, awaiting experimental confirmation. To date, this is the most complete study of bottom baryons that has been done using lattice QCD.

Jefferson Laboratory (JLab) is North America's premier electron beam scattering facility for nuclear physics. Located in Newport News, VA, the CEBAF accelerator at Jefferson Lab supplies intense beams of high-energy electrons to experiments that probe the quark substructure of the proton. The G0 experiment is a multi-year, international effort utilizing JLab's unique spin-polarized electron beams, aimed at unraveling the strange quark contributions to the proton's electric charge and magnetization structure. The experiment was first proposed in 1993; custom apparatus was installed in Hall C at JLab in 2003, and data taking took place in 2004 and 2006/7. Data analysis and publications commenced in 2004 and continue to the present.

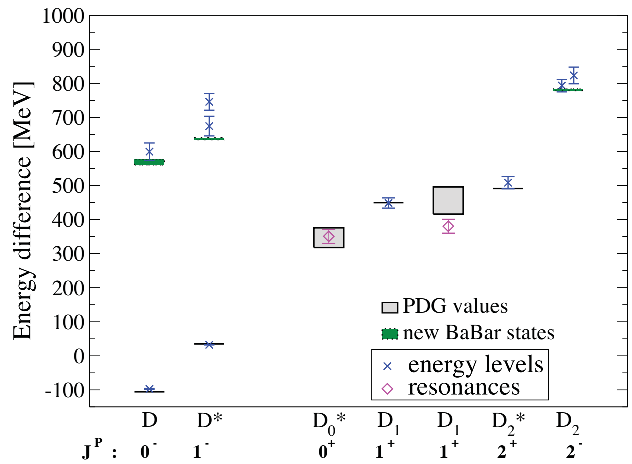

Figure 2: A study depicting two charmed mesons, D_0^* and D1.

In QCD, the proton is predominantly a bound state of the lightest quark constituents, two "up" quarks, and one "down" quark, and its properties are mainly determined by these. However, due to transient quantum fluctuations, heavier quarks—mainly the "strange" quark, may contribute to the proton's properties, e.g., its charge and magnetic moment distributions.

Suggestions that strange quark quantum effects could be responsible for relatively large effects, on the scale of 15% or more of the proton's magnetic moment [7], motivated several experiments to probe these effects. G0 is arguably the most ambitious and comprehensive of these efforts from the standpoint of kinematic coverage and instrumentation.

The G0 experiment was designed to shed light on possible strange quark contributions by using the weak interaction as a probe of the proton's structure. Much of the G0 detection system and corresponding support structures were designed and fabricated at TRIUMF. The weak interaction has a unique feature that it is not mirror-symmetric; this feature is referred to as its parity-violating property. By combining existing measurements from "ordinary" (parity-conserving) electron scattering with a set of new parity violating electron scattering measurements obtained with the G0 apparatus, it is possible to disentangle the individual quark contributions to the proton's electric charge and magnetization distributions. Thus, the strange quark contributions, predicted for example from lattice field theory, could be quantified for the first time by experiment.

In order to use the weak interaction as a probe of the proton structure, its parity-violating property had to be invoked. This meant that the basic electron-proton scattering process had to be compared in two distinct states related by a mirror reflection. This was achieved by manipulating the spin direction of the high-energy electron beam incident on a liquid hydrogen target. With the electron spin direction rapidly reversed with respect to its direction of motion parallel and antiparallel, a tiny change in the scattering rate results from the weak interaction (the dominant effect in this case is the electromagnetic scattering rate, which is mirror symmetric). Comparing this rate difference to its average value results in a scattering asymmetry. The scattering asymmetries in the G0 experiment were inherently very small, and high statistical precision was required in order to achieve adequate sensitivity to the suggested strange quark effects; typical asymmetries amounted to 5 parts per million, with required sensitivity at the 5% level.

The G0 apparatus used a cryogenic liquid hydrogen target, a superconducting magnetic spectrometer, and a segmented detector system to measure parity-violating asymmetries in electron-proton elastic scattering at a wide range of scattering angles, yielding information that could be related to the momentum transfer "Q" in the scattering process [8]—a key kinematic quantity that is needed to characterize the distributions comprising the proton's structure.

In order to disentangle the strange quark contributions to the proton electric and magnetic moment distributions, half of the data were taken in "forward angle" mode, and the second half in "backward angle" mode. In the forward angle mode, the recoiling protons from the e-p collision were focused through the 8-sector superconducting toroidal magnet onto arrays of scintillation and Cherenkov detectors; in backward angle mode, the entire apparatus was rotated and the scattered electrons were detected. Additional detectors were added to assist with particle identification, and some data were also acquired with a liquid deuterium target, to support the main physics analysis.

Data analysis of the first phase of G0, the forward angle measurement, constrained the strange quark contribution to a linear combination of electric and magnetic form factors of the proton [9]. Additional physics results based on measurements of asymmetries with the electron beam polarized transverse to its direction of motion were also extracted from the forward angle data set [10]. These latter effects are not parity-violating, but are extremely small, and are a sensitive probe of two-photon exchange contributions to the scattering process, which is normally neglected.

The second-phase of G0, the backward angle measurement, completed data-taking in 2007, and the analysis of these data was completed in mid-2009. Efforts then focused on computing the relevant radiative corrections, which needed to be applied before the forward and backward angle results could be properly combined and the strange quark effect contributions to the electric and magnetic distributions of the proton could be extracted separately and thus achieve the full physics goals of the G0 program.

The final results (see Figure 3) showed that strange quarks make small (< 10%) contributions to the ground state charge and magnetic form factors of the nucleon [11]. These results are consistent with lattice QCD simulations carried out in collaboration with the TRIUMF Theory group [12] and attracted considerable interest in the subatomic physics community. Additional physics results involving transverse beam spin asymmetry data were also extracted from the backward angle measurements [13]. As well, a description of the G0 apparatus was summarized and published [14] in 2011. In 2012, analysis and extraction of physics results involving pion electroproduction asymmetries was completed [15]. Present efforts are focused on the analysis and extraction of further physics results involving inelastic electron asymmetries. It is anticipated that these data will be released for publication in 2013.

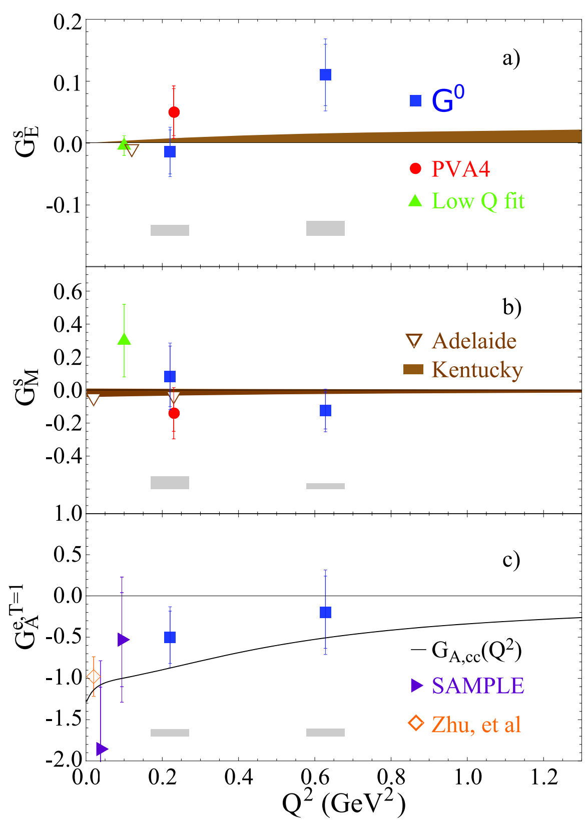

Figure 3: The form factors a) G sE b) G sM and c) G eA determined by the G0 experiment and others. Error bars show statistical and statistical plus point-to-point systematic uncertainties (added in quadrature); shaded bars below the corresponding points show global systematic uncertainties (for G0 points).

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4.2.2.2 NUCLEAR FORCES AND EXOTIC NUCLEI

Atomic nuclei are fascinating objects made up of protons and neutrons (called nucleons) and surrounded by electrons. Recent theoretical investigations predict the existence of roughly 7,500 different atomic nuclei (or isotopes) both stable and unstable ones.

Unstable nuclei have lifetimes that can be as small as a fraction of a second. The nucleons are held together, even if only for a short time, by effective forces originating from the fundamental theory of quantum chromodynamics (QCD). At the low-energy regime relevant to nuclear physics, QCD is highly non-perturbative and thus intricate. These diverse phenomena observed in nuclear physics have their roots in the complex nature of nuclear forces. As one moves away from the so-called valley of stability and investigates neutron-rich nuclei, new phenomena or structures emerge, and their interpretation is crucial to our understanding of nuclear physics. This poses one of the most challenging intellectual questions. What are the limits of nuclear existence? The intellectual challenge lies in being able to describe the nature of the atomic nucleus as a many-body system.

The following discussion will present experimental efforts and state-of-the-art theoretical methods to further our understanding of the complex interaction that holds nuclei together. The examples are taken from light nuclei, where the most extreme ratios of neutrons-to-protons can be reached. The reason for investigating those isotopes is two-fold. First, in order to probe neutron-proton interactions, one needs to understand the effects that a very asymmetric nucleon composition would have, hence comparing a He-4 nucleus (with 2p and 2n) or C-12 (with 6p and 6n, and an n-to-p ratio of 1) to a nucleus like He-8 (with the same 2p but 6n, and an n-to-p ratio of 3). Secondly, light nuclei are accessible theoretically in a very fundamental manner, because their total nucleon numbers are small enough for first-principle calculations to be performed, the last from the most neutron-rich calcium isotopes investigated to date. It is, in fact, crucial to extend theories and computational methods to heavier and heavier nuclei that also exhibit larger n-to-p ratios.

The first example of new and unexpected behaviours is the appearance of halo structures in light neutron-rich nuclei, where loosely bound neutrons surround a tightly bound core. He-6 is the lightest known halo nucleus. The configuration to form such a nucleus is approximated with a three-body problem, where all the three possible two-body subsystems (the di-neutron and the helium-5-core) are unbound, but the combination of three-body system is bound. Another striking feature is the fact that both He-5 and He-7 do not have bound ground states, but He-8 exists again, and is a so-called a two-neutron halo.

One powerful way to test nuclear theories is through precision mass measurements. The mass provides direct access to the total binding energy of the system, which in turn reflects the forces and hence gives fingerprints of the nuclear interactions. The measurement of masses is not limited to halo-nuclei and, in fact, over the past two decades, the high-precision direct mass measurements of short-lived nuclei have provided valuable information on a wide range of topics. The atomic mass is an important quantity for the determination of the neutron separation energy, the energy needed to liberate one or two neutrons, or, in other words, the quantity which describes how tightly the last neutron(s) is (are) bond to the core. The neutron separation energy depends on the difference in mass of neighbouring isotopes.

An equally important way to probe our understanding and the description of the nuclear system comes from a measurement of the charge radius. The charge radius is defined as the extent of the proton distribution within the nucleus. The other key measure to describe the nucleus is the matter radius. If the hypothesis of extra neutrons outside the core is true, then there would be a difference in the neutron and proton distribution of the nucleus, with more neutrons outside the proton distribution, but all nucleons obeying the rules of quantum mechanics. The charge radius of atoms is typically determined in electron scattering experiments, which are difficult for short-lived isotopes. The neutron distribution is derived from total cross-section measurements, a method that is applicable to short-lived exotic isotopes.

An alternative approach for the charge radius measurement comes from atomic physics, where the determination of atomic electron transitions provides a sensitive tool for probing the charge distribution in the nucleus via the hyperfine interaction. The atomic transitions are investigated with sophisticated laser spectroscopy. In fact, recent advances in online laser spectroscopy, in combination with precision atomic calculations, have allowed a precise, model-independent determination of the charge radius. However, these calculations have to take into account that the variation of the electronic transitions is caused in part by the change in the centre-of-mass movement when adding neutrons. In some cases, the largest source of uncertainty in these calculations stems from the knowledge of the actual atomic mass used to determine this so-called mass-shift.

One of the most effective ways to measure atomic masses is with ion trap techniques [1], and one of the most advanced systems in the world utilizing this method is TITAN (TRIUMF's Ion Trap for Atomic and Nuclear Science).

JOINT PUBLICATIONS DEMONSTRATE LABORATORY SYNERGY

July 1 2009

Two recent publications by the TRIUMF Theory Group highlight the great strides the group has made toward understanding the structure of light nuclei, and demonstrate the dynamic relationship between theoretical and experimental science.

The first, "Role of the Final-State Interaction and Three-Body Force on the Longitudinal Response Function of He-4," was published in Physical Review Letters. This work is triggering new experimental activity in Mainz (Germany) and it is relevant for the experimental program at Jefferson Lab (USA).

The second, "Helium halo nuclei from low-momentum interactions", will soon appear in the European Physical Journal. Here, the group's new first-principles (ab-initio) methods for solving the quantum many-body problem are used to derive theoretically the properties of halo nuclei. The results are then compared to experimental data from the TRIUMF ISAC program. These recent publications solidify the Theory Group's strong theoretical efforts, sustaining TRIUMF's world leadership role in nuclear physics.

Recently, the first direct mass-measurement of the two-neutron halo nucleus He-6 was carried out at TITAN together with a more precise measurement of the value for the four-neutron halo He-8 mass [2]. Measurements where performed using the TITAN Penning trap mass spectrometer.

In the Penning trap, a single ion (with mass m and charge-state q) is trapped in a combination of electric and magnetic (B) fields, and the characteristic cyclotron frequency is given by $\omega_c = q/m \cdot B$. The precise determination of the cyclotron frequency then allows the extraction of the atomic mass of the ion.

TITAN is currently the only system in the world where such measurements can be performed, due to its rapid measurement capabilities while preserving the required precision. The results of the new masses lead to improved values of the charge radii and the two-neutron separation energies, which combined provide the most stringent tests for three-body forces for neutron-rich isotopes, with n-to-p extremes. State-of-the-art *ab initio* calculations for He-6 performed at TRIUMF were compared to these findings and co-published with the new experimental data [3]. Due to the particular extended structure of the wave functions, taking into account that the halo neutrons are very far away from the core, these nuclei are difficult to investigate theoretically. The new calculations performed at TRIUMF were obtained with the so-called effective interaction hyperspherical harmonics (EIHH), which is a few-body method mostly used for lighter nuclei. Binding energies and charge radii were calculated together for the first time using chiral (low-momentum) potentials, which is explained in the following paragraph. Effective field theories are a modern theoretical instrument to construct interactions among nucleons. Starting from point-like nucleons as effective degrees of freedom and imposing chiral symmetry, which is found in the fundamental theory of strong forces (QCD), one can derive nuclear forces in a systematic way. They are the Goldstone bosons of this theory, where chiral symmetry is spontaneously broken. All the different diagrams can be ordered according to a power expansion in Q/Lambda, where Q is the relevant scale of the low-energy physics one wants to describe and Lambda is a breakdown scale, ~ 11 GeV. Beyond this scale the inner structure of the nucleons cannot be neglected and such expansion would break down. For low-energy observables instead, the relevant momenta involved are such that Q<< Lambda, and the expansion is expected to converge. Binding energies and charge radii are such low-energy observables.

One observes the appearance of nucleon-nucleon (NN) interactions, where only two nucleons are present, at the leading order of the expansion, i.e. $(Q/Lambda)^0$. Three-nucleon (3N) forces, where three nucleons interact simultaneously and four-nucleon (4N) forces instead appear at higher order in this expansion, namely at $(Q/Lambda)^3$ and $(Q/Lambda)^4$, respectively. In other words, there is a natural hierarchy among nuclear forces, where NN interactions are more important than 3N forces, 3N forces are more important than 4N forces etc. Because the theory can be worked out at different orders, this approach is systematic and theoretical error bars can be assessed, for example by comparing calculations at different orders.

The theoretical calculations performed at TRIUMF for the He-6 nucleus used only NN forces, neglecting 3N forces, as a first step towards a complete investigation. The two-neutron separation energy (energy necessary to remove two neutrons) and the charge radius were calculated. Results are shown in Figure 5 together with the TRIUMF experimental measurements and with other theoretical calculations based on more phenomenological approaches to nuclear forces. Evidently, all theories, except for the Green's function Monte Carlo (GFMC) red points fail to reproduce the data. This is due to the fact that three-nucleon forces have been neglected. In fact only the GFMC calculations include 3N forces. Thus, precise experimental data such as those on He-6 provide very stringent tests on modern calculations and will be crucial to test chiral 3N forces in the future.

The He-6 example described above shows how experiment and theory could work in synergy to advance our understanding of nuclear forces. Theoretical efforts are in fact directed towards utilizing chiral effective field theory to predict the properties of halo nuclei and other isotopes and will need to be tested against experiment. This should ultimately lead to an extension of the theoretical predictability of nuclear properties to all isotopes.

Another way to look at the charge distribution of the nucleus is by measuring its quadrupole moment. Recently a new, more precise technique was developed to measure ground state quadrupole moments using β-NQR [4]. This was applied to the halo nucleus Li-11 resulting in the best measurement so far for the ratio of quadrupole moments of Li-11 and Li-9 [5]. This ration is reliably predicted by *ab initio* theory, while the theory is challenged to reproduce the absolute values. The charge radius of Li-11 was previously measured at TRIUMF using laser spectroscopy [6].

Further studies, which were aimed at beryllium isotopes, made use of a different experimental technique but also aimed at providing two independent experimental observables. These could then be compared to theoretical prediction.

In these studies of the neutron-rich nuclei Be-10,11,12, one finds a unique nexus between TRIUMF ISAC's unsurpassed light-mass intensities and the unique experimental facilities available at TRIUMF. All of these experiments used the high-resolution, highly segmented germanium detector area TIGRESS for gamma ray detection in combination with the particle detector BAMBINO (please see Section 5.5.2.1). The experiments were carried out by accelerating the beryllium isotopes to a 2-3 MeV and then impinging on a target inside the BAMBINO detector. The beryllium isotopes react with the target atoms and excited states are generated.

The first excited state of Be-10 is a gamma-emitting 2^+ state that decays to the 0^+ ground state. This 2^+ state exhibits quadrupole deformation, the magnitude of which has been deduced from lifetime measurements. *Ab initio* calculations with local two-body forces, however, disagree on the sign of the deformation, that is, whether it is prolate or oblate. Other calculations, which include three-body forces, result in a predicted shape change from oblate to prolate, while another calculation by a group at TRIUMF using non-local two-body forces consistently calculates a prolate shape.

The sign of the deformation was measured by the reorientation effect of Coulomb excitation (Coulex) experiments [7]. Radioactive Be-10 beam produced by ISAC, ionized by the resonant laser ionization technique, and accelerated by ISAC-II to the TIGRESS beam station, have been scattered off a high-Z target foil and detected with BAMBINO silicon detectors. In inelastic scattering, the Be-10 2^+ state is excited by the electric field of the target nuclei and then decays by emitting gamma rays, which are detected with TIGRESS high-purity germanium detectors as shown in Figure 1. The excitation cross-section depends not just on the magnitude of the deformation but also its sign; when the measured yield is compared with lifetime data, it is concluded that the sign of the transition matrix element must be that of a prolate deformation (see Figure 2).

In the case of the one-neutron halo nucleus Be-11, the transition strength between the ½$^+$ ground state and ½$^-$ excited state is the strongest E1 electric dipole transition known. The strength of this transition and the structure of E1 strength in continuum states is a challenge that modern theory is able to address with accuracy. However, there is a troubling 10% discrepancy between lifetime and high-energy inelastic scattering measurements of the reduced matrix element. At TRIUMF the Coulex cross-section has been measured at low bombarding energies (below the Coulomb barrier to avoid additional production channels and keep the final states well defined), so that one key source of systematic uncertainty, the contribution of nuclear interference to the

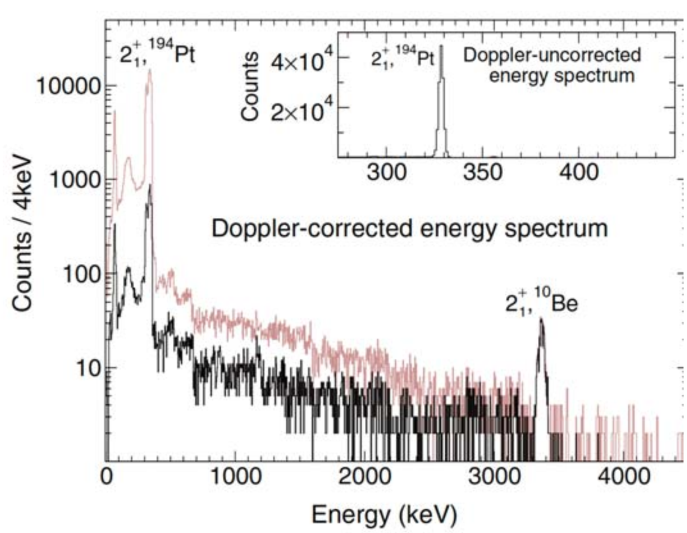

Figure 1: Gamma-ray spectrum from [7]. Brown, total spectrum; black, spectrum gated by the inelastic scattering peak in Bambino

excitation probability, is eliminated to the 1% level. Again, the scattered radioactive ions were detected with BAMBINO, and gamma rays emitted after inelastic excitation were detected with TIGRESS (see Figure 3) The new measurement has an uncertainty of 2%, which is both consistent with all the other inelastic scattering measurements and which is almost four times more accurate than the world average.

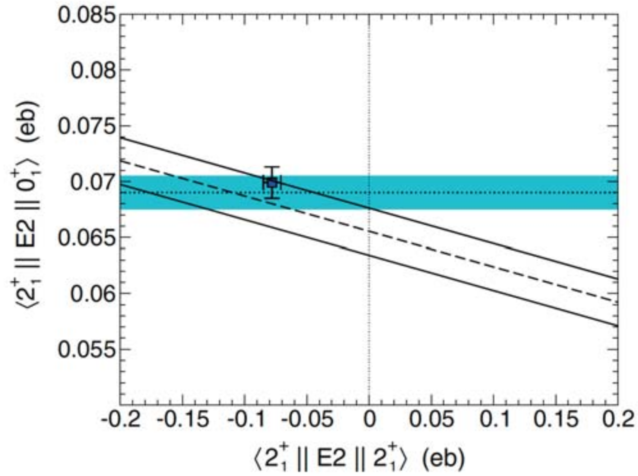

Figure 2: Exclusion plot combining lifetime and Coulex data, indicating a prolate shape. Data point is a calculation based on the methods of Navratil et al.

Both described cases in beryllium, Be-10 and Be-11, take advantage of TRIUMF's intense radioactive species production, efficient ionization, and acceleration and transport of high-quality low-mass beams to allow for precise measurements of nuclear properties for comparison to state-of-the-art models. The last example in this isotopic chain, Be-12 pushes the limits of sensitivity to provide qualitative insight into the properties of this nucleus. In this case, the BAMBINO detectors were used to measure reaction cross-sections and angular distributions, which can be compared to theory. The ^{11}Be(d,p) reaction populated [8] both the ground and several excited states in Be-12 (see Figure 4). Analysis of the transfer reaction angular distributions showed that the s-wave component of the excited 0^+ was in fact much larger than that of the ground state. In combination with low neutron binding, these are considered key parameters of a halo behaviour, which means that in this case the excited state is a halo state, i.e. the valence neutrons have a large spatial extent, as in the well-known case of the Li-11 ground state.

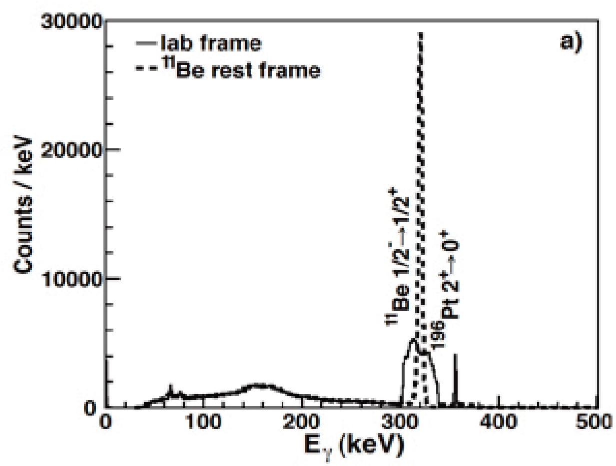

Figure 3: Gamma-ray spectrum with and without Doppler correction from the Be-11 high-precision B(E1) measurement.

These findings were compared to theoretical calculations performed at TRIUMF, using the No-Core Shell Model (NCSM) with the so-called CD Bonn 2000 two-body force. The theoretical results obtained are in agreement with other *ab initio* calculations performed within the Green's function Monte Carlo (GFMC) with local two- and three-body forces. This fact is interpreted as such due to the stronger spin-orbit component present in the non-local CD Bonn potential, which accounts for the additional spin-orbit effects obtained from the Illinois three-nucleon force used in the GFMC calculations.

In all effects, calculations agree with TRIUMF experimental data in assigning a negative sign to the quadrupole moment of the first excited state in Be-10. Hence, in order to clearly separate the validity of two-or three-body forces, additional experiments are needed; they should provide the resolution to distinguish between applications of the theoretical approaches. But, as seen in the case of helium, there is more and more evidence for the need to include three-body forces in describing very neutron-rich isotopes, hence atoms with extreme n-to-p ratios.

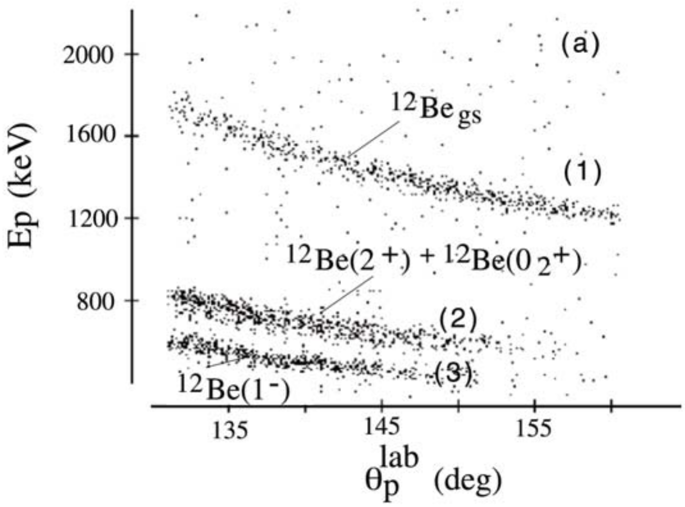

Figure 4: The kinematic loci of the protons identified in the upstream silicon detector in coincidence with Be-12 in the downstream silicon detector. The band identified with (2) was analyzed to extract a large s-wave component for the excited 0^+ state, leading to the conclusion that this is a halo state

Further reaction studies were carried out in light nuclei, such as inelastic deuteron scattering of Li-9 [9] as well as reaction studies using Li-11 to study various aspects of the interaction between a halo nucleus and Pb-208, such as elastic scattering below the barrier [10], inelastic break-up [11], and sub-barrier fusion [12].

As an extension of theoretical approaches developed for lighter isotopes, the case was made to try to describe, theoretically, neutron-rich calcium isotopes, which were chosen because a full body of data exists near the stable Ca-48, and because a promising theoretical framework was developed, based on the *ab initio* calculations for light nuclei, which has the potential to be further extended to even heavier nuclei. For this reason, calcium isotopes, Ca-49-52, were measured at ISAC to study the effect of three-nucleon forces in medium-heavy nuclei.

Neutron rich calcium isotopes are of keen interest to theorists. The calcium isotopic chain is the only chain that has two stable doubly magic isotopes, Ca-40 and Ca.-48. Magic nuclei occur when a nucleus has a closed nuclear shell of protons or neutrons. These magic nuclei are remarkably stable hence they have extra binding compared to their neighbours and can be compared to a noble gas configuration in the periodic table of elements. The magic numbers for nuclei are 2, 8, 20, 28, 50, 82 and 126. These magic numbers have been of immense help in describing the physics of nuclei; however, it has been found that "new" magic numbers can arise, and the well-known magic numbers can disappear or migrate. This is in contrast to the noble gases in the chemical periodic table, which are always at the same number of closed atomic shells, throughout the entire periodic table. In the calcium isotopes it has been predicted that new magic numbers can appear at neutron numbers 32 or 34. The exact location of the predictions depends on what kind of nuclear interaction

INTERNATIONAL TEAM CONVENES TO STUDY SODIUM-26

20 October 2009

During the month of August, an international team of researchers assembled at TRIUMF to run the first of a series of experiments in nuclear structure and astrophysics using neutron transfer reactions with neutron-rich sodium isotopes The experiment was run using the new SHARC (Silicon Highly-segmented Array for Reactions and Coulex) detector, which had been integrated into the existing TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer) apparatus. The goal of the experiment was to investigate the changes in shell structure in exotic nuclei (in particular sodium-26) through a reaction where a neutron is transferred into the already neutron-rich sodium-25 nucleus.

It was originally thought that the shell model used to describe nuclear structure would be the same for exotic nuclei as it is for stable nuclei. However, researchers have come to find that these shell structures change in exotic nuclei as the ratio between the number of protons and neutrons changes. Using the SHARC-TIGRESS detector system, experimenters are better able to probe the structure of these exotic nuclei.

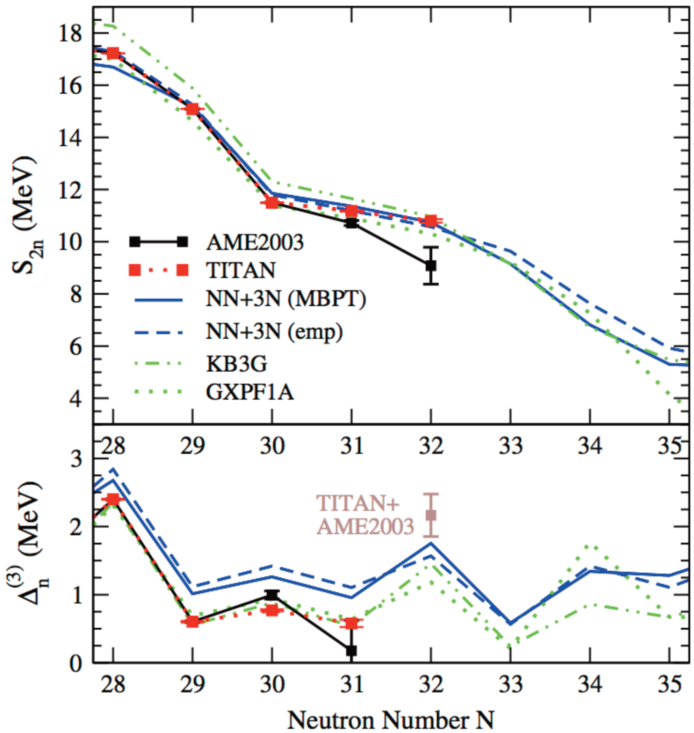

Figure 5: The new TITAN mass values for the neutron separation energies in calcium isotopes agree extremely well with theory, and show a large deviation from the values in the literature.

is used in the calculation. The verification of the theoretical prediction is possible by measuring the binding energies, or separation energies (via a mass measurement), and extra strong binding compared to the more n-rich neighbour isotope, would indicate a closed shell.

The calcium isotopes for the experiment were produced by bombarding a high-power tantalum target with a 70 μA proton beam of 480 MeV energy and using a resonant laser ionization scheme to enhance the ionization of the beam. The calcium isotopes were sent to the TITAN precision measurement Penning trap, where the mass of all isotopes was determined with unprecedented precision [13,14]. The agreement between experiment and theory is remarkable and is shown in Figure 5. While older phenomenological theories (green lines) also agree very well with the new experimental values, it is important to remember that they are based on interaction parameters adjusted to experimental inputs from nearby nuclei in order to give accurate predictions. The three-body (blue lines) have not had the same tweaking, and are equally as good at predicting the observed trend but are completely based on unadjusted interactions.

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4.2.2.3 COLLECTIVE STATES IN NUCLEI

The emergence of simple patterns in the behaviour of atomic nuclei, associated with collective behaviour such as rotational and vibrational motion, out of the underlying complex single-particle motion of protons and neutrons remains a fascinating area of nuclear physics. Why are there almost degenerate energy states of very different shapes (shape-coexistence) in nuclei and how does the nuclear many-body system transition between different shapes? Are there collective states in which protons and neutrons do not act in phase and what can one learn about the proton-neutron interaction from their study? How do collective degrees of freedom (rotational, vibrational) compete with single-particle motion? These are some of the questions currently driving the research on collective states.

The widely occurring manifestation of shape coexistence in nuclei leads to low-lying 0^+ states that have a very different shape than the ground state of the nucleus. The shape-coexistent state involves typically pair excitations across energy gaps that result from shell structure. This has led to the question of the role of pair excitations across energy gaps resulting, not only from shell structure, but also from subshell structure. Very little is known even about the occurrence of subshell gaps across the nuclear mass surface, let alone their involvement in nuclear collective behaviour.

While some low-lying 0^+ states are due to shape-coexistence the nature of other 0^+ states remains mysterious. While originally identified as vibrational states build on spherical or deformed ground states, more precise measurements have put this simple interpretation into question. This is also connected to the question to what extend multi-phonon states are realized in nuclei

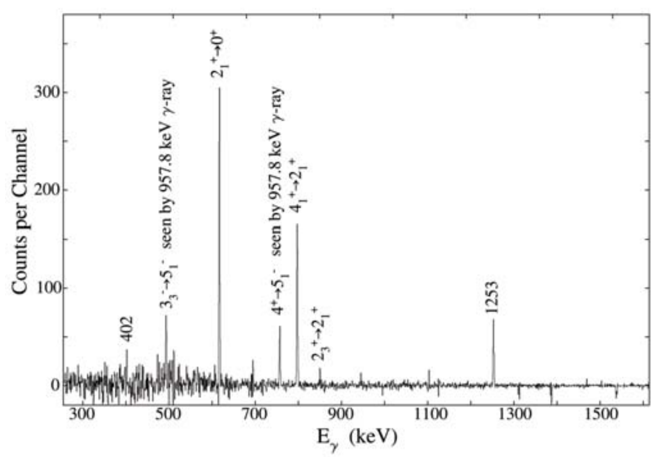

Figure 1: γ-ray spectrum gated by the 958.0-keV transition feeding the 1871-keV 0+4 level in Cd-112. The energies of the γ-ray transitions from the 0_4^+ level are labeled in keV, with the remaining transitions labeled with their placements in the level scheme [3].

Guided by the questions above there have been, two major lines of investigation have been carried out using the 8π spectrometer at TRIUMF in the past few years. The first has focused on detailed spectroscopy to resolve fundamental issues of collectivity in the Cd isotopes, long thought to be the best-known examples of quadrupole vibrational behaviour in spherical nuclei anywhere on the nuclear mass surface. This has led to published results on Cd-110 [1,2] and Cd-112 [3]. By using the sensitivity of the 8π spectrometer to measure weak γ-ray decay branches from highly excited states (see Figure 1), highly collective transitions predicted by sophisticated Interacting Boson Model-2 (IBM2) calculations were sought. These calculations were able to reproduce the decay of the second and third excited 0_2^+ and 0_3^+ levels by assuming strong mixing of the spherical phonon and deformed intruder states (the latter based on 2*p*-4*h* states involving a proton pair excited across the *Z*=50 gap). In Cd-112, the 0_4^+ level was reassigned from a 3-phonon vibrational state to an excitation based on the intruder configuration due to its lack of an observed decay to the 2^+ 2-phonon level thus removing any possible candidate for the 0+ 3-phonon state (see Figure 2). Using the high-sensitivity achieved in the decay of In-110 feeding levels in Cd-110, it was determined that the mixing of intruder and vibrational states was weak, thereby negating this mechanism as the explanation of the decays of the 0_2^+ and 0_3^+ levels. Reconsidering the properties of the 0^+ states, it was suggested that the underlying structure of the non-intruder states in Cd-110 was γ-soft, not spherical vibrational [2], raising the possibility that none of the stable Cd isotopes possess spherical vibrational multi-phonon states. The program has expanded to include detailed investigations of Sn-116 and Xe-124, with the ultimate goal of establishing the nature and evolution of low-lying collectivity in the Z=50 region by establishing detailed systematics of the structures of the Cd, Sn, Te, and Xe isotopes.

The second line of investigation has focused on initiating detailed studies of possible shape coexisting structures where subshells may be playing a role. Conventionally, nuclear collectivity has been regarded as weak or absent at closed shells and strong far away from closed shells. A few exceptions have been found in the form of shape coexistence. In general, evidence for such structures has been indirect, e.g., from the observation of excited rotational energy patterns in nuclei with spherical ground states, where there is a lack of direct evidence of quadrupole deformation.

The zirconium isotopes span a range of masses from a mid-open-shell deformed region (Zr-80), through a closed neutron shell (Zr-90), to a closed neutron subshell (Zr-96), and then to a sudden reappearance of deformation (Zr-100), which persists to a mid-open-shell region (Zr-108).

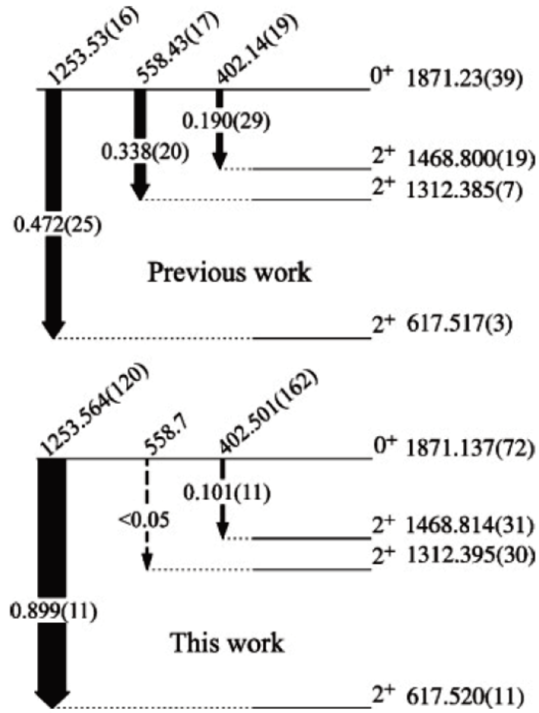

Figure 2: Previous and current level schemes for decays from the 1871-keV 0_4^+ level in Cd-112 [3].

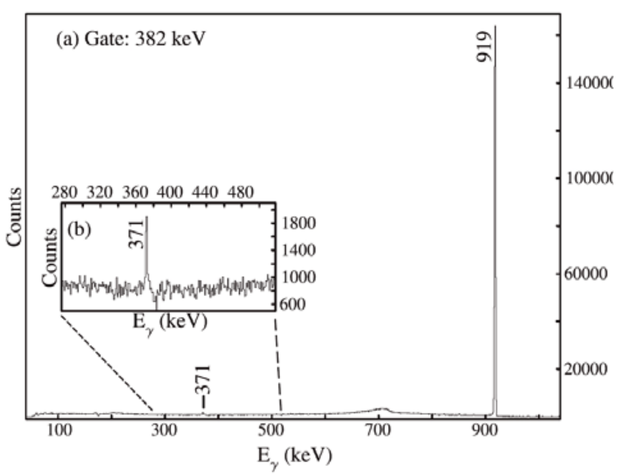

Figure 3: (a) Portion of the -ray spectrum gated on the 382-keV gamma ray in Zr-94 following the decay of Y-94. (b) Confirmation for the placement of the deexciting 371-keV 2_2^+ to 0_2^+ gamma ray is evident [4].

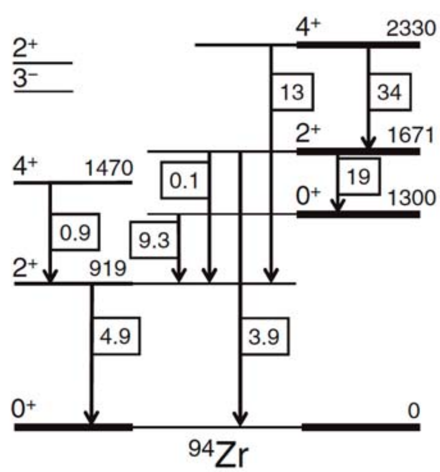

Figure 4: Levels of Zr-94 below 2350 keV, with the band based on the 1300-keV 0_2^+ state emphasized. The B(E2) values in W.u. are given in boxes [4].

This behaviour is unprecedented anywhere on the nuclear mass surface. Earlier hints of shape coexistence in the zirconium isotopes existed; however, these suggestions depended on the indirect evidence from rotational band energy patterns and electric monopole transition strengths. In a study with the 8π spectrometer, lifetime data obtained with the ^{94}Zr(n,n'γ) reaction were combined with a detailed study of Zr-94 (see Figure 3, 4) from the decay of Y-94 to form a consistent picture of shape coexistence in Zr-94 based on the direct evidence provided by electric transition strength *B(E2)* [4]. This observation raises the possibility that similar structures may have been overlooked due to the lack of knowledge of weak transitions amongst highly excited states, and that shape coexistence can be manifest in nuclei with closed subshell structure, rather than being present only in nuclei with closed major shells.

On the theoretical side, the investigations by the TRIUMF Theory Group into collective excitations are focused on the origin of alpha clustering in light nuclei. Starting from the realistic nuclear forces derived within the chiral effective field theory from the QCD, the theory group is developing and applying many-body methods that describe the structure, scattering and reactions of nuclei. Bound and resonance states of light systems with dominant alpha-cluster structure such as L-6i (*d*-alpha) [5,6], Be-7 (alpha-He-3), Li-7 (alpha-H-3) were investigated recently. A formalism to calculate alpha-alpha scattering from the first principles and, eventually, the collective Hoyle state (alpha-Be-8) and O-16 alpha-cluster states (alpha-C-12) is underway. Understanding of the emergence of collectivity in medium mass nuclei from the first principles can be facilitated by *ab initio* techniques such as Coupled-Cluster Method or the Self-Consistent Green's Function method applied recently to isotopic chains near oxygen and calcium using the chiral nucleon-nucleon and three-nucleon forces [7-9].

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4.2.2.4. NUCLEAR ASTROPHYSICS

Our current understanding of the universe puts the formation of the very lightest chemical elements just minutes after the Big Bang, with nearly all other naturally occurring elements arising from stellar mechanisms. These include quiescent nuclear burning in stars as well as explosive events occurring in stellar binary systems on compact objects such as white dwarfs. The heaviest elements are believed to have originated in energetic explosions such as merging neutron stars or core-collapse supernovae. Although the main processes leading to the formation of the elements are known in general, the details are not known, nor are the exact stellar locations for some of the more exotic processes. In addition, the physics of stellar systems, especially the explosive ones, is not known in detail and modeling is hindered by incomplete nuclear physics information.

The availability of accelerated radioactive ion beams, of short-lived species likely only to be seen in explosive stellar scenarios, affords us the opportunity to recreate the microscopic conditions inside stars and measure nuclear properties which eliminate nuclear physics as a source of uncertainty in astrophysical models and further our detailed understanding of the origin of the chemical elements. The experimental nuclear astrophysics and theory groups at TRIUMF have made significant advances in this field through diverse experimental and theory programs pertaining to a variety of astrophysical scenarios.

At temperatures characteristic of the quiescent stellar fusion occurring in the sun and other stars, the relevant thermonuclear reactions generally proceed non-resonantly, with some important exceptions. In contrast, at the higher temperatures found in stellar explosions such as novae, X-ray bursts, and supernovae, the higher density of compound nuclear excited states leads to large resonant contributions to the relevant thermonuclear reaction rates. Resonant reaction rate contributions may be calculated precisely from the properties of the compound nuclear states that serve as resonances. The most important of these is usually the excitation energies of the states. The spins and parities of the states must also be known. Finally, the partial decay widths of the states that serve as resonances are needed to calculate their contributions. Non-resonant reaction rates are not so readily calculated, but rather require high fidelity nuclear structure models coupled to reaction theory to enable extrapolation from energies accessible in the lab to those relevant to the sun and other stars. The astrophysical S factor, which is obtained from the cross-section by factoring out the dominant energy dependences on the de Broglie wavelength and the Coulomb penetrability, is the most convenient quantity for such extrapolations.

TUDA COMPLETES FIRST FLUORINE-18 EXPERIMENT ON NOVAE REACTIONS

27 June 2008

On June 10, 2008, The TRIUMF-UK Detector Array (TUDA) collaboration celebrated as they completed a three-week run using the world's most intense accelerated F-18 beam to investigate one of the most important nuclear reactions occurring in novae. The data obtained will aid in understanding observations made by satellite gamma-ray observatories such as the Gamma-ray Large Area Space Telescope (GLAST), which coincidentally blasted off from Cape Canaveral on the same day the TUDA experimental run finished.

The gamma-ray emission from novae is dominated by the beta-decay of the isotope F-18 (fluorine atoms, but containing one less neutron that usual). Scientists of the TUDA collaboration have been able to make a direct measurement of the fluorine-oxygen isotope reaction that is integral to understanding these cosmic events. The intensity of the beam reached about 10 million particles per second, making it the most intense beam of it's type in the world. Such an achievement allows for first-time measurements at energies of particular interest for resolving astrophysical uncertainties.

For laboratory measurements using radioactive ion beams, reaction cross-sections can be measured directly when sufficient beam intensity exists. If not available, indirect experimental measurements can be combined to determine the relevant nuclear reaction rates. Finally, where no laboratory measurements exist, theoretical estimates must be used.

Big Bang Nucleosynthesis

The initial abundances of the lightest elements, H, He, and Li, were determined by the nuclear reactions that occurred in the first few minutes after the Big Bang. Precise knowledge of the rates of these reactions is needed for comparisons of the primordial elemental abundances predicted by theory and inferred from observations. Both nuclear experiment and theory are crucial.

The primordial abundance of Li-7 inferred from astronomical observations is roughly a factor of 3 below the abundance predicted by the standard theory of Big Bang nucleosynthesis (BBN) using the baryon-to-photon ratio determined mainly from measurements of the cosmic microwave background radiation. In contrast, there is good agreement for H-2 and He-4. Taking into account the estimated uncertainties on the observationally inferred and the theoretically deduced Li-7 abundances, the significance of the discrepancy is (4.2–5.3)σ. This constitutes one of the important unresolved problems of present-day astrophysics and is termed the cosmological lithium problem. Among other possibilities, the discrepancy could be due to new physics beyond the standard model of particle physics, errors in the observationally inferred primordial lithium abundance, or incomplete nuclear physics input for the BBN calculations. In a recent theoretical paper, Cyburt and Pospelov proposed that destruction of Be-7 via resonant capture of H-2 could resolve the discrepancy. TRIUMF scientists have used data from a recent ^{9}Be(^{3}He,t)^{9}B measurement to definitively rule out this possible solution to the cosmological lithium problem [1].

With collaborators, TRIUMF's theory group has applied the *ab initio* No-Core Shell Model combined with the resonating group method (NCSM/RGM) to calculate the cross-sections of the ^{3}H(d,n)^{4}He and ^{3}He(d,p)^{4}He fusion reactions relevant to BBN and the future of energy generation on Earth [2]. Starting from a similarity-transformed chiral nucleon-nucleon interaction that accurately describes two-nucleon data, they performed many-body calculations that predict the cross-sections of both reactions. Virtual three-body breakup effects were obtained by including excited pseudo-states of the deuteron. The results are in satisfactory agreement with experimental data and will aid future microscopic investigations of polarization, electron screening, and other effects.

Quiescent Stellar Burning

In order to gain a detailed understanding of nucleosynthesis and stellar evolution, it is necessary to quantitatively understand the nuclear reactions that operate while stars are stably fusing hydrogen or helium in their cores. Among other things, the rates of these reactions determine the compositions of stars prior to supernova explosions, set the timescales of the longest phases of stellar evolution, and help determine the neutrino fluxes that can be used to infer the core temperature of the sun and test solar models.

The flux of high-energy solar neutrinos has now been measured with a precision of 5% or better. Since the decays of Be-7 and B-8 are the principal sources of this well-measured solar neutrino flux, the rates of the reactions that create and destroy these nuclides must be known with better precision to facilitate comparisons of predicted and observed solar neutrino fluxes.

The zero energy astrophysical S factor for the ^{3}He(α,γ)^{7}Be reaction, $S_{34}(0)$, is crucial for solar neutrino flux calculations because this reaction is the dominant means of producing the neutrino source Be-7 in the Sun and also because the neutrino source B-8 is formed by the capture of a proton by Be-7. In fact, the Be-7 neutrino flux is proportional to $S_{34}(0)^{0.86}$ and the B-8 flux is proportional to $S_{34}(0)^{0.81}$. Measurements at the relevant centre-of-mass energy (E_{cm}) of 23 keV are infeasible, so instead measurements at higher energies must be extrapolated with the aid of theory. To better constrain the extrapolation, the DRAGON group has begun a series of measurements of the ^{3}He(α,γ)^{7}Be cross-section at centre-of-mass energies between

1.5 and 2.8 MeV. These measurements are ongoing but the analysis of a preliminary run at 2.8 MeV is complete; in this run the beam suppression of the separator was found to exceed 10^{14} at the 90% confidence level, the highest value so far for any recoil separator [3].

As the only means by which the dominant high energy solar neutrino source B-8 is produced, the $^{7}Be(\rho,\gamma))^{8}B$ reaction and its zero energy astrophysical S factor $S_{17}(0)$ are of great interest to solar modellers. In the latest evaluation of solar fusion cross-sections, the theoretical error assigned to the extrapolation of the S factor from experimentally accessible energies to zero energy dominated the error budget. Recently Navratil, Roth, and Quaglioni used the NCSM/RGM to calculate S_{17} [4]. Starting from a selected similarity-transformed chiral nucleon-nucleon interaction that accurately describes two-nucleon data, they performed many-body calculations that simultaneously predict both the normalization and the shape of $S_{17}(E)$. They also studied the dependence on the number of Be-7 eigenstates included in the coupled-channel equations and on the size of the harmonic oscillator basis used for the expansion of the eigenstates and of the localized parts of the integration kernels. Their result for $S_{17}(0)$ is lower than, but consistent with, the latest evaluation and reduces the extrapolation uncertainty.

An indirect alternative to measuring radiative capture reactions at high energies and extrapolating to stellar energies is studying the asymptotic normalization coefficient (ANC) of a valence nucleon via transfer reactions. Using the TUDA facility, experimenters at TRIUMF led by Howell and Davids have studied the elastic/transfer reaction $^{7}Li(^{8}Li,^{7}Li)^{8}Li$ for the first time. By measuring the angular distribution in which interference between elastic scattering and single neutron transfer produces characteristic oscillations, the ANC of the $p_{3/2}$ neutron in Li-8 was inferred. Invoking isospin symmetry, the experimenters then deduced the ANC for the corresponding proton in B-8, which is directly related to $S_{17}(0)$. This result, recently accepted for publication, is consistent with both radiative capture measurements and indirect determinations.

A number of reactions that proceed in stars that have reached advanced stages of stellar evolution are important for nucleosynthesis and for energy release. Steady-state stellar helium burning mainly produces C-12 via the triple-α process at typical temperatures between 0.1 – 0.3 GK. This reaction can in principle be followed by further α-capture reactions. However, the $^{16}O(\alpha,\gamma)^{20}Ne$ reaction is very weak at these temperatures due to the lack of a suitable resonance in Ne-20. Its inverse reaction initiates the neon burning stage of stellar evolution. Most recent measurements determined only the S_2 component of the astrophysical S-factor (decay through the first excited state in Ne-20), with the S_0 component (directly to the ground state) derived from theory. In September 2010, Hager et al. carried out the first measurement of the total S-factor using DRAGON [5] at E_{cm} = 2.26 MeV, following up in April 2011 with additional measurements down to E_{cm} = 1.69 MeV [6]. Using the array of bismuth germanate detectors surrounding the DRAGON gas target to detect prompt γ rays from the reaction, it was possible to identify the contributions from the different decay cascades for all energies.

Up to half of the heavy elements were produced in stars by the capture of neutrons into intermediate mass nuclei. This so-called *s*-process can be inhibited if other nuclei capture the neutrons before they can participate in the heavy element building. At the time of formation of ancient massive stars, elements heavier than helium had not yet been synthesized in significant amounts. Consequently the neutron poisons usually present due to previous nucleosynthesis stages were absent. This lack of secondary neutron poisons, together with the large abundance of O-16, produced in situ during the helium burning stage, resulted in a high neutron capture rate on O-16. The O-17 thus formed could recycle the neutrons back into the stellar plasma, through the $^{17}O(\alpha,n)^{20}Ne$ reaction, having little impact on the subsequent *s* process. The efficiency of this recycling depended on the rate of the competing (α,γ) reaction that produces Ne-21 without releasing the captured neutrons. Limited experimental data are available on these reactions and the two theoretical calculations of the reaction rates diverge significantly at stellar temperatures, resulting in predicted *s*-process abundances that differ by up to three orders of magnitude. To address this discrepancy, the $^{17}O(\alpha,\gamma)^{21}Ne$ reaction was studied using DRAGON over a range of E_{cm} from 0.62 to 1.5 MeV. The resonance strengths of two states in Ne-21 were determined and off resonance data used to extrapolate the S-factor across the

Gamow window (the energy region of effective burning in the stellar environment). The calculated reaction rate indicates that sufficient neutrons are recycled and that *s*-process nucleosynthesis is not inhibited.

The bulk cosmic origin of fluorine is uncertain. Asymptotic giant branch (AGB) stars are the final phase in evolution for stars with an initial mass of approximately 2-8 solar masses. They are thought to be one of the main sites for the production of fluorine, but models do not produce enough F-19 to match observations. The $^{18}F(\alpha,p)^{21}Ne$ reaction rate is important in predicting the stellar abundance of F-19 in AGB stars as it competes with the $^{18}F(\beta^{+}\nu)^{18}O(p,\alpha)^{15}N(\alpha,\gamma)^{19}F$ reaction chain, reducing the number density of O-18 ($_{N}$O-18) but increasing the number density of protons (N_p). Effectively, as the reaction rate for $^{18}F(\alpha,p)^{21}Ne$ increases, the product $N_{18O}N_p$ increases, producing more F-19 via the reaction chain $^{18}O(p,\alpha)^{15}N(\alpha,\gamma)^{19}F$. At energies relevant to helium shell burning in AGB stars the uncertainty in the measured cross-section of the $^{18}F(\alpha,p)^{21}Ne$ reaction is almost two orders of magnitude. A direct measurement of the reaction is not currently feasible due to the limited F-18 beam intensity available but information on the cross-section can be extracted from a measurement of the time-reversed reaction $^{21}Ne(p,\alpha)^{18}F$ at TUDA (see Figure 1), which was filled with hydrogen gas at 330 mbar creating an extended gas target. Two arrays of silicon detectors inside TUDA were then used to detect the F-18 and α in coincidence at E_{cm} = 0.6 - 1.4 MeV in the $^{18}F + \alpha$ frame.

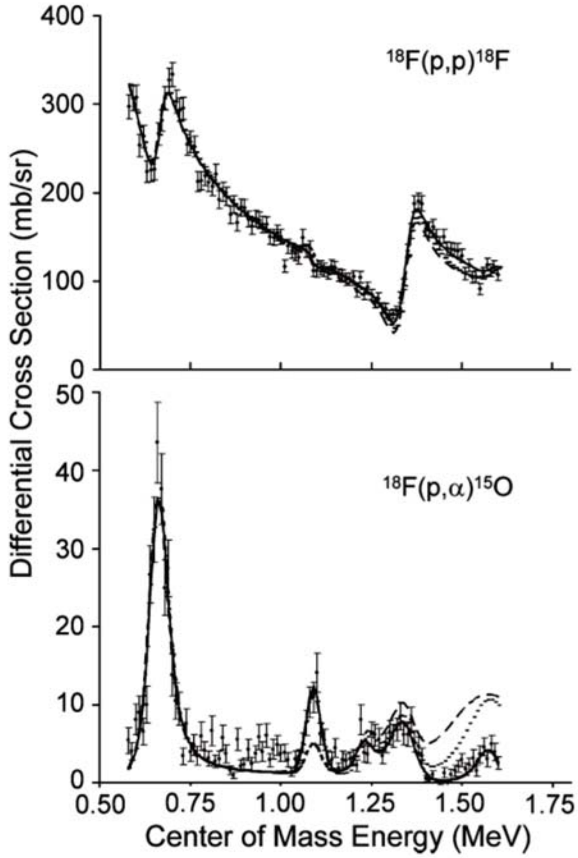

Figure 1: Differential cross-sections of the 18F(p,p)18F and 18F(p,α)15O reactions as a function of centre-of-mass energy obtained using the TUDA array. A simultaneous R-matrix fit, calculated for a centre-of mass angles of 156° for (p,p) and 151° for (p,α), is shown by the solid black line. The dashed and short-dashed lines show cross-sections calculated for different high lying resonance parameters, based on previous work.

The oldest stars in the Milky Way Galaxy fuse H stably into He via the CN cycle. Its slowest reaction, $^{14}N(p,\gamma))^{15}O$ controls the rate of energy release in the cycle and thereby determines the lifetimes of the ancient stars it powers. It is impossible to measure this reaction cross-section directly at the required astrophysical energy of 30 keV. The largest remaining uncertainty in the extrapolation to low energies is the width of the subthreshold 6.79 MeV state in O-15. At the DSL facility installed at ISAC-II, Galinski et al. have constrained the lifetime (and thereby the width) of this state using the Doppler shift attenuation method and the $^{3}He(^{16}O,^{4}He)^{15}O$ reaction.

Cataclysmic Binary Systems, Compact Objects, and Supernovae

Explosive nucleosynthesis under degenerate conditions occurs in a range of different systems from isolated massive stars to cataclysmic binaries in which matter is transferred from a relatively un-evolved star to a compact object such as a white dwarf or a neutron star.

Novae occur in cataclysmic binary systems in which hydrogen-rich material is transferred onto the surface of a white dwarf from the expanded envelope of a larger star. This material is compressed and heated, leading to the onset of nuclear burning, dumping more energy into the system and leading to a thermonuclear explosion which ejects a large amount of material. If the environment grows hot enough, nucleosynthesis involving proton capture reactions can occur up to the calcium region. In addition, long-lived radioisotopes such as F-18, Na-22 and Al-26 are synthesized. Such isotopes are observation targets for current and future satellite γ ray telescope missions, and could provide a powerful tool to observe and understand nova explosions. Novae are the simplest and most common type of explosive stellar event, with some 30 per year predicted to occur in the galaxy, and therefore provide the best test for models of explosive stellar hydrodynamics and nucleosynthesis that can be improved by comparing to observations. Nuclear physics input is a crucial part of this understanding.

The initial 511 keV and continuum γ-ray spectrum emanating from novae hours to days after onset arises in part due to decaying F-18. The flux of this spectrum varies from model to model and due to the particular qualities of the individual nova, but estimates suffer from large nuclear physics uncertainties, particularly those from reactions which create and destroy F-18 in the thermonuclear runaway such as $^{18}F(p,\alpha)^{15}O$, $^{18}F(p,\gamma)$ and $^{17}O(p,\gamma)^{18}F$, with the first reaction being the most significant. At ISAC, the world's most intense accelerated F-18 beams of 10^7 s^{-1} have been demonstrated, enabling studies of reactions on F-18.

At the TUDA facility, a simultaneous measurement of $^{18}F(p,\alpha)^{15}O$ and $^{18}F(p,p)^{18}F$ was performed at E_{cm} between 0.6 MeV and 1.6 MeV [7]. Elastically scattered protons and coincident α-particles and O-15 recoils were detected in large area segmented silicon arrays, leading to the measurement of an excitation function showing several resonances. Simultaneous R matrix fits to the elastic and (p,α) channels confirmed some existing resonance parameters while identifying two new resonances and providing widths for all of them. A state predicted by theory that could have significantly affected the cross-section at low energies via interference with partner states, and thus affected the reaction rate, was not seen, and in general the level scheme was elucidated, leading to a better constrained $^{18}F(p,\alpha)^{15}O$ reaction rate.

In addition, a direct measurement of $^{18}F(p,\alpha)^{15}O$ at low energies was performed using the full beam intensity of 10^7/s [8]. Cross-section measurements were obtained at E_{cm} of 0.250, 0.330, 0.453 and 0.673 MeV. The 0.330 MeV and 0.673 MeV measurements were made at the peaks of known resonances as a check on the consistency of the experiment, while the other two points were made in lower cross-section inter-resonance regions where interference between resonances is difficult to determine theoretically. Most importantly, the 0.250 MeV measurement is the lowest determination of this reaction cross-section to date, and is right in the energy region which dominates F-18 destruction at peak nova temperatures. With this data point and the previous R matrix work, much better constraints can be put on the role of the $^{18}F(p,\alpha)^{15}O$ reaction in F-18 destruction, and thus the resultant 511 keV flux from nova explosions.

The rate of the $^{18}F(p,\gamma))^{19}Ne$ reaction also affects the final abundance of F-18 in hot oxygen-neon novae. Of the two resonances thought to play a significant role, one (E_{cm} = 0.33 MeV) has a radiative width estimated from the assumed analogue state in the mirror nucleus, F-19. The second (E_{cm} = 0.665 MeV) does not have an analogue state assignment so this information is lacking. At the DRAGON facility the first successful direct measurement of the $^{18}F(p,\gamma)^{19}Ne$ reaction was performed [9]. The strength of the 0.665 MeV resonance was found to be over an order of magnitude weaker than currently assumed in nova models as a result. Reaction rate calculations show that this resonance is now expected to play no significant role in the destruction of F-18 at any astrophysical energy.

F-18 nucleosynthesis in classical novae also strongly depends on the thermonuclear rate of $^{17}O(p,\gamma)^{18}F$, which is part of the hot CNO cycle; the relevant temperature range is between 0.1 and 0.4 GK. The literature on $^{17}O(p,\gamma)^{18}F$ gives conflicting information for the direct capture (non-resonant) component of the reaction rate. In August 2011, Hager et al. measured the $^{17}O(p,\gamma)^{18}F$ cross-section with DRAGON between E_{cm} = 250 and 500 keV [10]. A second set of measurements was performed at DRAGON in September 2012. During this time, the cross-section on and 10 keV below the resonance were measured. Most recently a direct measurement of the $^{18}F(p,\gamma)^{19}Ne$ reaction was performed at DRAGON [11]. The strength of the 665 keV resonance was found to be over an order of magnitude weaker than currently assumed in nova models. Reaction rate calculations show that this resonance therefore plays no significant role in the destruction of F-18 at any astrophysical energy.

Other important radionuclides present in nova ejecta are Na-22 and Al-26. In particular Na-22 is a promising astronomy target because it is thought to be produced in large quantities, delivering a strong flux of 1.275 MeV γ rays. However, despite predictions to the contrary, none of these γ rays have been observed from an individual nova. Part of the problem again is nuclear physics uncertainties in Na-22 production and destruction reactions. Al-26 is unsuitable for observation from a single source because of its long lifetime, but novae are thought to produce up to 20% of the Al-26 observed in the galaxy, with the rest coming from massive stars.

A reaction that affects the abundance of both Na-22 and Al-26 in novae is $^{23}Mg(p,\gamma)^{24}Al$. This reaction had never been measured and thus contributed a large uncertainty to the final Na-22 and Al-26 predicted yields in nova models. With the highest intensity ^{23}Mg-23 accelerated beam in the world, some 5 x 10^7 s^{-1}, the $^{23}Mg(p,\gamma)^{24}Al$ reaction was measured directly for the first time at the DRAGON facility to a precision sufficient for nova yield purposes [12]. This experiment challenged the DRAGON facility due to the Mg-23 beam being embedded in a more intense Na-23 beam, such that the facility had to separate not only Al-24 recoils from Mg-23 and Na-23 beam background, but also from Mg-24 recoils from the $^{23}Mg(p,\gamma)^{24}Al$ reaction. Thus this was a successful experiment both in terms of scientific result and technical achievement.

The $^{22}Na(p,\gamma)^{23}Mg$ reaction directly destroys Na-22. Its cross-section had been measured over the years using chemically prepared targets, but recently a new excited state in Mg-23 was measured in γ decay studies that could significantly contribute to the reaction rate at nova temperatures. In a collaborative project with the Centre for Experimental Nuclear Astrophysics (CENPA) at the University of Washington, Seattle, the experimental nuclear astrophysics group at TRIUMF designed an experiment to measure the strength of this possible new resonance using Na-22 targets produced at ISAC by implanting a very pure and intense (10^9 s^{-1}) ^{22}Na beam into a pure copper backing. Subsequently the $^{22}Na(p,\gamma)^{23}Mg$ reaction was measured using this target and a proton beam from the accelerator at CENPA [13,14]. Strengths of all know resonances were re-measured, as was the potential new resonance. It was found that some of the previously measured resonances were in fact some 2.5-3 times stronger. All known contributing resonances were measured with the highest precision to date. The end result is a Na-22 destruction rate that is larger than previously thought, leading to smaller predictions of Na-22 1.275 MeV γ-ray flux from oxygen-neon novae or equivalently, an decrease in the maximum detectability distance for nova-produced Na-22. This is an important result that is being checked by other laboratories using different methods, as well as using indirect methods at TRIUMF such as lifetime measurements in Mg-23.

The CENPA and earlier Bochum experiments conclude that at nova temperatures the reaction rate is dominated by a resonance about 206 keV above the p + Na-22 threshold, corresponding to an excitation energy of 7.786 MeV in Mg-23, but the resonance strengths reported differ substantially. By measuring the spin, lifetime, and proton decay branching ratio of the 7.786 MeV state, one can derive its resonance strength. A recent β-decay experiment performed in Jyväskylä, Finland provides compelling evidence for the spin assignment and determines the proton branching ratio to be 0.037(7). At TRIUMF Kirsebom et al. have recently carried out a Doppler shift attenuation method measurement using the $^{3}He(^{24}Mg,^{4}He)^{23}Mg$ reaction to determine the lifetime of the 7.786 MeV level in Mg-23.

Another reaction that strongly affects the abundance of Al-26 in nova ejecta is $^{26}Al(p,\gamma)^{27}Si$. Having previously measured $^{26}Al(p,\gamma)^{27}Si$ at the DRAGON facility, attention turned to the role of the short-lived isomer, Al-26m in the destruction of Al-26 in novae. Since Al-26m beam intensity is much lower than the ground state intensity at ISAC, direct measurements of the lower energy resonances important at nova temperatures have been impossible. Therefore indirect studies are required to determine the $^{26m}Al(p,\gamma)^{27}Si$ reaction rate. Such a study was performed at the TUDA facility using the $^{26g}Al(d,p)^{27}Al$ reaction at 6 MeV/nucleon in order to populate states in Al-27 that are the mirror states of the ones of interest in Si-27 for novae. The experiment was able to achieve an excitation energy resolution of around 56 keV and populated many states of interest, enabling the identification of these states with their associated analogue states in Si-27. This will allow more precise calculation of resonance parameters for those Si-27 states where laboratory measurements are still lacking.

Presolar grains are micrometer-sized grains of material that are fossils of stars and stellar explosions, and remained unchanged during the formation of the solar system. These grains, found in meteorites, carry signatures of the nucleosynthesis processes that occurred in the environment in which they were formed. By measuring the ratios of different isotopes of certain chemical elements the origin of these grains can be determined. While grains from AGB stars and Type II supernovae are common, only a few grains from novae have been discovered to date, and their classification as novae grains is still under debate. There is one isotope that, if measured, has the potential to be a 'smoking gun' for nova origin, S-33. The current models of oxygen-neon novae predict 150 times more S-33 in these environments than is found in our solar system. However, the uncertainty of this overabundance is 200+ 200%, -99% due to uncertainty in the $^{33}S(p,\gamma)^{34}Cl$ reaction rate. This uncertainty comes from the fact that there were several resonances in the relevant energy region (corresponding to temperatures of 0.2 to 0.4 GK) that had no measured resonance strengths. Thanks to the offline ISAC ECR ion source, intense beams of S-33 became available and these resonance strengths were measured using DRAGON. All of the known resonances within the relevant energy region and below what could be studied previously have now been measured. Even with up to 4×10^{15} beam ions on target, very few Cl-34 recoils from the reaction were seen for any of the previously unmeasured states. As a result these states do not contribute strongly to the reaction rate at and above 0.3 GK and the resonance at an excitation energy of 5576 keV in Cl-34 dominates the rate. The four lowest-energy resonances may contribute at temperatures of 0.25 GK and below. While further work will be required to determine the resulting S-33 overproduction factor, the rate of $^{33}S(p,\gamma)^{34}Cl$ reaction is not significantly changed over much of the oxygen-neon nova temperature range as a result of these measurements, though the uncertainty is reduced. This is good news for studies of presolar grains as this implies that the large S-33 overproduction factor is preserved, making it a good identifier for grains of nova origin.

Computational studies of novae have been performed at TRIUMF using the state-of-the-art stellar evolution code MESA and associated NuGrid code [15]. This is part of a joint project led by the University of Victoria, the Joint Institute for Nuclear Astrophysics, and TRIUMF. Models of CO and ONe white dwarfs were set up and used to investigate nucleosynthesis and convective boundary mixing in the subsequent novae explosions from accretion from a companion star for a wide range of parameters. Dedicated computational hardware belonging to the TRIUMF Nuclear Astrophysics Group was used for this. Eventually, the models will be used to determine nuclear reactions of astrophysical interest as well as evaluate the impact of existing measurements.

Neutron stars, which are formed in core collapse supernovae, are exotic end states of stellar evolution that play an important role in some cataclysmic binary systems and are of considerable interest in their own right as laboratories for high density, asymmetric nuclear matter.

Theorists at TRIUMF showed that microscopic calculations based on chiral effective field theory (EFT) interactions constrain the properties of neutron-rich matter at sub-nuclear densities much more strongly than is reflected in commonly used equations of state [16]. Combined with neutron star masses inferred from observations, their results lead to a radius of 9.7-13.9 km for a 1.4 solar mass neutron star, where the theoretical range is due roughly equally to uncertainties in many-body forces and to the extrapolation to high densities.

With collaborators, TRIUMF theorists formulated a low-energy effective theory describing matter in the inner crust of neutron stars [17]. This region consists of superfluid neutrons and a lattice of nuclei. The low-energy theory can be written using symmetry considerations and describes the dynamics of the Goldstone modes-the lattice and superfluid phonons that arise due to the spontaneous breaking of continuous space-time symmetries of the lattice and the condensate, respectively. They showed that the underlying interaction between the neutrons and the nuclei gives rise to entrainment and mixing between the Goldstone modes. This reduces the contribution of the superfluid phonons to the transport of heat in the inner crust. Currently Sharma, Forbes, and Bulgac are investigating the dynamics of vortices in the neutron superfluid, in particular focusing on a reliable estimate of the pinning force exerted by nuclei on the vortices. This is a key quantity required for the phenomenology of glitches in neutron star rotation.

Type I X-ray bursts (XRBs) are brief recurrent bursts of X-ray emission and are a frequent phenomenon in the galaxy. Our current understanding is that they originate in binary systems where material from a relatively un-evolved star accretes onto the surface of a neutron star, leading to an eventual thermonuclear runaway. The elevated temperatures achieved in XRBs are thought to allow nucleosynthesis up to the tin/tellurium region via the rapid-proton capture (rp) process. In order for this to occur, the thermonuclear runaway must start via a break out from the β−limited hot CNO cycles through the $^{15}O(\alpha,\gamma)^{19}Ne$ or $^{18}Ne(\alpha,p)^{21}Na$ reactions.

Both reactions are extremely difficult to measure directly, and are targets for future studies at TRIUMF. However, the value of the $^{18}Ne(\alpha,p)^{21}Na$ reaction rate at XRB temperatures has been constrained through a study of the inverse reaction $^{21}Na(p,\alpha)^{18}Ne$ at TRIUMF [18]. This was performed at the TUDA facility using Na-21 beams at ISAC-II of energies between 4.1 and 5.5 MeV/nucleon, and intensities of 10^6 s^{-1}. As depicted in Figure 2, this work shows that the contribution of the ground state component of the $^{18}Ne(\alpha,p)^{21}Na$ rate is lower than previously thought, requiring higher XRB temperatures before breakout can be achieved and the burst can ensue. Further work on the direct reaction is required to completely solve this problem.

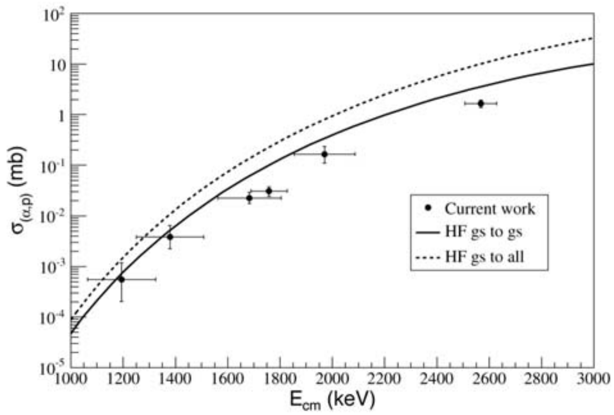

Figure 2: Experimental $^{18}Ne(\alpha,p)^{21}Na$ reaction cross section (black dots) as a function of centre-of-mass energy. Predictions based on Hauser-Feshbach calculations for ground-state to ground-state transitions (full line) and ground-state to all-states transitions (dashed line) are shown for comparison.

Davids et al. performed a Monte Carlo calculation of the astrophysical rate of the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction based on an evaluation of published experimental data. By considering the likelihood distributions of individual resonance parameters derived from measurements, estimates of upper and lower limits on the reaction rate at the 99.73% confidence level were derived in addition to the recommended median value. These three reaction rates were used as input for three separate calculations of Type I XRBs using spherically symmetric, hydrodynamic simulations of an accreting neutron star. In this way the influence of the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate on the peak luminosity, recurrence time, and associated nucleosynthesis in models of Type I XRBs was studied [19]. Contrary to previous findings, no substantial effect on any of these quantities was observed in a sequence of four bursts when varying the reaction rate between its lower and upper limits. Rather, the differences in these quantities are comparable to the burst-to-burst variations with a fixed reaction rate, indicating that uncertainties in the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate do not strongly affect the predictions of this Type I XRB model.

Core-collapse (or Type II) supernovae (CCSN) are perhaps the most familiar stellar explosions. They occur when massive stars run out of fuel after a series of core and shell burning processes and the resulting iron core collapses, electron degeneracy pressure being unable to resist gravity. The resulting explosion, reinvigorated by large neutrino fluxes, causes conditions of extremely high temperature, density, and free neutron and proton concentrations that may be suitable for rapid neutron capture or *r*-process nucleosynthesis, which is believed to produce about half of the elements heavier than Zn.

Neutrino interactions with nucleons are believed to play a critical role in the supernova explosion mechanism. Theoretical study of these interactions is necessary to quantitatively understand one of the most prolific nucleosynthesis sites in the universe. TRIUMF theorists investigated the neutrino response in pure neutron matter at sub-nuclear densities, estimating the neutrino-pair bremsstrahlung reaction rates based on modern EFT interactions [20]. In state-of-the-art supernova simulations, the standard rates for bremsstrahlung are based on the one-pion exchange approximation to the nucleon-nucleon interaction, corresponding to the leading order in EFT. When all orders are considered up to convergence, the neutrino rates are reduced significantly with respect to the standard rates.

With the new UC target capability at ISAC providing neutron-rich beams including some along the expected path of the *r* process, first experiments with heavy Rb and Sr isotopes have begun using TITAN, the 8π spectrometer, and the laser spectroscopy station. Masses are the most important nuclear quantities to measure in order to compute the nucleosynthesis expected under *r* process conditions, as they determine the neutron separation energies and thereby the path. Recently the TITAN Penning trap measured the masses of Rb-94,97,98 and Sr-94,97-99 with uncertainties of less than 4 keV/c^2, finding deviations of up to 11σ when compared to previous measurements and substantially reducing abundance prediction uncertainties [21].

CCSN are thought to be among the largest contributors to galactic Al-26. The actual galactic Al-26 abundance is known fairly well, and the Al-26/Fe-60 ratio is known very precisely. The CCSN models however suffer from considerable uncertainties in Al-26 production because of lack of experimental knowledge of the reactions that create and destroy Al-26 under CCSN conditions. In particular, The ^{26m}Al(p,γ)^{27}Si reaction plays a special role since Al-26m and Al-26g are in quasi-equilibrium in these conditions, and thus knowledge of both the destruction of the ground state and isomer is needed to determine the Al-26 effective half-life and ejected abundance. With the higher energy resonances that contribute to ^{26m}Al(p,γ)^{27}Si being significantly stronger than those for nova temperatures, direct measurements are within reach at the DRAGON facility, using the Al-26m intensities available. DRAGON recently performed the first measurement of a resonance in ^{26m}Al(p,γ)^{27}Si using a mixed Al-26g/Al-26m beam, with an isomer intensity of order 10^5 s^{-1}. This would represent the first ever measurement of radiative capture on a nuclear isomer, and constrain the ^{26m}Al(p,γ)^{27}Si reaction rate for CCSN.

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4.2.3 NUCLEAR MEDICINE

Isotopes have critical uses in medicine for the diagnosis, treatment, and management of both acute and chronic disease. The cost to the economy of some of the more prevalent conditions affecting Canadians is staggering: 70% of Canada's healthcare budget is spent on chronic disease management with cardiovascular disease accounting for $21 billion in lost economic activity[1], cancer for $23 billion[2], and mental illness and neurodegeneration for $51 billion[3]. All of these areas involve chronic care, affect many individuals, and draw substantial resources from a healthcare system trying to balance costs with demand for services. This balance will continue to remain a challenge for the foreseeable future, with expenditures expected to balloon as the Canadian population continues to age. One example is the cost of managing mental health, expected to grow to $293 billion/year by 2040[4].

During the 2008–2012 period, TRIUMF's Nuclear Medicine Program has evolved significantly. In addition to leadership of a national effort to develop accelerator-based production of key medical isotopes, the TRIUMF team has developed research thrusts in isotope-production target technology and radiopharmaceutical applications for advanced imaging of disease. Finally, TRIUMF's Proton Therapy Program has been pursuing improved analysis and control of exposure during the treatment process. This section reports on progress in these areas over the past five years.

4.2.3.1 INTRODUCTION

TRIUMF's Nuclear Medicine Division maintains core competencies in three key areas: (1) medical isotope production and isolation, (2) innovations in accelerator targets and nuclear chemistry for radiopharmaceuticals, and (3) radiopharmaceutical synthesis and application. The Nuclear Medicine Division continues to attract substantial funding from partners and these resources have been directed toward upgrades and research ranging from improving TRIUMF's aging chemistry facilities for radiopharmaceutical production under GMP (good manufacturing practice) guidelines, to leveraging TRIUMF's expertise in accelerator-based isotope production to address the recent medical-isotope crisis. Several of these opportunities provided a means to establish or enhance collaborations with new partners across the country.

Over the past five years, TRIUMF has emerged as a strategic centre for the innovation of novel isotope production technology and applications. The result has been the development of technology and training of highly qualified individuals for the Canadian and international cyclotron and radiopharmaceutical communities.

4.2.3.2 ALTERNATIVE PRODUCTION METHODS FOR TC-99M

The medical isotope technetium-99m (Tc-99m) is widely used in medical imaging (about 80% of procedures employ it), but in recent years its use has been beset by single-point-of-failure problems with the current reactor-based supply chain. That is, Tc-99m is conventionally produced in a handful of 50+ year old nuclear reactors that employ highly-enriched, weapons-grade uranium as the target material. Concerns about the reliability of these reactors as well as geopolitical pressure to restrict usage of fissile materials has generated considerable pressure to develop alternative production technologies.

North America is uniquely positioned to implement an alternative, large-scale Tc-99m production program by leveraging its existing fleet of hospital-based cyclotrons to produce this isotope on demand, where it is needed, when it is needed. By doing so, existing cyclotron centres will collectively showcase a decentralized Tc-99m production model to the world, ushering in a new paradigm involving multi-regional isotope production within a larger system capable of avoiding single-point-of-failures and the need to use enriched uranium of any grade.

One of the two reactors producing more than a third of the global supply of Tc-99m is the National Research Universal (NRU) reactor in Chalk River, Ontario. Recognizing the need for Canada to develop alternative sources not only for its citizens but also to retain a portion of the global market, Natural Resources Canada (NRCan) launched a series of competitive funding programs to support development and deployment of new technologies.

Building on its long experience with medical isotopes and cyclotrons, TRIUMF convened a national consortium consisting of a multidisciplinary team of physicists, engineers, chemists, and physicians from the British Columbia Cancer Agency (BCCA), Lawson Health Research Institute (LHRI), and the Centre for Probe Development and Commercialization (CPDC) to deliver an innovative solution to the medical isotope crisis. The consortium was awarded $13M federal funds to pursue the development of cyclotron-based production of Tc-99m (under the 2010–2012 Non-reactor Isotope Supply contribution Program, NISP, and the 2012–2016 Isotope Technology Acceleration Program, ITAP).

To date, all institutions in the consortium have successfully demonstrated the feasibility of producing Tc-99m using machines found in Canada's existing medical cyclotron infrastructure. Efforts established the parameters for optimal irradiation of Mo-100 targets to obtain high-quality Tc-99m for clinical translation. Results allowed the team to understand the control parameters that influence reproducibility and predictability of Tc-99m yields and radionuclidic purity. The results, which can be used as a baseline to implement a decentralized production paradigm, include:

- Calculated theoretical yields for (p,x) reactions of the various molybdenum isotopes that could potentially be found in enriched Mo-100. This established theoretical Tc-99m yields and radionuclidic impurities [1,2].

- A manufacturing process for Mo-100 target plates using novel Mo-100 coating methods [3];

- Design, assembly, and installation of target stations at TRIUMF (using a CP42 cyclotron), the BCCA (operating an ACSI TR19), CPDC and LHRI (using GE PETtrace cyclotrons; Mitigated risks associated with unique specifications for various cyclotrons at various institutions. For example, the GE PETtrace cyclotrons at CPDC (vaulted) and LHRI (self-shielded) maintain the same capabilities, but exhibit unique specifications in their upgrades and operations;

- Design, assembly, and installation of target transfer systems to move solid targets from the cyclotron to a shielded workspace (hot cell) at BCCA, CPDC, and LHRI;

- The development of new, automated purification methods to extract and purify Tc-99m at greater than 90% efficiency from irradiated targets [4].

- Demonstrated that high (Curie-quantity) production yields are achievable with radionuclidic purity in excess of 99.7%;

- Reconstituted commercial technetium kits, and demonstrated that the resulting preparations were well within existing quality control (QC) standards. However, the presence of minute quantities of other Tc isotopes will require new USP/EP standards. Radionuclidic impurities can be controlled through the isotopic purity of the Mo-100 feedstock, cyclotron irradiation energy, irradiation time, and transport/distribution time.

- Calculated human dosimetry of cyclotron-produced Tc-99m based on theoretical yields of the various radioisotopes [5].

- Developed an efficient method to recycle Mo-100 with over 90% recovery in order to make the production process economically competitive.

The end result is that, in less than two years, the team of investigators advanced the idea of cyclotron-based Tc-99m production considerably and demonstrated a viable alternative for this important isotope. With proof of concept in hand, the team is now working toward validating the technology on a commercial scale, establishing the final production yields, and running clinical studies under stringent quality requirements in order to assess economic feasibility and to establish a mechanism, and the receptors needed, to transfer this technology to the private sector and the global market.

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4.2.3.3 MEDICAL ISOTOPE PRODUCTION

Thirty years ago, the University of British Columbia (UBC) Department of Medicine entered a pioneering collaboration with TRIUMF that began the Positron Emission Tomography (PET) Program. While this relationship is still at the core of the TRIUMF's Nuclear Medicine Program, significant expansion has taken place.

Today, in an era of constrained budgets and increasing regulatory oversight, TRIUMF, teamed with key members of the imaging community at the British Columbia Cancer Agency (BCCA) and several other institutions across Canada, to bring radiotracer production programs in line with the explosive demand for non-reactor sources of isotopes with applications in science and medicine.

During the past five years, TRIUMF produced medical isotopes for neurological (primarily UBC-based programs) and oncological (primarily BC Cancer Agency) use in the surrounding region. (This specific performance is discussed in Section 5.6.1.) With the acquisition, installation, and commissioning of a modern TR-19 cyclotron at BC Cancer Agency, TRIUMF remains as the primary radiopharmaceutical provider for the Parkinson's (neurological) research at UBC and serves as a back-up supplier for oncology studies at VGH. TRIUMF continues to produce isotopes for novel applications in chemistry, biology, oceanography, and medicine at UBC.

FIRST PATIENT SUCCESSFULLY SCANNED IN LUNG CANCER HYPOXIA CLINICAL TRIAL

11 July 2008

With help from a team of TRIUMF experts, the radiopharmaceutical known as [^{18}F]EF5 is poised to take out the guesswork of deciding treatment for some cancer patients.

TRIUMF scientists delivered the first doses of [^{18}F]EF5 to the UBC Hospital for a clinical study in patients with lung cancer hypoxia, an oxygen deficiency that, when present in cancer cells, indicates resistance to traditional radiotherapy cancer treatments. The first patient was successfully scanned on July 8, 2008 using a radiopharmaceutical traced with the fluorine-18 isotope.

This imaging represents the first successful clinical PET scan performed with [^{18}F]EF5 in Canada. Currently, medical isotopes are used to image only the location and size of a tumor in the body. Now, with studies underway using [^{18}F]EF5, medical practitioners will be able to detect the important cellular characteristic of hypoxia, allowing them to develop customized treatment plans for the cancer patient based on the information the scans provide. If successful, [^{18}F]EF5 PET scans may be an important tool in the fight against cancer worldwide.

Radiometallic-Isotope Production in Liquid Targets

Nuclear Medicine at TRIUMF continues to focus on research to develop platform technologies that advance the field of accelerator-based medical isotope production and to better enable radiopharmaceutical development. The widespread acceptance of new and promising radioisotopes is typically challenged by their availability and accessibility, brought about by a need for solid target irradiation capabilities and/or the purchase of an appropriate isotope generator, if available.

Most medical cyclotron sites maintain an isotope production infrastructure that makes use of a pneumatic transfer of a liquid or gas from the cyclotron target to the radiopharmaceutical production workspace within a shielded hot cell, making solid target irradiation difficult. A need to install a solid-target transfer system necessitates a substantial technical and financial commitment by a facility in order to explore additional isotopes. Facility upgrades may prove to be cost prohibitive, especially if preliminary biological studies are required to warrant their purchase. These obstacles likely inhibit the development of novel tracers that may possess a better match between the physical half-life of a promising new radioisotope and the pharmacokinetic profile of the vector to which it is attached.

To enhance the availability of new and promising radiometallic isotopes, TRIUMF and BCCA are currently developing a platform technology to enable irradiation of select metal-salt solutions for the production of research quantities (or higher) of various radioisotopes using readily available liquid target equipment found in all cyclotron facilities. We are currently pursuing the production of Tc-94m ($t_{½}$=0.87 h), Ga-68 ($t_{½}$=1.1 h), Sc-44 ($t_{½}$=4 h), Cu-61/64 (Cu-61 $t_{½}$=3.3h, Cu-64 $t_{½}$=12.7h), Zr-89 ($t_{½}$=78 h) and/or Mn-52 ($t_{½}$=134 h) using the appropriate precursors in salt solution.

Tc-94m was produced by irradiating solutions of natural-abundance ammonium heptamolybdate tetrahydrate $((NH_4)_6Mo_7O_{24})\cdot 4H_2O$ on TRIUMF's TR-13 cyclotron in a standard liquid target at 5 μA for 1 hour [1]. Measured yields were sufficient to allow subsequent isolation and radiopharmaceutical chemistry. The purification chemistry applied was identical to that developed during the large-scale Tc-99m production effort discussed above.

To demonstrate the versatility of this approach, the same target system was used to produce Sc-44, an attractive isotope due to its 3.97 hr half-life and short positron range. Salt solutions of $^{nat}Ca(NO_3)_2$ were irradiated at low current (8 μA for 1 hour). Sc-44g was produced via the ^{44}Ca(p,n) reaction, isolated using commercially available ion exchange resins, and successfully used in radiolabelling experiments using established chelate systems. Studies toward new radiopharmaceuticals are currently underway. A new target design tested even makes it possible to irradiate the salt solution up to a beam current of 20 μA with an increased yield over the original target design. Moving forward, efforts will continue to demonstrate this technique for the production of Zr-89, Mn-53, Ga-67/68 and Cu-61/64. All will be generated and purified and put toward studies in which their use is deemed beneficial.

Given the low-current requirements and off-the-shelf availability of the hardware, the approach described here provides a simple method for most medical cyclotron facilities to produce useful quantities of radiometals by adapting liquid targets already in place for the production of other PET isotopes, such as F-18. The production of radiometals in liquid targets, as developed at TRIUMF, will allow many centres to produce a range of new and emerging isotopes without a significant investment in solid-target infrastructure, facilitating a quick turn-around for the investigation of these isotopes as alternatives for any imaging study.

Cu-64,67 Production for Oceanography Studies

Marine phytoplankton are estimated to reduce approximately 45 Gigatons of CO_2 from the earth's atmosphere to organic carbon each year, accounting for roughly half of the total carbon fixation on earth. A portion of the organic carbon sequestered this way is exported to the deep ocean as sinking particles. Variations in the magnitude of this macro-biological carbon pump affect the CO_2 content of the upper ocean, which in turn regulates atmospheric carbon dioxide levels and climate, on time scales ranging from hundreds to thousands of years.

In order to better understand the regulation of the global carbon cycle, Dr. Maite Maldonado at UBC has focused her research on determining the factors that control oceanic phytoplankton productivity. Research over the last several decades has revealed that the availability of certain micronutrients, such as the trace elements Fe, Mn, Zn, and Co may affect phytoplankton species composition, function, and community growth [2]. Copper (Cu) has been identified as a required redox element in enzymes involved in various metabolic pathways, such as respiration (e.g., cytochrome oxidase) in phytoplankton. Cu is also needed for the oxidation of organic nitrogen and the detoxification of superoxide radicals using a Cu/Zn superoxide dismutase in some phytoplankton. Most recently, Cu has been established as an important micronutrient for Fe-limited green algae and marine diatoms. This finding is important because 30% of the global ocean is Fe-limited. In Fe-limited waters, phytoplankton is observed to thrive and thus must have evolved either through a unique mechanism of Fe uptake and/or a lower Fe demand for growth. The replacement of Fe-containing enzymes with Cu-containing enzymes may explain the success of oceanic phytoplankton in open-ocean waters, where Fe concentrations are too low to support growth of coastal phytoplankton. To better understand the role Cu plays in phytoplankton subsistence and growth in low Fe waters, Dr. Maldonado has turned to radioisotopes of Cu to track and identify trace metal acquisition, metabolism and nutrition of marine bacteria and phytoplankton.

Typically obtained as a by-product of Ga-67 production, Cu-67 has recently experienced its own supply crisis as production emphasis at major commercial suppliers has moved away from both of these isotopes. In response, TRIUMF, in collaboration with Dr. Maldonado, mobilized to produce Cu-64 and Cu-67 for her studies as described above.

In summary, Dr. Maldonado's research aims to address fundamental questions in microbial physiology, ecology, and evolution in order to better understand how trace metal distribution and speciation may control global phytoplankton productivity in the present day and over glacial-interglacial cycles. In turn, these findings will elucidate how marine microorganisms may affect trace metal biogeochemical distribution and cycling in the ocean.

N-13 Nitrate Production for Botany Studies

A long-standing collaboration between TRIUMF and Dr. Tony Glass (UBC) utilized N-13 nitrate production capabilities at TRIUMF to enable studies on plant nutrition. Research in Dr. Glass's laboratory focuses on membrane transport processes responsible for transferring inorganic ions (particularly K^+, NH_4^+ and NO_3^-) across the plasma membrane, from external (soil) solution, into the roots of higher plants. $^{13}NO_3^-$ and $^{13}NH_4^+$ transport processes have been studied at the molecular level in both wild type and mutant (gene deletion) genotypes of various plant species [3,4].

Genes encoding high- and low-affinity NO_3^- transporters and high-affinity NH_4^+ transporters were cloned by Dr. Glass's group and experiments were conducted to understand the manner in which the gene products (proteins) participate in transport processes, and the manner in which they are regulated. As a testament to the complexity of the studies involved, one species (*Arabidopsis thaliana*) was found to maintain a total of 11 genes encoding NO_3^- transporters and 5 encoding NH_4^+ transporters. In the case of NO_3^- substantial quantities of this ion were found to be transported to the leaves of many plants, where it is reduced to NH_4^+ and converted to amino acids and other N-containing compounds. Thus, ion uptake is not exclusively a function of root cells only, but leaves too must reabsorb nitrate from the xylem sap.

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4.2.3.4 TECHNOLOGICAL INNOVATIONS

Despite over 80 years of cyclotron research and development, relatively little is understood about the environment within a cyclotron target during irradiation. Optimized irradiation conditions are typically deduced by indirect measurement of beam location, target body temperatures, vacuum levels, and other peripheral metrics of the cyclotron and target hardware. A better understanding of the conditions (beam energy, position and fluctuations, target temperature gradient, etc.) within the target will improve the reliability of cyclotron and target performance during isotope production. Knowledge of these parameters allows for the design and improvement of new cyclotron target technology as Canada shifts from relying on large-scale production and distribution of isotopes from the Chalk River nuclear reactor to widespread, routine, large-scale, reliable production of important isotopes in hospital-based medical cyclotrons.

During the past five years, target technology research and development has focused on enhancing cyclotron beam energy measurements, beam-profile monitoring, and radiometallic isotope production using liquid targets.

Fundamental Measurements of Cyclotron Energy

When used for medical isotope production, both new and old cyclotrons require periodic validation of beam energy to ensure optimal performance. This is not only part of good manufacturing practice and quality assurance but is necessary for optimizing target yields and minimizing the radiation dose overhead of radionuclide production. An example where such a validation is of particular importance is when undesired by-products result from competing energy-dependent reactions (e.g., production of I-123 via the (p,2n) reaction when producing I-124 from Te-124).

Although it is often claimed by cyclotron manufacturers that the energy of their machines never changes, field experience suggests that this assertion is not valid for the majority of present-day negative ion cyclotrons. The extraction of negative ion beams by a stripper foil can give useful beam on targets even with substantial orbit centre offsets. Changes in magnet shim or in distribution of the RF (radio frequency) field along the dees can cause the orbital centre to drift. Furthermore, the loss of position calibration or damage to extractors and stripper foils can also substantially affect the beam energy. While cyclotrons in nuclear physics institutions often have analyzing magnets with well-characterized energy definition, this diagnostic tool is not feasible for most medical cyclotron configurations because the production targets sit more or less straight on the beam port with little or no further collimation. As such, an off-line approach for evaluating the beam energy of a medical cyclotron is required.

For most applications the simple method of beam range determination will not be accurate enough due to straggling. Long stacks increase straggling, and it can be difficult by conventional “burn” methods to discriminate the Bragg peak end from thermal damage. For this reason, we investigated a new, simple-to-perform method for evaluating the cyclotron beam energy by exploiting the $^{nat}Cu(p,x)^{63}Zn$ reaction. By irradiating a stacked Cu-Al-Cu foil system and a universally available dose calibrator (a re-entrant ion chamber used in every nuclear medicine facility), TRIUMF, in collaboration with the Hevesy Laboratory at the Technical University of Denmark, developed a method sufficiently sensitive to achieve the necessary energy precision of a few tenths of an MeV. The proposed method was extensively evaluated and tabulated for protons in the 11-19 MeV energy range, but it can be straightforward to extend the general principle to protons, deuterons, and alphas of other energies that make it relevant to most modern cyclotron facilities. To facilitate the adoption of this technique into routine evaluation of the cyclotron beam energy, TRIUMF has published a list of recommended nominal aluminum degrader thicknesses as well as a list of the corresponding curve fit data for evaluation of the proton energy using the measured Zn-63 activity ratio [1]. Application of the proposed method to the monitoring of deuteron energies is a topic we plan to explore further in the near future.

Beam-Profile Monitors

Given the frequent (daily) and prolonged (~6 hour) irradiation times required for the production of Tc-99m on small medical cyclotrons, an ability to monitor cyclotron beam positioning in real time may become a crucial metric to ensure a reliable supply of medical isotopes for many Canadians. Three popular methods for determining the beam profile on a PET cyclotron have been: (1) using an autoradiography technique to measure the activity pattern induced in a target foil with a radiation sensitive film, (2) the remote movement of a wire through the beam, and (3) measuring the amount of current striking a set of collimators in front of the target. The drawback of these approaches is their inability to monitor the beam in real time at full beam power, which results in either an exhibiting non-linear correlation in signal response to the power deposited, or not being able to provide a two-dimensional beam profile.

Over the past five years, TRIUMF designed and successfully tested a beam-profile monitor that is able to withstand the high, absorbed power of a PET cyclotron and monitor the deposited energy linearly and in real time [2]. A prototype monitor, consisting of a water-cooled Faraday cup and two orthogonal rows of tungsten electrodes mounted on a water-cooled support frame and spaced closely together, was designed, built and tested. After applying a voltage potential to the electrodes, the beam current was measured using a custom electronic setup involving a current mirror and a current-to-voltage amplifier. With the growing prevalence of hospital-based cyclotrons, a real-time beam profile monitor will enable rapid and simple beam diagnostics, ensure optimal performance for isotope production, and reduce maintenance because of better beam alignment with the target port and hardware.

Miniaturization of Radiopharmaceutical Synthesis

Radiotracers such as [^{11}C]raclopride are produced in a process that can take between 45 and 60 minutes to complete. These conventional approaches can consume upwards of 75% of the ^{11}C ($t_{1/2}$ = 20 min) due to radioactive decay alone, even more if synthesis losses are considered. To compensate, a large starting quantity of radioactive precursors such as [^{11}C]methyl iodide is required to produce an adequate amount of the tracer for injection. In this investigation, a continuous-flow microchip was explored for the purpose of synthesizing C-11 radiotracers in a shorter time by exploiting the favourable reaction kinetics of using smaller reaction volumes. To enhance the mixing of reagents within the microchannel, a micromixer "loop" design was used in fabricating various polydimethylsiloxane chip styles. With a loop design implemented in an abacus-style chip for the production of nonradioactive raclopride, shorter reaction times, reduced precursor use, and improved yields were possible when compared with the use of a simple serpentine design (no loop-style chip). However, when performing the equivalent radiochemical reaction, the results were not as favourable. Using the loop design in a full loop-style chip, parameters such as premixing the reagents, reducing flow rate, and varying reagent concentrations were explored to improve the yields of [^{11}C]raclopride (in terms of relative radioactivity) formed.

We have demonstrated that the use of a microchip maintains advantages through improved yields and shorter reaction times for the production of nonradioactive as well as [^{11}C]raclopride [3,4]. Microfluidic synthesis has improved the nonradioactive synthesis results in comparison with the conventional process by reducing the reaction time by ~33% and required ~5% of the MeI used in conventional preparation. The abacus microchip was found to be a better design than the no loop or serpentine chip to provide a better yield. For the [^{11}C]Rac synthesis, the full loop chip produced better results, demonstrating higher [^{11}C]Rac relative radioactivity and higher conversion of [^{11}C]MeI to [^{11}C]Rac than the abacus microchip. To evaluate the microchip method further, the reactants were premixed, and we found that the full loop chip still produced better results than the abacus chip, thus reinforcing the importance of a micromixer design for this process.

We have also improved the [^{11}C]Rac synthesis by reducing the flow rate to 2 µL/min. Although we have demonstrated the advantages of lower precursor consumption and safer operation, this modification would not be the most efficient solution on a production scale because a lower flow rate will decrease production speed. The fabrication of a glass chip with the micromixer design is underway for the full investigation and optimization of the microchip radiosynthesis of [^{11}C]Rac and other labelled compounds. In addition, the behaviour of reagents in the microchannels is further explored in a computational fluid dynamics study.

Radiotherapeutic Isotopes

Beyond imaging, the radiometal family of isotopes is also home to a number of therapeutic β-, Ω, conversion and Auger electron emitters. The short path length and high-LET particles are very effective in killing cells. Since the time of Marie Curie, use of radiation for the destruction of cancerous tissues has been recognized as a potential application, but it remains as an unoptimized science to date. The medical community has come to utilize wide-field, external beam radiation as a means to treat tumours in the hopes of delivering a fatal dose of ionizing radiation to the tumour volume while sparing the surrounding healthy tissue. There have been dramatic improvements in patient and tumour dose control over time; however, the concept continues to experience challenges associated with controlling radiation dose, side effects that include depressed immunity in patients making them susceptible to post treatment infections, and an increase in secondary cancers.

An alternative approach is to deliver a therapeutic radiation dose selectively to the tumour. By employing a similar strategy to that for molecular imaging, therapeutic isotopes can be incorporated into more complex pharmaceuticals for specific, targeted delivery of a potent radiation dose.

Successful radiotherapeutics developed to date have relied on the inherent biodistribution profiles of simple chemical salts: [^{131}I]NaI (thyroid treatment), [^{153}Sm]$SmCl_2$, [^{32}P]phosphates and [^{89}Sr]$SrCl_2$ for palliative treatment of bone metastases. More recent advances have seen a small degree of chemical complexity introduced into the final formulations. Examples include [^{131}I]mIBG for neuroblastomas, as well as [^{90}Y] and [^{177}Lu]-labelled peptides for neuroendocrine tumour treatment to [^{90}Y]glass microspheres (Theraspere™) injected directly into the liver for primary or metastatic liver tumours. It is reasonable to expect that radioisotope therapy will continue to require a greater availability of isotopes and more sophisticated biochemical approaches. To this end, radiotherapeutic isotopes have been growing in popularity despite challenges associated with their availability, distribution, and use.

Recent studies have shown that Rhenium-186 (Re-186) is emerging as an optimal candidate for radioimmunotherapy (RIT). This is mainly due to its nearly ideal half-life of 3.72 days as well as its decay properties ($\beta-$, Emax=1.07 MeV and an imageable γ-ray at 137 keV with 9% abundance). The energy deposited to cells suggests that Re-186 is a promising candidate for therapy of tumours from millimetre to centimetre dimensions. Re-186 is currently available from neutron irradiation of Re-185 in low specific activity, although progress has been made toward improving this result. High specific activity Re-186 can be produced by proton bombardment of enriched tungsten targets. However, there are large discrepancies in the literature for the excitation function of the ^{186}W(p, n)^{186}Re reaction. In order to better assess the feasibility of producing multi-mCi levels of Re-186 for therapeutic applications via the ^{186}W(p, n)^{186}Re reaction, the excitation function was re-measured. Scientists at TRIUMF determined the cross-sections for the production of Re-181, Re-182m, Re-182g, Re-183, Re-184, and Re-186 from natural tungsten, using a stacked foil technique for proton energies up to 17.6 MeV. The results suggested that small quantities of Re-186 can be produced on TRIUMF's TR-13 cyclotron, but these quantities were insufficient to allow for a pre-clinical study to compare reactor-produced (low specific activity) with cyclotron-produced (high specific activity) Re-186. TRIUMF could explore this further with access to a higher energy, higher current cyclotron.

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4.2.3.5 ADVANCING RADIOPHARMACEUTICAL SYNTHESIS AND APPLICATION

TRIUMF's Nuclear Medicine Division is built upon a long-standing symbiotic collaboration with the PPRC (under current Director Dr. Stoessl). This joint venture has led to one of the best PET brain imaging centres in the world, one flagship of TRIUMF's activity. Historically the radiotracer production and imaging had been headed by Dr. Ruth, a TRIUMF senior scientist. In light of the expansion of the TRIUMF Nuclear Medicine Program and UBC imaging capabilities (two clinical and two pre-clinical scanners), the position is now split between Dr. Schaffer (TRIUMF, Head Nuclear Medicine) and Dr. Sossi (UBC Physics and Astronomy, UBC PET Director). The tight collaboration between them is formalized by cross-appointments in their respective institutions.

While the main clinical research focus of the imaging program is Parkinson's disease (PD), an increased emphasis is being placed on other neurodegenerative disorders such as Alzheimer's. Achievements of the collaboration include pioneering work in discovering: mechanisms of PD pathogenesis, progression and treatment-related complications, the neurochemical basis of the placebo effect, establishment of neurochemical changes that precede the clinical symptoms of PD, development of novel data analysis methods and quantitative high-resolution imaging as well as significant optimizing dopaminergic tracer synthesis.

The program has generated well over 150 imaging-related peer-reviewed papers in the last five years and secured over $15M CAD of funding.

Neurodegenerative Disease Imaging

Currently, seven compounds are produced on a routine basis using TRIUMF-designed automated synthesis equipment. Also, part of the radiopharmaceutical production lab was upgraded in 2010 with a contribution from Western Economic Diversification of Canada and PPRC, allowing the group to purchase new equipment and to better conform to GMP standards (see below).

Tracer demands are also changing as research at the PPRC and, more recently, the Centre for Comparative Medicine (CCM) at UBC evolves. Over the past two years, the core group has established the synthesis of [^{11}C] MRB (methyl reboxetine), a selective norepinephrine transporter (NET) blocker, for a collaborative study with Dr. Yu-Shin Ding, Departments of Psychiatry and Radiology, NYU Langone Medical Centre. [^{11}C]Yohimbine was developed for Dr. Doris Doudet for use in imaging noradrenergic receptors in the brain, and this was followed in early 2012 by [^{11}C] DASB, which will be used to assess the serotonin function in the brain, and by the inflammation tracer ^{11}C-PBR for Dr. Sossi's studies (in collaboration with Dr. Robert Mach, Department of Radiology, University of Pennsylvannia Perelman School of Medicine) on the role of neuroinflammation in PD. [^{18}F] EF5 was also resurrected for shipment to BCCA for a clinical trial on the use of PET in prostate cancer imaging. All tracer production is in the process of being transferred to the new GMP compliant facility.

In addition, a CFI-funded MIlabsMilabs microSPECT/PET/CT camera was installed at the CCM. This camera will expand the pre-clinical imaging capacity of the existing Siemens microPET located at the UBC hospital and will provide novel opportunities to develop and use gamma-emitting radionuclide-labelled compounds, thus motivating further expansion of TRIUMF's Nuclear Medicine Program.

Clinical Studies of EF5 and FDOPA

Hypoxia in tumours is associated with genetic instability and increased resistance to radiation and chemotherapy, with previous work suggesting that hypoxia may be an important prognostic and predictive factor in non-small-cell lung carcinoma (NSCLC). In addition, antiangiogenic drugs and standard chemotherapy agents may alter tumour blood flow, resulting in changes in tumour oxygenation, but this has never been demonstrated in living patients or during treatment.

FIRST SUCCESSFUL SCAN OF PATIENT WITH F-DOPA ANNOUNCED

26 May 2011

TRIUMF's Mike Adam, along with Doctors Daniel Levine, Daniel Metzger, Helen Nadel, Angelica Oviedo, and Erik Skarsgard from BC Children's Hospital, used the radiopharmaceutical F-DOPA in conjunction with PET/CT imaging to diagnose a 16-year-old patient with a neuroendocrine tumour syndrome. Conventional magnetic resonance imaging showed three soft tissue tumours within the abdomen but this and conventional nuclear medicine imaging with Iodine-123 labeled MIBG failed to provide a unifying diagnosis. The F-DOPA PET/CT clearly depicted all three tumours and implied a common diagnosis, which was subsequently confirmed on genetic testing following successful surgical removal. This represented the first reported use of F-DOPA PET/CT for pediatric neuroendocrine syndrome imaging and was recently reported in the journal Pediatric Radiology.

The synthetic organic chemistry performed to add the Fluorine-18 isotope can only be done at a limited number of places, including BC Cancer Agency and TRIUMF. As a result, these two organizations have been receiving referrals from all over Canada. TRIUMF has been doing work in the field of nuclear medicine for approximately 30 years, and has become a driving force within it.

BCCA and TRIUMF have partnered to implement the production and use of radiotracer [^{18}F]-EF5 (a nitroimidazole-containing compound) that is preferentially taken up by hypoxic tissues. EF5-PET thus allows clinicians to measure oxygenation, which can be compared to blood perfusion using complementary CT scanning (i.e. PET/CT), providing a quantitative, non-invasive means to quantify tumour blood flow and oxygenation before, during, and after chemotherapy (with and without the chemotherapeutic agent, bevacizumab) in patients with-advanced NSCLC.

Patients with incurable stage III/IV NSCLC, who are to receive first-line platinum-based doublet chemotherapy alone or in combination with bevacizumab (as part of other clinical trials), were recruited for a study. All patients had quantifiable hypoxia in their primary tumours at baseline and notable changes in oxygenation and tumour perfusion. There was also some data to suggest that there had been a near doubling of blood flow to the central tumour mass over the course of treatment, with corresponding decreases in hypoxia. These scans demonstrated that antiangiogenic strategies, and chemotherapy alone, may significantly impact tumour oxygenation and blood flow. In the limited studies done so far there have been clear changes in tumour blood flow and hypoxia. Many more scans are underway. This study represents the first non-invasive documentation of lung cancer oxygenation and changes with therapy, suggesting that hypoxia may be an important predictive and prognostic factor for NSCLC.

Novel Small Molecular Tracers for Oxidative Stress Imaging

Until recently, the tracers produced are often literature-established, small-molecule pre-clinical and/or clinical imaging agents with a heavy focus on safety and good manufacturing practices. Further expansion in this area is planned for the next five years.

Cellular reactive oxygen species (ROS) can be generated from a variety of sources, both endogenous and exogenous, and play an important role in a number of cell signaling pathways. When ROS regulatory mechanisms become overwhelmed, the cellular antioxidant capacity is exceeded and oxidative stress can result. Tumour cells generate high amounts of ROS and respond by upregulating various detoxifying antioxidant systems. Glutathione is the predominant endogenous cellular antioxidant, and plays a critical role in the cellular defensive response to oxidative stress by neutralizing free radicals and reactive oxygen and nitrogen species. With cystine as the rate-limiting substrate in glutathione biosynthesis, the cystine/glutamate transporter (system x_c-) represents a potentially attractive biomarker for PET to enable *in vivo* quantification and functional assessment of x_c- activity in response to oxidative stress associated with disease.

System x_c- was first described by Banna and Kitamura in 1980 as a sodium-independent amino acid transport system with a very narrow natural substrate binding profile, especially when compared to other known amino acid transporters. x_c- is a heteromeric protein composed of two subunits connected through a disulfide bridge; with 4F2hc as a heavy unit involved in trafficking the heterodimer to the plasma membrane, and a lighter subunit, xCT, conferring transport and substrate specificity. The level of x_c- transporter activity/expression in normal cells is very low but is significantly upregulated in cells under oxidative stress. Upregulation of the transporter has been observed in tissues under oxidative stress and is implicated in a wide range of conditions including cancer, diabetes, cardiovascular and neurodegenerative diseases.

The ability to image x_c- by PET means that it could be used to quantify oxidative stress as it is related to a particular disease state [1]. In collaboration with Dr. Jack Webster (GE Global Research), our team has established proof of feasibility for the use of ^{18}F-labelled aminosuberic acid (FASu) as an x_c- binder. Preliminary data, using diethylmaleate (DEM)-treated EL4 lymphoma cell uptake studies and *in vivo* biodistribution and tissue uptake in mouse EL4 xenografts, demonstrate FASu as a potential novel agent for the *in vivo* assessment of the cystine transporter. FASu demonstrates 5-fold enhanced uptake *in vitro* under oxidative stress, with effective blocking using sulfasalazine, a known x_c- inhibitor. FASu also shows *in vivo* uptake ratios exceeding 10:1 and 20:1 for tumour:blood and tumour:muscle, respectively, within two hours post injection. *In vivo* uptake was reduced when co-injected with unlabeled ASu, a structural analogue, suggesting specific uptake and competition between FASu and ASu.

With ^{18}FASu, a tracer that binds x_c-, we will enable real time, *in situ* information on oxidative stress activity at the site of disease with no perturbation of the biological system and without a need to rely on indirect *ex vivo* measurement of circulating systemic byproducts obtained through blood or urine analysis. This result represents an exciting opportunity for the TRIUMF molecular imaging community as a novel tracer with potential broad applicability across a number of diseases. The utility of ^{18}FASu will be the subject of future studies between the division and its partners.

Mn-52 for Manganese-Enhanced MRI

PET and MRI are complementary techniques from an imaging perspective. PET is one of the most sensitive imaging methods in clinical use, capable of detecting trace (femtomolarnanomolar) concentrations of injected tracers. An intrinsic trade-off in sensitivity involves image resolution, with modern PET scanners typically able to provide images with resolution in the millimeter range, making detailed anatomical studies difficult. To accommodate for this, the nuclear medicine community has been rapidly adopting multimodal imaging, in which one method, such as PET, is combined with another, such as CT or MR to afford co-registered images that map PET images on to those with greater anatomical detail.

MR allows anatomic imaging with exquisite resolution (sub-millimetre). In addition, the quantification reliability of MRI can be a challenge because the source of image contrast is complicated and depends greatly on details of image acquisition as well as the object being studied. MRI is also prone to spatial distortions from non-ideal magnetic field gradients as well as to localized susceptibility artifacts in image. Conversely, PET can provide quantitative and undistorted measurement of the spatial and temporal tracer distribution *in vivo* with a single image acquisition. PET is employed as a gold standard against which other potentially quantitative techniques, including MRI, are judged. In PET, concentrations of tracer are generally more easily related to biological function than are relaxivity parameters from an MRI experiment.

Mn-52 is a promising, yet poorly investigated, radionuclide for PET imaging. Mn-52 was selected primarily because of its low positron range and energy (0.63 mm, 244.6 keV), which is comparable to F-18 (0.62 mm, 250 keV) potentially preserving the spatial resolution of the proposed PET images. [^{52}Mn]$MnCl_2$ PET is particularly interesting because of the relatively novel MRI technique of manganese-enhanced MRI (MEMRI). In MEMRI, paramagnetic Mn^{2+} is used as a contrast agent *in vivo* that reduces T1 relaxation times and accumulates in areas of neuronal activity by uptake through voltage-gated calcium channels. MEMRI has been primarily used for imaging the brain of rats or mice and has also been employed for neural tract tracing in mice. The radionuclide Mn-52 is expected to accumulate *in vivo* by the same biological mechanisms as nonradioactive Mn in MEMRI, providing the opportunity to study similar systems and processes as MEMRI with PET, to independently investigate the effects of Mn administrations needed for MEMRI studies on live animals, and to use the quantitative aspect of PET to validate MEMRI results. Mn-52 has previously been used to study Mn absorption in humans, but its use for PET-MR imaging has not been explored.

For Mn-52 PET to be a useful tool, it is necessary to establish that Mn-52 produces images of similar quality to established radiotracers and to demonstrate biological applications for which it is well suited. In collaboration with Dr. Sossi (UBC), Mn-52 was produced on TRIUMF's TR13 cylotron via $^{nat}Cr(p,x)^{52}Mn$. PET images have been acquired with phantoms and rats, and similar images with F-18 have been acquired for comparison [2]. *In vivo* brain imaging after systemic injection in this work showed accumulation of Mn in the pituitary and ventricles, but did not observe Mn elsewhere in the brain in amounts distinguishable from background. This is inconsistent with published MRI signal enhancement, indicating that additional work is required to understand the biodistribution differences between tracer-level containing <240 ng of Mn to bulk level (non-radioactive) containing as much as 40 mg/kg of the metal. Despite this, Mn-52 has been established as a novel and potentially useful tracer for small animal PET imaging because of its manageable positron branching ratio and energy. With a longer half-life, Mn-52 remains detectable weeks after initial injection, allowing weeks-long study after a single injection.

Large Molecular-Weight Radiopharmaceuticals

There is an urgent need for companion diagnostics to provide detail on a person's predictive and prognostic markers so that physicians can diagnose disease while in a treatable state, select an optimal therapeutic course, and avoid ineffective drug treatment. Prognostic indicators of the long-term progression of a disease could also serve to enhance medical care for patients across a wide variety of indications. A growing number of experimental PET probes are being developed from peptide, protein, oligonucleotide and/or other large molecular weight platforms. Novel medical imaging (MI) probes are of paramount importance for elucidating the molecular origin of illness.

Having built a substantial program in the production and use of small molecule radiopharmaceuticals for *in vivo* analysis of the functional affects of disease, TRIUMF has been increasing research activity in the synthesis and radiolabelling of large molecular weight tracers with a goal of enabling *in vivo* analysis of changes in disease expression. With both small and large molecule labelling capabilities, TRIUMF maintains expertise and access to broadly enabling platforms for addressing a wide array of conditions.

Oligonucleotide (ODN) and Peptide Nucleic Acid (PNA) Labelling

There are approximately 200 different types of cancer, with some analyses suggesting that greater than five genes mutate in each tumour. With genetic heterogeneity across any given patient population, symptomatic diagnosis of cancer and/or classification of tumours are increasingly becoming insufficient means of dictating treatment and/or determining patient outcomes. Genetic profiling techniques have enabled the identification of specific genes that are over-expressed in various cancer types and, with that, the identity of unique gene clusters acting together in a specific subset of transformed cells driving disease forward. This knowledge offers a potentially powerful indicator of tumour function at the genetic level. Since individual gene alterations likely occur at too low a level to detect with existing imaging methods, mRNA over-expression resulting from gene modification could potentially serve as one of the earliest diagnostic indicators for the development of cancer in humans.

Genome BC has funded an effort through TRIUMF to advance the field of antisense PET. The effort involves conjugating peptide nucleic acids (PNAs) to cell penetrating peptides for enhanced access to the cellular interior. Specifically, the TRIUMF group will work progressively toward the proposed chimeras, first building complementary PNA constructs to known target sequences of two genes (GFP and HER2).

These sequences will be modified with a terminal azide to allow for "click" modification with a fluorescent dye or radiolabelling precursor followed by *in vitro* analysis. Once the selected PNA sequences have been validated, full construct synthesis will then be afforded by producing the CPP portion of the chimera on solid support. The conjugates will then be labelled using the radiolabelling methods discussed above. Once the *in vitro* work has been completed, the goal is to analyze the chimeras *in vivo*.

Aqueous Fluorination

Collaboration with Dr. Perrin (UBC) has seen the successful implementation of arylboronic acid bioconjugates as shelf-stable, stockable, precursors for one-step aqueous F-18 labelling of biomolecules. The feasibility of this approach was disclosed several years ago by examining the *in vivo* fate of F-18-labelled biotin-$ArBF_3$ and more recently with F-18-labelled marimastat-$ArBF_3$, a potent inhibitor of matrix metalloproteinases, which provided some of the first *in vivo* PET images of tumour-associated protease activity [3]. The synthetic advantages of this method, which include a one-step aqueous fluorination to provide radiochemically pure, labelled ligands, was detailed in a recent publication [4], conserving time and therefore the amount of F-18, radiochemical purity and higher specific activity. The team has recently overcome several issues in improving radiochemical yields, streamlining the experimental setup to work better with very small volumes and with low pH. Fluorinations can now be accomplished in ~25 minutes, with higher yields at lower fluoride concentration, therefore improving the specific activity. In a second effort, TRIUMF's chemists have successfully extended this labelling technique to "click" chemistry, a labelling procedure via two steps in only one pot, resulting in a very quick and reliable generation of radiopharmaceuticals with high yield.

This project continues to receive accolades from the broader community with numerous conference presentations, invited lectures and publications in high-impact journals [5].

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4.2.3.6 PROTON THERAPY

For large ocular melanomas or melanomas close to the optic nerve, the accepted best treatment choice is proton therapy. By the end of 2011, 20,761 patients, from all over the world, have been treated with proton therapy for ocular melanomas with 9 proton therapy centres using a dedicated beam line currently in operation. Here at TRIUMF, low energy protons (please see Section 5.6.3) from the main TRIUMF cyclotron have been used since 1995 to treat ocular melanomas [1]. By the end of 2012, the number of treated patients totals 170. The five-year local tumour control rate is 91%. The metastasis-free survival rate is an excellent 82% and the affected eye is saved in 80% of the cases. But there is always room for improvement, which translates into saving the lives of more patients.

Research during the past five years has focused on improving analysis and control of dose during the irradiation treatments. Simulations of the proton-therapy system have been improved and a novel approach to use PET scans immediately after treatment have been employed to analyze delivered dose profiles.

FLUKA Model of the Facility

In 2011, the computer program FLUKA [2], a particle physics Monte Carlo simulation package for simulating the interaction of particles with matter, was used to model the proton-therapy beam line. Figure 1 shows how the proton beam (in green) passes through the different elements in the beam line and the subsequent creation of secondary particles (in red and black). The simulation was verified against several sets of experiments. This computer model can now be used as a means to quickly and economically study changes to the beam line while avoiding significant disruptions in beam line operations. Modifications intended to improve beam characteristics can be tested experimentally with the goal of reducing patient dose from secondary particle emissions and as a direct consequence the occurrence of secondary cancer to the treated patient.

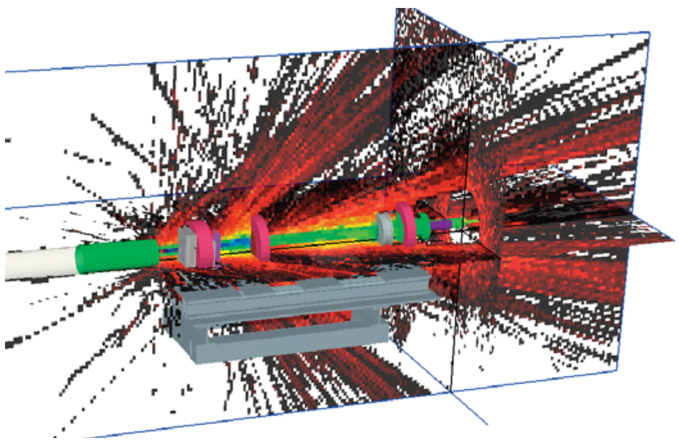

Figure 1: Simulation of the proton therapy beam line in 3D showing the incoming proton beam (green) and secondary particles (red to black).

PET after PT

The treatment plan for an ocular melanoma consists of four fractions administered on subsequent days. The dose planning involves measurement and marking of the tumour with tantalum clips and a sophisticated planning software to optimize the gazing angle, incoming beam energy and spread and the final patient collimator. Before each fraction, the patient is carefully aligned with the beam, an important step because proton therapy is a very precise form of radiotherapy with steep dose gradients at the target boundaries. Unfortunately, right now, there is no way to measure if the proton dose has been deposited exactly as planned. Currently, we are investigating the usefulness of position emission tomography (PET) after proton treatment (PT) as a way to visualize the proton dose deposited, since during proton irradiation, the PET isotopes O-15, N-13 and C-11 are produced. Several phantoms and one patient underwent a PET scan after proton irradiation [3] (see Figure 2). The production cross-section of the PET isotopes, produced during proton irradiation, will be included in the FLUKA simulation in the near future. The imaged activation profile will then be compared to the simulation and conclusions about the dose deposited by the protons will be drawn. The same technique will be applied to the patient data. If the resolution is sufficient, a

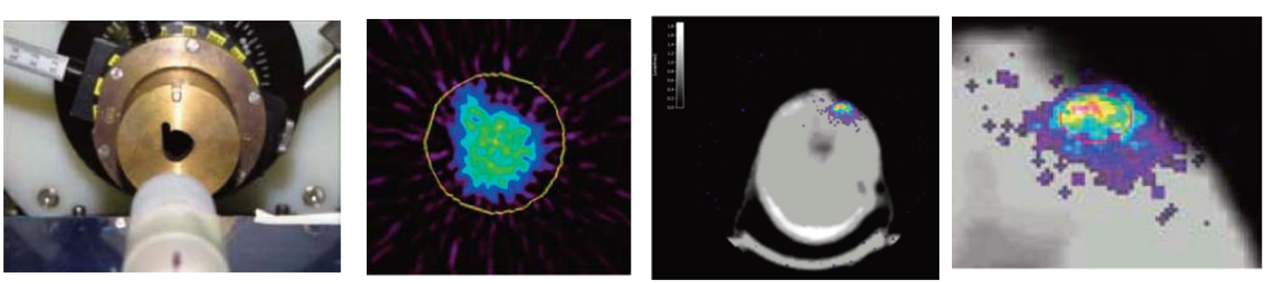

Figure 2: (a) The irregular collimator used for irradiation of a lucite rod phantom. (b) PET image of lucite phantom scan in the transverse plane. The outline of the phantom, determined from the transmission scan, is indicated by the yellow outline. (c and d) PET images of patient scan after proton treatment in the transverse plane. The activity in the tumor is clearly visible. The tumour size is indicated with the red outline. Scanning was performed at UBC PET Imaging Centre.

conclusion about the success of the patient alignment can be drawn. In the future, any misalignment could be compensated for in a subsequent fraction, avoiding missed dose to the tumour, and thereby reduced probability of local tumour control and excess dose to an adjacent structure with unnecessary collateral damage. This could ultimately lead to better patient care.

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4.2.4 MOLECULAR AND MATERIALS SCIENCE

As Canada's accelerator laboratory, TRIUMF has been at the forefront of using particle beams as probes of chemistry as well as the structure and behaviour of materials. Beams of muons were first developed at TRIUMF to study subatomic physics by generating other secondary beams of more exotic particles. Muons are now generated and employed regularly to probe the origin and behaviour of magnetism in condensed-matter and gaseous systems. Several decades ago, Professor Jess Brewer (UBC), Don Fleming (UBC), Toshimitsu Yamazaki (Japan), and Ken Crowe (UC Berkeley) pioneered this line of investigation at TRIUMF.

TRIUMF has also developed a sensitive magnetic nanoprobe of materials that employs exotic isotopes of lithium. The isotope beams are generated within the ISAC facility and then deposited into thin structures to analyze the behaviour of magnetism at the interfaces between different types of materials. Called β-NMR, the technique is complementary to muon probes because it provides access to depth-dependent properties for materials that are too thin to stop a conventional muon beam or to carry out conventional NMR.

Beginning in 1995 TRIUMF has built up several beam lines that provide low-intensity, energetic proton and neutron beams to simulate natural-radiation exposures either in space or terrestrial environments; these facilities are called PIF & NIF.

4.2.4.1. BACKGROUND

Muons are elementary particles with a mass one ninth that of the proton (or 206 times the electron mass), a spin of 1/2, and a magnetic moment 3.183 times larger than that of a proton. They are produced in the weak-interaction decay of pions (which are in turn produced from proton bombardment of a target material, typically beryllium or graphite, at 500 MeV), with a lifetime of 26 ns. These decay processes violate parity and result in an ensemble of muons being produced 100% spin polarized along (μ^-) or opposite (μ^+) to its momentum direction.

Though positive and negative muons have the same mass (105.7 MeV), their interactions in matter are quite different. The μ^+ has a lifetime of 2.197 μs, regardless of the medium it is implanted in, and can be thought of as a light proton. In contrast, the μ^- is regarded as a heavy electron and, due to nuclear capture, its lifetime is strongly dependent on the atomic number of the material in which it is implanted, being as short as 80 ns in lead. The polarization of an ensemble of μ^+ or μ^- can be monitored by measuring the asymmetry in the muon's radioactive decay.

The decay of the positive (negative) muon violates parity and as a result the positron (electron) is emitted preferentially along the axis of the muon's spin. This anisotropy or "asymmetry" in the decay of an ensemble of polarized muons provides a convenient means of determining the direction of the muon's spin and is the key feature that makes the μSR technique possible.

TRIUMF TO PLAY ROLE IN U.S.-FUNDED RESEARCH NETWORK

03 August 2010

The U.S. National Science Foundation (NSF) recently announced a $2 million award for an international consortium aimed at probing novel superconductors with neutrons, muons, and photons through its Partnership in International Science and Engineering (PIRE) initiative. TRIUMF will play a unique and critical role in the network through its muon-spin resonance program at the Centre for Molecular and Materials Science (CMMS). The principal investigator is Dr. Yasutomo Uemura, a professor of physics at Columbia University, a core contributor to the CMMS, and a regular visitor to TRIUMF. The project began August 1, 2010, with funding for three years.

The NSF's PIRE program is designed to, "Support bold, forward-looking research whose successful outcome results from all partners—U.S. and foreign—providing unique contributions to the research endeavor." In this case, the consortium will focus on exploring novel superconductors using the combined power of muon, neutron, and photon probes along with scanning-tunneling microscopy.

The high intrinsic polarization of an ensemble of particularly positive muons, in marked contrast to its parent technique, nuclear magnetic resonance (NMR), is independent of temperature or magnetic field, which is highly important as it endows μSR with a remarkable level of sensitivity in probing local magnetic environments that NMR simply cannot match. There is no need to first create spin coherence using a high-frequency preparation pulse, so the time resolution is significantly increased over that of conventional magnetic-resonance techniques. Thus, in a proton NMR experiment at 300 K and 9.4 T, the ensemble polarization is only $\sim 3 \times 10^{-3}$ %, which pales in comparison with the ~100% in μSR. The result of this is that a clear signal can be obtained in μSR from an ensemble of only about 10^8 stopping muons (measured, effectively, one at a time), whereas in NMR typically about 10^{19} polarized nuclei are required (produced from external RF pulse sequences), a succinct statement of the remarkably sensitive nature of the μSR technique. A unique aspect of μSR spectroscopy is that it can be performed routinely at very low (mK) temperatures and even in zero magnetic field, which is not possible in NMR (unless dealing with quadrupolar nuclei).

Muons can be implanted into solid, liquid, or gaseous samples. Implanted μ^+ initially have very high ("MeV") energy but are slowed down to near thermal energies on the nanosecond timescale. The final chemical environment of the muon depends on the chemical properties of the material in which it has been implanted. A fraction of the implanted μ^+ will end up in diamagnetic environments, as "bare" muons, solvated muons, or substituted for the proton of a diamagnetic molecule. The short lifetime of the muon limits the spectral resolution to ~70 kHz so it is not possible to resolve chemical shifts and distinguish between muons in different diamagnetic environments. Another fraction of μ^+ can pick up an electron during the slowing down process and form muonium (Mu = [μ^+, e^+]), a one-electron atom with the positive muon as the nucleus. The fraction of muons observed as Mu depends strongly on the material and its physical state, ranging from 0 in most metals to 1.0 in gaseous Kr. Due to the μ^+ mass being 200 times that of the electron, the chemical properties of Mu are virtually identical to those of any hydrogen isotope, even though there are no protons or neutrons in the nucleus. Muonium chemistry extends the normal isotopic H atom mass scale to its lowest value, 0.113 amu. Muons can also be incorporated in free radicals, which are molecules with an unpaired electron. These are formed by the reaction of Mu with unsaturated molecules.

The μSR techniques involve injecting a beam of spin-polarized positive muons into a sample and detecting the positron produced by the decay of each muon. The four techniques frequently used at the CMMS are: (1) transverse-field muon spin rotation (TF-μSR), (2) zero-field muon spin relaxation (ZF-μSR), (3) longitudinal-field muon spin relaxation (LF-μSR), and (4) muon level-crossing resonance (μLCR).

For TF-μSR the basic experimental geometry is shown in Figure 1. The muon is injected into the sample with its spin perpendicular to the external magnetic field. Each incident muon passes through a muon counter, which starts a fast electronic clock that is subsequently stopped by the detection of the corresponding decay positron in a positron detector (in practice there can be arrays of several detectors). Events where more than one muon or positron is detected within the sample during a time window of several microseconds are discarded. The data are displayed as a histogram of the number of decay positrons detected in a given direction as a function of the lifetime of the corresponding muon and resembles the free induction decay that follows a π/2 pulse in nuclear magnetic resonance (NMR). The muon spin precesses about the transverse field, with a frequency that is proportional to the size of the magnetic field at the muon site in the material. The TF-μSR configuration can be used to measure the magnetic field distribution of the vortex lattice in a type-II superconductor, the μ^+ Knight shift in metallic systems or the muon hyperfine coupling constant (hfcc) in a muoniated radical.

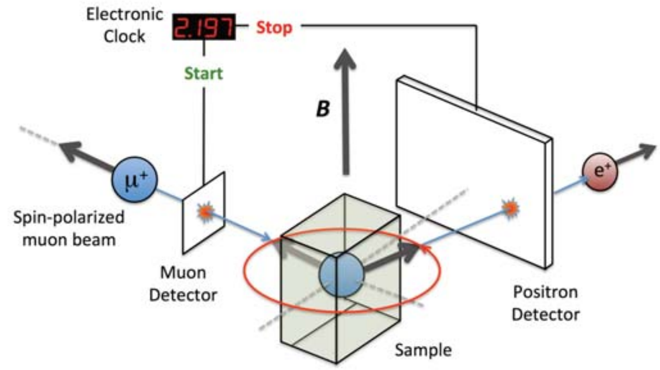

Figure 1: Schematic of the TF-μSR experimental geometry.

The setup for the ZF-μSR, LF-μSR and μLCR experiments is shown in Figure 2. The positron detectors are arranged in a way to measure the muon polarization along its original direction. The asymmetry parameter, A(t), is defined as (5)

$$A(t) = \frac{N_B - N_F}{N_B + N_F}$$

where N_F is the total number of positrons detected in the forward counters and N_B is the total number of positrons detected in the backward counters, and is proportional to the muon polarization. In both the ZF-μSR and LF-μSR techniques the time dependence of the asymmetry is monitored. No field is applied in ZF-μSR while an external magnetic field is applied parallel to the initial direction of the muon spin polarization in LF-μSR. ZF-μSR is a very sensitive method of detecting weak internal magnetism, that arises due to ordered magnetic moments, or random fields that are static or fluctuating with time. In μLCR, it is the time-integrated asymmetry that is measured as the magnetic field is scanned in a series of small steps. Resonances occur where there is crossing of spin states due to hyperfine or quadrupolar interactions. It is frequently used to determine the nuclear hfccs of muoniated radicals.

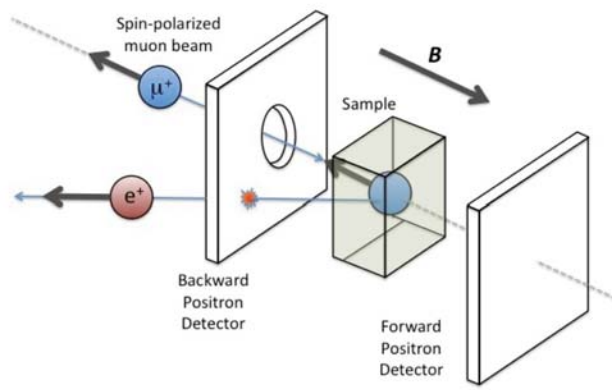

Figure 2: Schematic of the LF-μSR or μLCR experimental geometry. LF-μSR is a time differential technique while μLCR is a time-integral technique.

There are only four μSR facilities in the world, including CMMS, and of these only one other (Paul Scherrer Institute, PSI) provides continuous beams that are useful for studying materials with large magnetic fields and fast spin dynamics.

4.2.4.2. MAGNETISM

The application of µSR to the study of magnetic systems continues to be of great interest. µSR's utility stems from the sensitivity of the muon due to its large gyromagnetic ratio (more than 3 times that of a proton), and the fact that as a real space probe it complements reciprocal space probes such as magnetic neutron scattering. The volume sensitivity of µSR makes it especially valuable for studying phenomena such as phase separation, while LF-µSR is sensitive to a field fluctuation rate intermediate between inelastic neutron scattering and ac-susceptibility, making it especially well suited to studies of frustrated magnets.

Highly Frustrated Magnets

Frustrated magnetism is one of the most active fields in condensed matter physics as evidenced by the number of sessions devoted to it at the APS March Meeting and the rapid growth of participants in its major topical conference: Highly Frustrated Magnetism, held every two years, most recently in Hamilton, Ontario in 2012. The idea of frustration can be illustrated by considering three antiferromagnetically coupled spins on an equilateral triangle lattice. Satisfying the antiferromagnetic interactions between any two spins leaves the third spin unable to satisfy its interactions with the first two and as a result the system is unable to magnetically order at a temperature corresponding to the magnetic exchange interaction energy scale. The motivation for this interest is the now-realized expectation that frustrated magnetism provides a proving ground for discovering new states of matter; this concept of emergence is one of the most compelling paradigms in condensed matter research.

Pyrochlore are compounds of the general form $A_2B_2O_7$ that consist of two interpenetrating lattices of corner-sharing tetrahedra (for the A and B ions) that are a three-dimensional extension of the triangular lattice described above. The ability to place magnetic ions on either or both of the A and B sites provides considerable flexibility for exploring a wide variety of magnetic states. Miyazaki et al. studied a series of metallic ruthenium pyrochlores $Hg_2Ru_2O_7$, $Cd_2Ru_2O_7$ and $Ca_2Ru_2O_7$, finding a close relationship between the randomness of the frozen spin state with the degree of itinerence of the charge carriers [1]. Ofer et al. examined insulating $Y_2Mo_2O_7$, combining µSR, magnetic resonance and neutron scattering to deduce the source of spin glass magnetism in this nominally well-ordered material finding evidence for local lattice distortions on setting around the spin freezing temperature driven by a strong magnetoelastic coupling [2].

$Dy_2Ti_2O_7$ has been widely studied as an example of so-called spin ice (see Figure 3). In this system, crystal field interactions force the magnetic Dy ions to point along the local <111> crystalline axes, either inwards or outwards from the centre of each tetrahedron as effective Ising moments. Ferromagnetic interactions between the Dy moments result in a ground state configuration for each tetrahedron consisting of two spins pointing in and two pointing out. The statistical mechanics of this arrangement are analogous to that of proton arrangement in water ice, where each oxygen has two covalently bonded and two hydrogen bonded protons. The elementary magnetic excitations consist of a single spin flip which results in two neighbouring tetrahedra having 3 spins in and three spins out respectively, creating an effective dipole with a pole in each of them. These spin flips can then move away from each other with zero energy

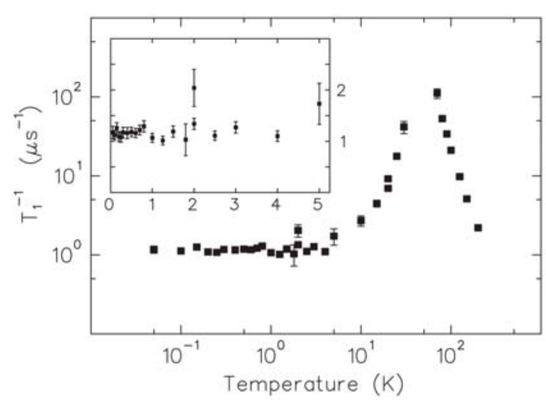

Figure 3: Muon spin relaxation rate in spin ice Dy2Ti2O7. The low temperature behaviour of $1/T_1$ is shown in an expanded linear scale in the inset [3].

cost, giving deconfined monopoles. A µSR study using pulsed muons claimed a direct detection of these deconfined monopoles, but Dunsiger et al. combined weak transverse field and longitudinal field µSR measurements to demonstrate that the direct observation of monopoles by µSR is impossible in principle, and that the measurements in the previously reported work reflected muons landing in the sample holder, rather than the $Dy_2Ti_2O_7$ sample under study [3]. Dunsiger et al. found that $Dy_2Ti_2O_7$ exhibited temperature independent spin fluctuations, which dominate any possible monopole signatures.

Fujihala et al. studied $Fe_2(OH)_3Cl$ [4] and Hagihala et al. studied $Co_2(OH)_3Br$ [5] where the magnetic ions lie on alternating triangular and kagome planes. These systems are strongly frustrated, although both compounds undergo magnetic ordering below 10K. In both systems strong fluctuations, detected by LF-µSR, persist to very low temperatures; an example of persistent spin dynamics, a still to be understood hallmark of frustrated magnetic systems. Zig-zag magnetic chains exhibit strong frustration due to the competition between nearest and next-nearest neighbour interactions. Ofer et al. studied the evolution of incommensurate spin density wave order with charge doping in $Na_xCa_{1-x}V_2O_4$ as the system varies from metallic (NaV_2O_4) to insulating (CaV_2O_4) [6] (see Figure 4). They found that a critical concentration, x_c, separated the insulating and metallic phases which possessed different magnetic ordering behaviour on the different sides of x_c. In a second study, Ofer et al. studied a series of zig-zag compounds EuL_2O_4 where L is the lanthanide Yb, Lu, Gd or Eu [7]. They found an evolution of the magnetic ground state from static antiferromagnetism to incommensurate spin-density-wave to a dynamic phase as the size of the lanthanide moment varies from 0 (Lu) to the largest value, giving maximum frustration.

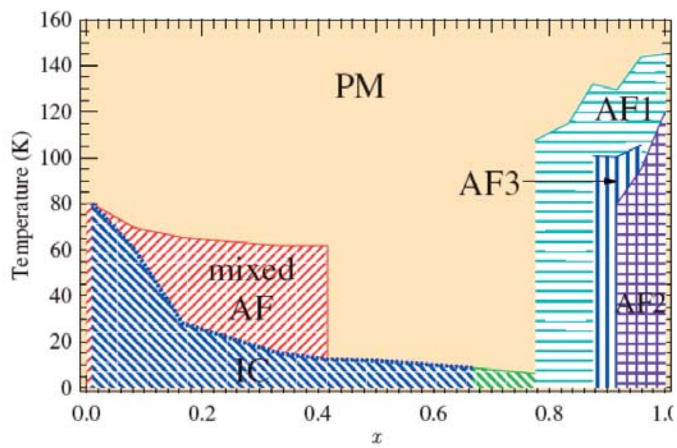

Figure 4: The phase diagram of $NaxCa_1{-}xV2O_4$. PM: paramagnetic, AF: antirerromagnetic, and IC: incommensurate [2].

Low Dimensional Magnetic Systems

Low dimensional quantum magnets are of great interest due to the rich collection of behaviour they exhibit. Tsujimoto et al. reported the synthesis and magnetic properties of the two-dimensional quantum isostructural antiferromagnets $(CuBr)A_2B_3O_{10}$ (A = Ca, Sr, Ba, Pb; B = Nb, Ta) which exhibit a 1/3 plateau in their magnetization whose stability is largely controlled by the A ion size [8]. Using µSR, they were able to identify two distinct phase transitions seen in specific heat as having magnetic and structural origins respectively. Uemura et al. studied the related $Cu(Cl,Br)La(Nb,Ta)_2O_7$ system and found that changing the Br concentration changed the ordering temperature without changing the size of the ordered moment and that the evolution of the system from a non-magnetic spin-gap state to one with magnetic order is associated with phase separation and/or a first order phase transition [9].

Magnetic Coordination Polymers

Coordination polymers are inorganic structures with metal cation centres connected by ligands forming an array. They are of great interest because of their potential for a variety of applications including molecular storage, optical materials and as sensors. Leznoff et al. have synthesized a variety of coordination polymers (see Figure 5) containing magnetic ions and have used ZF-µSR to study the effects of varying the metal cation and geometrical frustration on their magnetic properties [10,11].

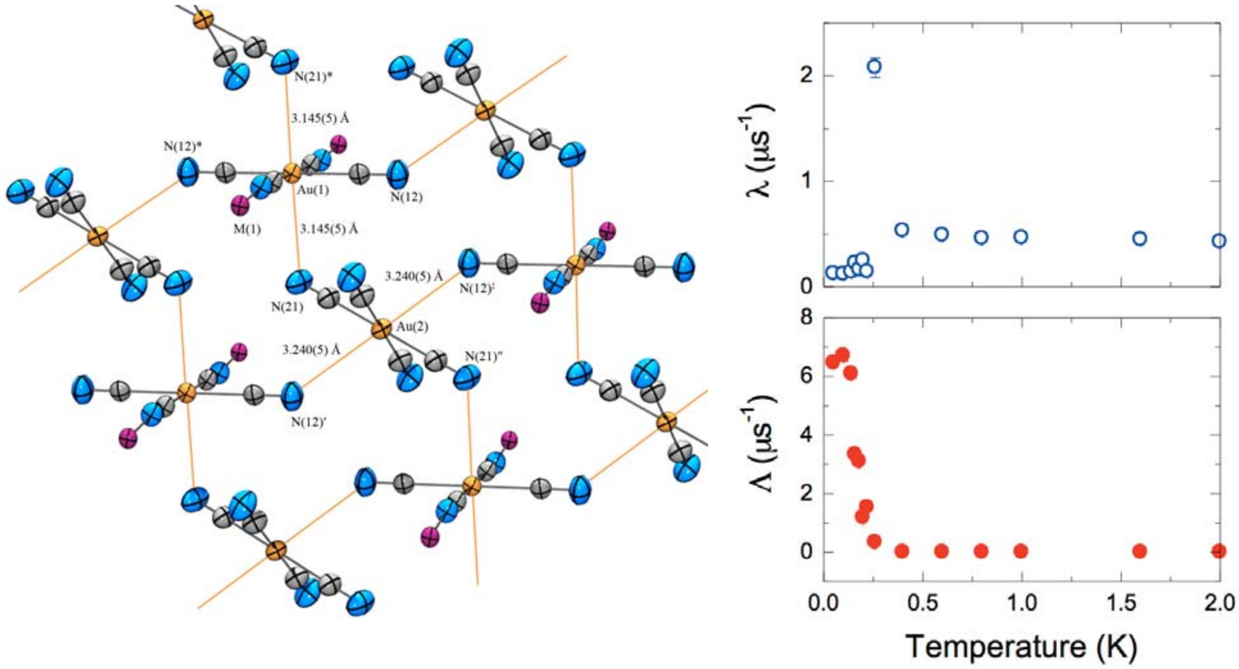

Figure 5: The $Co(H_2O)_4[Au(CN)_4]_2{\cdot}4H_2O$ coordination polymer consists of octahedrally coordinated metal centres with four equatorial water molecules and trans-axial $[Au(CN)_4]$– nitriles, generating a 1D linear rod of $M(H_2O)_4[Au(CN)_4]$-units. Only weak antiferromagnetic interactions along the rods are mediated by the $[Au(CN)_4]$-units. However, zero field µSR measurements indicate that there are also weak interchain interactions that yield a phase transition to a spin-frozen magnetic state below 0.26 K [11].

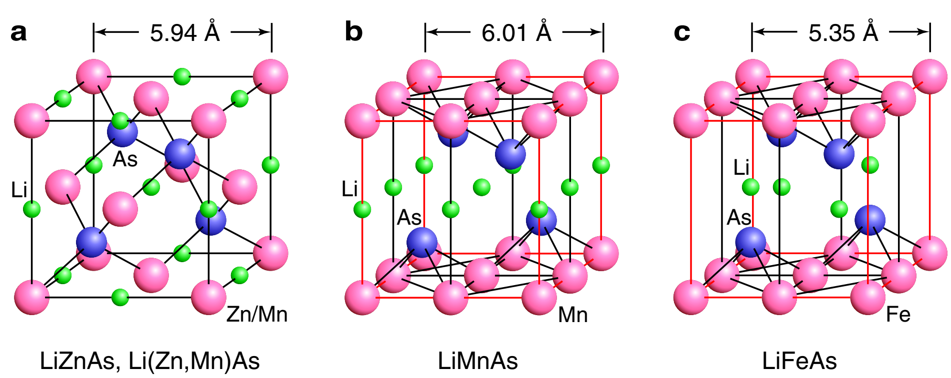

Figure 6: Crystal structures of cubic Li(Zn,Mn)As (ferromagnet), tetragonal LiMnAs (antiferromagnet) and tetragonal LiFeAs (superconductor) [12].

Magnetic Semiconductors

Ferromagnetic systems created by doping transition metals into semiconductors have received considerable interest due to their potential use in spintronics devices. The limited solubility of divalent Mn atoms into trivalent Ga or In sites in (Ga,Mn)As and (In,Mn)As has resulted in these systems being chemically metastable and only available in thin film form. Deng et al. synthesized a new generation ferromagnet Li(Zn,Mn)As based on the I-II-V semiconductor LiZnAs where the isovalent magnetic (Zn,Mn) substitution is decoupled from the carrier doping achieved with excess/deficient Li concentrations [12] (see Figure 6). Deng and collaborators used ZF-µSR and magnetization to detect and study the presence of ferromagnetism with critical temperatures as high as 50K. This ferromagnetic system contains square planar As layers, in common with antiferromagnetic LiMnAs and superconducting LiFeAs, which could lead to the development of new devices based on epitaxial junctions between these different compounds.

Materials for Battery Applications

The diffusion of Li^+ ions in solids is the underlying process in the operation of Li-ion batteries that are of enormous technological and economic interest. However, the diffusion coefficient of Li^+ ions (D_{Li}) has not been reliably determined for positive electrode materials because the most common technique for measuring D_{Li}, i.e. Li-7-NMR, is known to be unsuitable for materials that contain magnetic ions, due to the magnetic contribution to spin-lattice relaxation processes. Muons do not feel fluctuating magnetic moments at high temperature, but instead sense the change in nuclear dipole field due to Li diffusion. Even if magnetic moments still affect the muon-spin depolarization rate, such an effect can be distinguished by the application of a weak longitudinal field that decouples the magnetic and nuclear dipole interactions.

Sugiyama et al. have performed a series of studies of the magnetic and diffusive properties of a number of battery materials, starting with Li_xCoO_2 [13]. $LiFePO_4$ has many advantages as a practical battery material including high capacity and high stability during lithium extraction. Using ZF-μSR, they found antiferromagnetic order below $T_N = 52$ K in $LiFePO_4$ and by examining the temperature dependence of the field fluctuation rate they were able to determine $D_{Li} = 3.6\times10^{-10}$ cm^2/s at 300 K [14] (see Figure 7). Sugiyama et al. extended this study to other members of the $LiMPO_4$ family with M = Mn, Co and Ni, obtaining Li^+ diffusion rates for the M = Co, Ni versions [15].

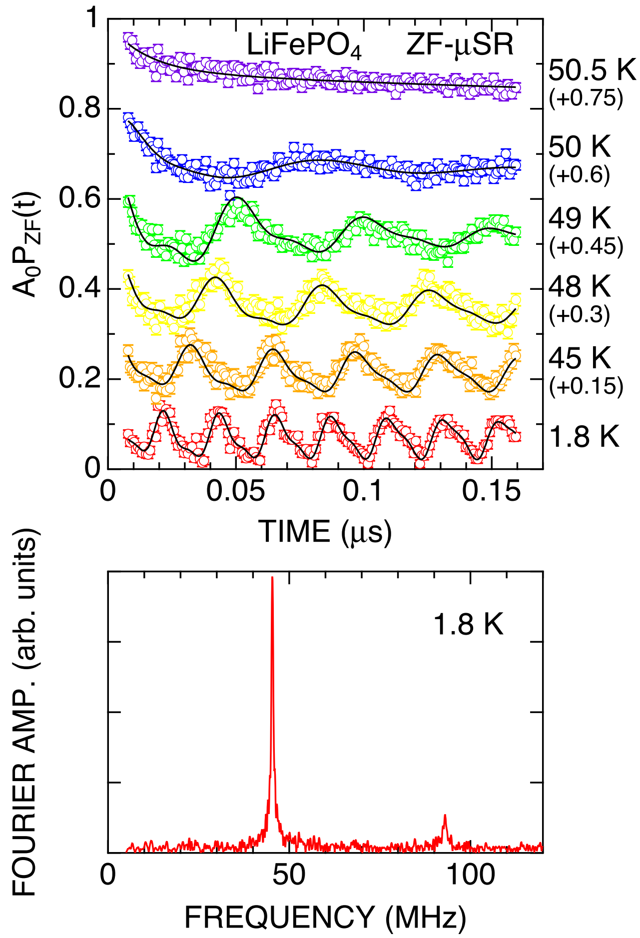

Figure 7: Temperature dependence of ZF-μSR spectra, showing precession in the spontaneous internal magnetic field and (bottom) Fourier transform of the time spectra measured at 1.8K [14].

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4.2.4.3 SUPERCONDUCTIVITY

Superconductivity is at the forefront of modern condensed-matter physics and materials science. A steady stream of newly discovered superconductors over the past 25 years has fuelled continual interest in this fundamental, yet partially understood phenomenon. Over the past five years alone, the first evidence for the existence of topological superconductivity has emerged, and high-temperature superconductivity has been discovered in a variety of iron-based compounds. High-temperature superconductors have garnered considerable attention, as they offer a myriad of potential applications. Yet the microscopic mechanism(s) responsible for zero electrical resistance and perfect diamagnetism in these materials remains elusive. There are also numerous exotic low-temperature superconductors that defy understanding.

Condensed matter physics theorists have put forth various proposals for both mechanisms of superconductivity and competing phases, which are based on approximate calculations. Most often these calculations are guided by input from experiments that also serve the purpose of validating the theories. The μSR technique has provided some unique insight into the role of magnetism in numerous novel superconductors, and has been widely used to investigate the local response of superconductors to an applied magnetic field.

Search for Loop-Current Order

A distinctive feature of high-temperature cuprate superconductors is the so-called "pseudogap" phase (see Figure 8), which exists at temperatures above the superconducting transition temperature (T_c) and over a wide range of doping (*p*). Prominent theories attribute the pseudogap phase to a "hidden order", and in particular a time-reversal symmetry breaking phase characterized by ordered circulating orbital currents, which either breaks or preserves translational symmetry. The theoretical predictions have been bolstered by the finding, in polarized neutron diffraction studies, of unusual translational-symmetry breaking and preserving weak magnetic orders in the pseudogap region. While the observed magnetic orders bear some resemblance to the theoretical models, unlike μSR, the neutron diffraction method does not provide information on the magnetic volume fraction.

In recent years, sensitive ZF-μSR experiments have been carried out at TRIUMF to investigate the possible occurrence of weak orbital-like magnetic order in the mysterious pseudogap region. Two independent μSR studies of $La_{2-x}Sr_xCuO_4$ show no evidence for magnetic order of any kind [1,2]. On the other hand, μSR measurements on high-quality $YBa_2Cu_3O_y$ single crystals indicate the presence of magnetism compatible with the translational-symmetry breaking magnetic order detected by neutron diffraction [3]. However, the μSR study shows that this magnetic order does not evolve with doping and, consequently, is unrelated to the pseudogap. Measurements on one of the samples studied by polarized neutron diffraction revealed a second kind of magnetic order, with characteristics in quantitative agreement with the translational-symmetry preserving magnetic order detected by neutrons (see Figure 9). However, the ZF-μSR measurements clearly show that this form

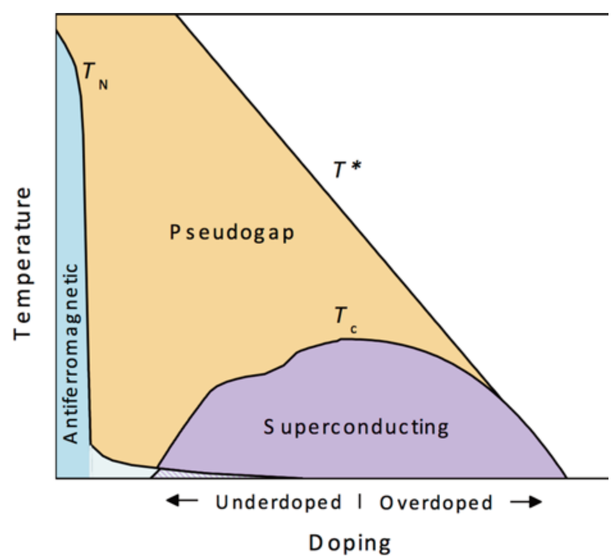

Figure 8: Generic phase diagram of cuprates. The undoped material is an antiferromagnetic insulator. The doping of holes in the CuO_2 layers destroys the antiferromagnetic phase, ultimately giving rise to a high-temperature superconducting state. Further doping eventually destroys superconductivity. Above the superconducting transition temperature (Tc) there is a highly anomalous "normal" state containing a so-called "pseudogap" phase. The pseudogap is believed to be either a precursor to superconductivity or a manifestation of a competing order.the relaxation rate Δ of the μSR signal at zero field [34].

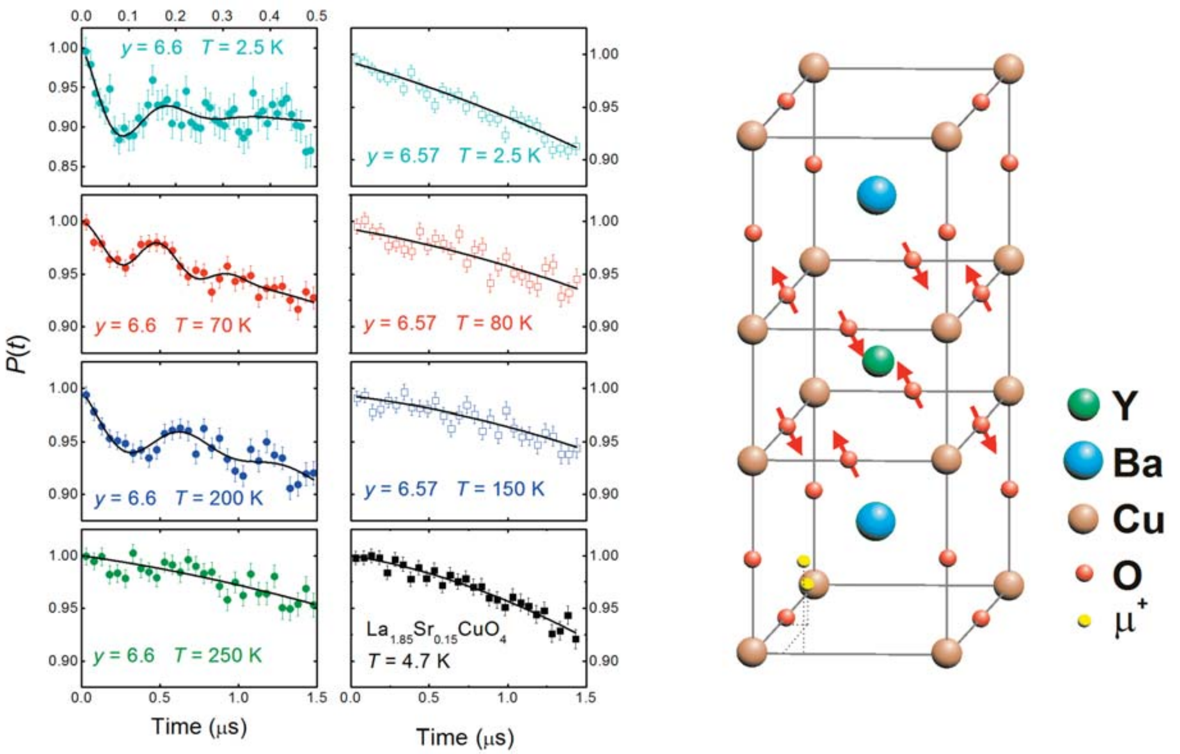

Figure 9: Search for loop-current order in the pseudogap phase of YBa_2Cu_3Oy by ZF-μSR. A coherent oscillation indicative of magnetic order is observed only in a $YBa_2Cu_3O6.6$ single crystal, which was previously identified as containing an unusual magnetic order by polarized neutrons scattering. However, as a local probe, the ZF-μSR measurements reveal that the magnetic order is present in only 3% of the sample, and can be explained by an impurity phase with local magnetic moments on the oxygen atoms in the CuO_2 layers [18].

of magnetic order exists in only about 3% of the sample, and hence is likely associated with an impurity phase. At present the evidence of absence of loop-current order from the μSR experiments is supported by nuclear magnetic resonance studies, but the issue is far from settled.

Magnetism Related to Superconductivity

Many exotic superconductors including high-T_c cuprates, iron pnictides, organics and heavy fermion systems have competing adjacent magnetic states, which has promoted pictures where the superconducting pairing is mediated by spin fluctuations. Carlo et al. combined μSR with magnetic susceptibility measurements to create a new magnetic phase diagram of $Ca_{2-x}Sr_xRuO_4$, which is a p-wave superconductor for the x=2 end-member [4]. They demonstrated that superconductivity in Sr_2RuO_4 occurs in close proximity to competing static magnetic order, providing strong evidence for the importance of spin fluctuations for superconductivity in this system.

Iron-Based Superconductors

Over the past five years, μSR has been widely applied to the study of recently discovered iron-based materials, which potentially offer a new path to room-temperature superconductivity. Superconductivity in these compounds is achieved by chemical doping of a magnetically ordered parent compound (similar to cuprates), and there is now strong evidence that Cooper pairing in the superconducting state is mediated by spin fluctuations. To date, the primary issues have been the symmetry of the superconducting order parameter, and the role magnetism plays in the pairing mechanism.

Shortly after the discovery of high-temperature superconductivity in iron-arsenic based compounds, and in parallel with μSR studies elsewhere, experiments at TRIUMF demonstrated the coexistence of macroscopically separated superconducting and magnetic phases for a certain range of chemical doping [5-9]. The temperature and magnetic-field dependences of the superconducting carrier density were also investigated via measurements of the transverse-field μSR line width [10-13] (see Figure 10). These studies contributed to the early understanding of the temperature-versus-doping phase diagram of iron-arsenic compounds, and placed limits on the possible symmetry of the superconducting order parameter.

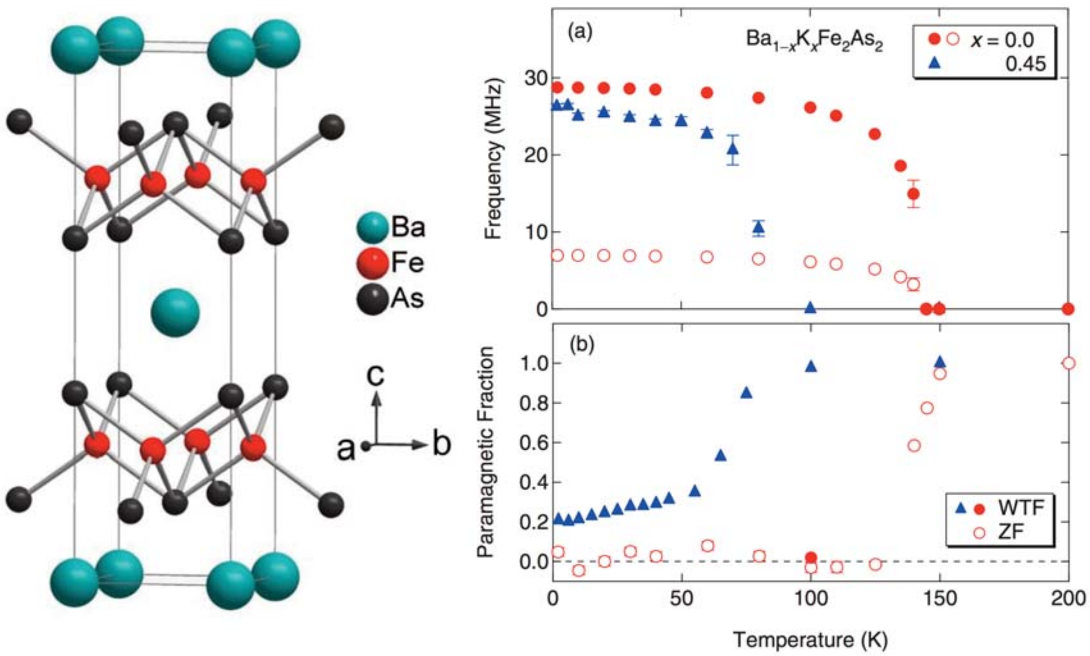

Figure 10: Magnetism and superconductivity in an iron based high-temperature superconductor [58]. An early μSR study of the hole-doped iron arsenide $Ba_{1-x}K_xFe_2As_2$ shows the coexistence of phase-separated static magnetic order and nonmagnetic/superconducting regions. The latter is indicated here by the finite paramagnetic fraction [21].

Inhomogeneous Magnetic-Field Response of the Normal State

In recent years the unique high-magnetic-field μSR capabilities of TRIUMF have been used to investigate the normal state of high-T_c cuprate superconductors. These studies have revealed an unexpected field-enhanced inhomogeneous line broadening persisting to temperatures high above T_c. Such measurements on heavily overdoped $La_{2-x}Sr_xCuO_4$ (see Figure 11) are dominated by an unusual Curie-like paramagnetism that grows with increased doping of charge carriers [14]. Recently it has been shown that this paramagnetic contribution to the μSR detected distribution of internal magnetic field extends back into the underdoped regime, and also decreases beyond the superconducting "dome" in the temperature-versus-doping phase diagram [15]. These findings suggest that the paramagnetic component is caused by holes progressively entering the Cu ,$3d_{x^2-y^2}$ orbitals with increased doping.

In $YBa_2Cu_3O_y$ the normal-state inhomogeneous field response is observed to track T_c, indicating that the origin of the inhomogeneity is related to superconductivity [16,17]. This and other trends of the data can be explained by superconducting fluctuations that vanish inhomogeneously with increased temperature. While there is evidence for superconducting fluctuations persisting above T_c from other techniques, there is no consensus on the temperature and magnetic field range over which they persist. The μSR experiments on $YBa_2Cu_3O_y$ provide evidence that superconducting fluctuations survive to higher temperatures than revealed by other methods, presumably reflecting the sensitivity of the muon. Furthermore, thus far only the μSR

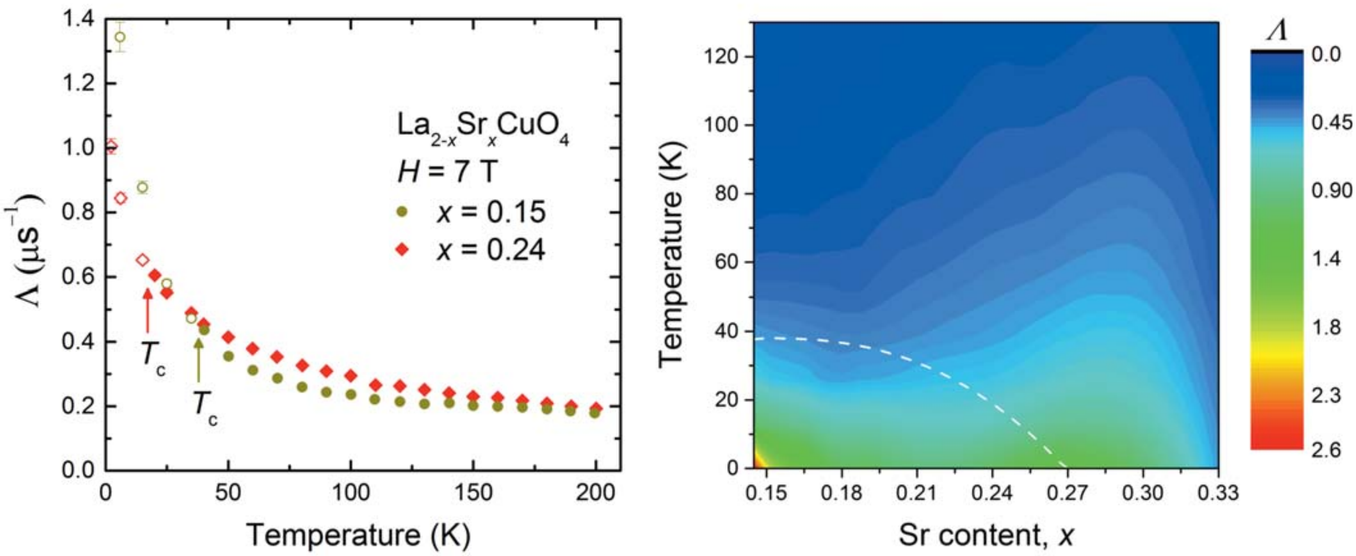

Figure 11: Inhomogeneous magnetic-field response of a high-temperature cuprate superconductor. The relaxation rate of the μSR signal (Λ) of $La_{2-x}SrxCuO_4$ induced by an applied magnetic field exhibits an unexpected temperature dependence above Tc (In the temperature-versus-x phase diagram, Tc is indicated by the white dashed curve). The finite relaxation rate above Tc is indicative of a distribution of internal magnetic fields, which appears to originate from paramagnetic moments and fluctuation superconductivity [30].

results on $YBa_2Cu_3O_y$ have found evidence for fluctuation superconductivity being spatially inhomogeneous in the bulk. Ongoing studies of this kind are aimed at determining whether inhomogeneous superconducting correlations at temperatures above T_c are a universal property of cuprates.

Heavy Fermion Superconductors

Heavy fermion compounds are metallic systems having electronic effective masses that exceed the mass of the free electron by up two orders of magnitude. This is due to the interaction of the conduction electrons with localized f-electrons. One of the most fascinating and mysterious phenomenon that occurs in some of these materials is superconductivity. This is because localized f-electron magnetic moments are intrinsically harmful to the formation of a superconducting state.

As the only known Pr-based heavy-fermion superconductor, there has been a great deal of attention focused on $PrOs_4Sb_{12}$. Measurements of the magnetic-field response of the superconducting state of $PrOs_4Sb_{12}$ by μSR at TRIUMF indicate that there is a complete energy gap that forms at the Fermi surface [18]. Moreover, the results are most compatible with the occurrence of two energy gaps on distinct Fermi surfaces, lending support to a body of evidence for multi-band superconductivity in this compound. The superconducting phase of pure $PrOs_4Sb_{12}$ at zero field is accompanied by the onset of a spontaneous static local magnetic field (revealed by ZF-μSR), indicative of a state that breaks time reversal symmetry (TRS). The occurrence of TRS-breaking places significant constraints on the pairing symmetry of the superconducting state. More recently, broken TRS has been investigated in the superconducting state of the $Pr(Os_{1-x}Ru_x)_4Sb_{12}$ and $Pr_{1-y}La_yOs_4Sb_{12}$ alloy systems by ZF-μSR [19]. This study shows that Ru doping is very efficient in suppressing TRS-breaking, whereas La doping is less so (see Figure 12). The results provide evidence for superconductivity mediated by itinerant crystal electric field excitations.

An interesting occurrence of the interplay between magnetism and superconductivity has been revealed in $CeCoIn_5$. Although there is no static magnetism in $CeCoIn_5$ at zero magnetic field, a μSR study at high magnetic field and low temperature has provided clear evidence for field induced magnetism [20]. This result, which has been confirmed by NMR and neutron scattering experiments, provided initial support for a theoretically predicted coupled superconducting and antiferromagnetically ordered phase transition. However, the origin of this high-field-low-temperature state is a matter of current debate and investigation.

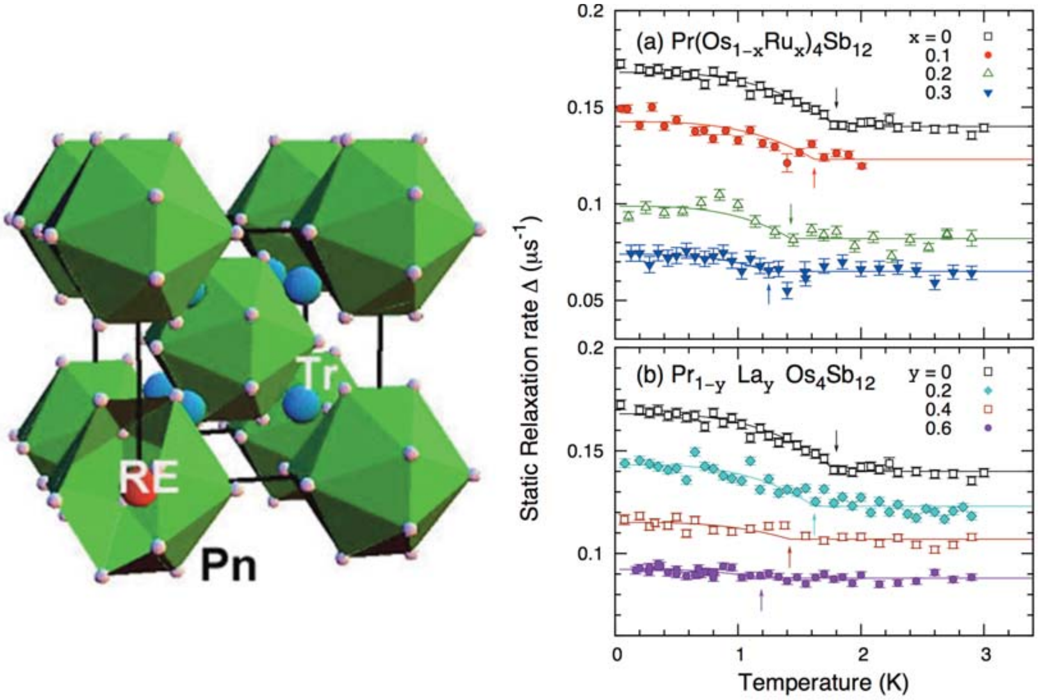

Figure 12: Effect of impurity doping on broken TRS in the superconducting state of PrOs4Sb12.The Ru or La ions substitute for the Os ions (blue spheres in the image). 12 Sb ions surround each Pr ion (red sphere). Broken TRS is signified by the onset of spontaneous magnetism, which enhances the relaxation rate Δ of the μSR signal at zero field [34].

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4.2.4.4 MUON CHEMISTRY

The muon chemistry program has been a part of the research enterprise at TRIUMF since the beginning, with the first chemistry paper published in 1978 on the subject of the Mu + F_2 chemical reaction rate in the gas phase. This program soon evolved into reaction rate studies in other environments, including pioneering work on the identification and molecular dynamics of muoniated transient free radicals, most of which cannot be identified by the long-standing technique of electron paramagnetic resonance (EPR). The μSR chemistry programs at CMMS are unique in the world.

Kinetic Isotope Effects in Chemical Reactivity

Low field TF-μSR is routinely used to measure the reaction rates of Mu with a variety of reaction partners and under a wide range of conditions. The μ^+ stop in a sample that is mounted in a weak transverse magnetic field (~ 5 G), which causes the muon spin in Mu to precess at a characteristic Larmor frequency of ~1.4 MHz G^{-1}, which is approximately 100 times faster than the precession of diamagnetic muons. The pseudo-first-order reaction rate of Mu is determined from the damping of the Mu precession signal. A large number of chemical reactions have been studied at TRIUMF over the years and these studies have provided unique information about the effect of isotopic substitution, which in turn provides insight into the electronic properties of the reacting molecules.

A recent landmark study has looked at isotope effects on the simplest and most fundamental chemical reaction: the H + H_2 abstraction reaction. H and D atoms differ by only a factor of two in mass so they don't generally give rise to large isotope effects and they are also difficult to produce, while tritium is rarely used because it is dangerously radioactive. It has thus fallen to muon science to extend the experimental H atom isotopic mass scale, first to Mu, the lightest isotope of hydrogen, with a mass of 0.113 amu, and recently to muonic helium (^{4}Heμ), the heaviest isotope, with a mass of 4.11 amu, where the negative muon is captured by the helium atom and effectively "disguises" it as heavy H. It is now possible to compare isotopic mass effects in the chemical reactivity over a heretofore unprecedented factor of 36 in atomic mass. The Mu +H_2 and ^{4}Heμ +H_2 reactions were studied at TRIUMF and a comparison between the experimental reaction rates and those predicted by fully rigorous quantum calculations are shown in Figure 13 [1,2]. The fact that the Mu +H_2 reaction is so much slower than the ^{4}Heμ +H_2 reaction indicates the dominance of zero-point energy effects over quantum tunnelling and the quantitative agreement seen between quantum theory and experiment over the full temperature range of both data sets and over a remarkable range of a factor of 36 in isotopic mass is totally unprecedented and is the most definitive example of the utility of TRIUMF's muon beams in testing reaction rate theory. This is in fact the only reaction, still today, where the underlying potential energy surface is so accurate that such experimental tests are even possible.

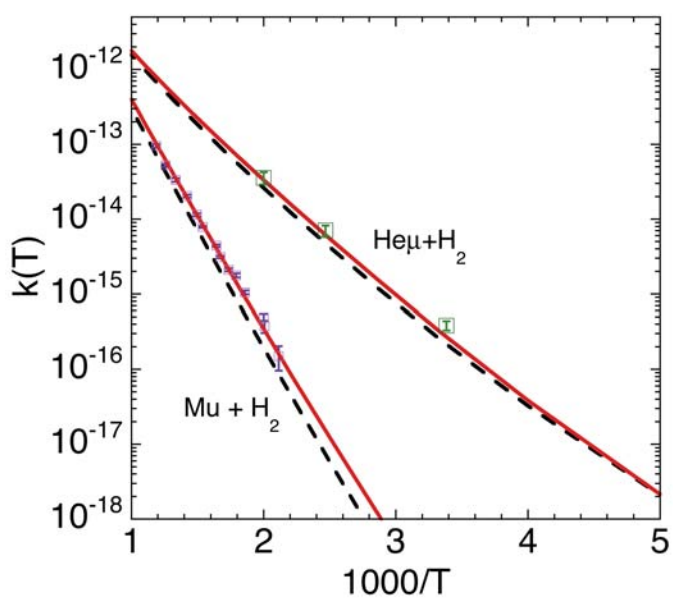

Figure 13: Muonic helium can be considered to be a super-heavy H isotope because the μ− shields the charge of the nucleus. The measured reaction rates, shown in the above Arrhenius plot, are in quantitative agreement with fully rigorous quantum calculations and indicate that zero-pointenergy effects dominate over quantum tunnelling in the abstraction reactions [36].

Chemical Reactions in Extreme Environments

Canada is part of the Generation IV International Forum (GIF), which is a consortium of nations that have agreed to collaborate on research and development in support of the next generation of nuclear power systems. Experiments have been performed at TRIUMF in order to assist in the development of Supercritical-Water-Cooled Reactors (SCWRs). Existing pressurized water-cooled nuclear reactors (PWRs) operate at lower temperatures than a SCWR, and a major technology gap identified by the GIF is radiolysis and water chemistry under supercritical conditions. Accurate modelling of aqueous chemistry in the heat transport systems of pressured-water reactors requires data on the rate constants of reactions involved in the radiolysis of water and the action of water treatment additives (e.g., those used to suppress corrosion or the production of hydrogen). Unfortunately, most experimental data do not even extend to the temperatures used in current PWRs, typically around 600 K. Clearly, this is well short of the supercritical conditions (675–925 K) required by Generation IV designs. The data can be described empirically but with unphysical parameters such as negative activation energies. Given the higher temperatures envisaged in a SCWR, it would be dangerous to rely on extrapolation of data from the subcritical regime. Thus measurements of rate constants up to at least 875 K are needed.

It is technically very difficult to make direct kinetics measurements on reactive intermediates in superheated water but muon spin spectroscopy is well suited to study samples under extreme conditions, and TRIUMF researchers have many years of experience at studying muonium chemistry in water up to 725 K. Over the past decade a collaboration of researchers from Simon Fraser University and Mount Allison University have detected and characterized muonium in water from ambient conditions to supercritical, and measured the decay of the Mu signal in dilute aqueous solutions, thereby determining the rate constants for various muonium reactions. A common feature of the results is that Mu rate constants initially increase with temperature (the expected behaviour) but then go through a maximum, only to rise again at still higher temperatures. Given the similar behaviour for different types of reactions it was concluded that a key factor in the unusual temperature dependence seen is a “cage effect”, namely the number of collisions between a pair of reactants over the duration of their encounter. The model for Mu reaction kinetics may be extended to the reactions of other radiolysis transients, such as the ·OH radical because the behaviour is characteristic of the solvent and depends only weakly on the nature of the reactants.

A good example where the simplicity inherent in Mu chemistry is an advantage is the controversy surrounding the importance of the $H + H_2O \rightarrow H_2 + \cdot OH$ reaction in the radiolysis of water (see Figure 14). Although very slow at low temperature, this reaction is a source of molecular hydrogen at high temperature, which is important because H_2 is added to the coolant in existing pressured-water reactors (including the CANDU models) to suppress O_2 production. Even if a different control strategy is used in the SCWR it will be necessary to model the H_2 yield as a function of temperature and density, both as a test of model accuracy and to produce data for input to other areas of the Generation IV project (safety and corrosion). Thus, determination of the rate constant for $H + H_2O$ is a high priority. Conventional radiolysis methods can only approach this problem via the rate of the reverse reaction, $\cdot OH + H_2$, and the equilibrium constant. Given the uncertainty in details such as the solvation energies of the transients under a variety of thermodynamic conditions, it is not surprising that there is disagreement on estimates of the rate constant for the forward reaction, $H + H_2O$. It can be measured directly for Mu. A preliminary analysis of TRIUMF results suggests that the competing reaction may be dominant below 575 K.

Probing the Structure and Dynamics of Free Radicals

Free radicals are species with unpaired electrons, which frequently makes them highly reactive and difficult to study. Moreover, they are often short-lived intermediates in chemical reactions, and it is necessary to determine their structure, dynamics and reactivity in order to fully understand the reactions in which they are involved (see Figure 15). The high reactivity of free radicals makes them difficult to study with most conventional spectroscopic techniques, including the principal method of electron paramagnetic resonance (EPR). EPR studies are frequently limited to conditions where the radicals are immobile. In contrast, muoniated radicals can be formed with high spin polarizations as a result of Mu addition reactions to

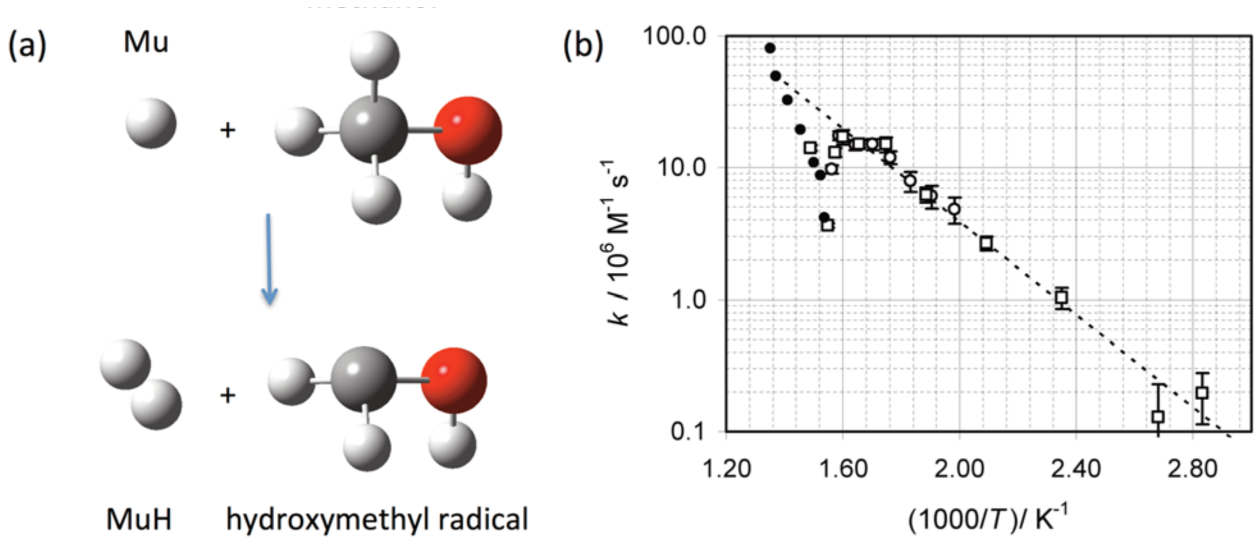

Figure 14: (a) The reaction of Mu with methanol proceeds by Mu abstracting an H from the methyl group of methanol (b) Arrhenius plot of the rate constant for the reaction of Mu with methanol in water. The rate constants deviate significantly from the Arrhenius behaviour (dotted line) near the critical point.

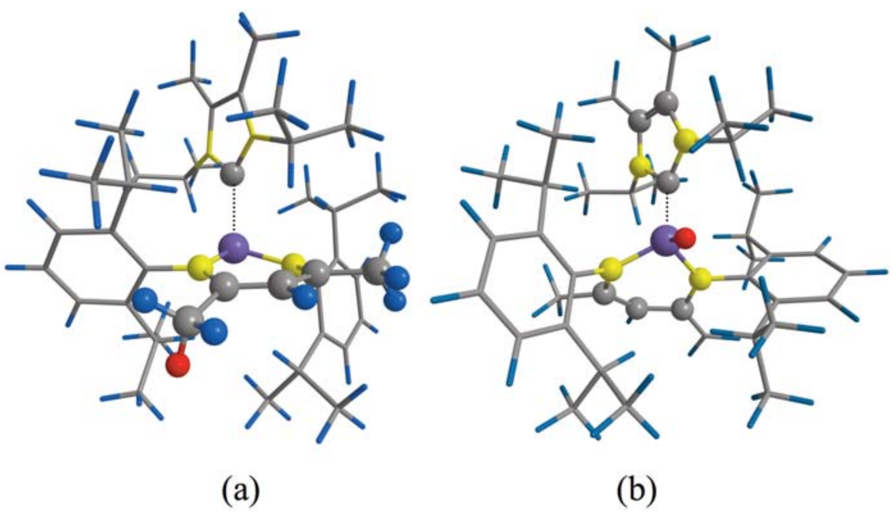

Figure 15: Muonium is an excellent, unbiased probe of reactivity, and using muon spin spectroscopy makes it possible to identify the site of Mu addition in quite complicated molecules. Two distinct free radicals were detected as a result of muonium addition to a silylene-carbene complex (Si violet, N yellow, C gray, H blue, Mu red) [42].

unsaturated bond systems in any environment and their time dependence studied. There are huge advantages in muon spin labelling over traditional labelling techniques and characterization using EPR spectroscopy.

As in EPR, the structure of muoniated radicals is inferred from the hyperfine coupling constants (hfccs), which map out the distribution of the unpaired electron. The magnitude and sign of the hfcc can provide information about the three-dimensional structure. Every muoniated radical has one muon hfcc but as many nuclear hfccs as there are different nuclei (mainly protons) in the radical, although in practice it is often not possible to observe all of them. The muon hfcc (A_μ) can be measured by TF-μSR or μLCR if the radical is undergoing anisotropic motion and the nuclear hfccs (A_X) are measured using μLCR.

Hundreds of organic muoniated radicals have now been studied with the work performed on muoniated radicals over the last five years focused on determining the structure of main group and inorganic radicals. The structure is interesting in its own right but also provides information about how inorganic molecules react with Mu, and by inference H, the simplest free radical. There has also been a considerable amount of work on studying muoniated organic radicals in complex environments such as zeolites or in experimentally challenging environments such as supercritical water.

Novel Main Group Muoniated Radicals

An active area of research at TRIUMF is the study of the reaction of Mu with molecules containing Group 14 atoms (the column in the periodic table from carbon to lead) and the determination of the structure of the resulting radicals. The Percival-West collaboration has studied the radical produced by the reaction of Mu with silylenes and germylenes, which are heavier analogs of carbenes [3,4]. These molecules contain a divalent electron deficient Group 14 atom and are generally highly reactive. This work is unique in that no other groups have been able to study the reactions between such highly reactive species.

Percival and West found that in silylenes with small substituents on the nitrogen atoms, the initial silicon-centred a-muoniated radical, which was formed by Mu addition to the silylene and has Mu attached directly to the radical centre, reacts rapidly with another silylene to give a secondary α-muoniated, where Mu is attached to a silicon atom that is adjacent to the radical centre [5]. This reaction was done by obtaining TF-μSR spectra of a mixture of two silylenes and observing that four types of radicals were formed by the coupling reaction. Silicon-centred α-muoniated radicals could be observed with sterically hindering groups on the nitrogen atoms to prevent dimerization [6]. Silylenes with tert-amyl and tert-octyl groups on nitrogen dimerized but the signal amplitude decreased due to the larger substituent groups on the silylenes slowing down the coupling reaction. The silicon-centred a-muoniated radicals have large A_μ values and this indicates the Si − Mu bond is oriented almost perpendicular to the ring. The Percival and West collaboration has gone on to study more complex silylenes with the results providing unique information about the reactivity of silylenes towards what is arguably the simplest free radical [7].

Experiments on germylenes have shown that Mu adds preferentially to the germanium atom to give a germanium-centred α-muoniated radical in which the germanium atom has a roughly tetrahedral configuration and that there is no dimerization as in the silylenes [3]. Percival and West have also studied muoniated radicals produced by Mu addition to silene (Si=C) bonds [4]. In some silenes Mu was observed to add to both sides of the Si=C bond while in others only addition at the carbon atom was observed. Further work is needed to determine what factors affect the reactivity of the Si=C bond.

Muoniated Radicals in Zeolites–Templates for Catalysis

Zeolites are basically aluminosilicate frameworks that have an ubiquitous presence in chemical industry due to their porous structure, both as molecular sieves and as heterogeneous catalysts, particularly in the petrochemical industry. Important in the latter case are the Y-faujasites (NaY, HY and USY) that consist of "supercages" (SC) with pore sizes of ~13 Å diameter and which are linked together by "windows" of mainly Si and bridging O atoms that have diameters of ~7.5 Å. Fairly large molecules like benzene (C_6H_6) can easily pass through these windows and reside at specific binding sites within the supercages. Though utilized by industry for many years, the understanding of the mechanisms of zeolite catalysis is still at a fairly rudimentary level. It is believed that protonation reactions involving H^+ transfer to adsorbed "guest" molecules in acidic "host" frameworks are important, but even so there is rather little detailed experimental evidence in support of this claim. Another possibility is H-atom transfer reactions to guest molecules for which there is even less evidence in the literature, partly because of the difficulty of identifying transient radicals by EPR in the geometric confines of zeolite frameworks and the limitations of studying the radicals far from the catalytically relevant temperature regime. This has prompted studies at TRIUMF by the Fleming group of Mu-substituted free radicals by the μLCR technique, as a "template" for their H-atom analogs, exemplified by recent studies of the muoniated ethyl and cyclohexadienyl radicals in NaY, HY and USY (see Figure 16). This is the first evidence of molecular dynamics of free radicals in catalytically important zeolites by *any* technique, and represents another uniquely important aspect of the muon chemistry program at TRIUMF.

This work can be exemplified by the muoniated cyclohexadienyl radical, which has been extensively studied in several zeolites [8]. mLCR studies of C_6H_6Mu radicals in NaY zeolite with loadings of 2-3 benzenes per SC found the radical in two different environments; bound to the Na^+ with Mu of the CHMu methylene group either pointing away (exo) or toward (endo) the SII Na cation, or adsorbed at the window sites between the SCs. The interaction with the Na cation gives rise to unprecedentedly large (~20%) shifts in

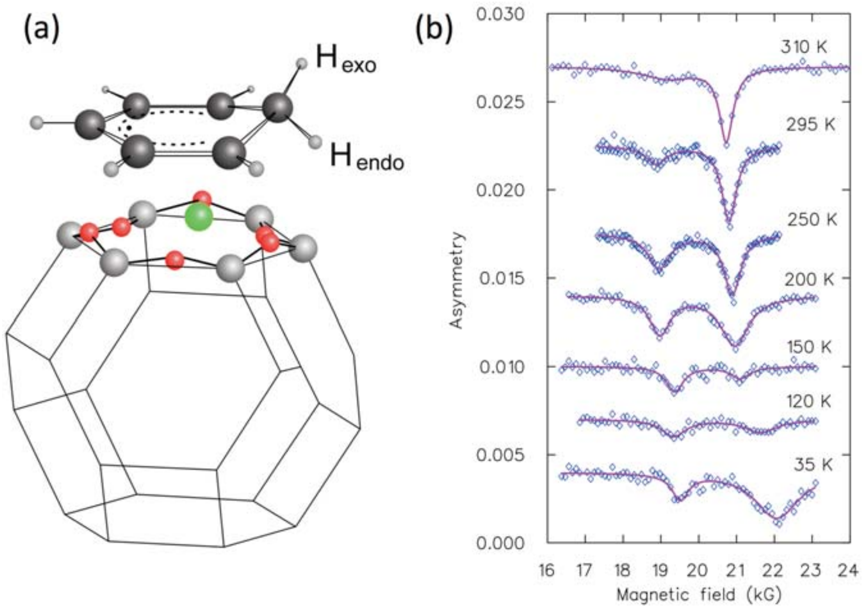

Figure 16: (a) Schematic diagram of the C_6H_6Mu radical interacting with the S_{II} cation in NaY (shown by the green circle), which causes distortion from planarity of the C-Mu bond above $_{(exo)}$ and below $_{(endo)}$ the plane, shown in the diagram as Hexo and Hendo, respectively. The Si atoms are shown by the light grey circles, with the O-atom bridges shown by the smaller red circles. Atom sizes are not to scale. (b) µLCR spectra over a range of temperatures for USY at a loading of 2 benzenes/SC. The disappearance of the low field resonance by broadening with increasing temperature indicates the onset of isotropic reorientation motion above 310 K [37].

hyperfine coupling constants, indicating that a strong bond is formed with the π electrons of the C_6H_6Mu radical. The endo and exo orientations of the C_6H_6Mu radical give rise to two different muon hfccs because coupling to the Na^+ distorts the cyclohexadienyl radical from planarity and causes the muon and the methylene proton to be inequivalent. The cyclohexadienyl radical is essentially frozen on the time scale of 50 ns, complexing the S_{II} Na^+, which is unlike the behaviour of the benzene molecule in NaY and other faujasites where there is clear evidence for rotation about the six-fold axis as well as long-range diffusion from H-2 NMR spectra. This has been explained by the electric dipolar interaction of the C_6H_6Mu radical with the zeolite framework. Anisotropic motion of the C_6H_6Mu radical is observed up to 470 K, but the radical remains bound to the cation site even at the highest temperature, independent of benzene loading. In contrast, studies of the C_6H_6Mu radical in HY and USY, which are used frequently as heterogeneous catalysts in the petrochemical industry, over a range of benzene loadings and temperatures, have revealed substantially different results to NaY. First, a pronounced loading dependence was observed. At a loading of 2 benzenes per SC in HY and USY the mLCR spectra of the C_6H_6Mu radical indicates it is in a polycrystalline environment over the whole temperature range studied, which includes data both above and below the bulk melting point of benzene. The magnitude and temperature dependence of the hfccs indicate that there is only a small amount of spin density transfer from the radical to OH binding sites with perhaps a slight distortion from planarity. Second, the mLCR spectra of C_6H_6Mu radicals in USY zeolite with loadings of 2 benzenes per SC indicate that the cyclohexadienyl radical undergoes isotropic reorientation above ~310 K, where guest-host interactions are most important. This is probably due to its desorption from OH binding sites and its random reorientation within the volume of the supercage. Very similar behaviour is seen at a loading of 4 benzenes per SC at higher temperatures, but an additional resonance is observed at low temperatures in USY with 4 benzenes per SC and this is believed to result from benzene in intergranular regions. In USY at a loading of 6 benzenes per SC benzene resides primarily in intergranular regions, where it exhibits almost pure bulk-like behaviour. In contrast to NaY, this loading dependence indicates the importance of guest-guest interactions.

Supercritical water (SCW) has attracted much attention in recent years because of its unique properties, such as low viscosity, low density, low polarity and the high solubility of organic compounds and its potential use as a green solvent. Studying free radicals in SCW is technically challenging due to the high temperature and pressure of the critical point (647 K, 221 bar). There are no reports of radicals in SCW using EPR and only one report of the observation of the triphenylmethyl radical in subcritical water (at 573 K) using EPR [9]. SCW is an ideal system to study using mSR because the m^+ can penetrate a thick-walled vessel required to withstand the high pressures and stop in the fluid sample and the high-energy emitted positrons, which convey the spectroscopic information, can also penetrate the walls and be detected outside the container.

Numerous muoniated free radicals have been observed in SCW over the last twelve years. The first radicals to be observed were the cyclohexadienyl radical and the tert-butyl radical. The success of this study was due to a thorough understanding of some unusual features of SCW. Benzene is only sparingly soluble in water under standard conditions, so it is impossible to obtain TF-μSR spectra of the C_6H_6Mu radical in aqueous solution at room temperature. Percival et al. were able to obtain TF-μSR spectra of the C_6H_6Mu radical in SCW because benzene is completely miscible with water at elevated temperatures and pressures. The magnitude and temperature dependence of the muon hfcc of the C_6H_6Mu radical provided information about the interactions between the radical and the surrounding solvent. The tert-butyl radical was produced by Mu addition to isobutene, which was produced in situ by the counter-intuitive dehydration reaction of tert-butanol in SCW.

The Percival group has shown that the structure of a molecule can be changed in SCW by studying the Mu adducts of acetone as a function of temperature. Acetone can tautomerize between the keto ($O{=}C(CH_3)_2$) and enol forms. The equilibrium constant for acetone at room temperature is firmly on the side of the keto form, with the enol content being approximately $6x10^{-7}$ %. Below ~520 K a single type of radical with a very small muon hfcc was observed. The magnitude of A_μ is consistent with the 2-muoxy-prop-2-yl ($MuO\text{-}\dot{C}(CH_3)_2$) radical, albeit with a small shift that is consistent with the difference in solvent properties for different concentrations of acetone. This indicates that the keto form of acetone dominates in this temperature regime. Above 520 K the muon hfcc of the observed radical is much larger than that of the 2-muoxy-prop-2-yl radical. The muon hfcc of the observed radical is about 250 MHz and falls with temperature, which is typical behaviour for a β-muoniated alkyl radical. The radical was assigned as the 1-Mu-2-hydroxy-2- propyl radical ($CH_3\dot{C}(OH)CH_2Mu$), which is formed by Mu addition to the enol form of acetone and indicates the equilibrium constant has changed dramatically in SCW.

Supercritical CO_2 ($scCO_2$) has been found to be a useful “green” solvent for a wide variety of chemical applications and the supercritical region (P_c = 7.38 MPa and T_c = 304.15 K) is technically much easier to generate than SCW. The mSR experiments on $scCO_2$ are unique because CO_2 has no hydrogen atoms, so it is not possible to produce reactive species like H and OH, which are needed to create neutral radicals. The first muoniated radical to be observed in $scCO_2$ was the muoniated ethyl radical ($MuH_2C\text{-}\dot{C}H_2$), which was produced by Mu addition to ethane [10]. The identity of this radical was confirmed by measuring the muon and proton hfccs using TF-mSR and ALC-mSR, respectively. The magnitude of the hfccs indicates that the $MuH_2C\text{-}\dot{C}H_2$ radical does not react with CO_2 as has been previously proposed. The temperature dependence of the hfccs may indicate clustering of the CO_2 molecules around the ethyl radical at some densities. Ghandi et al. studied the reaction of Mu with vinylidene fluoride in $scCO_2$ and found that small changes in the temperature and pressure near the critical point could result in large changes in the reaction rate [11].

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4.2.4.5 β-NMR

All electronic, magnetic and structural properties of a material are altered near a heterointerface between two dissimilar materials due to the broken translational symmetry and the delocalized nature of electrons such that the character of the electronic wavefunction extends from one material to the other. In some cases, these changes are small and confined to just a few atomic layers while in other situations, the character of the collective behaviour is modified over many nanometers or even microns. An important implication of this behaviour is that thin films and interfaces have unique properties that are distinct from the bulk. This is analogous to a molecule in chemistry where the molecular properties are determined by, but are nonetheless distinct from, the atoms that form the molecule. Interfaces are extremely important in both pure and applied areas of condensed matter physics. The reason is simple to understand. Devices are made from materials and as these devices get smaller the interfaces and finite size effects play an increasingly important role in their function. Giant magneto-resistance in magnetic multilayers is one notable example that had a dramatic impact on magnetic storage. Virtually all the read heads for hard discs rely on the giant magneto-resistance effect in magnetic multilayers. Although the transport properties of a device are relatively easy measure, there are only a few experimental methods capable of probing local magnetic and electronic properties in a depth resolved manner. We have developed one of them here in Canada at TRIUMF called low energy beta-detected nuclear magnetic resonance (β-NMR). The TRIUMF/ISAC facility has unique capabilities that are designed to use implanted radioactive spins as a depth controlled probe of thin films and interfaces. Although many different isotopes made at ISAC can be used for β-NMR, almost all the experiments done so far use a beam of Li-8, which is produced in large quantities and is easy to polarize (so that all the probe spins are oriented in the same direction before introduction into the sample). It is also the lightest isotope suitable for β-NMR and has the special property that it's daughter (Be-8) decays into two alpha particles, leaving nothing behind in the sample after the decay. This is similar to the positive muon (please see the discussion of muon spin rotation, mSR, in Section 4.2.4.1).

In fact the β-NMR technique is conceptually very similar to μSR. A schematic of the experiment is shown in Figure 17. A beam of low-energy spin polarized radioactive spins is injected into the sample. The depth of implantation is controlled by placing the spectrometer on a high-voltage platform so that the radioactive ions must climb a potential hill to land on their way into the sample. The stopped radioactive nucleus acts as a probe of the local magnetic/electronic environment. All forms of nuclear magnetic resonance NMR, the basis of the medical imaging technique MRI, involve generation of a non-equilibrium spin polarization followed by observation of the time-dependent nuclear spin polarization. μSR and β-NMR are distinct forms of magnetic resonance: a large non-equilibrium spin polarization is generated in a beam of particles before they are introduced into the sample. In addition, the polarization in such nuclear methods is detected through the anisotropic decay properties of the muon or nucleus. Consequently, a signal requires only about 10^7 spins, which is about a factor 10^{10} fewer than is required from conventional NMR.

β-NMR was invented in 1957, along with the discovery of parity violation in weak interactions; however, the particular variant developed at TRIUMF is relatively new. The key points are that, unlike conventional NMR, the signals in β-NMR are independent of sample size and can be monitored as a function depth on a nm length scale. Consequently, β-NMR is ideally suited to studies of thin films, heterostructures, and the near surface region of solids. One of the two main observables is the Larmor frequency, which is obtained most easily by measuring the time-averaged beta decay asymmetry as a function of the small RF magnetic field applied perpendicular to the initial polarization and large internal magnetic field. Some typical frequency spectra are shown in the top right of Figure 17. Alternatively, one can deliver short pulses of beam to the sample and measure the asymmetry as a function of time during and after the beam pulse. The resulting signal is a direct measure of the spin relaxation rate and temporal fluctuations of the local internal magnetic field. Some typical relaxation curves are shown in the bottom right of Figure 17. Both the Larmor frequency and spin-relaxation rate are sensitive monitors of the local electronic and magnetic properties in the thin film, interface or near surface region.

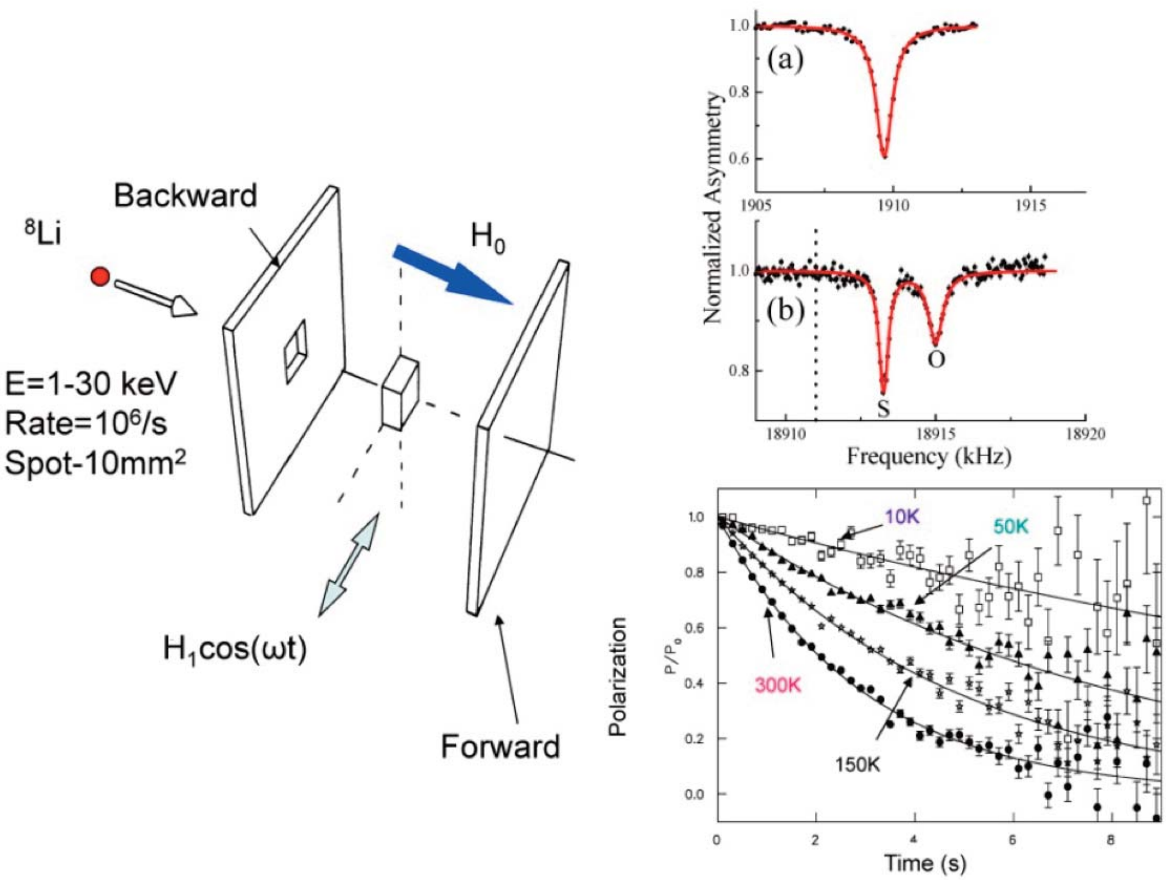

Figure 17: (Left) A schematic of a β-NMR experiment. The initial polarization can either be perpendicular to the beam direction or parallel and plastic scintillation detectors are used to detect the high-energy beta-decay electrons. (top right) The β-decay asymmetry can be measured as a function of a small RF magnetic field applied perpendicular to the main field. This results in resonances when the RF frequency matches the Larmor frequency of the Li-8 in the local magnetic field. The upper resonance corresponds to Li-8 in a thin 50 nm Ag film in a magnetic field of 0.3 T, while the lower spectrum was taken at 3.0 T, where signals from two different sites can be resolved. (bottom right) Alternatively one can pulse the beam with no RF field and simply measure the polarization decay as function of time. The observed relaxation in a 50 nm Ag film is due to Korringa scattering of conduction electrons at the Fermi surface [59].

β-NMR experiments at TRIUMF use the polarized low energy beam line at ISAC, which is a single user facility that can produce only one beam at a time, meaning that this experiment can only run when ISAC is not being used by another of the important experiments. For this reason, the amount of beam time that has been available to do these experiments is quite limited, amounting to a few weeks per year on average. In 2012, TRIUMF committed to providing five weeks of continuous beam time annually for the β-NMR program, making it one of the largest users of the ISAC facility. This is still a small amount of beam time relative to the muon beam lines that can be run in parallel, and one of the main limitations to growth of the technique is still the lack of available time. With the arrival of the ARIEL accelerator and planned photonuclear production of secondary radioactive ion beams, we anticipate another substantial increase in beam time available for these experiments in the coming five years.

While a few other laboratories are capable of β-NMR (notably ISOLDE at CERN), none have a dedicated facility to study materials science with depth-resolved capabilities, nor with the beam intensities and versatile spectrometers of CMMS. The TRIUMF β-NMR facility is a much needed complement to the low-energy μSR facility at the Paul Scherrer Institute due to the different timescales of the radioactive probes and this has resulted in a strong collaboration between TRIUMF and PSI.

Nature of Weak Magnetism in $SrTiO_3$/$LaAlO_3$ Multilayers

One of the most striking examples of how the electronic properties of an interface differ from bulk materials is in the case of simple $SrTiO_3$ (STO) and $LaAlO_3$ (LAO), both of which are nonmagnetic insulators; however, the interface of STO/LAO exhibits a wide variety of intriguing behaviours that include conductivity, superconductivity, and weak magnetism. The most direct evidence for the magnetism comes from β-NMR results at TRIUMF [1]. Figure 18 shows the spin relaxation rate in STO/LAO multilayers composed of alternating layers of STO (with a fixed thickness of 10 unit cells) spaced with LAO whose thickness can be varied. Note the spin lattice relaxation rate of Li-8 in superlattices with spacer layers of 8 and 6 unit cells of LAO exhibits a strong peak near ~35 K, whereas no such peak is observed in a superlattice with spacer layer thickness of 3 unit cells of LAO. The peak is attributed to weakly coupled electronic moments at the $LaAlO_3$/$SrTiO_3$ interface that are slowly fluctuating. These results show that the magnetism at the interface depends strongly on the thickness of the LAO spacer layer, and that a minimal thickness of ~4-6 unit cells is required for the appearance of magnetism. The magnitude of the relaxation rate indicates the fluctuating moments are only 0.002 of a free electron in the two samples with a larger $LaAlO_3$ spacer thickness. The results are consistent with a dilute concentration of moments that are highly disordered as in a spin glass.

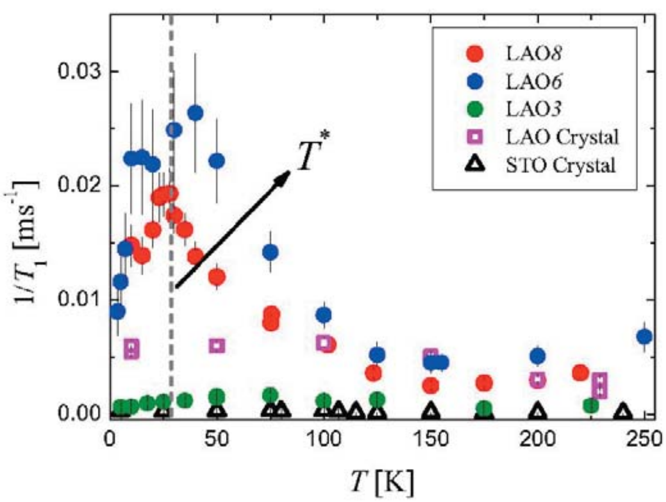

Figure 18: The spin lattice relaxation rate (1/T1) as a function of temperature in 3 mT applied field. The red, blue and green circles are measurements in samples with 8 (LAO8), 6 (LAO6) and 3 (LAO3) unit cells of LAO, respectively. The squares and triangles are reference measurements in LAO and STO bare crystals [53].

Slow Order—Parameter Fluctuations in Superconducting Pb and Ag/Nb Films

In any superconductor, thermodynamic fluctuations of the order parameter are predicted to occur near the superconducting transition temperature. This leads to the appearance of superconducting correlations above T_c. Such fluctuations cause enhanced conductivity and diamagnetism above the critical temperature. The importance of fluctuations increases in systems of lower dimensionality (on the scale of the Ginzburg-Landau coherence length) such as thin films, wires, and small particles. Unconventional superconductors such as cuprates, with their quasi-two-dimensional (2D) electronic structure, low superfluid density, and short coherence length, are even more susceptible to fluctuations. In these systems superconducting fluctuations are thought to be largely responsible for a new phase called pseudogap regime and may be connected to the presence of a quantum critical point. In principle such fluctuations should also be observed in the NMR relaxation rate but until now have not been observed. Recently β-NMR has been used to observe critical fluctuations in a thin film of Ag on Nb and in Pb for the first time [2] (see Figure 19). This is possible because of the enhanced sensitivity of β-NMR to spin relaxation in low magnetic fields where measurements are not possible with conventional NMR. The amplitude of the fluctuations appears to be much larger than current theories predict.

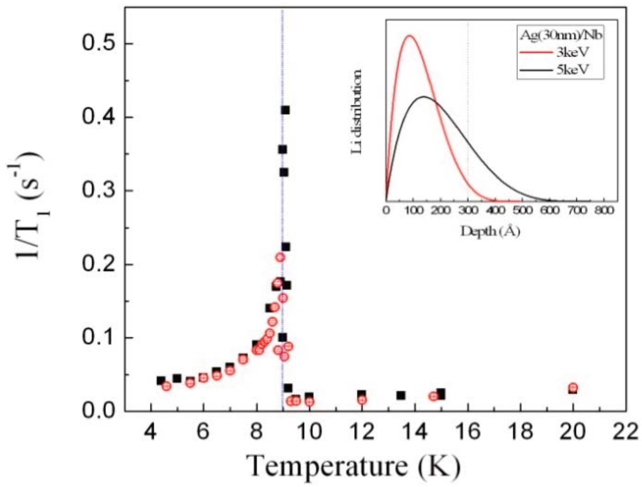

Figure 19: Nuclear spin relaxation rate of Li-8 in 30 nm of Ag on 270 nm of Nb. The signal comes entirely from the thin Ag film, which is not a superconductor. However the Nb with Tc = 9.0 K induces superconductivity in the Ag via a proximity effect. Note the sharp peak in the relaxation rate at the Tc. This is attributed to slow fluctuations in the induced superconducting order parameter in the Ag [54].

nterfaces of high-T_c superconductors (HTSC) are important from a fundamental viewpoint because they can be sensitive to fundamental symmetries, which may be regarded as the single most important observable in an unconventional superconductor. They may also have important applications because any device would involve such interfaces. While significant progress has been made in understanding the transport properties of such interfaces, very little is known about their magnetic properties, in part due to the lack of an appropriate local magnetic probe. A particularly unresolved issue is whether the superconducting order parameter (OP) breaks time-reversal symmetry (TRS) near the surface. A characteristic feature of TRS breaking (TRSB) is spontaneous magnetization; however, Meissner screening cancels this in the bulk, limiting the associated fields to within the magnetic penetration depth of defects and interfaces. To measure this magnetization directly, one requires a sensitive depth-dependent local magnetic probe. Recently Saadaoui et al. used β-NMR to perform a sensitive search for TRSB order near the surface of the high-T_c cuprate superconductor $YBa_2Cu_3O_{7-\delta}$ (YBCO) [3].

Low field resonance measurements were made on a thin Ag overlayer deposited on the surface of <110> oriented YBCO as shown in Figure 20. Note there is some additional line broadening at 4.3 K compared to 100 K; however, the observed line broadening scales with the applied magnetic field whereas and line broadening from spontaneous TRSB should be field independent. Therefore, we do indeed observe weak magnetic fields at the surface, but they are attributed to vortices running along the surface. Any fields due to TRSB must be less than 0.2 G. This is much smaller than previous indirect studies based on tunneling.

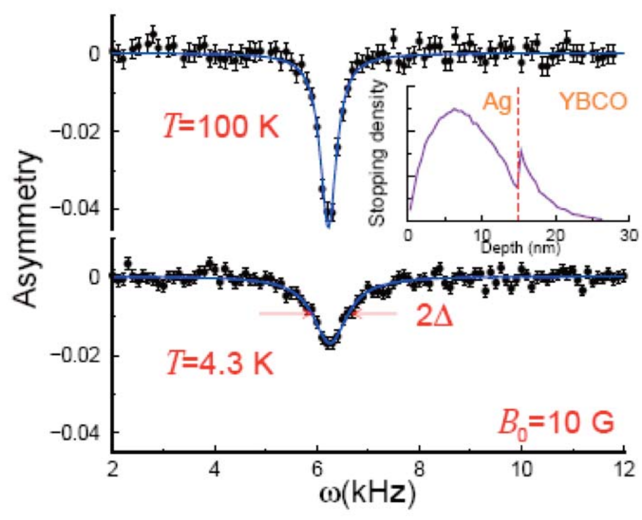

Figure 20: β-NMR spectra taken by implanting 2 keV $Li8^+$ into 15 nm Ag/YBCO(110), in an external field of B0 = 10 G applied along the surface of the film. Inset show the simulated implantation profile using TRIM.SP for $Li8^+$ of 2 keV in 15 nm of Ag on YBCO [55].

Magnetic Properties of the Multigap Superconductor $NbSe_2$

One of the most important experimental observables in any superconductor is the magnetic penetration depth λ since it is directly related to the superfluid density $\rho \propto 1/\lambda^2$ and hence to the magnitude of the superconducting order parameter. Its variation as a function of temperature, composition, and magnetic field provides important tests for any model of superconductivity. Recently Hossain et al. have shown that β-NMR can be used to locally probe the Meissner and vortex phases of a superconductor [4]. Figure 21a shows the low field spin relaxation rate in the multigap superconductor $NbSe_2$ for the field parallel and perpendicular to the surface. In the normal state the relaxation rates are virtually the same indicating that the internal field seen by the Li-8 is the same. When the field is perpendicular to the surface, the sample is in the vortex state where the average internal field is almost the same as in the normal state. Note the observed Hebel Slichter peak in $1/T_1$ due to the opening of a superconducting gap just below T_c. However, when the field is parallel to the surface, there is a dramatic increase in the relaxation rate below T_c. This is due to Meissner screening of the applied field. The magnitude of the increase is a direct measure of the London penetration depth plotted in Figure 21. The temperature dependence of λ confirms the multigap nature of the superconducting gap.

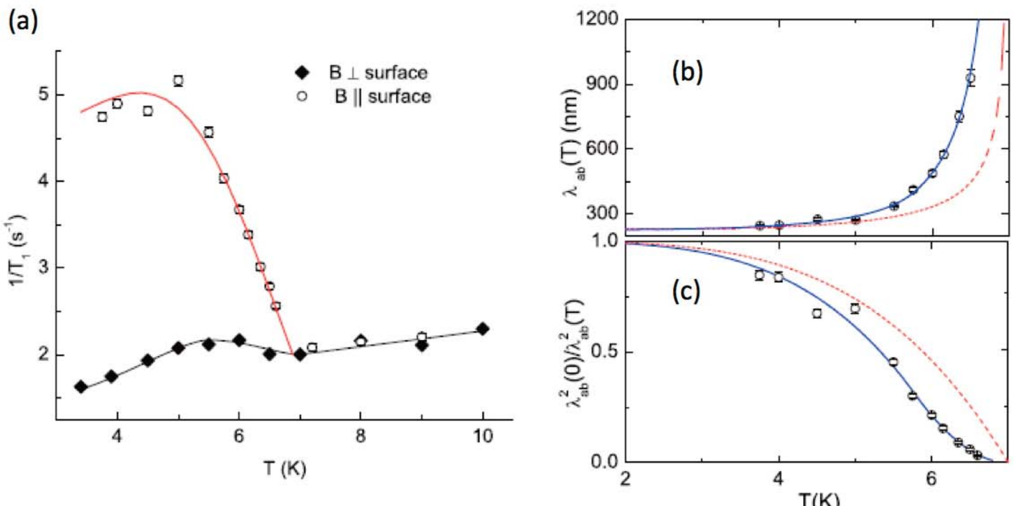

Figure 21: (a) The temperature dependence of the $1/T_1$ of Li-8 in NbSe2 with a small external magnetic field of 30 G applied parallel to the surface (open circles) and with a 100 G applied perpendicular to the surface (filled diamonds). The fitted curve through the vortex state data filled diamonds is based on the Hebel-Slichter theory assuming a multigap model. The curve through the Meissner state data (open circles) is also derived from this model, taking into account the reduction in magnetic field from Meissner screening. (b) The magnetic penetration depth in the Meissner state of $NbSe_2$ as a function of temperature. The solid lines are a fit to the multigap model, whereas the dashed line is a fit to the single gap model. (c) The inverse square of the penetration depth versus temperature normalized the value at T = 0 [56].

Finite Size Effects in Metals

The metals platinum and palladium are well known as heterogeneous catalysts with chemically active surfaces that can dramatically increase the rates of important chemical reactions such as the reduction of oxygen (O_2) which is a key limiting step in such devices as hydrogen fuel cells. It is thus interesting to study the properties of these metals in the form of thin films and arrays of nanoparticles. While Pt catalysts have been studied by conventional Pt-195 NMR, the signal limitations of NMR entail the use of gram quantities of Pt catalyst, with significant polydispersity and a rather broad range of local behaviour. In the conceptually simpler geometry of a monolithic thin film or monolayer array of nanoparticles, we will be able to make much more detailed and careful studies that could then be used in advancing our fundamental understanding of the processes of catalysis, with the aim of designing cheaper and more effective catalysts, e.g., employing transition metal oxides, rather than rare metals. In contrast to Pt, chemically similar Pd, which is also an important catalyst, cannot be studied effectively by conventional NMR because of the lack of any high sensitivity nucleus of Pd. We have established the sensitivity of Li-8 as a probe of the mobile d-electrons of Pt and Pd [5]. Figure 22 shows the large negative and temperature dependent Knight shift of the resonance in Pt. The role of the d-electrons is important in determining both the magnetic properties of these metals as well as their catalytic properties.

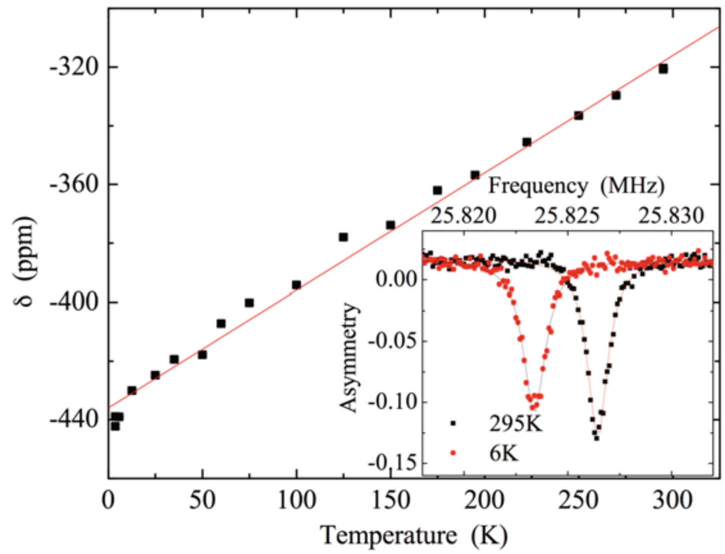

Figure 22: The inset figure shows the resonances of Li-8 in Pt together with the temperature dependence of the resonance shift. The negative, temperature dependent shift is characteristic of the mobile d-electrons of Pt [57].

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4.2.4.6 RADIATION INDUCED EFFECTS IN MATERIALS AND ELECTRONICS

For many decades, research scientists and engineers have been battling to understand how to mitigate against the errors caused in electronic devices by naturally occurring ionizing radiation. Such radiation can lead to a degradation of expected performance, the loss of information or control, and even the failure or destruction of a device. Trying to understand the mechanisms behind radiation effects in matter has been of paramount importance to today's society. The study of new materials and the development of new technologies to allow faster, more compact, lower power, and inexpensive devices has demanded the availability of testing facilities to both investigate future solutions as well as to characterize and verify existing products. In typical years about 100 users from 25 to 30 companies in Canada, U.S., and Europe make use of these irradiation facilities.

PIF & NIF regularly make use of three beam lines at TRIUMF. Protons and neutrons are available at energies up to 120 MeV with BL2C1, which is shared with TRIUMF's Proton Therapy Centre for the cancer treatment of ocular melanoma. Higher energies, up to 500 MeV, are available with BL1B, a testing facility truly unique to the world for both its broad range of energy and its intensity. More intense neutron irradiations can be done with the TNF location at the end of BL1A. Here, the “leftover” protons from the Meson Hall are converted to neutrons at the beam dump, yielding an energy spectrum well matched to that of atmospheric neutrons, ideal for testing avionics and ground-based electronic systems, such as network and power-distribution servers, automobile electronics, or even the latest cell-phone chips. As well, irradiations of microelectronics were also done using electrons from M11 and, more recently, muons from M20.

In addition to commercial electronics testing and qualification, fundamental research is also performed using PIF & NIF. Regular visits of researchers from several different institutes, laboratories, and universities happen each year to make use of the facilities and services offered at TRIUMF. The research is diverse and has impact. The data collected at TRIUMF are used in student theses, presented at international conferences, and are published in peer-reviewed journals and much of the research has won awards from the community both at the student and professional level.

For example, research supported by the Canadian Space Agency into reducing the increased incidence of cataracts in astronauts (and, to a lesser degree, pilots) has been done by examining the effects of dietary supplements; irradiations of pig eye lenses with protons and neutrons allow scientists to gauge progress. The different PIF & NIF beam lines have been used by several groups to characterize the design and performance of new detectors that need to survive in the harsh outer space environment.

Another impressive example is an in-depth, systematic program of study through modelling and measurement that has been undertaken by several leading groups to investigate the fundamental aspects of different electronic failures using irradiation from protons, neutrons, and now muons at TRIUMF. Experiments performed at TRIUMF have won the prestigious Outstanding Paper Award at the international IEEE Nuclear and Space Radiation Effects Conferences in 2008 (Enhanced Proton and Neutron Induced Degradation and its Impact on Hardness Assurance Testing) and in 2009 (Single-Event Upsets and Multiple-Bit Upsets on a 45 nm SOI SRAM).

Recent data have demonstrated that low-energy muons can cause direct ionization in specific types of electronic microcircuits just as has been found for low-energy protons. Leading-edge microelectronics exhibit sensitivity to lightly ionizing particles, such as protons, as the transport of a singly charged particle through semiconductor material generates sufficient charge in the device to result in an error. As the technology has moved to become more highly scaled and hence compact, less charge is required to potentially cause an error and the probability for an error increases significantly.

The first ever measurement of positively charged muons causing errors in electronics was performed at TRIUMF as part of the Ph.D. thesis of a student from Vanderbilt University, won the Top Student Paper at the 2011 IEEE International Reliability Physics Symposium, and has caused a stir in the microelectronics industry. The work demonstrated that a previously unobserved error mechanism could affect the latest devices. With the high reliability of equipment becoming ever more important, this work will have relevance to the design of data servers, medical equipment, and aerospace technology. The ultimate goal of this research is to understand if atmospheric or terrestrial muons will ever become a reliability issue for the semiconductor industry.

All of this research, enabled by PIF & NIF at TRIUMF, is allowing scientists and engineers to solve existing and minimize future problems, benefitting society with the training of highly qualified personnel and more reliable, better performing, more efficient and cleaner products as well technological advancement.

4.2.5 ACCELERATOR SCIENCE & TECHNOLOGY

TRIUMF is an exciting place to do accelerator physics: with primary beams of protons and electrons, and secondary beams of light to heavy ions for the rare isotopes program, and muons for the materials science program, there is present the complete range of accelerated particles. Each type brings different issues. For example, small permissible halo for the high power electron and proton beams; space-charge effects for the proton which is barely relativistic; high vacuum for the low energy electrons and for the high charge ion beams. The Accelerator Group's focus extends, also, outside the laboratory: there is active support for the LHC through lattice and beam-beam-effects studies, of accelerator simulation tools under the GEANT collaboration, and (to a lesser extent) of FFAGs under the Daresbury EMMA collaboration. All of these activities comprise reason for accelerator codes development and support.

The TRIUMF accelerators are varied: they range from the 40-years old maturity of the main cyclotron, through the decade of operation of the ISAC facility, to the e-linac still under construction. They span, too, a range of acceleration technologies: normal conducting structures in the cyclotron and ISAC-I, quarter-wave superconducting structures in ISAC-II, and elliptical SRF cavities for the e-linac. The main cyclotron has components at or reaching end of life, and there is an active program of refurbishment; with this comes the opportunity not just for replacement but for improvement of technology and of ideas. The refurbishment is supported by a proton beam development program that has as its second purpose the pursuit of 400 μA as a routine operations mode. Contrastingly, the e-linac generates the need and focus for design studies of beam optics in SRF linacs and beam lines; and ancillary studies of electron gun optics, wake fields and impedances, diagnostics, orbit correction, collimation, etc. Notably, these are not mere "paper studies", but rather must and have led to engineering design; and this commands an exacting degree of certitude.

An emerging imperative across the accelerator complex is for the introduction of more efficient and semi-automated tuning of the individual accelerators and beam lines. While the number of accelerators has increased, the overall size of the operations crews has not. Moreover, we recognize that the platforms and algorithms for beam-and-model-based computer control and tuning developed offsite have improved significantly; and the time is ripe to begin their deployment here. The e-linac injector, and particularly its low energy beam transport line, is identified as a rich and fertile testing ground for Accelerator Application Language (XAL) procedures.

The following tour of Accelerator Physics activity at TRIUMF begins with overall highlights and hands on development, and continues to design and modeling, and finishes with beam line technology advance and an account of work performed under external collaborations.

4.2.5.1 SYSTEM DEVELOPMENT AND UPGRADES

Over the past five years, a number of improvements to accelerator systems and operations were made—-some refurbishments, some upgrades to modernize. Additionally, a test facility for electron beam optics was developed in cooperation with VECC in India.

New Cyclotron Vertical Injection Line Design and Design Methodology

After 36 years of continuous service, the original vertical section of the beam line that transports protons to the TRIUMF 520 MeV cyclotron has been decommissioned and replaced with a new one. The line's function is to transport the beam to and match into the electrostatic inflector. This line is 12 m in length, and consists of 26 electrostatic quadrupoles. The old line transported as much as 0.6 μA H-, but with bunching, this represents a peak current of 5 μA. The old line had issues with space-charge effects and voltage hold-off of the electrostatic optics.

DOUG STOREY RECEIVES PRESTIGIOUS NSERC AWARD

04 June 2013

The Natural Sciences and Engineering Research Council (NSERC) has announced the winners of this year's Alexander Graham Bell Canada Graduate Scholarship. One of them is a familiar face at the lab: accelerator physics Ph.D. candidate Doug Storey of the University of Victoria. Doug has worked closely with TRIUMF in both his graduate and doctoral research.

Storey's master's research has already proven highly beneficial to implementing safe operations procedures for the electron linear accelerator (e-linac) as part of the Advanced Rare IsotopE Lab (ARIEL) that is currently under construction at TRIUMF.

For his doctoral research, Storey is developing a superconducting radio-frequency separator cavity for the e-linac that will become a crucial element in a future upgrade of the e-linac to include an Energy Recovery Linac and later a Free Electron Laser (FEL) which could be the first in Canada and a unique facility within North America.

Research such as Storey's will help Canadian and international scientists produce and study isotopes to advance our understanding of the nucleus, the origins of the chemical elements, and potential medical applications. Furthermore, the e-linac projects are driving new applications of accelerator technology for environmental remediation projects such as PAVAC Industries' pollutant scrubbing technology.

The new line optics were designed entirely using the TRIUMF code TRANSOPTR. This is first order and fully 6-dimensional; it can track all 21 second moments, and space charge is included by solving, at every integration step, the three elliptic integrals and rotating the forces to the lab frame. This is essential as the vertical injection line couples both transverse directions because of the axial magnetic field of the cyclotron, and subsequently couples completely to the longitudinal dimensions in the inflector. TRANSOPTR has been extended to include: varying axial magnetic fields, electrostatic spiral inflector, and motion through the first few turns of the cyclotron including acceleration effects.

Commissioning began in April 2011 and was very successful. Using settings derived purely from theory at start-up, the beam line reproduced the historical best transmission between buncher and cyclotron circulating beam (60%) after less than an hour of fine-tuning the steering correctors.

VECC Test Facility Commissioning

The VECC Injector test stand is a facility at TRIUMF-ISAC developed and implemented to prototype the injection complex for the e-linacs both at TRIUMF and at VECC in India. It provides a proving ground for the physics design and hardware/software developed for these applications. Equally important is the use of VECC to establish procedures before we move to routine operation.

The VECC test stand consists of an electron source, a beam transport system and infrastructure such as alignment, vacuum, power supplies, acceleration systems, electron beam diagnostic and control hardware and software. Through VECC commissioning from 2011 to 2013, we have validated design premises and principles of various components, used the test facility to pin down several design option issues such as beam loss monitors and element sequencing, established diagnostic and control procedures, characterized machine performance to some detail, identified areas for improvement such as dipole bipolar power supplies, and started the process of developing operational protocols and procedures.

4.2.5.2 IMPROVEMENTS TO MACHINE PERFORMANCE FOR EXISTING ACCELERATOR COMPLEX

Improved analytic and computational models, as well as physical control systems, of the accelerator complex have been implemented that allow operators and scientists to more precisely control and optimize the system.

Correction of Cyclotron Resonance

Imperfections in the TRIUMF cyclotron main magnet are a source of field errors which slightly violate the 6-fold symmetry. Among them, the third harmonic of the magnetic gradient drives the ν_r=3/2 resonance; this results in a modulation of the current density versus radius observed from the resonance crossing (at 428 MeV) all the way to the extraction (480 MeV) (see Figure 1). The cyclotron has sets of harmonic correction coils at different radii, each set composed of 6 pairs of coils arranged in a 6-fold symmetrical manner, and designed to correct the first harmonic of the cyclotron magnetic field. The symmetry of this layout cannot create a third harmonic of arbitrary phase, and so a single set of harmonic coils cannot provide a full correction of third harmonic errors driving the ν_r=3/2 resonance. However, the two outermost sets of harmonic correction coils are azimuthally displaced, and the 3/2 resonance occurs where they overlap radially. By careful combination of the excitation amplitudes, it was possible to completely compensate the resonance. The feasibility of the idea was first demonstrated using simulations. Experimental measurements later demonstrated the full correction of this resonance. Operationally the advantage is that the ratio of extracted currents in the two high current beam lines, 1A and 2A, becomes insensitive to RF dee voltage.

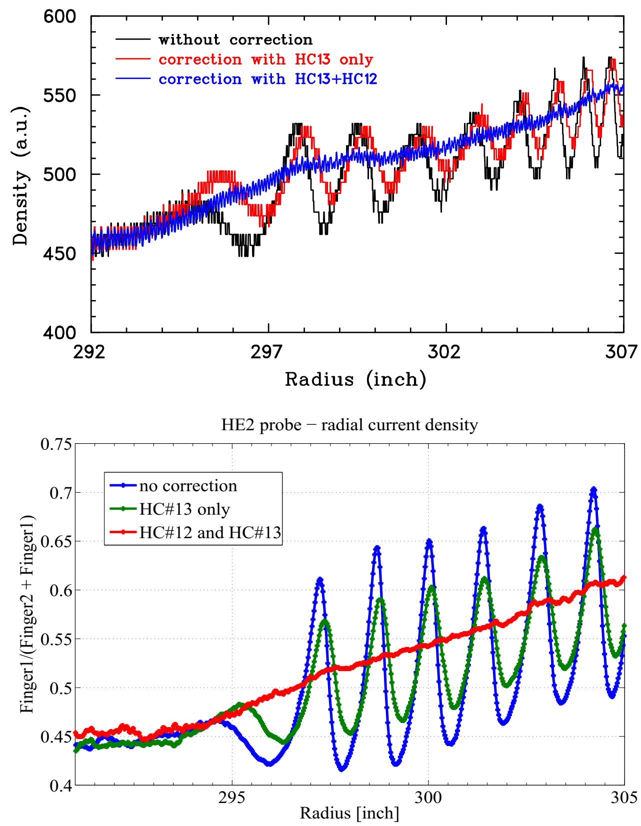


Figure 1: Suppression of the ν_r= 3/2 resonance: Radial beam density around extraction with 0, 1 and 2 correction coils. Top: simulation; Bottom: experimental results. The full correction results in greatly reduced fluctuation.

Cyclotron Beam Dynamics with Space Charge

The TRIUMF 500 MeV cyclotron accelerates H^- ions, and uses charge exchange extraction. No turn separation is required for extraction, leading to the very large phase acceptance of this machine (about 60°). Bunches are very long, and have a very large energy spread between the head and the tail. Each bunch therefore occupies a large volume in real space. Solving the Poisson equation in a particle-in-cell (PIC) code over such a large volume would require significant computation time. In addition, at high energy the turn separation is several times smaller than the radial beam size. It is therefore essential to take into account the effect of many neighbouring turns. The multi-bunch calculation in the commonly used simulation code is most appropriate when bunch length and width are comparable, whereas in TRIUMF's case the bunch length can be 400 times its radial width (see Figure 2).

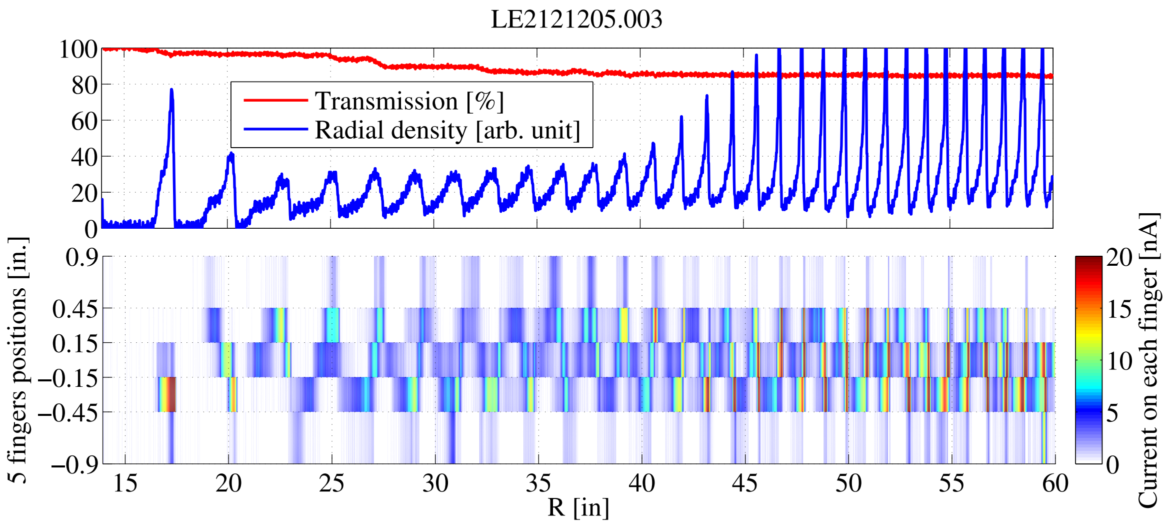


Figure 2: Top: turn pattern (from turn #2) seen by the LE2 probe. Bottom: detail of the signal on each individual finger.

To rise to the challenge of simulating space charge effects in the TRIUMF cyclotron we must take advantage of symmetries inherent in this problem: if we make the assumption that the beam shape evolves slowly compared to the turn-to-turn timescale, we can use periodic boundary conditions in the radial direction. This can reduce the computation time by orders of magnitude. The new code has just been benchmarked against results obtained with CYCO. Exciting outcomes are expected from this new simulation tool.

Improvement of Cyclotron Probes Data Processing and Visualization

New tools to process and visualize data from low-energy and high-energy cyclotron diagnostic probes using MATLAB© have been developed. Compared to the old VMS-based tools, we now benefit from a much larger library of modern data processing and visualization algorithms. We used these tools to improve our understanding of the beam dynamics in the cyclotron central region, and improve the accuracy with which we can measure the vertical position/size of the beam, its phase, and its radial density.

Tune Development for Primary Beam Lines

The TRIUMF cyclotron operated at 500 MeV for nearly four decades. Since 2010, the two primary beam lines 1A and 2A have been reconfigured for running at 480 MeV. The objective was to reduce by ~30% the beam losses caused by the electromagnetic stripping. New tunes were developed for 480 MeV and have performed smoothly. The loss reduction is confirmed both by online measurements and residual activation field mapping after eight months of beam production. In order to improve the stability of both primary beams, two of the harmonic coils were configured in Bz-mode to correct the ν_r=3/2 resonance and stabilize the beam-split ratio fluctuations discussed above. The Br-mode of a harmonic coil plus two trim coils were used to correct the vertical position of the beam at extraction.

Tomographic Display of Beam Density Near Target

For ISAC at TRIUMF, radioactive isotopes are generated with proton beams of energy > 480 MeV. The beam power of up to 50 kW can easily melt the delicate target if too tightly focused. The target is protected by closely monitoring the distribution of the incident proton beam. There is a three-wire scanner monitor installed near the target; this gives the vertical profile and the ±45° profiles. Our objective is to use these three measured projections to find a 2D density distribution. We have developed a computer program to realize tomographic reconstruction of the beam density distribution by implementing the maximum entropy (MENT) algorithm. This program performs a calculation that is sufficiently efficient and robust that an operator can obtain the distribution within a few seconds of the scan. This program has become part of the routine operation of Beam Line 2A. In addition, we have developed the MENT technique to perform phase space reconstruction and have applied it to the injection line.

Beam Development at β-NMR

A polarized low-energy ion beam with a β--NMR/b-NQR spectrometer is one of the probes to study the magnetic properties of a material via radioactive decay. In this study one would typically need several million nuclear spins to generate a good NMR signal with stable nuclei. The β-NMR/b-NQR experimental setup at ISAC requires count rates in the range 1-2´10^6/s. In order to fulfill this requirement, production and transport of high intensity and high brightness beam to β-NMR/b-NQR is essential. In order to improve the transmission, systematic beam tuning was performed by using C-12, Li-7 and Li-8 beams with beam energy about 20 keV. We have established a reliable common tune between the β-NMR and β-NQR beam lines by using simulation and diagnostic tools. This work led to improved transmission by 20% and a significant gain in count rate. The results obtained in the β-NQR beam line show some room for improvement. In order to understand the transport properties through the β-NQR spectrometer we have initiated a full 3D simulation of ion beam transport through the β-NQR beam line.

Beam-Based Machine Characterization of VECC Test Facility

A comprehensive plan was completed at the VECC test facility to use electron beam to characterize the full phase space behaviours of both the beam and the machine transport. These data are then cross-compared to both the low-β empirical model for high-level applications and hardware bench data. The VECC diagnostic and control configuration has been designed, to the extent allowed by space and budget, to facilitate this program in both the main line and the spectrometer. As a by-product of this process, the performance of these diagnostic and control elements are also characterized. Longitudinal measurements benefited from the RF-deflecting cavity implemented in the spectrometer arm. A method developed using beam imaged from

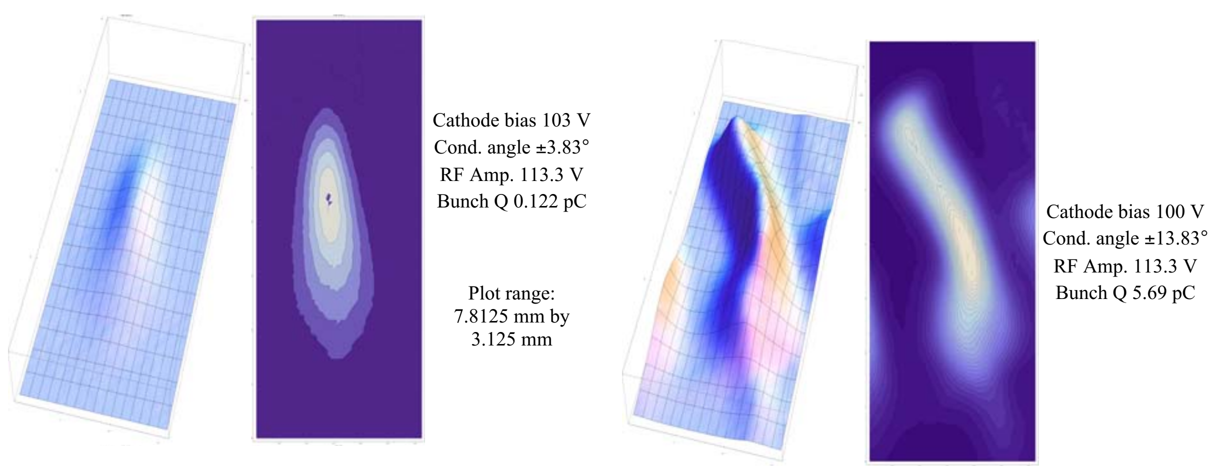


Figure 3: VECC Longitudinal beam phase space under two gun RF settings of a grid beamlet projected onto a screen in the spectrometer. The long dimension corresponds to the RF phase, with the full gun RF cycle spanning 13.08 mm. The short dimension corresponds to a momentum spread where dispersion is 2 m. Bunch lengthening, tail formation and time-momentum correlation as bunch charge increases can be directly seen from such plots.

the cathode grid to view-screens allowed direct and unambiguous measurement of intervening transport, as well as more accurate longitudinal beam determination from isolated grid beamlets (see Figure 3). Two major goals to be achieved from this program are accurately calibrated 6D beam and transport models, and completely debugged diagnostic and control procedures to be turned into high-level applications.

Study on Extraction Optics of H^- Ion Beams from a Negative-ion Source

Performance of an ion source is mainly validated by the extracted ion beam intensity and brightness. Also important is the ion beam matching to the transport line. Negative ion beam extraction is more complicated than positive ion extraction because of the co-extracted electrons and also the dynamics of the space-charge force. We have performed simulation and experimental study to understand the physics of negative ion beam extraction optics and to optimize the extraction system for higher beam intensity with better brightness. Based on simulation results, we have shown experimentally that the extraction system can be optimized for high-intensity, high-brightness beams by tuning the arc current along with the extraction voltage. Results are shown in Figure 4, projecting a gain of around 25% in beam intensity.

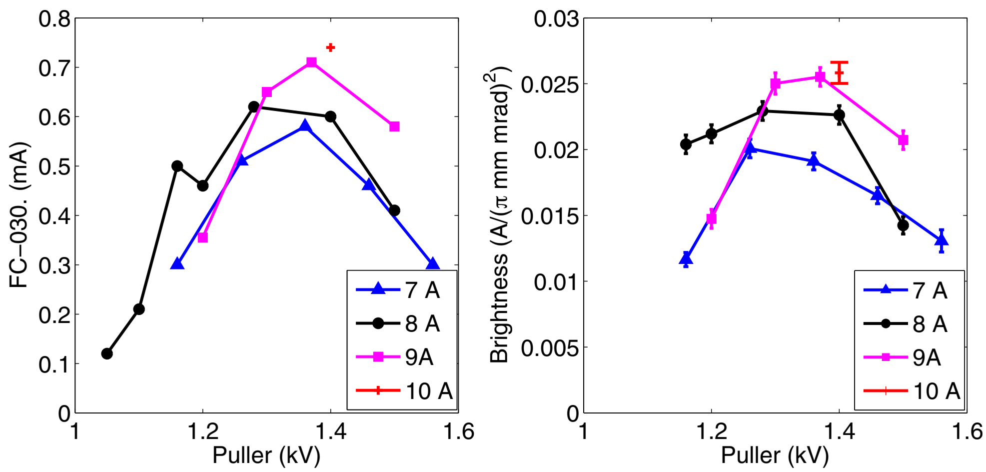


Figure 4: Beam intensity at the location of emittance measurement device (a) and beam brightness at the same location (b) for 294 kV H^- ion beam.

4.2.5.3 DESIGN AND MODELING

TRIUMF's accelerator team has improved the designs and working models of the accelerator complex to improve performance and contribute to the world-wide community. TRIUMF's involvement in the Geant4 collaborative software package has generated some of the most widely-cited scientific papers.

Geant4-based Tracking and Simulation

Geometries of TRIUMF beam lines have been simulated and studies conducted using the G4Beamline application, in particular modelling of losses in BL2A due to the cyclotron extraction foil, and simulations of the ISAC target module and the effect of the vacuum window on performance. We have also assisted the Muon Beam Lines group in their M9B study by making code modifications for muon spin tracking.

New applications have emerged with the ARIEL project, where the e-linac and beam transport lines have been simulated to study a momentum collimation device. The geometry of a novel design for the 100 kW beam dump has been constructed and used to estimate performance and heating effects. Initial optics results for simulating the entire system from the electron gun to the photo-fission target are encouraging and it remains to fill in more details to realize a comprehensive model.

TRIUMF-developed Codes

A number of accelerator-related codes developed at TRIUMF remain in frequent use both here and at other facilities. The Beam Physics Group continues to distribute, maintain, and support codes such as the tracking and simulation program Accsim, Long1d for longitudinal dynamics, Intran for beam line design, and Relax3d for static electric, magnetic and heat computations.

Design of Compact Dipole Magnets for the ARIEL Electron Beam Line

The main challenge was to design compact magnets to satisfy space constraints and minimize cost, while satisfying some field quality requirements. The quality of the field produced by a dipole magnet is usually expressed in terms of flatness of the field. Nevertheless, this notion is not easily translatable in terms of what really matters: does the magnet fulfill its role of steering (and focusing) the beam with a small enough impact on the beam quality? In this design study we have thus chosen to write the field quality requirements directly in terms of maximum emittance growth the electron beam may encounter due to non-linear field components.

The different beam lines comprise a total of fifteen dipoles, which have been divided into five different types, depending on the required integrated field and field quality. Five different magnet designs have been produced, based on magnetic modelling using OPERA-3D. To analyze the field quality, second order transfer maps were obtained from particle tracking with COSY-infinity.

E-Linac Beam Transport Line Design

Comprehensive beam dynamics studies as the foundation for the e-linac design were performed. This work included establishing the machine model from the electron gun to the acceleration and transport components through the entire line, purpose-built optimization platform for reaching best design parameters, and extensive configuration and tolerance analysis and operation scenario simulation. Our designs have anticipated that the facility will evolve over time. Phase One is an era in which the linac is operated solely for RIB production; this era begins with the injector and first accelerator cryomodule, and is completed by the addition of the second accelerator cryomodule. Phase Two anticipates that a recirculation ring is added between the exit and entrance of the accelerator cryomodules; this era would support either energy doubling for RIB production, or simultaneous beams for RIB on the straight-through path and an energy-recovered beam through the ring and linac for a FEL or other light source application.

Design of the entire Phase One e-linac beam line is complete, encompassing the electron gun, injection complex, low-energy, medium-energy and high-energy transport lines terminating at a 100 kW tuning dump, a 100 kW and a 500 kW convertor/target module, as well as the respective spectrometer arms. This design covers the magnetic optics, geometrical layout and element coordinates, and performance specifications for the dipoles, quadrupoles and correctors etc., in sufficient details for proceeding with engineering design.

RF Beam Separation Scheme and Hardware for E-Linac Multi-Pass Operation

The e-linac design work also covered Phase Two: future inclusion of a recirculating loop for energy doubling for RIB application, and high efficiency energy recovered beam for a free electron laser.
A self-consistent beam separation configuration following the main linac, with RF separation for energy recovered operation and static magnetic separation for RIB energy doubling operation, was designed and incorporated into the e-linac baseline configuration. Multi-pass parameter and error tolerance studies were performed. Hardware design of the beam separation system was carried out in some detail. The extended optimization platform is expected to be useful in finalizing this design.

Beam Breakup Threshold for E-Linac Recirculation

In view of a possible future extension of the e-linac to include a recirculation ring for high-intensity energy-recovered free electron laser (FEL) applications, the beam breakup (BBU) threshold as a constraint on SRF cavity higher order modes becomes a deterministic factor in the cavity design. A comprehensive study was carried out to obtain this threshold covering a wide range of recirculation optics, operation scenarios, and beam parameters. A universal criterion relating higher-order modes was found necessary to ensure suppression of beam breakup modes in recirculation operation up to 20 mA, safely above the design FEL current. This HOM criterion was made into one of the requirements for the e-linac SRF cavity.

Generalized Global Optimization Platform

Building on the framework developed to optimize e-linac beam dynamics, a project was launched under partial NSERC funding to develop an integrated, general purpose optimization platform built to rigorous software standards, enabling the global optimization of a wide range of beam delivery systems of arbitrary topology as a unique accelerator design tool.

The optimization software is implemented and tested. It is parallel capable and works in a distributed computing environment such as WestGrid. The XML input file provides flexibility in defining the optimization variables, constraints, parameters, and also the tracking engine topology. The software was applied to the design of the beam transport of the VECC test stand. The next phase of VECC assembly is the installation of the cryomodule and the 10 MeV dump. We propose to increase the beam size at the dump to reduce heating and create a restrictive "neck" in the upstream beam pipe to prevent backscattering at the dump. The software was used to search for the optimal optics to satisfy the objectives, using a combination of ASTRA and MAD. The optimization results show that the beam at the neck can be squeezed to sub-mm while at the dump the beam can be blown up to 6 cm, satisfying all objectives. The software will be used on further problems for the e-linac. Another problem involving CSR is underway in 2013. The objective is to find the chicane design that produces the best beam characteristics. This design should be useful for DESY and also TRIUMF in preparation of the energy recovery linac (ERL) design. New features involving prototyping are also planned.

Low-b Empirical Model for Online Modelling and High Level Applications

An efficient but accurate beam dynamics model suitable for high level applications at low energy (< 10 MeV for electrons), despite its importance, has not been developed for machine control anywhere. We attempt to bridge this gap with an online empirical model through capturing tracking results into interpolatable and polynomial-expandable data as inputs to an online empirical model. This is more efficient than on-demand tracking but more accurate than analytical models over a considerable range of beam and hardware parameters. Optimal physical data formats and software structures have been worked out to take advantage of the mature XAL framework developed at SNS (at Oak Ridge National Laboratory). On this basis several high-level applications have been created as demonstrations, and beta-tested against data taken from the VECC test facility.

Geant4-Based Tracking and Simulation

An important development in the field of computational accelerator physics is the application of the Geant4 simulation toolkit to the study of beam lines and accelerators. Geant4 makes advances on several fronts. Its state-of-the-art models of particle interactions in matter contribute to our understanding of particle loss processes, foils, collimators, beam dumps and other vital components, but Geant4 also provides a powerful tracking and ray-tracing tool. Its 3D geometry builder allows modelling of accelerators and beam lines in far greater detail than traditional tracking and optics codes; there is great flexibility in defining electric and magnetic fields; and it provides high-precision tracking in these fields with user-settable error controls.

Start-to-end Tracking and Simulation Models of Accelerator Systems and Beam Lines

Construction of start-to-end computational models is driven by advances in accelerator codes which have become more accurate and comprehensive. For the ARIEL electron linac (from the electron gun to the photo-fission target) we plan to employ state-of-the-art codes such as GPT and ASTRA, together with fully 3D tracking and geometry provided by Geant4, via the G4Beamline application. This scenario allows accurate beam line element descriptions via detailed field data, as well as the treatment of overlapping and ambient fields. The extensive development of scripts, data converters, and modifications will be required to achieve full inter-operability between the primary codes, as well as optics and tracking codes such as TRANSOPTR, DIMAD, and Accsim which are essential for the configuration, data preparation, and test-case validations.

The use of Geant4 allows the simulation model to include particle interactions in matter, for studying beam losses, and also allows the extension to multiple beam paths and energies, such as in an ARIEL recirculating ring for ERL/RLA applications.

The same collection of codes, centred around Geant4/G4 Beam Line at the most accurate level, can be applied to other TRIUMF beam lines, in particular towards the redesign of Beam Line 1A, and to sub-systems such as collimators, beam dumps/stops, and diagnostic devices.

The versatility of Geant4 in terms of field descriptions, as well as precise control over error propagation, prompt its use in computational studies of isotope separation. In designing the CANREB facility it will provide a useful adjunct to traditional analysis and ray-tracing codes such as COSY-Infinity and Zgoubi.

Visualization of Beams and Beam Lines

An indispensable part of developing and employing 3D beam simulations is to be able to interactively visualize the geometry and particle trajectories from any viewpoint and at varying levels of detail. By leveraging the basic visualization platform provided by Geant4 we have produced a prototype Open Inventor viewer with features useful for beam lines or other extended structures and have used it extensively in daily work. TRIUMF plans to modernize the user interface and extend this viewer in a number of ways to support accelerator physics applications and Geant4 applications in general. This tool will be useful in educational and media applications as well.

4.2.5.4 ACCELERATOR SCIENCE

Over the past five years, researchers at science have contributed to key progress in several topics in accelerator science including quadrupole magnet design and novel accelerator designs.

Quadrupole Shaping

As originally conceived, the multipole elements commonly used to control charged particle beams are two-dimensional. They correspond to solutions of the Laplace equation $\nabla^2 V=0$, namely, in polar coordinates (r,θ), $r^n x \cos(n\theta)$ in the system where the potential on axis is zero. Thus n=2 for a quadrupole, 3 for a sextupole, etc. This implicitly assumes the elements are infinitely extended in the axial z direction, and of course in real beam lines, they are not. For n=2, the intended linear dependence of the fields upon transverse coordinate is thus broken by the finiteness of the quadrupole. This results in nonlinear force terms and aberrations, often incorrectly blamed on the fringe fields when in fact the real cause is simply the broken symmetry of being longitudinally finite.

It is not obvious how to terminate the poles of a quadrupole. Often, they are simply truncated. For very long quadrupoles, it can be argued that hyperbolic equipotential surfaces given by $r^2 x\cos(2\theta)$ constant are optimal, but this is only true sufficiently far from the ends. However, for quadrupoles whose length is comparable to or shorter than the aperture, the 2D hyperbolic shape is clearly not optimal. We have analytically derived a new shape, and demonstrated that this shape yields smaller aberrations. Though the exact shape is impractical, for short quads it can be approximated with a simple spherical pole provided the sphere's radius is correctly chosen: it must be 1.54 times the quadrupole's aperture radius.

Quadrupoles with this spherical pole shape have been built and measured by Buckley Systems Ltd of New Zealand (see Figure 5). The field imperfections are found to be no larger than those of conventional long quadrupoles, and in some cases are significantly smaller.

Figure 5: Newly designed and built short quadrupole for ARIEL, as it arrived in its packing crate, February 2013.

Cyclotron Orbit Codes for FFAGs

In recent years fixed-field alternating gradient (FFAG) accelerator designs have generally been developed using synchrotron lumped element codes–or adaptations of them. But synchrotron codes are poorly adapted for use in accelerators with fixed magnetic fields, where the central orbit is a spiral rather than a closed ring, and the magnetic field must be characterized over a wide radial range. Cyclotron orbit-tracking codes, on the other hand, are specifically designed for such situations. We have evaluated the orbit properties of several proposed FFAG designs using two sister codes developed at TRIUMF: the equilibrium-orbit code CYCLOPS, and the accelerated-orbit code GOBLIN. A crucial preliminary stage in each case was the creation of a field grid in polar coordinates from the specified magnet positions, dimensions and strengths. We have also explored the potential of incorporating in cyclotrons the radial-sector-FFAG feature of reverse-bending magnets, in order to achieve maximum proton energies in the GeV region.

Poincaré Analyticity and the Complete Variational Equations

Work was done to generalize to all orders the usual first-order variational equations associated with any specific solution of any given (ordinary) differential equation. In so doing, it provides an explicit procedure for computing the Taylor map: the series that describe how the final conditions of a solution depend on the initial conditions and, if present, arbitrary parameters. Such Taylor maps are commonly used in accelerator design. They are expected to be of general utility for many other applications of ordinary differential equations including control theory. For example, it is illustrated that an eighth-order polynomial approximation (including parameter dependence) accurately reproduces the behaviour of the exact stroboscopic Duffing map including infinite period doubling cascades and strange attractors. This work has been published in Physica D with co-author A. Dragt.

4.2.5.5 EXTERNAL COLLABORATIONS

TRIUMF's success in accelerator science and technology is founded on a close collaboration with other key partners around the world. Several are mentioned here.

VECC Collaboration

The extensive collaboration with the Variable Energy Cyclotron Centre (VECC) in Kolkata, India, during the period of 2009–2013 is founded upon personnel exchange as a means to facilitate study of issues ranging from SRF system development to beam dynamics research and e-linac design optimization. In addition to SRF work, this sharing of skills and resources has greatly facilitated work on e-linac longitudinal and transverse dynamics optimization, electron gun beam dynamics modelling, beam breakup threshold studies, and beam-based measurements in the VECC test facility.

CERN Collaboration

The Canadian contribution to the LHC has continued in the form of beam dynamics studies, notably in beam-beam effects and their impact on LHC performance. For coherent beam-beam simulations TRIUMF is working with CERN physicists on developing a next-generation parallel code which can accommodate the complexities of the bunch population patterns in the counter-rotating beams and model their mutual electric-field effects in multiple interaction regions. An important step was to extend the electric field calculation from a soft-Gaussian model to a more accurate self-consistent model using a parallel grid-multipole method.

CERN is intensively pursuing plans for LHC future operations and upgrades, including the High-Luminosity LHC (HL-LHC). They wish to collaborate with us on studies of coherent beam-beam instabilities which may limit the LHC performance with increasing ranges of bunch populations, fill patterns, and active interaction regions. TRIUMF's part in this is the optimization and extension of our parallel self-consistent multi-bunch code COMBI to accommodate the operational scenarios and changes to interaction region components, together with the required output and analysis, as well as the validation of the COMBI code against LHC measurements.

When the LHC beams are brought into collision, a particle in one beam sees the Coulomb field of the other beam, which is strongly non-linear and repeats itself at every revolution. This unwelcome beam-beam effect is by design set at an unprecedented level in the present LHC. It also constitutes the largest obstacle for the High Luminosity LHC, planned for 2016. We have devised a mathematical model to describe incoherent (single particle) beam-beam effects of the more important, but difficult, long-range kind, the so-called parasitic encounters. The model was successfully applied to explain measurements made during dedicated Machine Development sessions at CERN, and promises to become an essential tool in designing the high-luminosity LHC upgrade.

Geant4 Collaboration

TRIUMF is a long-standing member of the Geant4 Collaboration devoted to developing, extending and supporting this software toolkit. The Accelerator Division contributes 0.25 FTE to the collaboration as part of our membership obligations. This work has focused on Hadronics, where we have developed and documented a process to extract cross-section data from the SAID interactive partial wave analysis facility and incorporate it into Geant4; and in Visualization, where we are developing a new visualization driver for Geant4 based on the Open Inventor (COIN3D) libraries and implementing features that are needed to streamline the viewing and navigation through beam line geometries or other extended structures.

XAL Collaboration

TRIUMF is a partner in the XAL collaboration in developing accelerator modelling and control infrastructure with the main purpose of self-contained and efficient online high level accelerator controls. This infrastructure is used worldwide in facilities such as SNS, SLAC, MSU-FRIB, ESS, GANIL, IHTP and other places. The collaboration aims to define a unified platform for all participant labs so that software developed for modelling and control can be shared. We requested and expect to take advantage of new models developed by the collaboration, such as electrical focusing elements. Tools developed at TRIUMF for XAL, on the other hand, including conversion between time-based and distance-based propagation modes, and low-b empirical model have been identified for inclusion in the next release package.

EMMA Collaboration

EMMA (Electron Model for Many Applications), funded for construction at the STFC Daresbury Laboratory in the UK in 2007 and completed in 2010, is a “non-scaling” FFAG accelerator designed to test the practicality of allowing particles to cross betatron resonances and follow a serpentine acceleration path in phase space (see Figure 6). TRIUMF contributions had been in three main areas: devising and analyzing the novel “serpentine” acceleration technique; choosing the basic design parameters for the ring and RF system, and setting equipment specifications for the RF system and beam diagnostics. This work culminated in tracking the electrons through the measured field of the prototype quadrupole magnets. This was carried out using the cyclotron equilibrium orbit code CYCLOPS, developed at TRIUMF, and confirmed that the orbit time and betatron tunes varied with energy in the ways anticipated. Further studies with its sister accelerated orbit code GOBLIN showed a small but acceptable growth in longitudinal beam emittance during acceleration. Since 2010 a series of experiments have been carried out by other members of the collaboration to evaluate the beam properties and behaviour. The main aims were to verify (i) that the beam could be accelerated through several betatron resonances without significant loss, and (ii) that TRIUMF’s proposed “serpentine” acceleration technique works. These aims have now been achieved, and a variety of more detailed information is emerging.

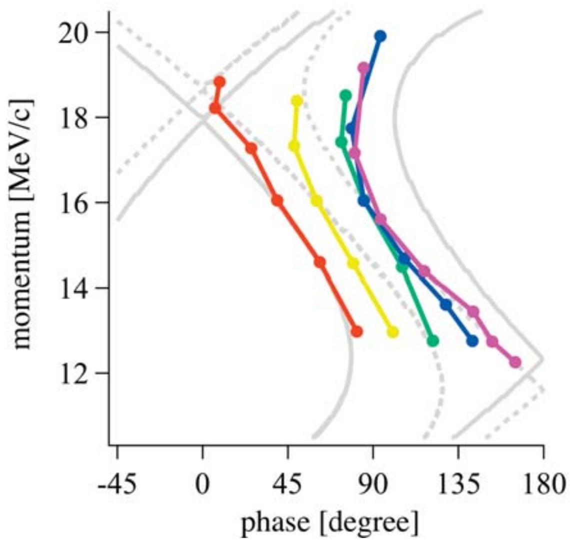


Figure 6: The observed serpentine behavior in momentum-phase space.

4.2.5.6 OTHER ACTIVITIES

Two undergraduate students at UBC plan to build a small (~1-MeV) cyclotron, emulating the successful efforts of a handful of North American students over the last 60 years. TRIUMF has agreed to provide laboratory space, redundant equipment and guidance. Once operational, this device will provide an ongoing resource for undergraduate experiments in accelerator and nuclear physics.

The project began in 2012 with a computer study of the pole shape needed to produce the desired magnetic field. The students are currently designing the vacuum chamber and investigating the RF requirements. They are also forming a Cyclotron Club at UBC, with the aim of involving more students in the project.

4.2.6 DETECTOR SCIENCE AND TECHNOLOGY

All experiments in particle and nuclear physics, as well as condensed-matter experiments at TRIUMF, require instruments to detect energetic subatomic particles. 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. New scientific opportunities arise from advances in detector capabilities, such as enhanced precision in kinematic properties; the rate at which particles may be detected, which leads to improved statistical precision; and in reduced costs, which make possible larger systems with greater sensitivity to rare processes.

Over the last several decades, TRIUMF's Detector Group has established a strong international reputation for developing, designing and constructing state-of-the-art detectors, as well as developing new detector technologies. A steady progression of new instruments has been successfully deployed in measurements at TRIUMF and in collaborative projects elsewhere in Canada and abroad. As was typical in previous years, every detector or detector element produced by the Group during 2008–2013 has performed as required, with no disappointments. These successes are noted in the corresponding descriptions of those experimental activities elsewhere in chapters 4 and 5 of this document; the detector facilities are described in section 5.5.4.

The Detector Group has broad expertise in various detector technologies, in particular related to scintillation and gaseous detectors. The most prominent example of scintillator construction during 2008–2009 was a close collaboration with the T2K collaboration in the construction of two large fine-grained plastic scintillator arrays for the T2K neutrino experiment in Japan, as described in Section 5.5.5.3. This was a large and ambitious project, successfully employing a new photo-sensor technology on a large scale for the first time. The group also provided the design concepts and construction techniques for a potentially commercial application of scintillator technology on a substantial scale to the identification of subterranean ore bodies through the detection of cosmic-ray muons by scintillator assemblies deployed underground, as described in Section 4.4.1.

The largest gas detectors constructed during 2008–2009 were three large Time-Projection Chambers for precisely tracking charged particles produced by neutrino interactions in the T2K Experiment. This was the first large-scale application to TPCs of a recently developed technology for sensing clouds of electrons drifting in the gas.

The Detector Development Group is focused on the investigations and applications of new detector technologies, for example leading to the application of the new optical sensors to the T2K project, and the design and construction of the signal processing and digitization electronic system. Upon completion of T2K, solutions were developed to enable the use of SiPMs in other applications: positron emission tomography, muon spin rotation spectrometers for smaller samples, radiation monitoring and in particle physics experiments like TREK at J-PARC, Japan, and possible applications for anti-Compton shields for the gamma-ray spectrometer GRIFFIN (please see Section 5.5.1.3). The Detector Development Group has been promoting the development of a new photo-detector solution by providing expertise and resources, and applications in large underground experiments like nEXO will be investigated.

The activities of the Group in this five-year period include:

Design and/or construction of detector systems:

- time projection chambers and active target fine-grained detectors for T2K
- submerged optical test system for Super-Kamiokande PMTs
- precise mechanics and vacuum coupling, 110-element CsI micro-ball detector, and PIN-diode wall, CsI wall detectors for TIP (TIGRESS Integrated Plunger)
- in-beam multi-sampling ion chamber and associated low-pressure gas system, target vacuum chamber with multi-detector deployment (silicon-strip wheels and associated segmented CsI) for IRIS in ISAC-II
- focal plane vacuum vessels and detector vessels, low-pressure wire chamber, and low-pressure gas supply system for EMMA in ISAC-II
- 500-scintillating fiber active target in dark-box for TREK experiment at J-PARC
- 280 large light-guides DEAP (dark-matter search at SNOLAB)
- gas detector for NEURAL tracking detector for astrophysics
- prototype high-resolution detector for Liquid Xenon (LXe)-PET for medical imaging
- Muon Tomography scintillator arrays for underground mineral search
- SPICE (SPectrometer for Internal Conversion Electrons) for TIGRESS at ISAC-II
- diamond detectors ATLAS Upgrade including irradiation tests
- 25 rad-tolerant scintillator/PMT assembles and 30 linear ion chambers for the ARIEL e-linac Machine Protection System

R&D on applications of silicon photo multipliers (SiPM):

- SiPM-based spectrometer for muon spin rotation
- SiPM-based solution for positron emission tomography

Detector electronics design and construction:

- trigger and readout electronics system for DEAP at SNOLAB
- amplifier/discriminator for diamond tracker of QWEAK at JLab:
- preamps for Silicon detectors of SHARC detector for TIGRESS
- preamps for silicon detectors, MCP readout for TRINAT
- front-end repeater upgrade and amplifier for microwave system for ALPHA
- modules for beam diagnostics of 500 MeV cyclotron vertical injection line

GEANT4 Collaboration for simulation of particle interactions and propagation:

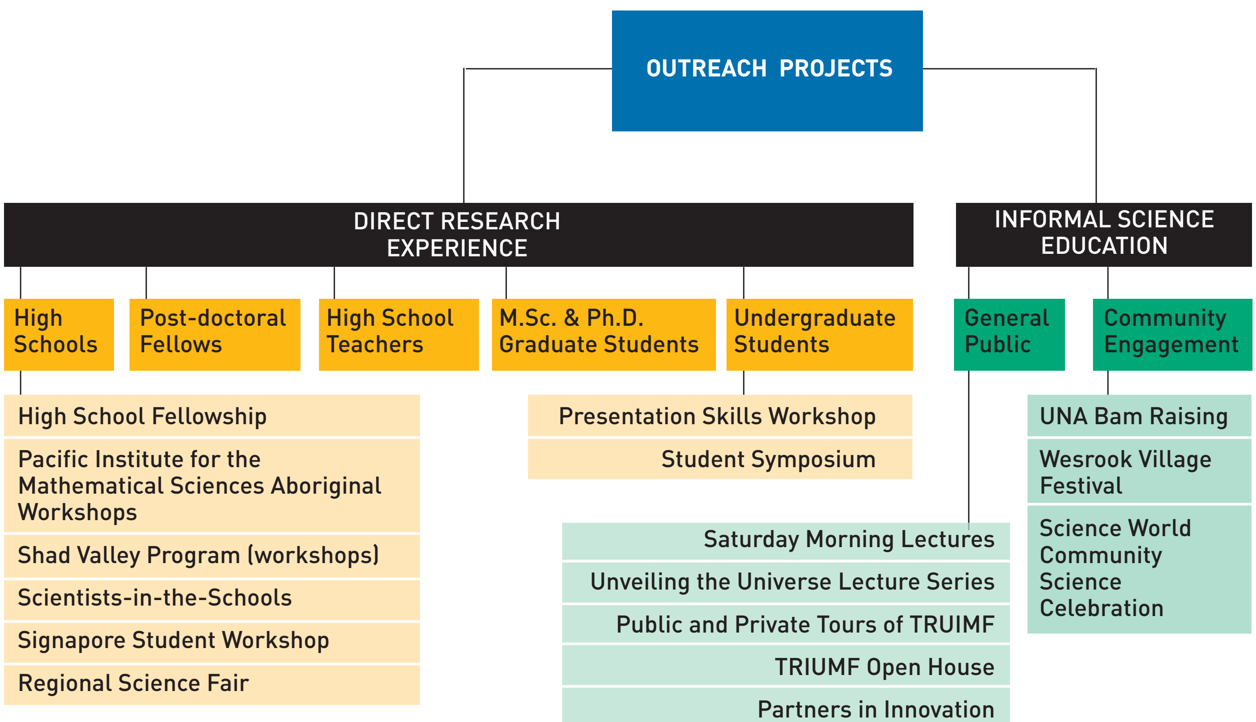
- Steering Board Member
- Deputy Working Group Coordinator (EM Physics, Basic/Extended Examples)
- Principal Developer: Optical Photon Physics and Fields Navigation
- System Testing Team and Publications Board Member
- User Consultation: HyperNews, Bug Report, User Requirements Report
- System Testing Team Member
- GEANT4 simulation support for experiments in the TRIUMF community: development of simulation code implementations
- Principle Developer: TWIST, PIENU, T2K/ND280 (TPC & FGD), Hyper-Kamiokande
- Team Developer: UCN/nEDM, ALPHA
- Consulting advice for a dozen experiments at TRIUMF

4.3 CREATING FUTURE LEADERS

The scientific enterprise generates three categories of benefit: advancing knowledge, creating future leaders, and generating societal and economic growth. This section discusses the second category: inspiring and attracting talent (see Figure 4.3-1 for an overview).

Sharing the process of research and development excites scientists and inspires participants, especially young students, to pursue training in science, technology, engineering, or mathematics (STEM). A solid STEM education in turn makes it more likely that such people will become leaders in research, business, social development, or public policy.

As a basic research laboratory, TRIUMF takes seriously its contribution to trained talent. The lab continuously seeks ways to enhance or adapt its practices to allow ever more students and members of the public to experience science, technology, and innovation activities. TRIUMF concentrates on those programs where its contributions can be unique and (increasingly) measured: offering direct research experiences for students (and sometimes teachers) and providing a number of informal science education activities. Strategic partnerships with other science promotion organizations are utilized to expand TRIUMF's reach and impact.



4.3.1 DIRECT RESEARCH EXPERIENCES FOR YOUNG PEOPLE

TRIUMF is a unique environment, bustling with international activity as teams of multi-disciplinary scientists, technicians, and engineers collaborate to conduct world-class research using ultra-sophisticated technical infrastructure. Everyday-normal to scientists, this environment is breathtakingly inspirational to students and members of the public unaccustomed to science. As such, the unique value of TRIUMF's outreach activities is offering "direct research experiences" to high school, undergraduate and graduate students, as well as teachers.

High School Students

In 2004 TRIUMF created the High School Fellowship program with the Science Council of British Columbia (now BC Innovation Council). The Fellowship consists of a $3,000 award and a six-week work term at TRIUMF, and attracts 60-100 applications from the very top high school physics students from across BC. One measure of the program's success has been the high return rate of Fellows as undergraduate co-op students, with several being taken on in their first year of university by former supervisors. The program now offers three Fellowship positions, and TRIUMF is actively coordinating with Science World at the Telus World of Science (including its Future Science Leaders program) to expand the Fellowships to even more deserving students.

TRIUMF also participates in the Shad Valley program and regularly hosts several young entrepreneurial students who assist with research and technology at the lab in multi-week work experiences.

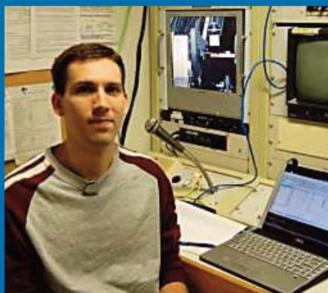
The laboratory worked with UBC, SFU, and UVic in launching ATLAS Master Classes in Canada (2011, 2012, and 2013). The program is spearheaded by CERN and creates daylong education and training sessions for talented high school students. The students learn about particle-physics data and analysis, work on real data from the ATLAS experiment, and then participate in an international videoconference to share their results with peers around the world.

The Vancouver School Board (VSB) and UBC established a working group dedicated to improving aboriginal educational opportunities. TRIUMF joined this group in 2008 and, for its initial pilot project in 2009, brought a Manitoba aboriginal high-school student, Dylon Martin, to TRIUMF for a six-week work experience. The goal was to inspire Dylon with a breadth of science outside his normal experience, and then have him share his experience with his peers. He spent a week each with five experimental groups and summarized his work in a weekly front-page web site story.[5] Since then, each summer has brought one or two aboriginal high school students from the Pacific Institute for the Mathematical Sciences to TRIUMF to experience cutting-edge research and technology with different research groups.

TRIUMF also works with many local high schools to offer work experiences or job shadowing experiences for student in grades 10-12. The high school work experiences provide students an opportunity to experience a 'real world' employment environment as well as the experience of working in a research laboratory. Each experience lasts between one and three weeks and is part of their high school curriculum.

Undergraduate Students

TRIUMF is among the largest employers of undergraduate students in Canada, attracting students from university co-operative education programs across the country. The positions are in high demand; almost every single opening attracts 50-75 distinct applications. Students are hired three times a year, at the start of each school term and are employed for a minimum of four months. The work term may be part of their co-operative education program or a summer work experience. In addition, the TRIUMF Undergraduate Summer Research Award offers five $2,000 scholarships every year to undergraduate students from each of Canada's five regions (Atlantic, Quebec, Ontario, Prairies, and BC) for summer research work. Students



STUDENTS DEMONSTRATION OF MUON-RELATED GLITCHES WINS AWARD

01 September 2011

Since 1995, the TRIUMF Proton and Neutron Irradiation facilities have delivered low-intensity, energetic proton and neutron beams to test sophisticated electronics, simulating years of natural-radiation exposures in space or terrestrial environments in just a few minutes.

Such tests probe the susceptibility of microelectronic devices to "soft errors" (switching a memory bit from 0 to 1, or vice versa). It has been known for over 30 years that natural proton and neutron radiation can cause such errors, but Brian Sierawski, a Ph.D. student at Vanderbilt University, reasoned that ever-smaller microelectronics might become susceptible to less-ionizing forms of cosmic radiation.

Sierawski and his Vanderbilt colleagues used TRIUMF's M20 beamline to demonstrate that soft errors indeed could be induced by low-ionizing muons produced in cosmic-ray proton interactions in the upper atmosphere.

Demonstrating muon-induced soft errors earned Sierawski the Top Student Paper award at the 2011 IEEE International Reliability Physics Symposium. With ever-shrinking microelectronics, Sierawski's work could impact the design of data servers, medical equipment, and aerospace technology. TRIUMF offers the only such muon beamline in North America for this research.

participate in activities as diverse as particle and nuclear physics research, nuclear medicine, engineering, accelerator operations, and communications and outreach. Some of their experiences were captured in blog posts and uploaded to the Quantum Diaries platform[6] and to TRIUMF's Headline News on its web site as well as several YouTube videos.

Undergraduate students are offered activities to enhance their experiences, including social events, weekly lectures, a Presentation Skills Workshop (with UBC), and the Student Symposium, where students give 10 to 15 minute talks to their peers for a chance to attend the Winter Nuclear and Particle Physics Conference in Banff. As a result, students consistently rank their TRIUMF experience very highly and many undergraduate students later return to TRIUMF as graduate students.

To fine-tune TRIUMF's involvement in high school and undergraduate education, TRIUMF's outreach coordinator began teaching entry-level university physics at UBC in 2011. Not only did he receive the highest ratings from students across the department, but he now determines what types of events and information are shared with students when they visit TRIUMF.

Funding Source		NRC		NSERC		CIHR		Other	Totals
Foreign Status	CAN	FOR	CAN	FOR	CAN	FOR	CAN	FOR	
FY2008–2009	56	3	5	1	0	3	4	0	72
FY2009–2010	53	5	2	1	0	5	2	0	68
FY2010–2011	60	6	3	1	0	6	0	0	76
FY2011–2012	58	4	9	2	0	4	1	0	78
FY2012–2013	58	3	10	1	0	3	1	0	76
SUBTOTALS		285	21	29	6	0	21	8	0
TOTALS		306		35		21		8	370

Table 1: Undergraduate students who worked at TRIUMF (and received stipends via TRIUMF) during the 2008–2012 period. Also shown is the source of funding and whether the students came to TRIUMF from Canada or abroad. Informal surveys of TRIUMF supervisors suggest that at least another 75 undergraduates worked at TRIUMF during this five-year cycle but were not paid through TRIUMF and therefore not tracked.

Graduate Students

TRIUMF's primary impact in university education is through graduate students, who come to TRIUMF from universities where they are participating in a degree program. Once at TRIUMF, each student works with a local supervisor to ensure that his/her learning and research are on track and will fulfill the requirements of their degree.

During the 2008-2012 period, graduate students working at TRIUMF completed 85 M.Sc. and Ph.D. theses. Two graduate students working at TRIUMF were also selected for the prestigious Vanier Canada Graduate Scholarships: Stephan Etteneuer (UBC) in 2009 for work in nuclear physics and Simon Viel (UBC) in 2011 for work in particle physics. In 2011, Patrick-Rey de Perio (Toronto) also received a Vanier Scholarship for work related to the T2K experiment, spearheaded by TRIUMF.

Funding Source		NRC		NSERC		CIHR	Totals
Foreign Status	CAN	FOR	CAN	FOR	CAN	FOR	
FY2008–2009	3	6	12	14	0	6	41
FY2009–2010	7	5	13	9	0	5	39
FY2010–2011	3	6	17	10	1	6	43
FY2011–2012	5	5	8	13	1	5	37
FY2012–2013	4	4	8	14	1	4	35
SUBTOTALS	22	26	58	60	3	26	
TOTALS	48		118		29	195	

Table 2: Graduate students who conducted research at TRIUMF and received stipends processed through TRIUMF's finance office. Students arriving from outside Canada are denoted as well, based on their residency status (SIN number).

Post-Doctoral Fellows

TRIUMF hosts advanced post-graduate training for many people. In the physical sciences, post-doctoral research experiences are an invaluable component of pursuing an academic career, a position in industry, or just in broadening one's research skills independent of career endpoint. Post-doctoral fellows (PDFs) at TRIUMF are usually supported with NRC or NSERC funds that focus the research contributions on specific topics. PDFs usually work on research in subatomic physics theory, experimental particle and nuclear physics, nuclear medicine, or accelerator physics and engineering. The experience at TRIUMF propels these researchers to become leaders in their field. For instance, Carleton's Dean of Science Malcolm Butler, Manitoba's chair of the physics department Peter Blunden, York University's Randy Lewis, former president of the Canadian Association of Physicists Shelley Page at Manitoba, and UBC's Javed Iqbal were all PDFs at TRIUMF.

	PDFs
FY2008–2009	40
FY2009–2010	44
FY2010–2011	44
FY2011–2012	46
FY2012–2013	49

Table 3: Post-doctoral fellows at TRIUMF. Six to eight PDFs each year are funded through the NRC Contribution Agreement.

High School Teachers

TRIUMF works with the BC Association of Physics Teachers to host a biennial professional development day for BC high school teachers. The event is at capacity every time with more than 75 teachers coming to TRIUMF for a full day to attend lectures, conduct hands-on experiments, and participate in teaching and instruction learning sessions. Over the five-year period 2008–2012, TRIUMF hosted the event three times (2008, 2010, 2012) and interacted with more than 225 teachers.

From time to time, TRIUMF also provides hosted internships for high school teachers to spend a week or two in the summer at TRIUMF during which they contribute to an active research project. Funding constraints and teacher availability have restricted the uptake of this offering.

TRIUMF also sponsors the Canadian Association of Physicists High School Teacher Award to promote and encourage enthusiasm for physics at the high school level. This award recognizes excellence in teaching physics in Canadian high schools and is awarded annually to four teachers across the country.

TRIUMF ALUMNUS RECOGNIZED FOR MO-99 PAPER

01 September 2010

On August 4, the TeraChem 2010 Committee awarded a Marino Nicolini Prize to Dr. Suzanne Lapi and her collaborators for their paper titled, "An alternative route to the production of High Specific Activity Mo-99". The paper is based on the MoRe isotope-separation project, sponsored by Advanced Applied Physics Solutions, Inc., located at TRIUMF.

Dr. Lapi was a graduate student at Simon Fraser University working at TRIUMF and is now an Assistant Professor at the Washington University, St. Louis Campus. The Nicolini Prize is dedicated to the memory of Professor Marino Nicolini, awarded based on innovation in the proposed work, principal applications foreseen, and beneficial impact on society. MoRe (Molybdenum-Rhenium) technology aims to purify Mo-99 by mass separation of a Mo-98,99 source mixture created from a nuclear reaction on stable Mo-98. Radioactive decay of the purified Mo-99 leads to 99mTc, the most widely used medical imaging isotope. The MoRe project is under active development, but once operational, it could have a significant impact on the "isotope crisis" currently facing hospitals and cancer patients.

4.3.2 INFORMAL SCIENCE EDUCATION

Informal science education has been identified as one of the crucial drivers of a modern, sophisticated society.[7] Informal science education, such as that conducted at zoos, museums, and research institutes, develops out-of-school learning that encourages lifelong learning, both "life-wide" (occurring across multiple venues) and "life-deep" (occurring at different levels of complexity). TRIUMF supports informal science education through a number of programs that provide public lectures, tours of the laboratory, and community engagement activities.

Public tours, educational programs, and outreach activities in the schools help guide young minds towards promising careers in science, technology, engineering, and medicine. In fact, informal science education targets all levels of curiosity and education backgrounds. At TRIUMF, the focus is programs that appeal to high school students and early university or college students. A side benefit is that these programs also attract the interest of mature adults interested in science and technology.

Saturday Morning Lectures

For over a decade TRIUMF has offered the Saturday Morning Physics Lectures in conjunction with the UBC and SFU Departments of Physics and Astronomy. These lectures are free and held one Saturday monthly, between October and April (except December). Guests are treated to two talks on topical subjects at a level suitable for a lay audience. The lectures have grown in popularity over time, so much so that the 100-seat auditorium was filled over capacity for most of the 2008–2009 and 2009–2010 series. Guests come from all over Vancouver and nearby municipalities and as far away as the Fraser Valley. Consequently the Lectures were expanded to include a second monthly presentation at SFU Surrey to better service guests from the east. The Lectures have attracted a devoted following of about 75% high school students and 25% adults. Future Lectures will be webcast with the new MediaSite system (operated in partnership with UBC) in an effort to extend TRIUMF's reach into communities further afield.

Partners in Innovation

In 2011, TRIUMF entered into a five-year cooperation agreement with Telus World of Science, British Columbia's leading science outreach agency for children from kindergarten through ninth grade. The Partners in Innovation program now combines TRIUMF's high school focus with Telus World of Science's younger-student focus to provide an additional opportunity for students to engage with and consider science, technology, engineering, and mathematics as a potential career path. Examples of new initiatives under this framework include: gallery space at the Telus World of Science building for student artwork generated after tours and studio time at TRIUMF; evening lectures for the public, featuring speakers such as CERN's Director-General; and summer camps for "future science leaders." The collaboration saw the outreach and communications groups from both institutions working together on a number of different facets of the program, ranging from facility coordination to social media marketing.

Unveiling the Universe Lecture Series

These at-your-doorstep lectures remain immensely popular, selling out in just a couple days and attracting curious minds to the OMNIMAX Theatre at the Telus World of Science, filling the 400-seat capacity. The demand for seats at these talks is so great that simulcasts of the talks are made available. One reason that the demand is so high is that the talks are given by leading scientists in their fields, working on some of the most exciting research and development currently taking place. Four examples are:

- Dr. Hitoshi Murayama, theoretical physicist and director of Japan's Kavli Institute of Physics and Mathematics of the Universe, discussed anti-matter, neutrinos, and (the still-elusive) dark matter, explaining how these enigmas fit into our understanding of the Universe.

- Professor Gino Segrè, physics professor emeritus at the University of Pennsylvania and author of three popular science books, presented "Physics in Florence from Galileo to the Higgs Boson" in which he charted the history of physics as it grew from the influence of Galileo, his disciples, and the spirit of exploration in 17th-century Florence, to the present day, with the most dramatic event being the recent discovery of the Higgs boson. This event was co-hosted by the Italian Embassy.

- Rolf-Dieter Heuer, the director-general of CERN, delivered an illuminating talk called "Unveiling the Universe." Heuer addressed why the search for the Higgs boson is so important and why the search for antimatter and dark energy are so integral to understanding the Universe, and our place within it.

- Dr. Lyn Evans, project leader for the Large Hadron Collider (LHC) construction, detailed some of the design features and technical challenges that make the LHC such an awe-inspiring scientific instrument. He discussed recent results from the LHC and what is next in the world of high-energy physics.

After each lecture, TRIUMF and Telus World of Science co-host an evening reception for community leaders to meet the speaker and local scientists and ask further questions. Where appropriate, these events have been co-hosted by the foreign consulates in Vancouver (e.g., German Consulate in Vancouver for Rolf Heuer, the Italian Embassy for Gino Segrè, the British Consulate in Vancouver for Lyn Evans).

Public Tours of the Laboratory

TRIUMF's public tours, which are typically led by selected TRIUMF staff or trained students, continue to attract nearly 3,000 people per year. Working with results from surveys as well as updated best practices from the expert science outreach and engagement community, the laboratory is presently revising its tours program to tailor tours more closely to the interests of schools and the community.

Category	2008-09	2009-10	2010-11	2011-12	2012-13
General Public					
# of people	475	1845	616	820	891
# of tours	143	150	179	208	214
Science					
# of people	666	1004	1581	1184	1089
# of tours	45	55	83	91	78
Students					
# of people	491	574	952	844	751
# of tours	23	26	37	47	35
VIP					
# of people	356	198	190	97	99
# of tours	72	54	38	28	41
Total					
# of people	1988	3621	3339	2945	2830
# of tours	283	284	337	374	368

Table 4: History of public tours at TRIUMF. Note that the Community Open House in 2009 elevated the results for that year.

Engagement with Formal Education

TRIUMF has explored contributing expert materials for high school curriculum usage. One foray has been the *Physics in Action* educational videos series. These videos relate and demonstrate the work TRIUMF does with high-school physics concepts being taught. The first pilot video (on relativity) was done on a small budget but in 2006 TRIUMF was granted funds by NSERC's PromoScience to create three new videos. In 2009, the relativity pilot video was re-edited to bring the look and production up to the standard of the second video, "Electromagnetism and Circular Motion in a Cyclotron," which was also completed in late 2009. This video's scope was the biggest project of its kind attempted at TRIUMF and has been enthusiastically received by teachers. The free DVDs, which included the new video, and the relativity re-edit, began shipping in early 2010 and to date almost a thousand copies have been distributed to teachers across Canada and around the world.

TRIUMF staff is also involved in the Canadian "Let's Talk Science" and "Scientists in the Schools" programs that send trained scientists into school classrooms. Since 2009, TRIUMF has also participated in Virtual Researcher on Call, which uses modern-day videoconferencing to connect classrooms with scientists for hour-long discussions on breaking news topics.

The BC Science Fair Foundation organizes elementary school science fairs in BC, with support extending to local, regional, national and international science fairs. TRIUMF annually supports travel expenses to the national science fair for regional winners.

American Association for the Advancement of Science (AAAS) Annual Meeting

The annual meeting of the American Association for the Advancement of Science (AAAS) was held in Vancouver during February 2012, marking the first time in 30 years that the meeting was held outside the U.S. TRIUMF was heavily engaged in the local organizing activities and was an active coordinator of national involvement. Working with the BC Innovation Council and the Government of British Columbia, TRIUMF organized the BC AAAS Student Scholar program that provided scholarships to 200 high school students from across the province. These scholarships allowed students to register for the conference and become members of the AAAS for a year. Students attended science sessions, met the Governor General of Canada, pressed speakers with questions about the forefronts of research, and contributed to the record-breaking attendance at the AAAS conference. TRIUMF also partnered with the UBC Department of Physics and Astronomy to host a double-wide booth at Family Science Days. Nearly 5,000 visitors dropped by the booth to talk about the Higgs boson, medical isotopes, and radiation.

Community Engagement and Participation

TRIUMF is regularly involved in several local neighbourhood festivals and at community picnics such as the University Neighbourhood Association's Annual Barn Raising and the local Wesbrook Village Festival, TRIUMF and the community get to know one another. TRIUMF wants to inspire confidence and pride in people living near and around TRIUMF and make them feel comfortable and safe and so far it's working.

TRIUMF also participates in the Community Science Celebration organized by Telus World of Science each year and contributes programming to Canada's autumnal National Science and Technology Week. Finally, TRIUMF was heavily involved in the BC Year of Science celebration in 2011 and organized an exhibit on science and art at the Royal BC Museum.

To reach larger audiences, TRIUMF has piloted a number of events to "meet people the lab wouldn't ordinarily meet." For instance, TRIUMF's communication team worked with theory post-doc Abishek Kumar on a dark-matter public talk that was featured in TEDxStanleyPark in early 2013. And research scientist Anadi Canepa was nominated and selected to participate in the Global Civic Society's Public Salon evening in April 2013 that featured short talks by "amazing individuals" in the Vancouver metropolitan area. Anadi's presentation received thunderous applause and generated new contacts and interest in TRIUMF, particle physics, and science.

Community Open House

The largest recent public outreach event was undoubtedly the 40th Anniversary Open House on August 8th, 2009, where over 1,300 enthusiastic adults and children took part in self-guided tours and physics demos and enjoyed free food. The Open House also demonstrated TRIUMF's community spirit—around 100 staff volunteered their time and energy to make the event a big success. TRIUMF is readying its staff for another open house in September 2013 which promises to attract more people than ever.

TIM MEYER RECOGNIZED AS TOP 40 UNDER 40

14 December 2011

TRIUMF's own Tim Meyer, Head of Strategic Planning and Communications, has been recognized as one of the Top 40 Under 40 by Business in Vancouver. Those who work with him at the laboratory know he is very deserving of this honour in recognition of his hard work and leadership.

Dr. Don Brooks, a member of TRIUMF's Board of Management, remarks that Tim "is one in a million and we are delighted to have him with us. This is a richly deserved award." Since beginning at TRIUMF, Tim has made great contributions to the lab's outreach, long-term planning and partnership efforts.

After earning his Ph.D. in experimental particle physics from Stanford University, Meyer Meyer worked for the National Academies in Washington, D.C., where he was a senior program officer on the Board of Physics and Astronomy. Arriving in Vancouver in 2007, at TRIUMF he focuses on public and internal relations, and oversees the scientific publication and outreach programs.

Artist in Residence Program

As the practice and inquiry of science becomes more integrated into contemporary culture, TRIUMF's Artist in Residence (AIR) program has become more and more relevant. The program—managed day-to-day by a pair of TRIUMF co-op students—exists to generate a broader interest in the imaginative and inspirational side of scientific inquiry through the impressions of visiting artists.

Through an initial partnership with faculty at the Emily Carr University of Art + Design, TRIUMF regularly hosts classes of artists-in-training who learn about black holes and other transformations of energy and then spend studio time at the laboratory generating new artwork. Building on these initial forays, TRIUMF has now developed collaborations with the School of Art and Design in Berlin, Germany (a partnership that successfully obtained funding from the Goethe Institute) as well as advanced programs of study at the University of British Columbia and Simon Fraser University.

The Global Particle-Physics Photowalk in August 2010 attracted more than 200 photographers around the world to behind-the-scenes tours of the participating laboratories around the world. A local Vancouver photographer was awarded first place by an independent jury of experts for his photograph of the 8π nuclear physics experiment. Output from the AIR program now graces the walls at TRIUMF as well as several buildings in the community.

In summary, TRIUMF's informal science education programs touched the lives of many people during the 2008–2012 period:

- 350 undergraduate and high school students participated in Virtual Researcher on Call, Scientists in the Schools, and Let's Talk Science programs involving TRIUMF scientists;
- 2,500 people attended public science lectures as part of programs at Telus World of Science, British Columbia, Global Civic Society's Public Salon, and TEDxStanleyPark; and
- 25,000 people interacted with TRIUMF booths and activities at events such as the University Neighbourhoods Association Annual Barn Raising, Wesbrook Village Festival, Telus World of Science Community Science Days, BC Year of Science exhibitions, and the American Association for the Advancement of Science Family Science Days.

4.3.3 OUTCOMES

Evaluating the impact of its direct research experiences for students as well as its informal science education activities is important to TRIUMF. Although the lab has several indicators that measure throughput and surveys to measure immediate satisfaction with events; longitudinal studies suffer from resource constraints. An informal survey of supervisors revealed, however, that students working in the TRIUMF environment tend to continue their success in academia, business, and beyond. For instance, after studying at CERN, students via TRIUMF end up at Canadian universities (25%), foreign universities (25%), government labs (25%), or in the private sector (25%).

Several young people participating in TRIUMF's direct research experience programs have received national and international recognition. For instance, Nick Zacchia was an undergraduate co-op student at TRIUMF in the Nuclear Medicine Division and ended up building a small electron accelerator for his Capstone project in Mechanical Engineering at Concordia University. As a result, he was selected to give the opening keynote address at TEDxKids@BC.[8] Elsewhere, Brendan Baartman at Simon Fraser University received the Coryell Award in Nuclear Chemistry from the American Chemical Society for his contributions at TRIUMF under the tutelage of Professor Kris Starosta. Similarly, Eric Price, a graduate student with UBC's Chris Orvig in the Department of Chemistry won the U.S.-based Society of Nuclear Medicine Berson Yalow award in mid-2013. Eric was a co-op student with TRIUMF senior scientists Mike Adam in the Nuclear Medicine Program a few years earlier, an example of how TRIUMF inspires students in multiple areas of scientific research and development.

Finally, the Subatomic Physics Long-Range Plan "Canada in the Age of Discovery" (2012) did some investigations into the career paths of undergraduate and graduate students working in subatomic physics. The overwhelming findings of that report indicate that these graduates have found careers broadly distributed through the Canadian economy, including:

- Business entrepreneur (software and engineering companies);
- Electronics and engineering;
- Finance (quantitative analysis, financial risk management);
- Geophysics
- Government (radiation standards, radioactive threats, defense);
- Medical imaging;
- Nuclear power (reactor design); and
- Software (web applications, data mining, programming).

Not all of these students were influenced by TRIUMF, but as one of the major engines of subatomic physics in Canada, TRIUMF finds itself in a unique position. With even more resources for more outreach programs, the lab could build on its successes and attract new generations of scientists (and science followers) to the wonder and excitement of scientific research and development.

4.4 GENERATING SOCIETAL AND ECONOMIC BENEFITS

The public at large, via taxes and support for the government, invests in scientific research. Around the world, the level of public investment in science continuously exceeds that of the arts and traditional cultural expression. The implicit assertion is that science generates an additional stream of benefits that merit these additional resources beyond the intrinsic cultural and aesthetic appreciation of knowledge. Traditionally, we associate this additional level of impact with the societal and economic growth that arises from the practice of science: both in terms of trained and motivated personnel and short- and long-term economic impact. In this report, the inspiration and attraction of youth to science is discussed separately and provided in Section 4.3.

> “Research in the sciences is fundamental to a 21st century economy. It underpins the continuing improvements in living standards that Australians expect and deserve.”
>
> Australian Department of Industry, Science, and Research, Oct. 2011

This section discusses TRIUMF's economic and societal impact over the past five years. It is organized to present results related to the activities of Advanced Applied Physics Solutions, Inc. (AAPS) followed by a report on innovation and industrial-partnership activities based at TRIUMF. The final topic examines models for measuring economic impact and presents results from a recent independent assessment.

TRIUMF & LOCAL FIRM JOIN ELITE LEAGUE ABLE TO PRODUCE SUPERCONDUCTING CAVITIES

14 April 2008

A team of B.C. scientists and engineers drawn from the TRIUMF laboratory and PAVAC Industries, Inc., announced today they have entered into an elite league of worldwide groups able to manufacture ultra-sophisticated superconducting accelerator technology. The B.C. team was able to fabricate, assemble, and test a high-tech device known as a "superconducting radio-frequency cavity" or SRF cavity. The modules are so technologically sophisticated that until now, only four other industry-based groups in the world have had the capability to produce them. 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 milestone is truly significant," said TRIUMF director Nigel S. Lockyer. "The push for this technology started in particle-physics research but is growing in demand all over the world. And Canada now has the ability to compete for and contribute to that market."

This technology is at the leading edge and rapidly expanding; laboratories around the world are lining up to incorporate it into their future projects. Literally tens of thousands of the devices will be needed over the next decade.

4.4.1 RESULTS FROM ADVANCED APPLIED PHYSICS SOLUTIONS, INC.

AAPS was created as a Centre of Excellence for Commercialization and Research (CECR) in February 2008 with initial support of $14.95M from the Networks of Centres of Excellence program of the Government of Canada (see Section 5.10 for a complete discussion). AAPS provides business-management and market-analysis expertise to TRIUMF and actively maintains a broad network of contacts and takes note of commercialization opportunities that may be relevant for TRIUMF and its partners (see Figure 4.4-1).

AAPS was the only physical sciences based CECR funded in the original tranche of 11 CECRs created in February 2008. The five-year award was scheduled to expire in early 2013. In summer 2012, AAPS was invited to apply for an extension of the performance period and to apply for additional funding. Results of the competition were communicated in December 2012 and the NCE Secretariat indicated that the CECR performance period for AAPS would be extended without adding new funds. Two considerations were (a) the level of unspent funds at AAPS at that time (close to $5M) and (b) the observation that AAPS might achieve self-sufficiency without needing new CECR investment.

The AAPS executive team has negotiated a new agreement with the CECR program that extends the performance period to 2017. The present governance structure (e.g., Board of Directors, NCE ex officio status, CEO & President) will continue.

AAPS expects to exhaust the CECR funds by 2015 and would then move out of that program. The extension decision has triggered several adjustments to AAPS and especially its interactions with TRIUMF. It is expected that this relationship will evolve further in 2015 when AAPS transition out of the CECR program. Briefly, AAPS and TRIUMF are moving toward improved synergies and cost-saving measures.

At end of FY2012–2013, AAPS has continued to maintain strong relationships with 23 partners this year and initiated new relationships. NDAs were signed with 6 companies to facilitate discussions on potential collaborations. Six MOU / Collaboration agreements were signed, 3 of which generate revenue. An inaugural “Innovations and Industrial Partnerships Workshop” was jointly organized by TRIUMF and AAPS in July 2012, where the directors and senior managers of TRIUMF’s member universities’ university-industry liaison offices came together to share best practices and explore collaborative opportunities.

Deal flow to AAPS comes from three areas (entrepreneurs who approach AAPS, TRIUMF’s network of industrial contacts and partners, and from within TRIUMF or its academic-research network). The ripest opportunities arise from TRIUMF’s relationships with existing vendors and its academic-research network.

IKOMED Technologies, Inc.

AAPS scouts for externally generated opportunities to incubate in the TRIUMF environment. Local Vancouver entrepreneurs generated an invention that would reduce the radiation exposure during standard medical fluoroscopy procedures, for example, inserting stents into the heart. AAPS recognized that the early stages of prototyping, software testing, and radiation modeling could benefit from a partnership with TRIUMF.

IKOMED Technologies, Inc. was launched as a start-up company in 2010, using a loan from AAPS, Inc., and floor space in the AAPS wing of TRIUMF’s main building. In June 2011, IKOMED secured its first round of private sector funding. This round enabled IKOMED to develop and test its technology for fluoroscopy radiation reduction. IKOMED has been granted the first of a series of patents by the U.S. Patent and Trademark Office and establish IKOMED’s intellectual-property position. Following

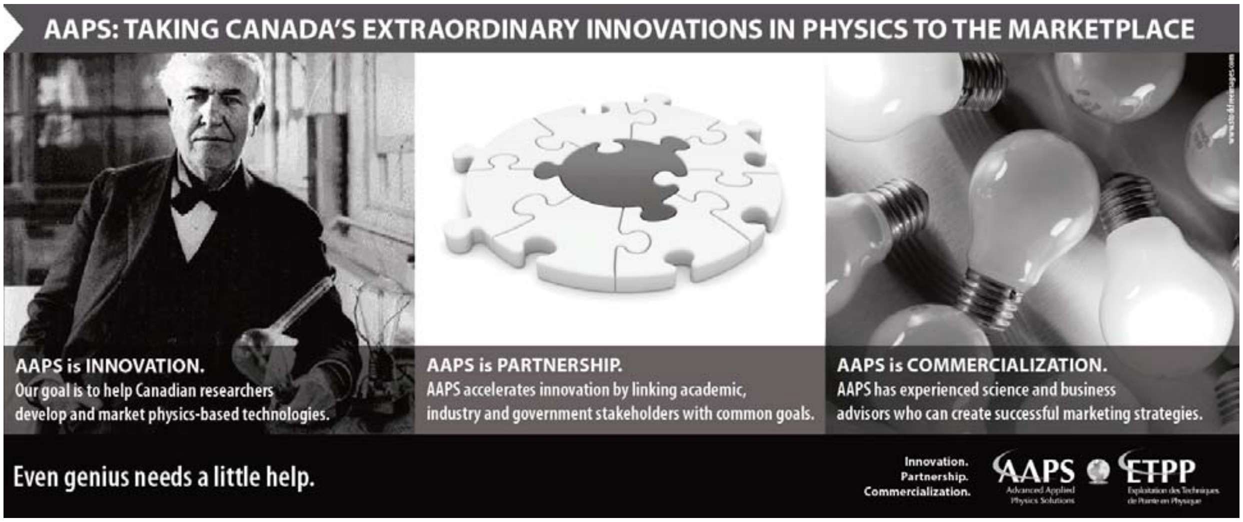


Figure 1: AAPS, Inc. serves as TRIUMF's key commercialization partner.

Figure 2: CRM Geotomography Technologies, Inc. is a recent spin-out from AAPS that seeks to use cosmic-ray muons for underground imaging of candidate ore bodies.

Figure 3: AAPS builds on TRIUMF's expertise in nuclear medicine to create new markets and opportunities.

successful demonstration of IKOMED's patented X-ray radiation reduction technology with commercial fluoroscopy imaging equipment, the start-up finalized its second round of private-sector financing totaling several million dollars. Led by a group of Canadian private investors, this latest round of investment will enable IKOMED to expand its product offering and build manufacturing capability for its X-ray radiation reduction system. AAPS provides incubator facilities throughout these initial start-up phases.

IKOMED has recently signed a terms sheet with GE Healthcare and will become a preferred provider of their proprietary dose-reducing shutter systems that integrate with existing fluoroscopy machines as well as new ones. Discussions with other fluoroscopy-system manufacturers are in progress.

CRM Geotomography Technologies, Inc.

In 2013, AAPS spun off a wholly owned for-profit company to commercialize intellectual property developed at AAPS with a TRIUMF/UBC inventor. The technology uses cosmic-ray muons, particle detectors underground, and proprietary electronics and software to identify ore bodies that lie underground between the surface and the detectors (see Figure 4.4-2). CRM is expected to be transferred to a third party for remuneration (i.e., the company will be sold for a combination of cash and long-term royalties subject to negotiation).

Geotomography detector units were installed at Nyrstar Price 13 mine on Vancouver Island, survey data collected at 12 locations and inverted using AAPS proprietary software, and images created of the rock density above the detectors. Units were installed in Novemeber at TECK Resource's Pend'oreille mine in Washington State with survey completion in June 2013. CRM will continue to pursue contract revenue from other partners.

GPN Petroleum Technology, Ltd.

In early 2013, AAPS signed a Memorandum of Understanding and has just signed a Cooperative Research and Development agreement with GPN to develop an advanced neutron well-logging system for use in detecting oil in underground deposits. GPN is investing $800k in the joint venture and AAPS in investing $400k (in August 2013, the first $400k from GPN was received). Upon successful completion of this project a Canadian controlled company will be established to manufacture and market the product.

Advanced Cyclotron Systems, Inc. High-Resolution Separator

A key element of TRIUMF's future success in rare-isotope physics is the ability to select and separate out rare isotopes from a milieu of products generated in a target. One tool of the trade is a high-resolution magnetic separator (HRS). TRIUMF may have built one of these devices on its own as part of the ARIEL project; however, AAPS recognized that a niche, global market existed for these devices.

AAPS put together a business framework that proposed the transfer of HRS technology from TRIUMF to a Canadian company as part of a deal to deliver the first HRS magnet to TRIUMF and to make future sales to laboratories in Switzerland, France, Germany, Japan, and India. The framework was approved by the AAPS Board of Directors. After scanning the industry, Advanced Cyclotron Systems, Inc. (ACSI) of Richmond, BC, expressed serious interest in the core technology and the future business opportunity.

AAPS is now assisting ACSI with developing and delivering a high-resolution magnetic separator valued at ~ $2.5M to TRIUMF while building capacity for worldwide sales of the technology. AAPS will invest $1.2M and ACSI is investing several hundred thousand dollars. When complete, ACSI will be able to market and deliver these high-precision magnets for isotope separation to dozens of major research laboratories around the world. AAPS will recover its initial investment and TRIUMF will provide technical back-stopping to ACSI with an ongoing service and royalty model. The final details are presently being worked out.

PAVAC Industries, Inc.

AAPS guides TRIUMF on opportunities to convert industrial R&D relationships into protected, licensed, royalty generating partnerships. As mentioned earlier, TRIUMF has been working with PAVAC Industries, Inc. to manufacture SRF cavities for advanced accelerators. When PAVAC indicated an interest to move from manufacturing and selling SRF cavities valued at a few hundred thousand dollars to manufacturing and selling the full cryomodule system valued at a few million dollars, AAPS proposed a structure for developing and licensing this know-how and intellectual property to PAVAC in a way that was transparent and offered downstream revenues. The first cyromodule manufactured by PAVAC will be sold in India. The company is presently negotiating contracts with Korea as well.

The world market for these superconducting devices is expected to grow, and quite dramatically, well into the next decade with applications in healthcare, environmental mitigation and remediation, advanced materials science, and high-energy physics. With an international interest in developing applications for this technology and building the industrial capacity to supply the demand, Canadian capability assures the country a good share of the global market since there are a limited number of companies capable of producing these devices.

Through its involvement with TRIUMF, PAVAC has expanded from 9 to 55 employees in five years and has tripled its floor space at its Richmond plant.

Tc-99m Target Commercialization Company

The advent of the medical-isotope crisis in late 2007 triggered TRIUMF's participation in a national effort to develop cyclotron-production of Tc-99m (see Section 4.2.3.2). AAPS is playing a key role in developing business plans, assessing market conditions, and advising on where to "monetize" this disruptive technology (see Figure 4.4-3). AAPS is providing seed capital to launch a company (ARTMS, Inc.) that will commercialize the intellectual property associated with the new supply chain (i.e. target manufacture and recycling). TRIUMF's intellectual property is rooted in the challenge of target geometry including fabrication, mounting, and recycling after production. A provisional patent has been issued.

4.4.2 RESULTS FROM TRIUMF'S INNOVATION AND INDUSTRIAL PARTNERSHIPS

In addition to direct commercialization opportunities pursued with AAPS, TRIUMF engages in innovation and industrial partnership activities that generate commercial revenues and build powerful relationships.

Commercial revenues flowing to TRIUMF during the 2008–2012 period are shown in Table 1.

	Total	2012–13	2011–12	2010–11	2009–10	2008–09
Royalties						
Nordion	4,879,360	580,745	999,812	1,546,033	1,019,872	732,898
D-Pace, Other	87,655	9,233	13,713	24,924	24,965	14,820
Subtotal	4,967,015	589,978	1,013,525	1,570,957	1,044,837	747,718
Other Income						
PIF & NIF	1,720,768	204,753	330,451	451,837	733,727	0
F-18 Production	1,688,320	39,600	3,300	493,760	490,196	661,464
Miscellaneous	689,886	293,134	94,652	112,114	69,447	120,539
Subtotal	4,098,974	537,487	428,403	1,057,711	1,293,370	782,003
Grand Total	9,065,989	1,127,465	1,441,928	2,628,668	2,338,207	1,529,721

Table 1: Commercial revenues flowing to TRIUMF for the past five fiscal years.

Nordion, Inc.

Every year Nordion, Inc. produces 2.5 million patient doses of medical isotopes from its TRIUMF-based manufacturing facility and its three dedicated medical cyclotrons. Headquartered in Ontario and with sales of $15M-$20M each year from this plant, Nordion is a successful publicly traded company. Nordion co-located its cyclotron-production facilities with TRIUMF because of the laboratory's national and globally unique expertise in cyclotron maintenance, repair, operation, and development. A dedicated Applied Technology Group of about 30 FTEs operate Nordion's cyclotrons at TRIUMF and funded by Nordion. This group provides an extraordinary level of reliability and performance for Nordion's machines. This activity generates a royalty revenue stream for TRIUMF as well as enormous value to patients around the world. Nordion and TRIUMF received the 2004 NSERC Synergy Award for Innovation that recognized "best practices" between the commercial and public sector.

In other examples, TRIUMF produces specific isotopes under contract, such as silicon-32 for the U.S. labs at Oak Ridge and Los Alamos.

PIF & NIF

TRIUMF's PIF (proton irradiation facility) and NIF (neutron irradiation facility) represent a competitive option for computing, networking, and aerospace companies seeking irradiation testing of their equipment. Companies pay TRIUMF for the right to access of beam and technical staff time and leave with enhanced understanding of their products, or even with certification of their products to operate in a radiation environment.

Over the past few years, many PIF & NIF customers have requested more and regular access to our high-energy facility BL1B because, while the peak of the energy distribution of protons in space is at roughly 100 MeV, the distribution does extend as high as 500 MeV. This makes testing with higher energy protons crucial.

There are very few places in the world that can offer such high neutron energies for testing; alternatives include the facility at the Los Alamos National Laboratory in the U.S. and the Svedberg Laboratory in Sweden. With access to Los Alamos sometimes difficult, a shutdown of the Swedish facility a possibility, some customers began looking for a replacement testing facility. In particular, Cisco Systems, Inc. approached TRIUMF with the idea of performing all of its focused neutron-beam testing using BL1B. TRIUMF management agreed to proceed, and the upgrade began in 2012 with Cisco Systems investing $150k. This arrangement was brokered by AAPS, Inc. Table 2 summarizes industrial use of PIF & NIF over the past five years.

PIF & NIF Commercial Use	Number of Companies	Beam Time
2008	42 companies	737 hours
2009	39 companies	610 hours
2010	39 companies	711 hours
2011	36 companies	589 hours
2012	43 companies	667 hours

Table 2: Industrial use of PIF & NIF irradiation services at TRIUMF for the past five years.

As discussed in Section 4.2.4.6, PIF & NIF also provides beam time for academic research.

Training and Transfer of Skilled Personnel

Although difficult to model and predict, certain individuals trained at TRIUMF (either as students or as professionals attending workshops and conferences) will go on to develop technologies, start businesses, and pioneer disruptive technological advances. In the absence of a key metric, several examples are reported here.

D-Pace, Inc. is one example of the highly qualified personnel aspect of TRIUMF's impact. D-Pace was co-founded by Morgan Dehnel in 1995 after he earned his Ph.D. from UBC based on his doctoral studies at TRIUMF. The company started as a specialized contract engineering design firm catering to research facilities and private companies in the accelerator industry. Dehnel says that his company "owes its existence and almost all of its knowledge base to TRIUMF. This includes Ph.D. training, intellectual technology transfer in accelerator-related physics and engineering, technology license agreements, and business advice related to the licensed technology items. TRIUMF and D-Pace work together in a truly team effort." In 2007, the TRIUMF and D-Pace partnership was celebrated with an NSERC Synergy Award for Innovation.

Another example is Moe Kernani. Trained by TRIUMF as a physics Ph.D. at UBC, Kernani is Vice President of NetApp, Inc., a leading provider of enterprise data storage solutions. Prior to that Kernani was President and CEO of Bycast Inc., the world leader in storage virtualization software for large-scale digital archives and storage clouds. Bycast was acquired by NetApp in the spring of 2010. Kernani currently serves on the board of directors of the British Columbia Technology Industry Association. He is a recipient of the *Business in Vancouver* "Forty under 40" award and was named the BC Technology Industry Association's Person of the Year for 2011.

A final example is Juergen Wendland, a 2003 particle physics Ph.D. student who worked on HERMES at Simone Fraser University and TRIUMF and later was a post-doctoral fellow on T2K and SNO. He currently leads a group of quantitative analysts in a financial software company in Surrey, BC, called FINCAD.

During the 2008–2012 period, TRIUMF organized several dozen conferences in Canada that resulted in 39,000 person-days of visitors spending funds on lodging, food, and entertainment. The result is a five-year economic impact of about $9.8M. Given that most people attending such international conferences are from outside of Canada, the money they spend on food, lodging, and other purchases is an economic benefit to the region and to Canada. This has had a high degree of success given the international scientific reputation of TRIUMF.

Societal Benefits

TRIUMF provides research experiences and informal science education activities for students, teachers, and the public. As part of the "STEM to STEAM" movement (Science, Technology, Engineering, and Mathematics to S,T,E, Arts, and M), TRIUMF has an arrangement with Emily Carr University of Art + Design that created an Artist in Residence at TRIUMF and a Scientist in Residence at Emily Carr. This team coordinates science-art interactions students and faculty (see Section 4.3). In August 2013, the director of TRIUMF and the president of Emily Carr conducted an evening debate in downtown Vancouver discuss the role of the "creative economy" in driving progress and growth; the event launched a one-year program that will place TRIUMF research scientists in student art studios at Emily Carr on a regular basis.

TRIUMF uses beams from the main cyclotron to provide proton therapy for ocular melanoma patients primarily from across Western Canada (see Section 5.6.3 for details). Since 1995, patients with ocular melanomas have come to TRIUMF to receive treatment, achieving a local tumour control of 91%. Between April 1, 2008 and April 1, 2013, 40 patients were treated with protons during five scheduled treatment sessions each year. This brings the total number of patients treated with protons at TRIUMF since the start of the program to 170.

After ARIEL is commissioned, TRIUMF's cooling-water plant will be regularly discharging 8-10 MW of waste heat from the main accelerator facilities at the laboratory. The nearby UBC campus has made a public commitment to sustainability and is exploring options to develop a district-energy system for pooled and shared heating and cooling for a complex of residential housing of several million square feet. The heating requirements for this neighbourhood would vary seasonally but would be less than 10 MW at peak times. The estimated savings in carbon emissions is expected to be in the order of 13,000 ton per year.

Laboratories in Europe, particularly the European Spallation Source (ESS), are pioneering efforts to connect these "suppliers" and "consumers" of heat energy. The ESS has committed to operating as a carbon-neutral research-intensive facility. In Switzerland, the PSI laboratory already provides some heating of the local neighbourhood by repurposing waste hear from its research facilities.

Together, TRIUMF and UBC are exploring the feasibility of a pilot project that would use the waste heat from TRIUMF's cooling systems to generate heat and/or energy for the nearby residential areas. This district-energy system would be the first of its kind in North America and would demonstrate a new level of energy efficiency and innovation as well as the value of partnering to achieve greater level of sustainability.

A process is now in motion to select the private partner that would work with UBC and others including TRIUMF to deliver a viable neighbourhood utility using the district-energy concept. UBC will with the selected partner to perform due diligence on project feasibility and enter a period of exclusive negotiation in order to prepare Definitive Agreements. These Agreements would then be submitted to the BC Utilities Commission for regulatory approval, if UBC decided to move forward with development of the system with that partner. A Request for Information was issued in early 2013 and Project Information Sessions were held in March 2013. Shortlisted candidates have been interviewed and negotiations are being completed with the successful company.

TRIUMF has already made some adjustments to ARIEL infrastructure in order to accommodate this opportunity.

4.4.3 RESULTS FROM MODELING ECONOMIC IMPACT

Several approaches are used to measure the impact of scientific research, although none purport to capture it in a systematic and conclusive way. "Narrative summaries" of technological advancement arising from scientific research often focus on conjectures and reports of active exploration of potential applications. Some use "input/output models" that are indexed by spending via the laboratory—sometimes separating out labour and sometimes lumping direct capital with labour—include direct, indirect, and induced economic impacts of the spending. Others include opportunity costs, social safety nets, and/or open/closed models for induced economic impacts. At other times, these input/output models are parameterized with a representation of a laboratory's activities, one that uses a proportional combination of existing multipliers based on the sectors in which the laboratory operates (e.g., higher education, forestry, pharmaceuticals, and contract research services) or by directly inputting the laboratory's spending patterns into an economic model of regional economic activity. The "data collection model" uses analysis and interpolation of sample economic activities (e.g., spin-off companies and sole-source consulting/service contracts). Yet another model measures "talent" and/or activity concentration in terms of uniqueness, value added, or development/maintenance of an absorptive capacity for scientific developments.

Approaches and Limitations

One limitation to these present-day economic impact models is their limited utility in capturing and projecting the powerful underlying contributions of science-driven breakthroughs. No contemporary economic impact study is able to project which developments in science will generate whole new industries and technologies akin to quantum mechanics, transistors, computers, and e-commerce although some economists say they are able to measure retroactively the inputs that led to these outputs.[9]

TRIUMF itself has not developed a model of economic impact; that is, the laboratory does not maintain a system of "mechanisms" that relates specific activities and decisions to future impacts, nor does it maintain a matrix of metrics or indicators that images these impacts. Instead, we rely on the opinions, models, and assessments of other experts for authoritative statements of TRIUMF's economic impact. Two such examples are 2009's "Economic and Social Impacts of TRIUMF" by MMK Consulting, and, more recently, the May 2013 "Return on Investment in Large Scale Research Infrastructure," by Hickling Arthurs Low (HAL).

With respect to measurement in general, the HAL study makes the following observations:

This raises an important question: "If fundamental, curiosity-driven, research is economically important, why should it be supported from public, rather than private, funds?" There are a number of classic economic arguments for why government should support basic research, all based on the concept of "market failure", the idea that the free market, if left to itself, will under-invest in science. These arguments are founded on the belief that science is in the public interest and therefore is deserving of pursuit.
...
Because basic science is in the public interest, and because it is supported by the public, there is a strong rationale for making scientific information freely available. Because no one is excluded from using the information, and it is freely available, scientific information is, in economic terms, a "public good".
[HAL, p18]

This observation records what is considered to be conventional wisdom: Science is good the economy, but the challenge is how to measure and manage that benefit for optimal returns. TRIUMF is no exception, and in this discussion, we press on both the academic approach as well as where conventional wisdom tells us to look for impacts.

One of the difficulties in assessing TRIUMF's benefits is finding a way to measure downstream, value-added benefits are hard to capture in present-day modeling. HAL explicitly notes that while TRIUMF derived technologies have, for example, created Advanced Cyclotron Systems, Inc., a 110-employee company that manufactures and sells compact medical cyclotrons, the downstream impact of these sales and their subsequent operation (e.g., the Edmonton, AB, acquisition of a TR-24 device from ACSI that will generate medical isotopes and directly impact the quality of healthcare for tens of thousands of Alberta patients dealing with cancer over the next decade) is something that cannot be measured and is therefore discarded as a measure of output value and impact [HAL, p61]). In another recent example, TRIUMF has agreed to provide radiotracers via the BC Preclinical Research Consortium for use at the Centre for Comparative Medicine for two separate companies to benchmark their drug-development processes (one of Lou Gehrig's disease, the other for protein markers associated with neurodegeneration). This involvement is critical for those business but has not yet created measurable, independent benefits.

In addition, the HAL study notes explicitly that, the "…return from a million dollars worth of technology development is essentially the same as from a million dollars worth of road building (or any other activity)" [HAL, p10]. This statement sets aside the challenge of understanding the distinct difference in economic value of labour-driven activities and high-technology goods and services activities. Put another way, quantification of the difference in value between digging trenches and manufacturing high-technology devices for international sales and distribution is difficult for present-day economic models.

Perhaps one of the largest challenges in prospective studies of economic impact is attribution, i.e. what proportion of Company X's true value and revenues is directly attributable to its interactions with Scientific Research Establishment Y? Some studies use surveys and interviews to try and measure this attribution; others use document reviews and direct observations from investors or valuators. In reality, however, cause and effect is a human-perception phenomenon. The real world is more arbitrary and complex.

> "The outputs of basic research rarely possess intrinsic economic value. Instead, they are critically important inputs to other investment processes that yield further research findings, and sometimes yield innovations."
>
> P.A. David, D.C. Mowery, and W.E. Steinmueller,
> Center for Economic Policy Research, Stanford University

Finally, the ultimate challenge for economic impact models is establishing causation. In the simplest sense, "Which investment at what moment of time will give rise to what economic impact?" The economic impacts of science are often expected to accrue over the course of a decade, even of a complete generation. In this manner of speaking, it would seem most appropriate to consider economic inputs to TRIUMF from 1995–2005 to be cross-correlated with output measures in the 2005–2015 timeframe.

Moreover, the HAL study notes,

Despite the difficulties in quantifying the social and economic benefits, the basic policy rationale for supporting research is now effectively beyond political debate, with relevant policy discussions concerned not with whether to fund research, but how best to support research to achieve maximum benefit."
[HAL, p17]

In short, "everybody knows" that basic research is good for the economy, but a systematic framework to monitor and manage these impacts is still missing. Nevertheless, and despite all these challenges, HAL collected considerable date from TRIUMF and contacted several leading industrial partners. The HAL analysis was based on three inputs: expenditures by TRIUMF and AAPS in Canada, revenue by Canadian businesses attributable to their relationship with TRIUMF, and spending by delegates to scientific conferences located in Canada as a result of TRIUMF's hosting role.

Results

HAL found that four Canadian businesses have significant revenues that are attributable to their relationship with TRIUMF: Nordion, ACSI, D-Pace, and PAVAC. The value of these revenues was adjusted to prevent double counting by accounting for royalties paid to TRIUMF, contracts with TRIUMF, and fees for services from TRIUMF. The adjusted total of these revenues is $249.7M over the last decade.

Combined with a narrative that addresses disciplinary metrics, cross-disciplinary metrics, and strategic metrics, the study reported the following:

TRIUMF has received $630 million over the last ten years, of which $541 million was grants from public sources and $16 million was commercial revenue. The remaining $73 million was flow-through transfers from other organizations. During that time, TRIUMF spent $622.4 million on operating and improving its facilities, realizing an increase to fund balances of $7.3 million. AAPS has received $12.4 million since it was created four years ago, of which $11.3 million was grants from public sources, and $1.1 million was commercial revenue. During that time, AAPS spent $11.8 million on its operations, realizing an increase in balances of $0.6 million.

As a result of that investment, TRIUMF and AAPS had a direct GDP impact of $424.9 million for the study period; the total GDP attributable to TRIUMF and AAPS was $941.1 million. British Columbia has received 80% of this total [Hal, pg. iii].

Over the past decade, direct economic impact totaled $424.9M; indirect economic impact totaled $181.3M; and induced economic impact was $334.7M. These values come from an input/output economic model developed by HAL. The total impact for Canada from TRIUMF over the last ten years was 11,733-person years of employment. About 82% of this was in British Columbia, and 45% was a direct effect.

In addition, HAL examined TRIUMF's return on investment from five perspectives: the return to British Columbia, the short-term return to Canada, an investment choice return, the long-run return to Canada, and the return to government.

Return to British Columbia

All but $27.3 million of $552.2 million, or 95%, of TRIUMF's and AAPS's public funding has come from federal sources. Given that British Columbia's GDP is about 12% of the Canadian total, BC's total involvement in the economic model for TRIUMF can be estimated at $90.3 million, with the remainder coming from the rest of Canada. For this, BC received an increase in its GDP of $752.3M; a return of 8.3 times their investment.

Short-Term Return to Canada

In the short-term, public spending on TRIUMF is a stimulant to economic activity. The $552.2M of public spending resulted in an increase of $940.9M in the country's total GDP for a return of 1.7 times the investment. Note that the MMK 2008 study reported on this same indicator and found a similar multiplier of 1.91.

Investment Choice Return

Investment in TRIUMF creates indirect and induced economic impacts, but then so does most other investments of public money. Therefore, under this model, the indirect and induced impacts are irrelevant; the direct impacts are the ones that should be used to compare investment choices. From this point of view, the $552.2M of public spending resulted in an increase of $424.9M in direct GDP for a return of 0.77 times the investment.

Long-Run Return to Canada

In this perspective, HAL narrows the economic model to pure loan and return-of-principal economics, ignoring societal benefits altogether. Accordingly, they say that public spending on TRIUMF contributes to the nation's debt, which in the long run must be paid back. From this point of view, the public expenditures should not be considered as contributing to the benefit. This leaves $291.1M of the increase in the country's total GDP, for a return of 0.53 times the investment.

Return to Government

From one view of government, the return on investment in TRIUMF comes from the increase in taxes generated. From this perspective, the $552.2M investment of public money resulted in an increase of $252.3M in tax revenues for a return of 0.46 times the investment.

It should be noted at this point that TRIUMF generates economic benefits that were not included in the HAL return-on-investment calculations, including:

- Future business revenues: technologies developed which have not yet been commercialized;
- Past business revenues: prior to the last 10 years;
- Consumer surplus benefits: some firms will receive additional benefits and stimulus from interactions beyond the specific services they charged for;
- Technology diffusion benefit: those benefits attributed to personnel trained at TRIUMF who went on to achieve benefits elsewhere; and
- Skills improvement benefits: the improvement in a company's expertise and competitiveness as a result of working with TRIUMF.

4.4.4 CONCLUSION

TRIUMF has had definitive successes in stimulating societal and economic growth, and documenting these impacts is an active challenge. Be it the patients who have retained their eyesight by proton therapy to treat their ocular melanoma or the jobs created by ACSI's success in selling TRIUMF-designed cyclotrons around the world, the laboratory is fueling the innovation chain.

Salter and Martin paraphrase the OECD: "Knowledge and information abound, it is the capacity to use them in meaningful ways that is in scarce supply." Therefore, as they say:

"No nation can "free-ride" on the world scientific system. In order to participate in the system, a nation or indeed a region or firm, needs the capability to understand the knowledge produced by others and that understanding can only be developed through performing research. [HAL, p19]

With TRIUMF's network of international connections (see Section 3.2.2), the laboratory ensures that Canada stays abreast of key science and technology developments in subatomic physics and nuclear medicine around the world, thereby contributing to overall competitiveness and, more importantly, the ability to absorb and distribute breakthroughs for Canadians.

[1] Source: Heart and Stroke Foundation
[2] Source: Charity Intelligence Canada
[3] Source: Canadian Mental Health Association
[4] Source: Alzheimer's Society of Canada
[5] See, for example, http://www.triumf.ca/research-highlights/student-stories/dylons-corner-where-physics-medicine-collide.
[6] See http://www.quantumdiaries.org, a globally shared blogging platform organized by the InterAction Collaboration of communications leaders at the world's major particle-physics laboratories.
[7] National Research Council, Surrounded by Science: Learning Science in Informal Environments, Washington, D.C.: National Academies Press, 2009.
[8] See http://www.triumf.ca/research-highlights/student-stories/former-student-builds-mini-accelerator and http://www.triumf.ca/headlines/current-events/past-triumf-student-tedxkidsbc.
[9] See, for example, B. Godin and C. Doré, "Measuring the Impacts of Science: Beyond the Economic Dimension," retrieved from URL http://www.csiic.ca on 01 Aug 2013; R. Solow, "Technical Change and the Aggregate Production Function," Review of Economics and Statistics, 39, August, pp. 312-320; and Smith, Llewellyn (1997) "What"s the Use of Basic Science?" http://www.jinr.ru/section.asp?sd_id=94.

5

Assets

Physical and Intellectual Infrastructure

COMPLETE TABLE OF CONTENTS

This chapter gives an overview of the resources available at TRIUMF with an emphasis on changes and enhancements over the past five years. It is not intended to be a comprehensive description of everything at TRIUMF, but it will give the reader a good sense of the laboratory's capabilities and capacities.

5.1 INTRODUCTION

TRIUMF brings a lot to Canada's national research agenda: experimental facilities; a network of accelerators, detectors, production targets, and beam lines; supporting infrastructure and systems; highly trained personnel with unique knowledge, skills, and abilities; a set of practices and procedures for conducting business in a safe, efficient, and reliable manner; and a portfolio of intellectual property and industrial partnerships. The combined physical and intellectual capital, accumulated over more than four decades, can be valued at approximately 1 billion dollars.

While the most valuable assets at TRIUMF are its human people: the talented and dedicated staff who are responsible for TRIUMF's success (see Sections 5.2 and 5.7), the laboratory also has substantial intellectual property in terms of patents, know-how, and established collaborative relationships with the private sector (see Section 5.10). For example, TRIUMF received a provisional patent to develop cyclotron production of the world's most popular medical isotope, technetium-99m.

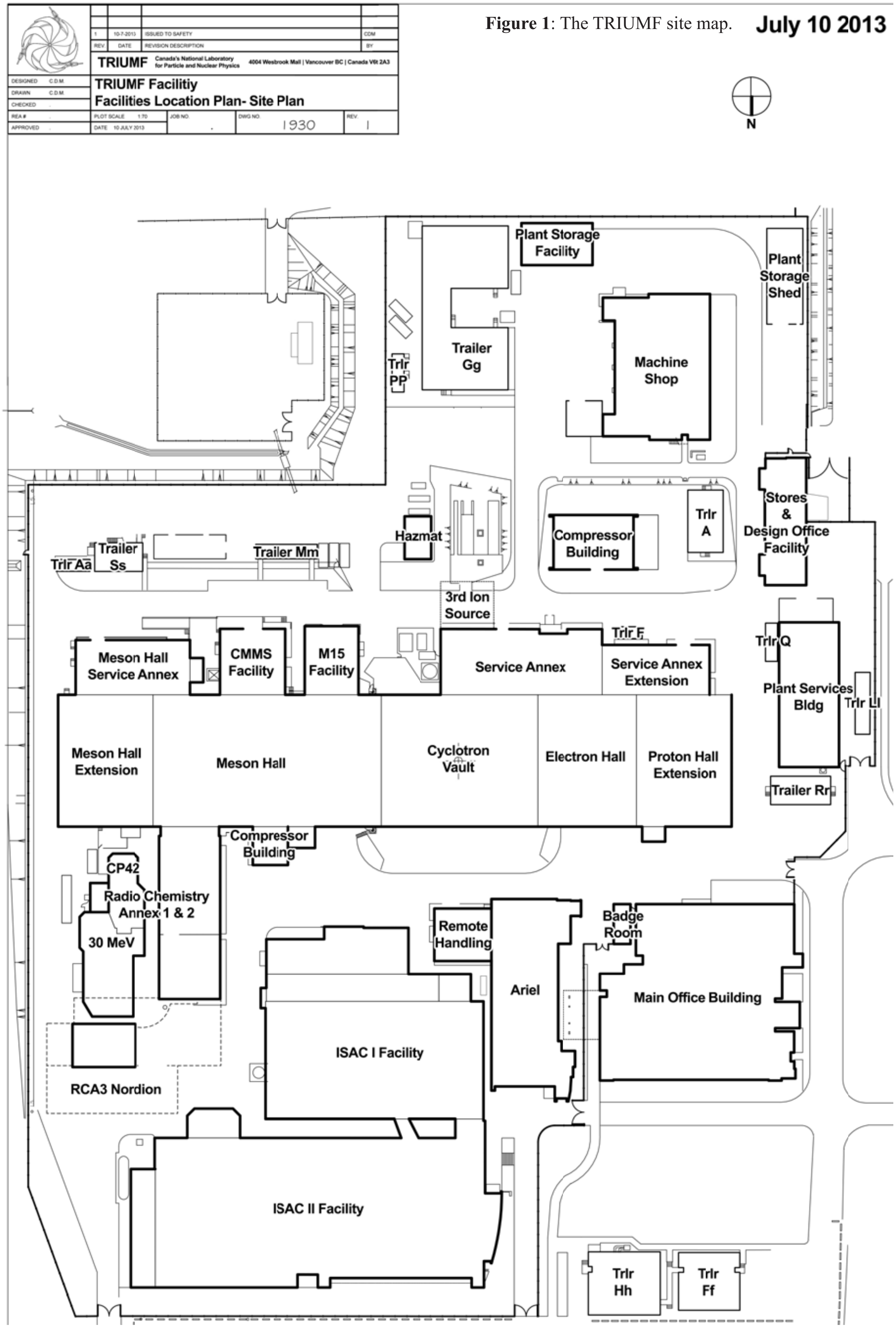
TRIUMF is located on a 12-hectare site on the south end of the University of British Columbia's Vancouver campus. The land is leased from UBC on a 99-year contract. It has three large building complexes, a number of stand-alone buildings and temporary structures. Three buildings are new in the present five-year plan. Housed within the buildings are an array of accelerators, experimental halls, support facilities, and offices.

At the center of site (see Figure 1) is the main accelerator building, which houses the cyclotron vault for the main cyclotron, the electron hall for the new e-linac accelerator, the meson hall for muon physics and the ultra-cold neutron facility, and a number of annexes and extensions. North of the main cyclotron building are the ISAC and ARIEL buildings used for the rare-isotope program. These two building are both connected to the main cyclotron building by tunnels that contain the proton and electron beam lines. ISAC consists of an isotope-production complex mostly located underground and two experimental halls (ISAC-I and ISAC-II) that contain a suite of detector facilities for studying isotopes. To the south of the main cyclotron building are the machine shop and the new stores and compressor buildings.

TRIUMF has an array of particle accelerators: the main 520 MeV cyclotron, a TR-13 cyclotron, a number of low-energy medical cyclotrons (three are owned by Nordion, Inc.), various rare-isotope beam accelerators, and the e-linac. The accelerators in turn feed the many experimental facilities on site. The experimental facilities are mainly in the ISAC-I and ISAC-II experiment halls, the meson hall and its annexes (see Sections 5.3–5.6 for a description of the accelerators and experimental facilities). The main cyclotron has been recognized as a feat of modern engineering; in 2010, it received the IEEE Engineering Milestone Award (one of only 11 in Canada),[1] and in 2012, on the occasion of its 125th anniversary, the Engineering Institute of Canada named TRIUMF an honourary member as one of Canada's six "Great Engineering Achievements."

Support facilities are located throughout the site but special attention should be drawn to the Machine Shop on the south part of the site, the Design Office located in the top floor of the Stores Building, and the ATLAS Tier-1 Data Centre (see Section 5.8.1) located on the upper floor of the ISAC-II building. Although the Machine Shop is not described in this chapter, it contains some of the industry's most advanced equipment for forming, shaping, and assembling materials. The Machine Shop is a unique resource in Canada because it provides advanced, one-of-a-kind, fabrication and assembly services to TRIUMF and the Canadian research community. The Machine Shop maintained a complement of

Figure 1: The TRIUMF site map.



16-18 FTEs over the past five years and performed an average of 550 "jobs" each year. The Design Office provides mechanical and engineering design services to TRIUMF and the Canadian community with a team of 10-11 FTEs, completing an average of 60 complex design jobs each year.

Tying this all together are the TRIUMF administrative and business offices, including safety and licensing, procurement, human resources, and project- and quality-management systems. The management structure has undergone some changes in the last five years and the current structure is described in Section 5.9.

5.2 EXPERT PERSONNEL

TRIUMF, over the 45 years of its existence, has assembled a core staff of approximately 350 people with a strong and diverse skill set. The staff can be divided into five categories: senior management, scientific staff, engineering staff, technical staff, and administrative staff. Senior management runs the laboratory and sets the tone for its efficient operation. The scientific staff in collaboration with university-faculty colleagues define the scientific goals and manage the laboratory's many research activities. The engineering and technical staff provides the essential skills needed to undertake the complex and challenging technical and mechanical tasks that allow Canada to achieve its goals and meet its challenges. The administrative staff provide effective support in areas ranging from safety and quality management to communications and financial accounting. Both collectively and on their own, these groups deserve a closer look.

5.2.1 SENIOR MANAGEMENT

The Senior Management team is made up of key leaders from all Divisions and the Office of the Director. The Senior Management team meets weekly to stay current with TRIUMF news and ongoing projects, to ensure effective coordination of operations, and to regularly share information. It acts coherently to help the laboratory reach the objectives established by the larger community and approved by TRIUMF's Board of Management. Senior management personnel have a wide variety of skills, including:

- Environment, Health and Safety
- Financial Strategy in a Research Environment
- Management, Administrative Management, and Human Resources
- Project Planning and Management
- Quality Assurance and Quality Management
- Scientific and Engineering Leadership
- Strategic Communications

Retirements over the last five years have resulted in a renewed senior management team with new division heads for all divisions and a new Chief Financial Officer. Most of these individuals have come to TRIUMF from abroad or from industry.

5.2.2 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 is resident at Canadian universities, strengthening both TRIUMF's and the universities' intellectual and scientific abilities. Scientists from Canadian universities and laboratories, as well as from international institutions, visit TRIUMF for periods ranging from a few days to weeks or a year. These visitors add to TRIUMF's intellectual and

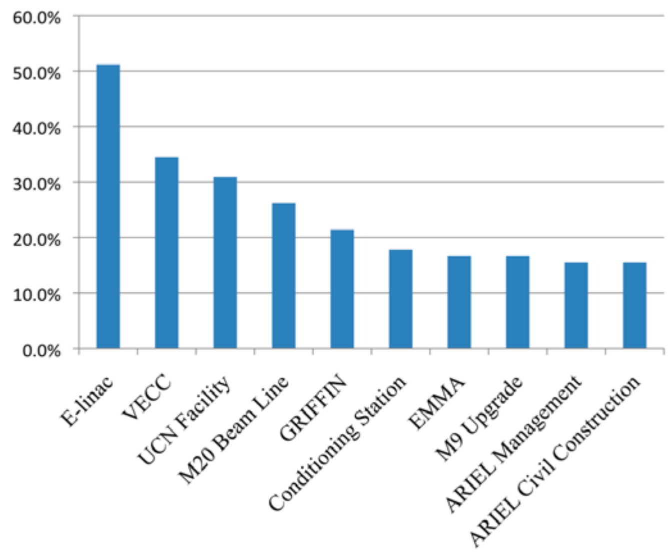


Figure 1: Fraction of the organization chart groups used by the larger projects in 2012.

scientific strength and diversity. The list below illustrates the skills of the scientific staff. These skills match the core research areas of the laboratory as well as provide a key resource for technology transfer to Canadian industry.

- Accelerator Physics
- Chemistry and Radiochemistry
- Experimental Subatomic Physics
- Nuclear Medicine
- Molecular and Materials Science
- Theoretical Subatomic Physics

5.2.3 ENGINEERING STAFF

TRIUMF's engineering personnel are primarily qualified at the B.Sc. and B. Eng. level and have a diverse skill set that ranges from high-power radio frequency engineers to specialists with unique skills in magnet design, cryogenics, digital electronics, or civil construction. One of the engineering staff is resident at a Canadian university. The engineering staff fall into the following categories.

- Accelerator Engineers
- Civil Engineers
- Computing Engineers
- Electrical Engineers
- Mechanical Engineers
- Nuclear Engineers
- Project Engineers

5.2.4 TECHNICAL STAFF

Technical personnel represent 65% of TRIUMF's core staff. Many of them hold M.Sc. or technical degrees and more than 15% of them have a diploma from local technical colleges or institutes such as Camosun, Kwantlen, the British Columbia Institute of Technology, and Okanagan College. Many are provincially registered with professional associations such as the Applied Science Technicians and Technologists of BC.

TRIUMF technicians perform the extremely complex technical tasks required to achieve the scientific goals of the laboratory. Our technicians maintain, operate, and upgrade TRIUMF's infrastructure. They are also responsible for the smooth and safe operation of the cyclotrons that produce medical isotopes for

Nordion, Inc. TRIUMF technicians are integral to the job of providing isotopes to the BC Cancer Agency and to the TRIUMF/UBC PET Centre. The machine shop has specialized equipment and machinists with the talent to fabricate the specialized apparatus technicians and technologists need in an advanced science facility.

In addition to maintaining and operating existing facilities, the technical staff are essential in developing new capabilities such as mechanical components and the increasingly complex electronics, controls, and data acquisition systems.

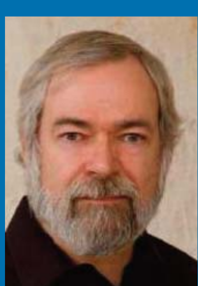
The list below illustrates just some of the unique skills of TRIUMF's technical staff.

- Accelerator Operations
- Beam Lines
- Chemistry
- Controls Electronics and Software
- Data Acquisition Systems
- 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

5.2.5 ADMINISTRATIVE STAFF

TRIUMF's small but effective administrative staff, which makes up 19% of the total staff, provides and maintains the administrative infrastructure necessary for the efficient operation of the laboratory. These staff have a wide variety of skills which covers several different areas, including:

- Accounting
- Business and Office Administration
- Human Resources
- Logistics
- Procurement
- Treasury
- Safety: Environmental Management; Occupational Health; Radiation Protection and Shielding; Radiation Monitoring and Safety Systems.



GERALD OAKHAM HONOURED AS ONE OF OTTAWA'S TOP 50 PEOPLE

12 September 2008

Gerald Oakham, a TRIUMF research scientist, was recently selected as one of the "Top 50 People in the Capital," an annual feature produced by Ottawa Life magazine. In addition to his position at TRIUMF, Oakham is a physics professor at Carleton University, one of TRIUMF's member universities. He is also the principal investigator and team leader for the Carleton University group contributing to the ATLAS project at CERN.

Before joining TRIUMF to work on ATLAS, Oakham participated in both the Omni-Purpose Apparatus at LEP (OPAL) and the European Muon Collaboration (EMC) projects at CERN. Since then, Oakham has returned to the university from which he earned his Ph.D. in 1981, this time as a professor in particle physics.

From 2002 to 2005, Oakham served as the director of the Ottawa Carleton Institute for Physics. He became Graduate Chair of the physics department at Carleton University in 2008. Additionally, Oakham is a member of the SNO Institute Board of Management and Chair of the SNOLAB Scientific and Technical Committee.

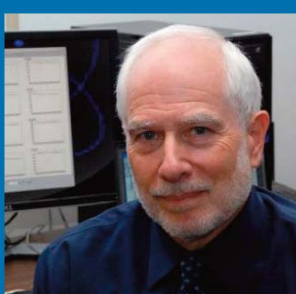
COMBINING SKILLS

TRIUMF's real strength is its ability to bring a variety of skills to any given project. Its matrixed organizational structure allows expertise from across the laboratory to be used on any project as needed (see Figure 1 again). Some groups, such as the machine shop and the design office, work on almost all projects while others have a more specialized role.

The e-linac (part of the ARIEL project) drew resources from about half of the organization-chart groups, and even more modest projects like GRIFFIN (a gamma-ray spectrometer) drew resources from one fifth of the groups. For other projects, a specific skill set is more important than a range of resources. For example, TRIUMF was able, with support from the University of Calgary, to build a cryostat for the ALPHA project at CERN because it had the required welding and cryogenic engineering expertise.

In addition to projects, TRIUMF staff is also responsible for the day-to-day operations of the laboratory. Just over 50% of the staff, primarily accelerator operators and administrative staff, has only operational duties while about 35% of the staff, mostly engineers and technicians, make significant contributions (more than 15% of their time) to both operational and project activities.

The TRIUMF technical and engineering staff have also contributed their unique skills and talents to international collaborations; for example, at CERN in Switzerland and J-PARC in Japan. These contributions from the TRIUMF are highly valued by the international community and facilitate the participation of Canadian scientists in international experiments.



TRIUMF'S DOUG BRYMAN SHARES PANOFSKY PRIZE

03 May 2011

Doug Bryman (UBC and TRIUMF), Laurie Littenberg (Brookhaven National Laboratory), and Stew Smith (Princeton University) have been awarded the 2011 American Physical Society's W.K.H. Panofsky Prize in Experimental Particle Physics, which recognizes outstanding achievements in experimental particle physics. The prestigious prize was awarded for the joint work on Experiment 787 at Brookhaven National Laboratory, a project analyzing billions of particle decays looking for an unusual decay pattern of a kaon particle involving two neutrinos.

The physicists were cited for discovering and measuring a very rare decay of a positively charged subatomic particle called a kaon, or K meson — a feat first reported in 1997 by a team of 50 collaborators from around the world after ten years of searching through the remains of the decays of 1.5 trillion particles.

Bryman's research has focused on flavor physics through the study of rare decays of muons, pions, and kaons. He has also been involved in detector instrumentation development for which he has received several patents. His current research involves measurements of rare pion decays, positron emission tomography, and cosmic ray muon geotomography.

AWARDS

The talent and dedication of TRIUMF's staff have been recognized with a number of awards over the previous five years (see Section 7.3 for more detailed accounting):

- Young Professionals Committee Award for Best Science, Society for Nuclear Medicine (U.S.)
- Tom Fairley Prize for Editorial Excellence, Editors' Association of Canada
- Fellow, American Physical Society (U.S.)
- Bunka Korosha Prize (Japan)
- Michael J. Welch Award of the Radiopharmaceutical Sciences Council (U.S.)
- W.K.H. Panofsky Prize in Experimental Particle Physics of U.S. American Physical Society
- U.S. DOE Early Career Research Award
- Yamazaki Award of the International MuSR Society (International)
- Special Fundamental Physics Prize of the Milner Foundation (shared) (International)
- Scientist of the Year, Radio Canada
- Business in Vancouver "Top 40 Under 40"
- CAP-TRIUMF Vogt Prize for Outstanding Contributions to Subatomic Physics (Canada)
- John Dawson Award for Excellence in Plasma Physics Research, American Physics Society (U.S.)

5.3 ARIEL

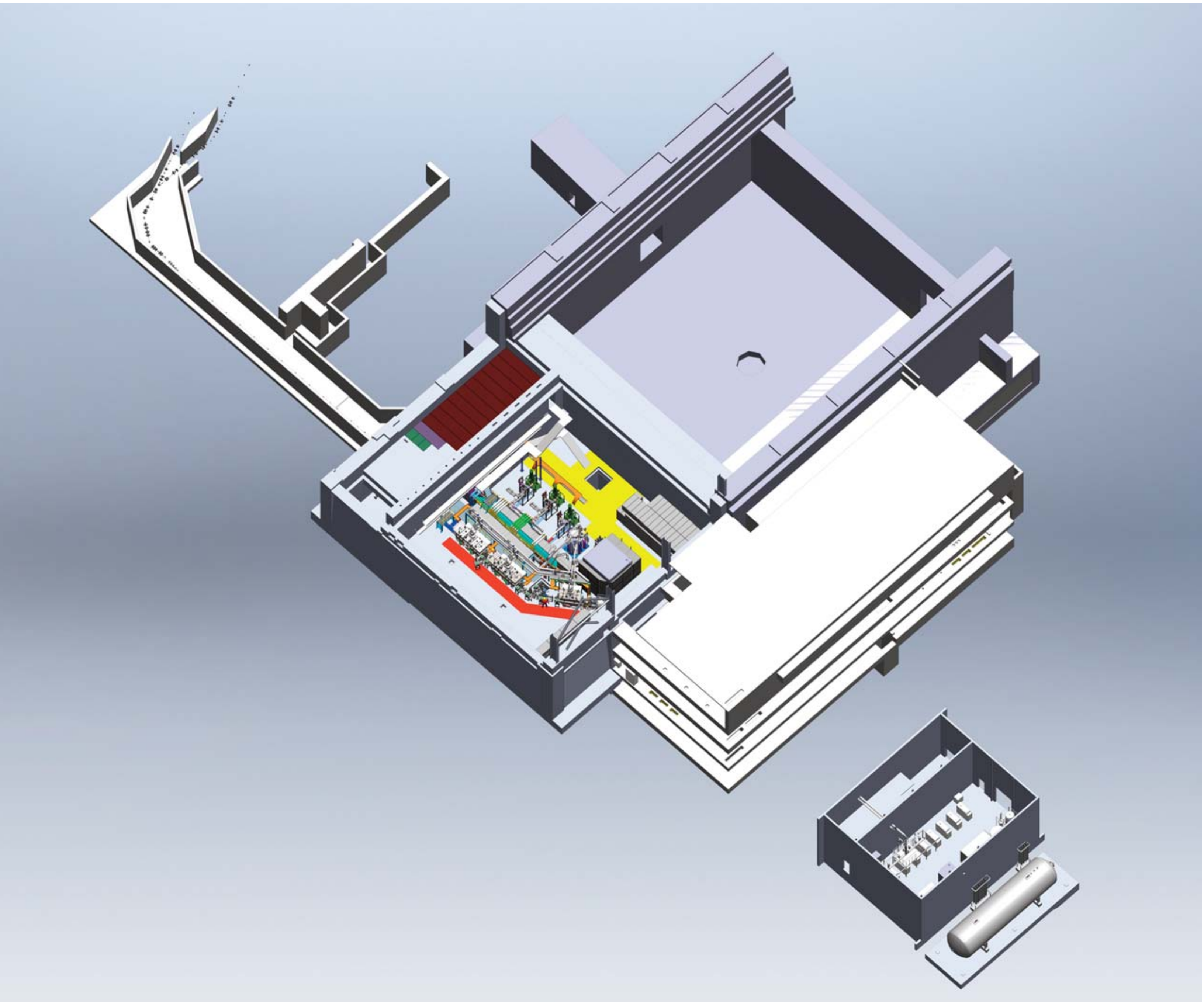
Construction of the Advanced Rare IsotopE Laboratory (ARIEL) at TRIUMF began in 2011 after funding for Phase I was secured in mid-2010. The flagship project is led by the University of Victoria in collaboration with the federal and provincial governments and multiple agencies. The project consists of a civil construction and conventional facilities element (i.e. the buildings and infrastructure) that will be completed in mid-2013; the electron linear accelerator will be subsequently installed and will begin commissioning in 2014.

The primary mission of ARIEL is to deliver unprecedented intensities of rare, short-lived exotic isotopes, in particular those with extreme neutron excess, to simultaneous and multiple experiments, at the existing and world-leading ISAC accelerator complex. A secondary mission of ARIEL is to anticipate future uses of e-linac technologies such as free electron lasers, and including commercial uses such as the production of medical isotopes by photo-fission.

When fully installed and commissioned, ARIEL will increase TRIUMF's annual scientific productivity by up to three times its current level: ARIEL will provide two additional beams of rare isotopes to augment the existing single beam line.

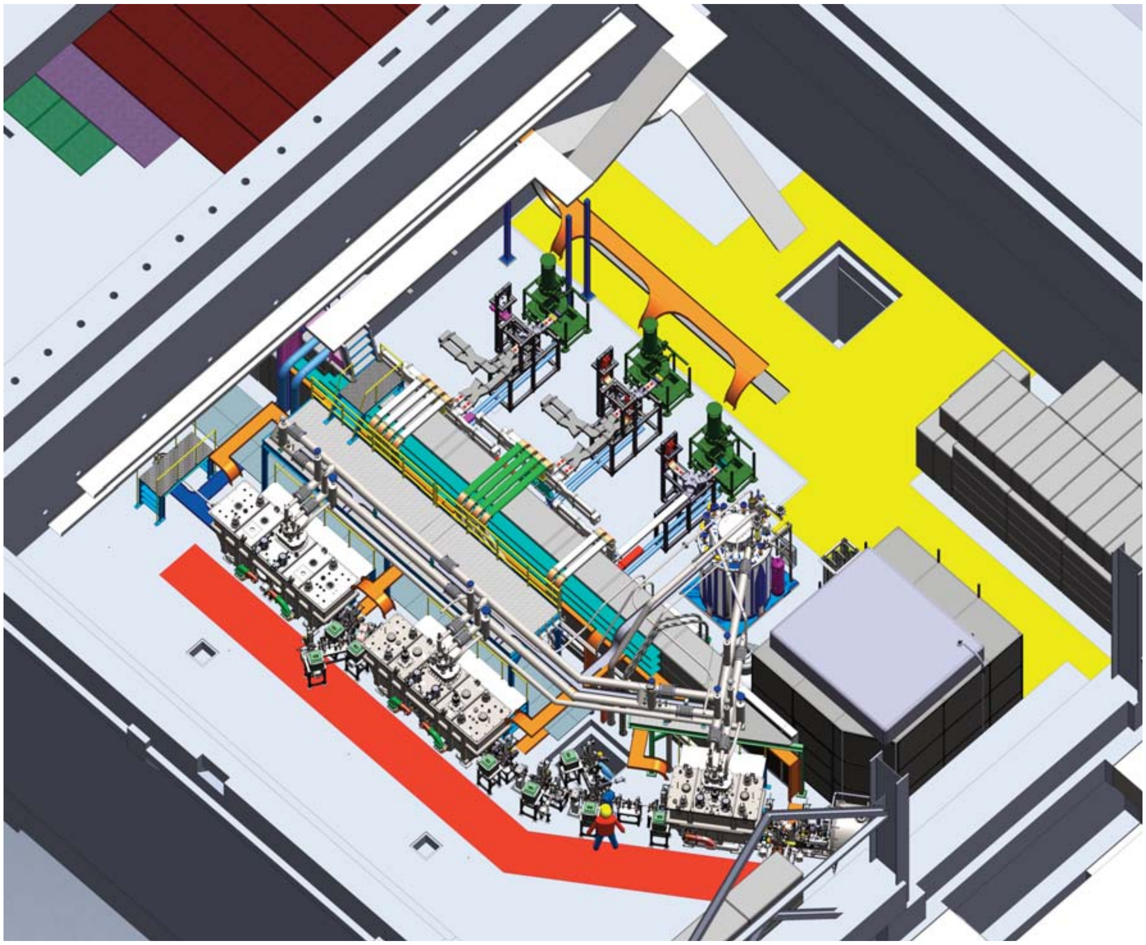
The project brings together accelerator technology expertise from British Columbia, as well as India, to develop an electron accelerator capable of using less electricity by roughly a factor of five, as compared to conventional technology. Once complete, the laboratory will have profound impacts on isotopes for science, isotopes for medicine, and next-generation accelerator technologies.

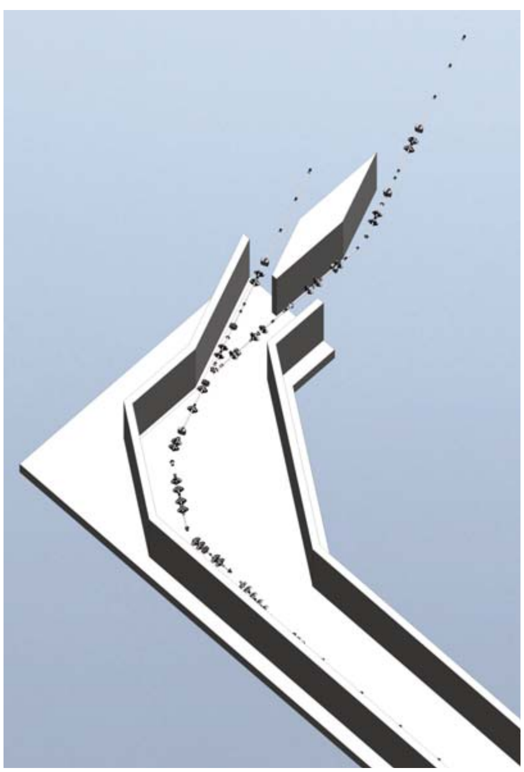
ARIEL construction is now effectively complete. Technical infrastructure is being installed in the Electron Hall, an existing vault adjacent to the main cyclotron repurposed to house the e-linac. The new ARIEL building, which houses the target hall, rooms for the beam delivery and remote handling infrastructure as well as laboratories for target preparation, has been completed and is connected to the Electron Hall via a new underground beam line tunnel. Support facilities including the cryogenic compressor building and a new building for the displaced stores facility have been completed as well.

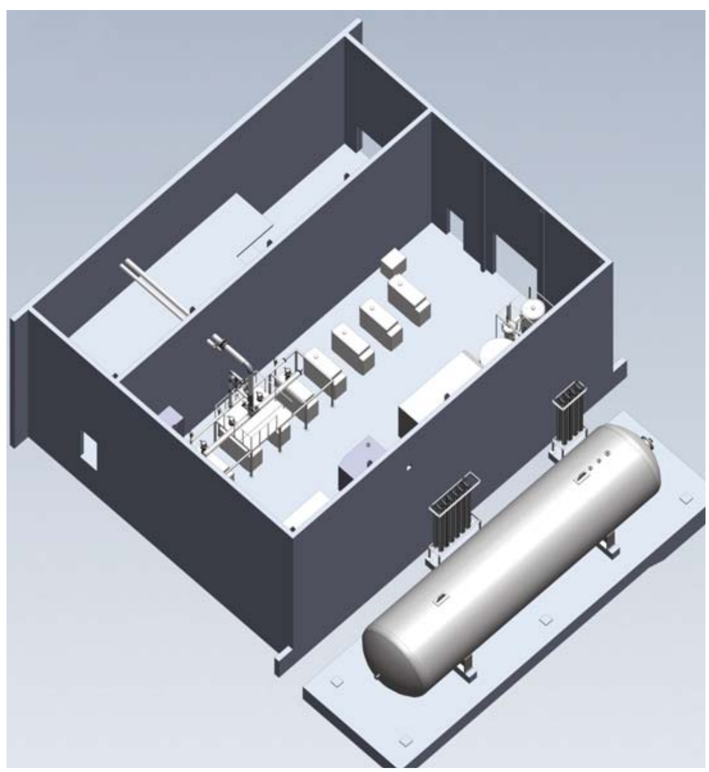


Shown here are the chief elements of the ARIEL facility that have been funded for completion by the end of 2014. The helium compressors and storage are located in detached building at the south end. The e-linac is shown in the Electron Hall and the underground tunnel connecting it to the isotope-production areas extends to the north.

Not shown is the ARIEL RIB building that will house the the targets, mass separator complex, and laser room.







In parallel to the construction of the physical buildings, much work has been done on the accelerator technology. The 4 K cryogenic plant is being assembled and tested, a 300 kW c.w. klystron and the first two 1.3 GHz niobium 9-cell cavities from PAVAC Industries, a local Canadian supplier, have arrived on site and are being prepared for installation. Procurements were received in mid-2013 for the klystron's 600 kW HV power supply and all quadrupole magnets for the electron beam. The 300 keV thermionic gun has been installed and is undergoing testing and the 10 MeV injector cryomodule is being assembled for first tests in fall 2013. The 25 MeV Accelerator Cryomodule will follow in 2014.

5.3.1 CIVIL CONSTRUCTION

In June 2010, the Province of British Columbia provided the University of Victoria with $30.7M through the British Columbia Knowledge Development Fund for design and construction of conventional infrastructure to house the Advanced Rare IsotopE Laboratory (ARIEL) at TRIUMF. The conventional infrastructure consisted of five facilities: Stores/Design Office Building, Badge Room, Compressor Building, Electron Hall, and the Main ARIEL Building.

Functional programming began immediately upon award of the funding, as did preparation of the Request for Proposal (RFP) for Architectural and Engineering Services for design and inspection of the facilities. The RFP was issued through BC Bid in late July 2010, and proposals were received a month later from five teams. Following analysis of the proposals and interviews of the proponents, the Selection Committee consisting of University of Victoria and TRIUMF representatives selected the design team lead by Chernoff Thompson Architects: Structural Engineer—Bush Bohlman and Partners; Mechanical Engineer—Stantec Engineering; Electrical Engineer—Applied Engineering Solutions/Lex Engineering; Building Code Consultant—LMDG; Landscape Architect—Durante Kreuk; Civil Engineer—HY Engineering; Envelope Consultant—Read Jones Christoffersen; Acoustics/Vibration—BKL; and Elevator Consultant—John W. Gunn Consultants.

Competitive selection processes were also held for supporting consultants and testing agencies including: Cost Estimating—Hanscomb Limited; Geotechnical—Thurber Engineering; Surveying—Murray Associates; Concrete Testing—Metro Testing and Exova; Commissioning Services—KD Engineering; and Steel erection Inspection—Elander Inspections.

Design work began in October 2010 with the issuance of construction documents for the Stores/Design Office Building in December 2010, the ARIEL Schematic Design Report in March 2011, the ARIEL Design Development Report in July 2011, construction documents for ARIEL Excavation in September

WORK BEGINS ON THE ARIEL RESEARCH TUNNEL

31 October 2011

Today, the first of 300 BC workers began building a tunnel and lab that will be used to demonstrate new ways to solve medical isotope shortages, keep BC and Canada leading in particle and nuclear physics, and create 160 permanent jobs.

The $62.9-million project is underway at TRIUMF with $30.7 million provided by the provincial government. By 2015, ARIEL is expected to demonstrate a new way to produce medical isotopes, which are used to diagnose and treat cancer, heart disease, Parkinson's and Alzheimer's.

ARIEL, which stands for Advanced Rare IsotopE Laboratory, features an underground beam tunnel surrounding a next-generation linear accelerator, or e-linac. The e-linac is being designed and built by a 13-university consortium led by the University of Victoria. The team is also collaborating with researchers in India, Germany, the U.S., and the U.K.

Figure 1: Newly constructed Compression Building.

Figure 2: A view towards the north of the completed Electron Hall interior.

Figure 3: The ARIEL building, as of July 2013; the south elevation (a) and the north elevation (b).

Figure 4: South elevation of ARIEL building, with the Badge Room (right corner).

2011, and construction documents for the Compressor Building, Electron Hall, and the Main ARIEL Building in December 2011.

The construction was implemented in four packages: (1) Stores/Design Office Building; (2) Badge Building; (3) Demolition of existing facilities and excavation for the Main ARIEL Building; and (4) Compressor Building, Electron Hall, and Main ARIEL Building (see Figures 5.3-1 through-4).

The first construction contract was awarded in February 2011 to Scott Construction Group for construction of the replacement Stores and Shipping/Receiving Building. Construction began after an official groundbreaking ceremony on March 28, 2011. This building was completed September 2011 for move-in, enabling demolition of the old stores building to make way for site construction for ARIEL.

A second construction contract was awarded to Scott Construction in July 2011 for construction of the replacement Badge Building. This building is the controlled access portal to the TRIUMF site, replacing the function demolished with the old Stores building. A temporary badge room was erected until construction of the new building was complete. The new building opened in December 2011. Final cost of the two construction contracts awarded to Scott Construction was $2,618,000.

A third construction contract was awarded to EllisDon in September 2011 for the demolition, excavation, and shoring of the site for the ARIEL building. An official groundbreaking ceremony was held on November 1, 2011. Excavation was completed at the end of March 2012. Final cost of this contract was $2,025,000.

The fourth and final construction contract was awarded in February 2012 to EllisDon. This contract included construction of the ARIEL Building, the Compressor Building and the Electron Hall. The Compressor Building and the Electron Hall were completed in early 2013 with the Main ARIEL Building being completed in the summer of 2013. Final cost of this contract was $21,244,000.

In conjunction with the construction work, significant scientific equipment, electrical services, and shielding concrete was removed from the Proton Hall in the Main Accelerator Building to allow conversion into the Electron Hall to house the electron linear accelerator (e-linac).

The design and construction of the ARIEL Project entailed: 44,000 architectural, engineering, and project Management person hours; 300,000 construction worker hours; over 1,000 tandem dump truck loads to remove the 14,500 cubic metres of excavation; and over 600 concrete trucks loads to deliver 6,100 cubic meters of concrete.

The photographs on page 210 and 211 document the major milestones of the construction.

5.3.2 E-LINAC AND BEAM LINE

TRIUMF's 2010–2015 Five-Year Plan outlined a strategy to at least double the rare-isotope beam (RIB) program, which targets nuclear structure, nuclear astrophysics, and fundamental symmetries studies; and quadruple the time available for β-NMR, which targets materials science. A centrepiece of the ARIEL project is an electron linear accelerator (e-linac) that will serve as a driver for production of RIBs via photo-fission of actinide targets and a parallel source of Li-8 produced by photo-reactions on Be-9. The e-linac ultimate 0.5 megawatt (MW) beam parameters (50 MeV, 10 mA) derive from the requirement of in-target fission rates up to 10^{14}/sec, and the production efficiency versus energy which falls steeply below 20 MeV and starts to saturate above 60 MeV; after that it is a better investment to increase the electron flux. Continuous wave (c.w.) operation increases integrated yield and avoids thermal cycling of the targets, which can be damaging. Due to funding limitations, the ARIEL project is phased: the e-linac first stage is limited to 30 MeV, and Beam Line 4 North (BL4N) proton beam line is delayed until after 2015.

E-Linac Baseline Design

Three goals shaped the design of the e-linac: (1) high average power c.w. operation; (2) the utilization of existing technology wherever possible; and (3) flexibility towards operation and reconfiguration. Superconducting radio-frequency (SRF) technology has been chosen for the e-linac because the dramatically reduced power consumption makes feasible c.w. operation. The selection of elliptical cavities has two collateral benefits: (1) it prepares Canada for SRF projects worldwide (such as the future Linear Collider); and (2) it qualifies a Canadian commercial partner (PAVAC) to build niobium (Nb) elliptical RF cavities operable at 1.3 GHz and 2 K.

Major components of the e-linac are a 300 keV 10 mA electron gun, a 1.3 GHz NC bunching cavity, a 10 MeV injector cryomodule (ICM), followed by a 10 to 50 MeV main linac composed of two 20 MeV accelerator cryomodule (ACM) sections. Due to heavy beam loading, five 9-cell cavities at 100kW/cavity are required to reach the 0.5 MW beam power. The ICM has one 9-cell cavity, and the two ACMs will each contain two 9-cell Nb elliptical cavities. Initially there will be only the ICM and one ACM.

Downstream of the linac are 75 MeV capable electron beam lines to the ARIEL target stations and a tuning dump in the in the Electron Hall (e-hall). Division of the linac into a low-energy injector and high-energy accelerator section allows the facility to be reconfigured for multi-pass operation by the installation of a return arc.

Project Timeline

In October 2008 the University of Victoria other collaborating university partners applied to the Canadian Foundation for Innovation (CFI), the federal agency for science infrastructure projects, to fund the e-linac project in the context of the Advanced Rare IsotopE Laboratory (ARIEL). In July 2009 the application was approved, contingent on matching funds for the civil construction from the British Columbia provincial government. In June 2010 the ARIEL became a funded project: the Government of British Columbia funded the construction of a new target building, connecting tunnel, and ancillary buildings were awarded, and the CFI funds were released for the construction of the electron linear accelerator and rehabilitation of an existing vault to house the machine.

In 2008, TRIUMF entered into a collaborative agreement with the Variable Energy Cyclotron Centre (VECC) in Kolkata, India, for development of a 10 MeV injector for e-linac leading to a systems integration test at ISAC-II. The collaborators completed the Injector Cryomodule detailed design and constructed a 100 keV electron source test stand and low-energy beam transport. Beam testing of diagnostic equipment prototypes was conducted at the ISAC/VECC test stand throughout 2012.

Subsequent to the full funding, in 2010 June, TRIUMF embarked on three parallel activities: (1) definition and construction of the ARIEL buildings; (2) specification, design, and procurement of the e-linac infrastructure (cryoplant, high-power RF sources, beam lines) starting with the long lead items; and (iii) development of the RF cavities and elaboration of the cryomodules designs leading toward construction of the first 20 MeV ACM in 2014. TRIUMF started construction of a 300 keV thermionic gun and 10 MeV injector cryomodule (ICM) in 2012, leading to completion in 2013 June and October, respectively.

TRIUMF has now signed contracts for most of the major equipment purchases: the 4 K cryogenic plant, 4 K liquid He distribution system, and four 2 K sub-atmospheric pumps, a 290 kW c.w. klystron and 600 kW high-voltage power supply, the entire facility quadrupole magnets, ICM tank and lid, and four 1.3 GHz niobium 9-cell cavities from PAVAC, a local Canadian supplier. All items, except the HV power supply and two SRF cavities, have been received. The He cryoplant and klystron RF system will be commissioned in 2013. The Electron Hall beam lines will be installed 2013 to spring 2014, and the ARIEL tunnel beam lines installed in 2014. A second klystron RF system will be procured in fiscal year 2013.

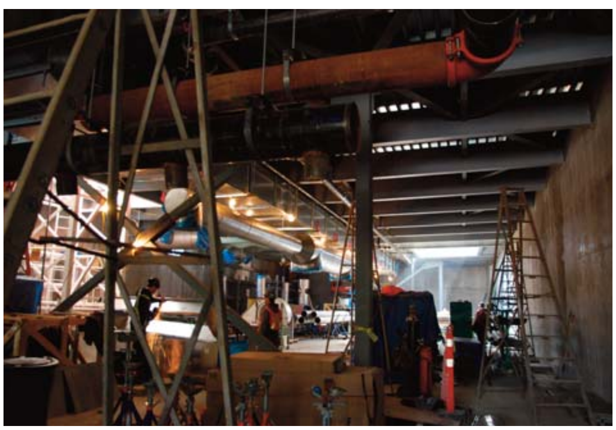
Conventional Infrastructure

The conventional infrastructure consists of four contracts: the main ARIEL construction, demolition and excavation, and replacement of the Stores and Badge Building, which is necessitated by site congestion. The new He Compressor Building forms part of the ARIEL package. In addition, major renovations have transformed the former Proton Hall to the Electron Hall (e-hall).

Chernoff-Thompson Architects led a successful bid for the overall architecture and engineering contract, awarded in October 2010. The Stores and Badge building construction was completed in September 2011 and occupancy was taken in December 2011.

The demolition and excavation work started October 2011, and completed April 2012. The ARIEL main construction package was awarded February 2012 and at time, there has been substantial completion of all the building components: the tunnel, actinide target preparation lab space, target hall and Rare Isotope Beams annexe; occupancy was allowed in August 2013. Occupancy of the compressor building was taken December 2012, and the He compressors were delivered to this space in February 2013.


VOLVO



AIR LIQUIDE BRINGS WORLD-CLASS TECHNOLOGY

22 December 2011

TRIUMF has just signed a major contract with Air Liquide Advanced Technologies (AL-AT) to provide major components of the cryogenic system for the new ARIEL laboratory. The deal will provide ARIEL with the world-class engineering and infrastructure for maintaining the ultra-cold temperatures required for the flagship e-linac accelerator. Air Liquide will have the opportunity to showcase its technology at a major scientific laboratory in North America.

The cryogenic technology from AL-AT is critical to the ARIEL facility and its associated electron accelerator (e-linac). The facility will feature a next-generation superconducting accelerator, which will require supercool temperatures - just two degrees above absolute zero - in order to operate at its peak performance. The equipment to be delivered by Air Liquide will be a major component of realizing the ultra-low temperatures required for operating the ARIEL e-linac. Air Liquide will design, manufacture and deliver custom cryogenic equipment, and provide its expertise for installation and inspection of the system.

The e-linac will be housed in the e-hall and linked to the ARIEL target halls by an 80 m beam line in a new tunnel. The hall is divided into three areas: (1) linac; (2) equipment (klystrons and 4 K coldbox); and, (3) BL4N p-beam line. Klystron HV and magnet DC power supplies, along with controls and beam diagnostic electronics racks, will be located above the linac on concrete roof beams at ground level. Installation of the racks is 30% complete at the date of this report. A 10-ton full-coverage crane at the underside of the roof beams will allow easy transport of cryomodules and other large equipment in an otherwise congested area.

The e-hall was emptied of legacy proton spectrometers in March 2012. The e-hall shielding, south wall upgrade and new north wall, which will protect the e-hall from the future BL4N proton beam, are complete. The 10-ton crane, NE egress stairway, new floor covering and lighting system are all installed. The concrete roof beams are sealed and are now the base for the rack farm and the 12.5 kV supply. Occupancy of the e-hall was taken November 2012. Communication between the Meson Hall space and the e-hall is via a 3×6 m^2 concrete shielded hatchway; the hatch blocks were completed 2013 February.

To accommodate the power requirements of ARIEL systems, a new 12.5 kV 5 MW switchgear is installed atop the e-hall roof beams. The gear will be close to the klystron power supplies and other local loads, including a 0.5 MW emergency power bus. Furthermore, the gear will feed north to the ARIEL building (2 MW) and south to the compressor building (1 MW) that houses the He compressors and sub-atmospheric pumps. The 12.5kV was connected to the TRIUMF grid and energized in December 2012. An uninterruptable power supply (UPS) system to support emergency operation of critical systems in the event of a power outage was installed in March 2012.

The e-linac power supplies, klystrons, and beam dumps present a significant heat load that must be removed, predominantly by cooling water. This task is accomplished by tying into the existing raw water cooling circuit via a 2 MW heat exchanger installed at the B3 service annex. The contract for this work was awarded in February 2013, and the tie-ins are complete. The next step is to bring this cooling water to manifolds in the e-hall.

Electron Gun

A thermionic gridded gun was chosen as the electron source based on low cost, simplicity, and ease of maintenance. Pre-bunching the beam at the gun obviates the need for a chopper and beam dump in the low-energy beam transport (ELBT). The beam is modulated by applying a radio frequency (RF) field between the cathode and the grid. To explore the operating parameters of such a source, construction of a gun test stand was begun in 2009.

A 100 keV DC gun was acquired from Jefferson Laboratory for the purpose of emittance characterization and the implementation of a 650-MHz modulation scheme similar to that developed for the FELIX accelerator. The gun was modified from diode to triode operation by the addition of a gridded cathode. To minimise RF reflection and to ensure stable operation, an RF network was designed to impedance match the 50 Ω transmission line to the cathode-grid structure. Modulation was successfully demonstrated in April 2011. The inferred conductance angle ±16° at 650 MHz and 16 pC per bunch meets the e-linac spec. The same source confirmed that the beam intensity can be varied from 99.9% down to 0.1% by applying a macro pulse structure with variable duty factor; the lowest value is essential for intercepting profile monitors.

In 2010, it was realized that the complicated SRF capture cavity scheme contemplated in the Conceptual Design Report (CDR) could be eliminated if the gun voltage was raised to 300 keV. At this energy, the longitudinal acceptance of the first cell of the 9-cell cavity becomes sufficient; moreover, some of the space-charge effect and phase-dependent RF focusing at entrance to the cavity are ameliorated. 300 keV enables efficient matching to a ß=v/c = 1 TESLA style cavity, but is not so demanding as to risk voltage breakdown and unreliable operation of the gun.

The main components of the 300 keV electron source are a gridded gun in a 2 bar (gauge) SF6 filled vessel, and in-air HV power supply. The pressurized SF6 insulating gas reduced the required length of the ceramic to stand off 300kV. The gun bias and heater power are applied through an isolation transformer. The gun ceramic, anode-tube internal steering coil, gun solenoid, isolation transformer, conditioning resistors and 350kV Glassman HV power supply have all been delivered.

The gun has two unique features. To minimize dark current, the design has an inverted electrode profile compared to the classical electron gun design. This reduces the surface area of the high-voltage electrode, reducing the likelihood of field emission. The second feature is the transmission of RF modulation via a dielectric (ceramic) waveguide and chokes through the SF6. The latter obviates the need for a HV platform inside the SF6 vessel to carry the RF transmitter, and results in a significantly smaller/simpler vessel. The modulation is applied to a CPI Y-845 gridded dispenser cathode via a stepped coaxial line impedance matching section from the RF-collecting choke. The ceramic waveguide was subject to bench testing on scale models and extensive simulation and optimization with HFSS. The ceramic was received from Kyocera 2012 September and subsequently installed at the 100 kV test stand where it operates with the expected performance.

The gun electrodes, the vessel internal corona domes and shroud, were subject to extensive 3D electrostatic modelling and optimization. The electrodes are fabricated and polished. Detailing of all HV cage and SF6 vessel components is complete. Fabrication of the gun HV cage, SF6 vessel, HV shroud and gun support struts are all near completion. Components assembly and integration will take place June 2013, and gun conditioning follows thereafter.

Injector Test Facility

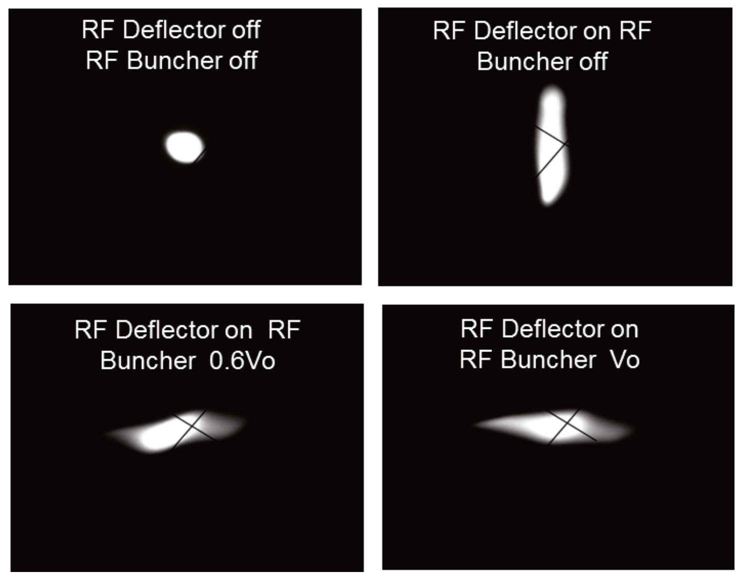
The test facility at ISAC-II, under collaboration between TRIUMF and VECC of Kolkata, India, provides an ideal proving ground for e-linac design and operation strategies. It prototypes the injector from gun through ELBT and up to the exit of the cryomodule, with enhanced diagnostic capability for benchmarking the performance of the gun, various diagnostic devices and procedures, and demonstrating the sustained operation at the design parameters.

The extant part of the ELBT comprises the sequence: box DB1A after first solenoid; DB1B after buncher cavity, DB3 after third solenoid, all in the mainline; and MB0 dipole, RF deflector cavity, DB0 in the analyzer stub. Button BPMs are installed between the first and second solenoids. View screens VS1A, VS1B, VS3 are installed and tested at each of the diagnostic boxes. An Allison type emittance scanner, a wideband capacitive pickup (a.k.a non-intercepting monitor, NIM), and fast Faraday cup (FC) are moveable. A crane was installed for shielding block lifts and moves, and the complete downstream section comprising ICM and transport and beam dump is, at time of writing, in fabrication or being installed.

To date there have been three rounds of beam tests: phase (1) to ELBT:DB1B; (2) transport along the straight to ELBD:DB0; and (3) along the analyzing leg to ELBD:DB1.

The outcomes of the phase-one test were: (1) the solenoid and correctors successfully controlled beam trajectory and shape as designed; (2) the low-level control of the 1.3 GHz buncher cavity and phase lock to the 650 MHz gun grid were demonstrated; (3) the beam horizontal emittance was measured directly with the Allison scanner, and indirectly with scintillator screen and solenoid scan. Both methods confirmed the Gaussian distribution from the gun; and, (4) BPM, Faraday cups, slit scanner, chromox and YAG scintillator screens, capacitive pickup, photo-multiplier tube-based loss monitor, were tested, and areas for improvement identified. The time structure of the electron source was measured with the NIM. The measured bunch length of 200 ps agrees with beam dynamics simulations.

For the phase-two test, two solenoids and diagnostic boxes were added; and the Allison rig and FC reinstalled after DB3. This set-up enabled comprehensive beam-based characterization of 6-dimensional transport and phase space properties of the beam as functions of intensity. The analyzer magnet MB0 and RF deflecting cavity are now installed for measurement of longitudinal parameters.



The e-gun, buncher, and deflector LLRF have all been synchronized and their operation has been demonstrated with beam at the phase-three test. The 1.3 GHz deflecting cavity utilizes the TM110 mode to generate a time-dependent vertical kick to the beam. The bunch length can be measured with high resolution by noting the vertical spread of the deflected beam at a downstream screen. Figure 1 shows a series of screen images from ELBD:VS1 downstream of the deflector. In (a) the final solenoid focuses the beam on the screen; in (b) the deflector is turned on to disperse the beam vertically; in (c) and (d) the buncher is then turned on at $0.6V_0$ and V_0 to rotate the longitudinal phase space to create a time focus. In the screen image, the momentum dispersion from the magnet has transformed energy spread into horizontal width.

Beam Dynamics

The primary objective of e-linac is to deliver 50 MeV electrons to RIB and Li-8 production targets as efficiently as possible by a single-pass through linac and beam lines. Nevertheless, with recirculation arcs introduced between the exit and entrance, the linac could be reconfigured either: (1) as a recirculated linear accelerator (RLA) producing a 75 MeV beam for RIB production, or (2) an energy-recovery linac (ERL) for the production of photon beams. For example, configured as a 70 MeV ERL and coupled to a high-Q cavity Free Electron Laser (FEL), the e-linac could produce hundreds-watts-level infrared radiation in the range 2–200 μm.

This range of applications motivated a beam dynamics study with three objectives: (1) ensuring the baseline layout is compatible with a future recirculation ring configured either as RLA or ERL, (2) ensuring the cavity design is compatible with two-passes and impervious to beam break up (BBU) instability, and (3) ensuring the injector and accelerator are compatible with a high-brilliance beam (100 pC bunch charge) for FEL operation in addition to the low brightness beam (16 pC bunch charge) for the photo-fission RIB application. This study resulted in the current machine geometry and criterion for the cavity High Order Mode (HOM) spectrum. All studies completed, the primary focus returned to a detailed beam optical design of the e-linac and its beam lines for RIB production. Several detailed design notes were issued on the beam line optical and diagnostic elements, and form the basis for the engineering design. In addition, impedance and wakes of beam line in-vacuum elements, such as gate valves and bellows and diagnostic boxes, were evaluated for their contribution to emittance growth, and an impedance budget was established for the machine.

Beam Lines

Beam lines transport the electron beam between accelerator components and then on to the RIB targets. The e-gun and cryomodules are linked by short beam line sections. The electron low-energy beam transport (ELBT) operates at 300 keV and contains three solenoids in-line to the injector cryomodule, a variety of diagnostics, and a spectrometer stub (ELBD). The injector is followed by a 10 MeV merger section (EMBT) consisting of small angle dipole magnets and quadrupole optics. The merger presages the recirculation ring and is achromatic. The merger optics provides the opportunity for clipping momentum tails, emanating from the gun, and could be equipped with collimation jaws. Transport between the accelerator cryomodules is by quadrupoles, and the first such transport (EABT) at 30 MeV is equipped with a spectrometer stub (EABD).

At the 50 MeV exit of the second accelerator cryomodule, the Electron High-energy Beam Transport (EHBT) leads northward to the target stations 80 metres distant. This line begins with a matching section, a dogleg that bends in horizontal and vertical planes, and a quadrupole matching system to the following periodic lattice. The dogleg implements a change in beam line height between the linac vault and tunnel that accommodates the future necessity of running the electron beam below the 500 MeV proton beam line magnets. At the end of the tunnel, a vertical dogleg brings the e-beam into the plane of the targets. Thus far, the transport is achromatic. Finally, the line divides in two branches with bends and matching quadrupoles and a rastering system before each target. The EHBT is the “main line”, but there is a branch (EHDT) inside the linac vault leading to a 100 kW capable beam tuning dump. To date, a “requirements” document and a preliminary design note for the dump have been issued.

To summarize, the beam line sections are: ELBT, the 300 keV transport; EMBT 10 MeV transfer between ICM and first ACM, EABT 30 MeV transfer to future second ACM; EHAT 30–50 MeV transport downstream of the cryomodules to a switching magnet; EHDT leading to a 100 kW beam dump; and EHBT 25–75 MeV transport to the photo-fission targets. The EHBT, in the tunnel, consists mainly of a periodic section consisting of six 90^{o} FODO cells, each 4m in length. The EMBT contains a 36^{o} bend section, the EHDT, a 90° section formed of four bends, and the EHBT two doglegs and bend sections to the west and east targets. All insertions are achromatic.

Presently, the beam line is being designed in detail with all components (diagnostic, vacuum, magnets, etc.) integrated prior to issuing engineering drawings for support stands, flanges, beam tubes, and vacuum boxes, etc.

Quadrupoles

From the injector linac onward, the most convenient focusing device is the magnetic quadrupole; however, at the lowest envisioned beam energy of 5 MeV, the focal power required is rather small. This forces us to shortest possible quadrupoles, or else the fields are too low compared with expected remnant field of low-carbon steel. A theoretical study was made to derive the optimal pole shape for short quadrupoles whose lengths are comparable to, or smaller than, the aperture. Conventional 2D treatment and fabrication practice, assuming sufficiently large pole length, break down in such cases. A new 3D shape was derived analytically, and demonstrated yields with smaller aberrations. For short quads it is well approximated by a simple spherical pole, provided the sphere radius is 1.65 times the quadrupole aperture radius.

The beam lines in the e-hall adopt weak and medium quadrupoles, with integrated strengths up to 0.2 T and 0.7 T respectively. This is easily achieved with the short quadrupoles of aspect ratio 1 and cylindrical poles with spherical faces. The weak quads are also used for the periodic section in the tunnel. At the highest envisioned energy of 75 MeV, the shortest required focal length is 0.24 m in the EHBT dogleg sections. The required integrated gradient is 1.05 T; this will be achieved with a more conventional strong quadrupole design with rectangular cross-section poles and hyperbolic faces. The strong quads will be water-cooled, the weaker ones air-cooled, and the medium ones indirectly cooled. All have aperture diameters equal to 52.0 mm. In total, there are 89 quadrupoles; the contract for their manufacture was awarded to Buckley Systems Ltd., New Zealand, August 2012 with delivery March to June 2013.

Dipoles

The different beam lines contain a total of fifteen dipoles, which have been divided into four groups, depending on their required integrated field and field quality, for the purpose of design and procurement. Longitudinal space constraints in the beam line layout, particularly in "merger" and doglegs, lead the team to design the magnets as small as possible. Thus, many of these dipoles are short compared with their aperture leading to low strength because the field does not "plateau" inside the magnet. Proximity of other magnets implies the use of field clamps to contain the field fall-off. These features combine to make it essential that their modeling be done with a 3D finite element code such as OPERA. Moreover, one must ensure that the second order aberrations (sextapole) will cause negligible emittance growth (<0.01% per dipole). To study the non-linear optical properties of our models, we used the differential algebra and particle tracking code COSY INFINITY, with field maps imported from OPERA. Satisfactory pole, field clamp and yoke geometries were obtained and are being used as the basis for a series of tenders. The first dipole, the EMBT momentum analyzer, was received from Alpha Magnetic Inc. in January 2013 January, and the design of EMBT merger dipoles was conducted with the vendor in March 2013 and the contract for seven 34° bends for the EHBT was awarded that same month.

Vacuum

The electron beams are transported in vacuum. Vacuum also provides thermal isolation in the cryostats. ARIEL e-linac has 13 vacuum volumes with requirements ranging from 10^{-9} in the gun and ELBT, 10^{-8} in EMBT and EABT, to 10^{-7} in EHAT, EHDT and EHBT when the beam is present. The limits arising from residual gas (Rutherford) scattering and ion neutralization are an order of magnitude relaxed compared with these values. The beam pipes inside the cryomodules will naturally cryopump to 10^{-11}Torr, and the issue there is of cleanliness and particulates free. The cryomodule insulating and coupler vacuums are 10^{-6} Torr. The beam line volumes, from the e-gun to exit of the second cryomodule will be separated by RF-screened, all-metal electro-pneumatic gate valves. A large pumping capacity NEG pump will protect the cryomodules from volatile hydrocarbons in the manner of a "cold finger". The remaining beam lines leading to the ARIEL target stations and 100kW beam tuning dump will be separated by all-metal electro-pneumatic valves. The vacuum volumes will be evacuated from atmospheric pressure to high vacuum level with turbo-molecular pumps, which are also used during the *in-situ* bake-out. After the bake-out is completed, the turbo-pumps are isolated via gate valves, and the pressure lowered further by ion pumps. The ion gauges are used only during the initial evacuation and bake-out. Once the ion pumps are turned on, the ion gauges are turned off, and the pressure is observed on the ion-pumps' controllers.

The master e-linac vacuum system design note was released March 2013. This document constitutes the primary reference for vacuum components procurement and installation and is the basis for the EPICS-controlled vacuum system interlocks. As of 2013 March, 60% of all e-linac vacuum components were received from vendors and available for installation into the beam line. A clean area for assembling high vacuum components has been identified and will soon be modified for e-linac assembly needs.

Beam Diagnostics

Initial electron beam threading at e-linac and its beam lines will be with view screens, followed by orbit correction with 4-button type beam position monitors (BPMs), each measuring in two planes H and V. Beam stops will be used as temporary *termini* during this procedure.

Four complete view screen systems were built and installed at ISAC/VECC; the camera data acquisition and processing was built by the University of Victoria. Remaining parts for 16 view screen monitors at e-linac have been built and assembled. All button electrodes (224 in total) for the BPMs have been ordered from Kyocera. Sixty buttons were delivered, inspected, and verified to be within tolerance of 0.05 mm. The position sensitivity is 1.4dB/mm between opposite pick-ups. The signal power of -27dBm was measured at ISAC/VECC with the beam current of 10 mA (peak), and agrees well with the expected value of -30dBm.

The BPM electronics design is complete; a prototype unit has been successfully tested in the laboratory. This consists of a commercially available Bergoz analog front-end (AFE) customized for 650 MHz and a TRIUMF-developed intermediate frequency (IF) processing unit based on a 125 MHz 14-bit ADC and Spartan-6 FPGA. The output bandwidth is around 1 MHz. Most of the BPM electronics components have been procured. The University of Victoria has designed 75 MeV-capable, 100 W beam stops and a prototype is under fabrication. An off-the-shelf diagnostic box prototype was made and is being tested.

A Bergoz DC current transformer for absolute current measurement is housed in a magnetic and vibration shielded and temperature stabilized enclosure. Initial bench tests reveal a drift of ~ 40 uA over 48 hours; the cause is being investigated.

A fast wire scanner prototype, for the measurement of beam profiles at high beam power, has been assembled. Preliminary tests demonstrated that speeds of 0.5m/s are achievable. Further tests are required with a goal of 3 m/s. The vacuum test stand for this scanner has also been designed and is under construction. The prototype of a strip line BPM is being manufactured for testing at the VECC Test Facility in ISAC-II.

Cryomodules and Cavities

A cryomodule is essentially a vacuum-insulated cryostat that isolates the 2 K cavity volume from room temperature. The injector cryomodule contains a single 9-cell cavity and has been designed and constructed in collaboration with VECC. The accelerator cryomodules each house two 9-cell SRF cavities. Because of the c.w. requirement, the cryomodule design was driven by the large dynamic heat load on the input couplers and 9-cell niobium cavities; a situation very different from the 1% duty factor TESLA, ILC or XFEL where the static heat loads dominate; the 4 K thermal shield is not needed and the suspension heat load can be larger. At an early stage, the Cornell/CPI 50 kW couplers were adopted over the TESLA design. The cavity heat load was dealt with by adopting a 90 mm ID chimney for thermal transport across the L-He to the 2-phase pipe.

The cryomodule design utilizes a box vessel with a top-loading cold mass. The cold mass cavity string and 2-phase He pipe is supported from a strong back which, in turn, is held by 2-point and 3-point suspension rods from the lid. The tuner actuating motors are warm and also mounted on the lid. Adopting this configuration allows e-linac to benefit from the crane and clean room infrastructure at ISAC-II. In contrast to ISAC, the e-linac cryomodule must be made compatible with 2 K (rather than 4 K), elliptical cavities, high beam loading (10 mA average current), the fixed location of horizontally mounted input couplers, and separate beam line and isolation vacuums. The comparatively long suspension rods provide the interior headroom to install within each module a 4 K/2 K cryo-insert to produce 2 K liquid right where it is needed.

The cold mass is suspended from the lid with mounting posts, struts, and, a strong back, and is surrounded by a LN2-cooled copper box for thermal isolation. A 1 mm warm mu-metal shield is fastened to the inside of the vacuum vessel to exclude magnetic field from the SRF cavities. The cold mass consists of the cavity hermetic unit, a cold mu metal layer and the tuner. The hermetic unit includes the cavity(ies), power coupler, RF pick-up(s), the warm-cold transition) with HOM damping material and warm isolation valves. A carbon fibre-reinforced silicon carbide material, CESIC, was chosen for the damping material, with measured conductance at 1.3 GHz and 80 K of 2200 Si/m.

The cavity operates in the heavily beam loaded regime leading to comparatively low loaded Q, obviating the need for fast Piezo control. The very small number of cavities makes the linac vulnerable to ceasing of the tuner actuator. For these reasons, the tuner cold part is the Jefferson Lab–styled scissor type, which is and is followed by a long actuator and warm ISAC-II-style rotary servomotor mounted on the lid.

The 4 K/2 K cryoinsert was built and tested as a separate package. It includes a 4 K phase separator, 4 K/2 K heat exchanger, Joule-Thomson expansion valve, and a 4 K cool down valve plus siphon circuit for intercept cooling. The prototype heat exchanger is from DATE, France, with an estimated capacity of 2.5 gm/sec. A cold test of the cryoinsert was completed in November 2012 to verify performance. The tests included a LN2 thermal shock test, a static load test of the 4 K and 2 K volumes, a 2 K liquid production efficiency test for various heat loads, and a test of the thermal intercept siphon circuits. The measured static load of the 2 K and 4 K volumes were 1.6 and 0.4W respectively. The 2 K production efficiency is 66% at 0.6 gm/sec mass flow. This efficiency is expected to increase towards the design goal of 80% as the He mass flow increases to the design value. Further tests are planned for 2013.

The fabrication of the lid, tank, support posts, strong back, and cavity support for the injector cryomodule are all complete. Assembly of the LN2 (77K) thermal shield is also complete. The cryomodule tank has been assembled with outer (warm) layer of mu metal awaiting the top assembly.

SRF Cavities

The cavities support RF electrical fields that accelerate the electron beam. Our nine-cell 1.3 GHz elliptical cavity borrows the TESLA/ILC-type inner-cell geometry but uses modified end groups to accommodate the large power couplers and to mitigate HOMs. A multi-pass beam break up (BBU) criterion establishes an impedance limit of $R_d/Q^*Q_L < 10^7$ Ohm; and $Rd/Q^*QL < 2\times10^6$ Ohm has been achieved. End group beam tubes with inner radius 48 mm and 39mm, respectively, are used for the power coupler and RF pick-up end. Consistent with the high beam load, the nominal cavity gradient E = 10 MV/m is modest – as can be achieved with buffered chemical each alone. Nevertheless, the Q_0 of 10^{10} to manage the c.w. heat load is challenging and will require cavity baking at 650 ^{o}C.

The first of four niobium cavities is presently being fabricated at PAVAC Industries, Inc. of Richmond, BC. A seven-cell cavity in copper was completed February 2012 to test all fabrication procedures and manufacturing jigs; lessons learned are now being applied to the Nb cavity production to improve quality assurance.

Processes have been developed at PAVAC that will expedite the fabrication of future cells and cavities in terms of reproducibility, true to shape and frequency. A main study was on forming. The original dies produced cells too short at the equator—causing material stress and some multipacting. PAVAC developed a forming tool with male die against a plastic that becomes almost fluid at high pressure and “hydroforms”—all cells formed since then are exceptionally reproducible. Next the fixturing during welding of half-cells became an issue. Our equator weld set-up initially was a butt weld of two identical half-cells. During forming and machining, and due to grain structure, the niobium (Nb) half-cells can go slightly out of a true circle. The question became how to hold them nicely true to a circle while not touching the newly etched weld zone. A self-fixturing solution is adopted: an interleaving feature is machined into the equator of unique male and female half-cells so they fit together and "self-fixture" during welding. Multiple Nb cells have been prepared in this way, and frequency is very repeatable. Success at the equator suggested that we prepare the iris in the same way to control the weld better and reduce centroid drift over multi-cell length. All cell parts are coming out very true and the self-fixturing is better suited for production.

TRIUMF has prepared significant equipment to develop and test the e-linac multi-cell cavities. These include a single cell 1.3GHz cryostat, a warm tuning station for plastic deformation of the nine-cell cavity for frequency tuning and field flattening, a high-pressure water rinse station for cavity cleaning, a BCP etching station, fixtures for chemical polishing, and a multi-cell cryostat for cavity cold testing prior to final assembly in the cryomodule.

Cryogenic Equipment

The cryogenic equipment is the infrastructure needed to provide a 2 K environment for the SRF activities. The system supplies three cryogens: (1) liquid helium at 4 K - in a closed liquefaction and refrigeration loop; (2) liquid He at 2 K - produced in the cryomodules and returned to the close loop; and (3) liquid nitrogen, LN2, at 77 K - delivered from an external supply and exhausted to the atmosphere. The 4 K He is produced by expansion of pressurized gaseous He delivered to the cold box at near room temperature. The 4 K LHe is distributed to individual cryomodules by vacuum–jacketed trunking. The 2 K He is produced by Joule-Thomson expansion into 30 millibars maintained by sub-atmospheric (SA) pumping. The LN2 is used to pre-cool the cold box and to cool the 77 K thermal shield and intercepts. The cold-box, with 1,000-litre liquid helium storage Dewar, are positioned in the immediate vicinity of the e-linac in order to minimize losses associated with LHe transfer. The warm part of the installation, including two Kaeser He compressors, OR/GMS, and sub-atmospheric helium pumps, will be located outside the e-hall in the separate compressor building. A warm gaseous He piping brings the pressurized gas from the compressor building to the e-hall. A cold gaseous sub-atmospheric trunk returns the He to the compressor building. A counter-flow heat exchanger between these flows restores the SA gas to ambient temperature. The main compressor may also send He to a storage tank. The He circuit design places a strong emphasis on monitoring and maintaining He purity that is free of oil, moisture, or other contaminants. A low power recovery compressor returns the He to second tank in the event of failures or power outages and may invoke a bypass for He scrubbing.

The e-linac cryogenic distribution is based on a parallel feed of atmospheric LHe from a main trunk to each cryomodule. The LHe is drawn from a main Dewar supplied from the 4 K cold box. A LHe reservoir in each cryomodule acts as a phase separator. Cold gas returns in parallel back to a common return trunk and is delivered back to the cold box where it represents a refrigerator load. Then, 2 K liquid is produced in each cryomodule (see 4 K/2 K cryoinset above) by passing the 4 K liquid through a heat exchanger in counter flow with the returning exhaust gas from the 2 K phase separator and expanding the gas to 31 mbar through a Joule-Thomson expansion valve. The header pipe above the cavity string acts as a 2 K phase separator. The cold helium gas passes through a 4 K/2 K heat exchanger, and then, after warming up to ambient temperature, reaches the warm sub-atmospheric pumping system. This fraction constitutes a liquefaction load to the He cryoplant. A siphon circuit from the 4 K reservoir is used to cool the 4 K intercepts, with vapour return back to the reservoir. Initial cooldown is done by delivering 4 K liquid from the 4 K phase separator to the bottom of the cold mass through a dedicated cool down valve.

Conceptual design of e-linac cryomodules and cryogenic system went through external reviews September 2010 and March 2011, respectively. Subsequently, the refrigerator-liquefier specification for helium supply to three cryomodules (ICM and two ACMs) was produced and tendered in June 2011. The contract for supplying He cryoplant consisting of HELIAL 2000 cold-box, main, and recovery compressors with oil removal and gas management systems (OR/GMS), and multi-component purity analyzer was awarded to Air Liquide Advanced Technologies (France). This is class 700 W cooling power at 4.6 K machine with maximum liquefaction rate of 288 l/h. The final design was approved June 2012. The Kaeser compressors were received January 2013; and the OR/GMS and cold box were delivered March 2013. The contract for helium gas storage tank was awarded May 2012 and delivery taken January 2013. The refurbished He Dewar and auxillaries was received December 2013. The 4 K LHe distribution was awarded November 2012, and delivery is anticipated for the first quarter of 2014.

The sub-atmospheric units will pump continuously on He gas to maintain a suction pressure within 24–28 mbar measured at the pumps inlet. The exhausting clean He gas is sent to a helium compressor at 1.05–1.1 Bara. A modular design is adopted with 4 units for ICM and first ACM having a combined throughput totalling 5.6 gm/sec, and 6 units totalling 9.3 gm/sec after the addition of the second ACM. The contract for supply of four sub-atmospheric helium pumps, type DS3010-B, was awarded to Busch Vacuum Technics Inc. in August 2012; and delivery was taken in March 2013.

At the time of writing, efforts are concentrated on preparedness for the 4 K cryoplant acceptance tests in the summer of 2013. Further developments are related to the forward GHe lines, sub-atmospheric The He return lines, and LN2 distribution from an existing storage tank exterior to the south face of the Cyclotron Building.

Radio-Frequency (RF) Equipment

The injector cryomodule (ICM) contains one cavity and the two accelerator cryomodules (ACM) will each contain two superconducting radio frequency (SRF) cavities. Each cavity is equipped with two 50 kW c.w. input couplers for a nominal minimum power of 100 kW per cavity. The couplers are manufactured by CPI following the design adopted for the Cornell ERL injector prototype. The cryomodules will be installed in stages. In the first stage, to be completed in 2014, the ICM and the first ACM will be installed and each will be powered by a high-power c.w. klystron. For the ICM, the klystron is run at half power, while for the ACM, the full power is divided between the two cavities. Six input couplers for three cavities have been procured. At a later stage, a second ACM will be added and will take over one of the klystrons; at that time a 150 kW-level RF source will be developed for the injector. The e-linac radio frequency systems procurement will be a challenge because there are few high-power c.w. sources available at 1.3 GHz, and few vendors. Indeed, one of the established vendors ceased production of scientific klystrons shortly after the project was funded.

Buncher Cavity and Amplifier

The buncher is installed between the electron gun and injector cryomdule and acts to match the longitudinal emittance of the beam to the acceptance of the 9-cell cavity. The buncher is a 1.3 GHz normal conducting cavity of the Daresbury-EMMA design, and has been procured from Niowave Inc., USA. The measured Q and shunt resistance are 20,000 and 3.3 Mohm respectively. With these parameters, a gap voltage of 30 kV and beam current of 10 mA exists, while the maximum generator power is 290 W. A solid-state amplifier, model BLA500CW operating in class AB and providing 400W has been procured from Bruker BioSpin, France. The buncher is installed at ISAC/VECC and operates routinely.

Inductive Output Tube and HVPS

As part of the collaboration agreement with VECC, an injector cryomodule will be tested in 2013, with beam at peak power up to 25 kW and duty factor of 1% at the ISAC/VECC test stand. A 30 kW-rated inductive output tube (IOT) has been selected as the RF power source for that test. The IOT is also the RF source for the coupler conditioning facility (see below). An IOT with solenoid and trolley was purchased from CPI, USA, in 2010. A HV power supply and drive amplifier from Bruker BioSpin, France, was purchased on behalf of VECC and is on long-term loan to TRIUMF. The IOT system is installed and was tested in 2011 to the maximum-rated output power of 30 kW on a water-cooled load, and is now run routinely for the coupler conditioning stand.

High Power c.w. Klystron and HVPS

The continuous-wave (c.w.) klystron is specified with a saturated power of 290 kW and usable linear range (incremental gain of 0.5 dB/dB) up to 270 kW, which leaves plenty of margin for transmission loss to the 200 kW nominally rated EACA. After a tender process, coordinated as a joint venture with Helmholtz Zentrum Berlin (HZB), orders were placed with CPI, USA: one for TRIUMF and 3 units for HZB. The klystron is a factory-tuned multi-cavity, high-efficiency, high-gain, broadband, water-cooled tube. The final design was completed in August 2012 and factory tested to 300 kW output power in February 2013. TRIUMF took delivery in March 2013.

The contract for the klystron high-voltage power supply, rated at 65 kV 8.65 A, plus focus, filament, vacuum ion pump power supplies, and trunk RF distribution system, including all control, interlocks, protection and integration of the klystron was awarded to Thomson Broadcast in June 2012. The power supply is based on a voltage controlled power module type *PM-14-10-VR-1* derived from the modulator PSM12-2400 for DESY. The factory acceptance test is scheduled 2013 May, and delivery to TRIUMF in 2013 July. The 300 kW c.w. circulator and loads are subcontracted to AFT Microwave. Waveguide layout of the high-power RF system has been completed and support structures for the waveguides are being designed.

RF Conditioning of Power Couplers

An important step before mounting the power couplers into the accelerating cavities is their conditioning with RF power to process the surfaces and eliminate multipacting. The couplers have been tested under conditions differing from those under which they will be operated. Tests are performed at room temperature with compressed air cooling for inner conductors and watercooling for flanges at the waveguide to coax transitions, whereas operation will be with the cold RF window at 77 K on a LN2 intercept. Very roughly, 5 kW operation at 300 K translates to 50 kW capability at 77 K.

After baking, the couplers were subjected to various regimes of pulsed and c.w. RF power conditioning for prolonged durations. RF Power from the IOT was applied either in travelling wave or in standing wave mode. In the latter, a waveguide short circuit terminates the couplers leading to voltage levels double that in traveling wave mode for the same RF power. In the standing wave mode, the couplers were conditioned at 10 kW peak power at 1% duty cycle (in January 2013) Prolonged pulse conditioning was very effective in cleaning the couplers. CW conditioning was done in traveling wave mode: 5 kW was reached and held, with good vacuum, for several hours.

Control System

The control system provides control and monitoring of most or all subsystems. Those subsystems include cryogenics and cold distribution, ARIEL building nuclear ventilation, cooling water, beam line vacuum, beam line optics and diagnostics, RF systems, e-gun, oxygen depletion monitoring, and machine protect systems. All controls will employ the EPICS software toolkit that is used to produce controls for the ISAC-I and ISAC-II projects. Except for the machine protect subsystem, all controls will use technologies previously employed in ISAC. The control system will use strategies and standards developed with the experience gained in the ISAC project, and will use in-house productivity and quality control tools and methods. Adherence to ISAC standards is intended to result in consistent end-user interfaces as well as minimizing maintenance efforts by control system personnel and minimizing equipment costs for spare components.

Roughly speaking, controls for each subsystem will be based upon one or more predominant technologies. The cryogenics subsystem will employ a PLC for control of cold distribution elements and a network interface to the turnkey cryogenics plant. RF systems will use a different programmable logic controllers (PLC) network interface for control of RF power supplies, as well as the LLRF interface developed in-house for ISAC. Beam line controls will use PLCs, CANbus and VME-based technologies for vacuum, optics, and diagnostics respectively. Nuclear ventilation and oxygen depletion monitoring will be done using PLC systems, replicating as much as possible of prior ISAC designs. Beam loss monitoring for the machine protect system is in development, but will use a VME module designed and produced at Thomas Jefferson Laboratory. Cooling water controls will be integrated with beam line vacuum and cold distribution control PLCs.

Some control system components have been or will be developed as part of the VECC project, and will be migrated to the e-linac. These include controls for the e-gun, including SF6 gas control, RF controls, and optics controls. Also developed and test in VECC will be controls for the cryogenics sub atmospheric pumping system and beam line optics, diagnostics and vacuum. The beam line vacuum control system incorporates a new portable roughing system that introduces new requirements for control system flexibility. Gathering of information for procurement, assignment of work, and detailed design are underway for all controls subsystems.

Radiation Safety System

The personnel radiation safety system for ARIEL/e-linac will consist of two sub-systems: (1) the Access Control System, which will keep people away from prompt radiation hazards inside shielding during facility operation; and (2) the Radiation Monitoring System, which will directly measure prompt radiation levels outside shielding and terminate facility operation should unacceptable levels occur. Functional requirements documentation for both sub-systems have been written, reviewed, and approved. Detailed design for both sub-systems is progressing well. Operational beam inhibit devices, which will define e-linac as being “off” or “on,” have been identified and interface specifications communicated to device owners. A first version of Access Control System PLC logic is being tested on a simulator system. Radiation Monitoring System gamma and neutron detectors have been selected based on measurement requirements. The data acquisition components for this system are being developed and will be used for radiation monitoring of VECC/ICM in the ISAC vault before being moved to ARIEL/e-linac.

The ARIEL e-linac project has witnessed outstanding progress across all areas. The building’s construction will be complete in June 2013. Beam lines, cryogenic, and high-power RF equipment design and procurements are on schedule. Two key facility milestones are anticipated: the ICM beam test in May 2013 and the ACM initial beam test in October 2014.

5.3.3. ISOTOPE PRODUCTION RESEARCH AND DEVELOPMENT

ARIEL will use proton-induced spallation and electron-driven photo-fission of ISOL (isotope separation on-line) targets for the production of short-lived rare isotopes that are delivered to experiments at the existing ISAC facility. ARIEL will support delivery of three simultaneous rare-isotope beams (RIBs), up to two accelerated, new beam species, and increased beam development capabilities. To do so, the ARIEL complex will include, in addition to the electron accelerator and beam line, a new proton beam line from the 500 MeV cyclotron to the targets; two new high power target stations; mass separators, and ion transport to the ISAC-I and ISAC-II accelerator complexes. Conceptual design work on these elements has proceeded as Phase 1 of the ARIEL project moves toward reality.

Beams of rare isotopes are challenging to produce, especially the short-lived ones, which do not occur naturally. They have to be produced artificially in the laboratory. The ISOL method can be described as a process in which the isotope of interest is fabricated artificially by bombarding the nuclei in the target material nucleus with fast projectiles. In a thick target, the reaction products are stopped in the bulk of the material. The target container is attached directly or indirectly to an ion source, allowing the reaction products to be quickly ionized and accelerated to form an ion beam that can be mass analyzed and delivered to experiments. The requirements for producing high intensity RIBs are: (1) a high-energy driver with sufficient intensity; (2) a target material inserted into an oven made of refractory material, connected to an ion source; (3) an ion source at high voltage to produce an ion beam; and, (4) a high-resolution mass separator.

In ISAC, the target stations are located in a sealed building called the Target Hall, which is serviced by a specialized remote-controlled crane. The Target Hall facility includes a hot cell for active materials handling, conditioning station for testing of targets off-line, mechanical service systems for activated target cooling water and active gas from the target vacuum system, a nuclear ventilation and exhaust filtration system, a decay storage vault for spent target materials, and storage space for shielding and equipment modules. The target area is sufficiently shielded so that the building is accessible during operation at the maximum proton beam current.

Beam line elements near the target are installed inside a large T-shaped vacuum chamber surrounded by close-packed iron shield. This general design eliminates the air activation problem associated with high-current target areas by removing all the air from the surrounding area. The design breaks naturally into modules; an entrance module containing the primary beam diagnostics, an entrance collimator and a pump port; a beam dump module containing a water-cooled copper beam dump; a target module containing the target/ion source, extraction electrodes and first guiding component and heavy ion diagnostics; and two exit modules containing the optics.

The ARIEL project will use some of the technologies developed and exercised over the past 14 years at ISAC, but by and large it will be based on an improved, second-generation target station design for high power RIB production, which incorporates the ISAC experience and lessons learned. To guide the detailed design of the ARIEL target station, we evaluated the existing ISAC technologies and practices using a method called Design Failure Mode and Effect Analysis (DFMEA), used primarily in product development and manufacturing. The findings from this analysis, both positive and negative, were incorporated in the design concept of the ARIEL target stations and target module.

As with ISAC, the ARIEL target stations are located in a sealed building serviced by an overhead crane. The target maintenance facility includes a hot-cell for target diagnostics and storage preparation, decontamination facilities, and a radioactive storage vault. And, as in ISAC, the ARIEL target stations will be surrounded by steel and concrete blocks.

In a departure from the ISAC paradigm, the two ARIEL target stations are designed with completely independent services (e.g., cooling water, vacuum system, electrical, and nuclear ventilation), and adequate shielding such that personnel access to one target station will be permitted while the other is producing and delivering beam. In addition, the target stations will employ new vacuum joint technology and will be equipped with remote connection and disconnection of services for rapid target exchange (2-3 days).

Figure 5 shows a 3D view of the next generation of target station proposed for the ARIEL project. The new target station concept consists of a target module, heavy ion beam line, pre-separator and beam dump. In ARIEL, the heavy ion optics modules will be replaced by beam pipe sections with a vertical pumping duct, surrounded by shielding blocks composed of steel and concrete. As in ISAC, the pumping duct may serve to insert diagnostics at the beam level, specifically Faraday cup, slit, and beam profiler. The rationale is to keep the turbo pumps and sensitive equipment as far as possible from the high-prompt-radiation field. The beam dump and the entrance module might also be replaced by a stand-alone diagnostics box, and beam dump with a water-cooled copper plug, respectively. Again, the rationale is that these devices never had to be replaced since ISAC went into operation 14 years ago. These decisions simplify the vacuum envelope of the target station compared to ISAC. It also reduces the cost of the target station since 4 module steel plugs with intricate service chase penetrations are replaced by less expensive, simpler, solid shielding.

The ARIEL target hall will house two ISOL target stations, east and west, actinide and conventional laboratories, target assembly laboratories, and a dedicated hot-cell facility for target diagnosis. The two target stations will be compatible with actinide target operation and up to 500 kW electron beam and up to 50 kW proton beam power. The west ARIEL target station will be initially operated with electrons. Once the new proton beam line becomes operational, it will receive proton beam only, and electrons will be confined to the east target station, where RIB delivery to users will take place simultaneously with development activities, primarily of the photo-converter. During the operation of both targets with electrons, the sharing of the beam current on the targets will be flexible, to maximize both the user and the development programs.

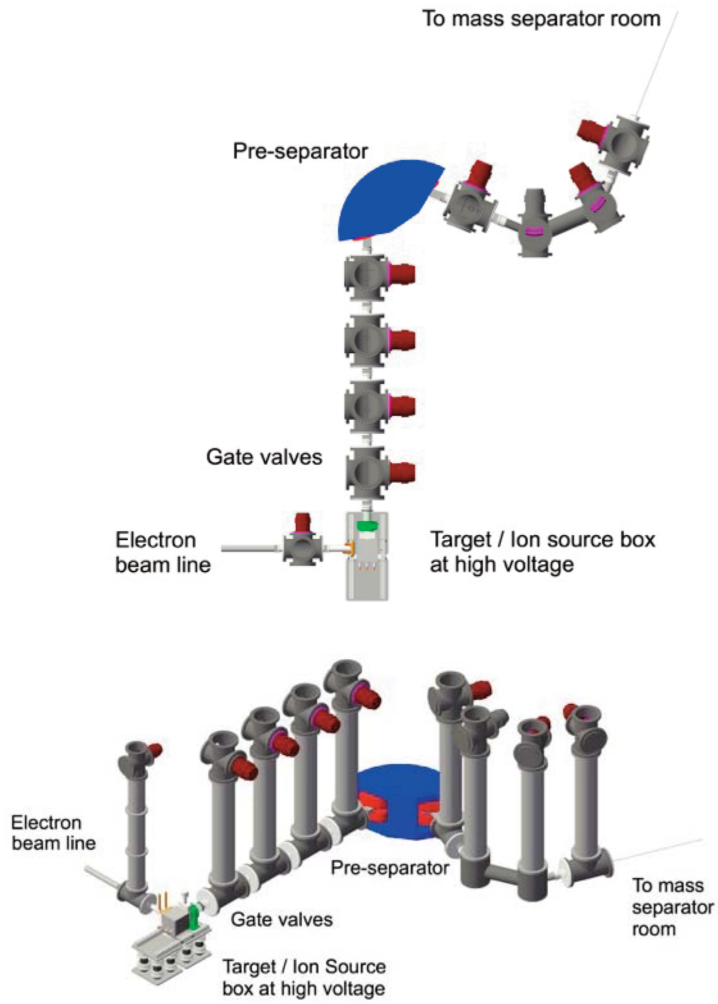


Figure 5: 3D view of the next generation of target stations proposed for ARIEL.

During Phase 1 of the ARIEL Project, the e-linac will deliver a 100 kW, 25 MeV electron beam on target. The electron beam will impinge onto a converter made of water-cooled Ta discs; an Al disc placed after the converter will stop the remaining electrons before they reach the target. Since most of the services required to operate actinide targets will not be present in the first phase we envision using a non-actinide target to carry out the ARIEL target and front-end commissioning. It is advantageous to consider the production of Li-8 using Be-9 target via the $^{9}Be(\gamma,p)^{8}Li$ reaction. There are multiple advantages to using Li-8 on a ^{9}BeO target, including:

The level of radiation is not extremely high and the Li-8 has a very short half-life of 840 ms. The longest half-life nuclei produced is Be-7 with half-life of 53 days. With Li-8, we can start the experimental program while we are preparing for operation with an actinide target. This will allow a complete commissioning of the whole system from target station to the experimental facility.

The Li-8 beam is used by the β-NMR material science community. The Li-8 beam is polarized using | a collinear optical pumping system in which the polarized light from a laser beam is directed along the heavy ion beam axis. This method is well established at ISAC. The first step is to neutralize the Li-8 ion beam by passing it through a Na vapour cell. The neutral atoms then drift nearly 2 m in the optical pumping region in presence of a small longitudinal magnetic holding field of 1 mT. Then the beam goes through a He cell where a large fraction of the now polarized Li-8 is ionized and then sent to the β-NMR or β-NQR station.

Results from FLUKA simulations show that the in-target production of Li-8 is as much as 10^9 particles/s during Phase 1.

Looking beyond this five-year plan, the e-linac energy may ultimately be upgraded to 50 MeV and the power to 500 kW. At these power levels, the simple water-cooled Ta discs approach will no longer work. Due to the large power density, it may be preferable to use a liquid metal converter, such as Hg or Pb because of their high Z. Lead is preferable to mercury because of health concerns, active waste disposal, environmental issues, and chemical compatibility with the system. Furthermore, mercury produces more long-lived isotopes by (γ,n) reactions than lead does. Simulation shows that 375 kW is deposited into the converter and 75 kW in the target itself. This is 7 times larger than the power we can handle in one single target. To handle the power deposition in the UCx material, we may use a composite target technique, involving coated graphite foils. We may also divide the target into assemblies of the smaller targets or investigate alternative coolants.

Partners

In Canada: University of Victoria, University of British Columbia, Simon Fraser University, University of Alberta, Carleton University, l'Université de Montréal, University of Toronto, University of Guelph, University of Saskatchewan and Canadian Light Source, McMaster University, University of Regina, Saint Mary's University, Laval University, PAVAC Industries Inc.
International Partners: France (1), India (1).

TRIUMF's Role

The design and construction of ARIEL e-linac is led by TRIUMF under the guidance of Principle Investigator Dean Karlen (University of Victoria). TRIUMF's contribution includes workforce for general management, technical design and development, procurement and fabrication, assembly, installation and commissioning. Materials and equipment are contributed by the CFI grant.
The TRIUMF labour contribution to e-linac falls under the contribution agreement with the NRC.

5.4 ACCELERATOR AND BEAM LINE INFRASTRUCTURE

At the heart of TRIUMF is the 520 MeV cyclotron. It supplies a proton beam to ISAC to produce the rare isotopes that are then accelerated and delivered to the experimental area. This is not as easy as it sounds. The production target must handle high heat and radiation load. The desired isotope must then be extracted from the production target, separated from other unwanted isotopes and delivered to the experiment either accelerator or unaccelerated. The main cyclotron also supplies protons to the meson hall for muon and pion production.

Also included in this section is a discussion of the helium recycling. To reach temperatures required for most superconductors it is necessary to use liquid helium. Recently there has been a shortage of liquid helium and the price, when it is available, is prohibitively large. It thus becomes imperative to recycle the helium used in the meson hall. The plans for this are also given in this section.

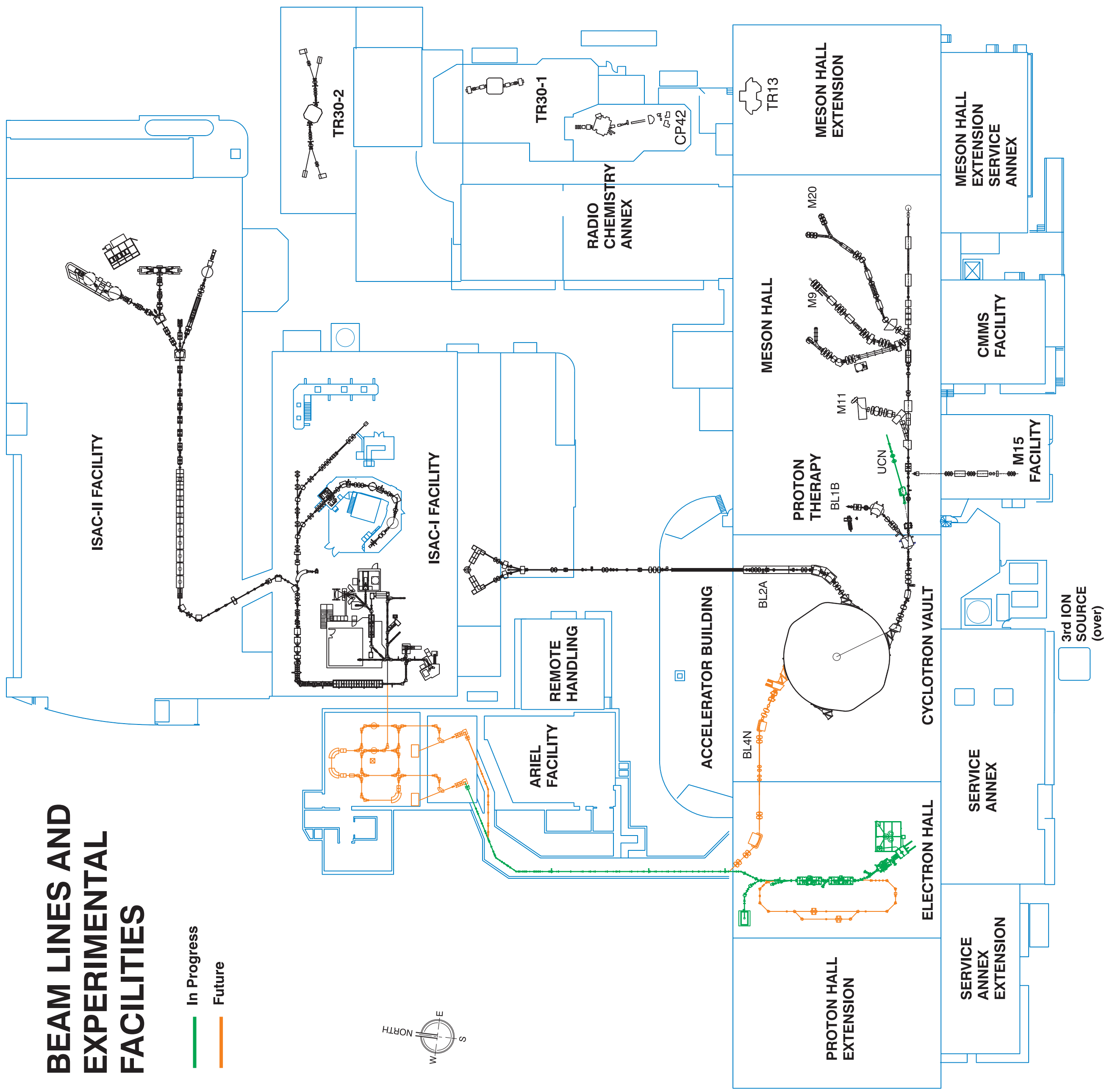


Figure 1: Main beam lines of the cyclotron.

5.4.1 MAIN CYCLOTRON AND PRIMARY BEAM LINES

At the heart of TRIUMF is the 520 MeV cyclotron that produces the primary proton beams and supports many of the laboratory's programs, including: ISAC, the Centre for Molecular and Materials Science programs in μSR and β–NMR, 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 520 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 46 m to the cyclotron. The 520 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 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 cyclotron is capable of delivering four independently controllable proton beams at energies from 70 to 520 MeV with a total current of up to 300 μA. This flexibility is made possible by the use of negative hydrogen ions, which have a binding energy of only 0.75 eV, and so can be extracted in a simple and highly efficient way by stripping them to protons in thin pyrolytic graphite foils. The fragility of H^- ions, however, means that they can also be readily disrupted in strong electromagnetic fields or by collisions with gas molecules. Their use therefore incurs design penalties: to limit the beam power loss by electromagnetic stripping to 7% by 500 MeV, the magnetic field strength must not exceed 0.58 T; to limit that by collisions to 3%, the vacuum must be better than 10^{-7} Torr. The former requirement implies much larger orbits than in a proton accelerator, perhaps by a factor of 3. Thus the TRIUMF cyclotron has the dubious distinction of having the largest diameter of any yet built: for the magnet poles, 17.2 m; for the yoke, 21.5 m. As the electromagnetic stripping is only significant above 450 MeV, it is possible to run higher currents for the same absolute loss by extracting the beam at energies below 500 MeV.

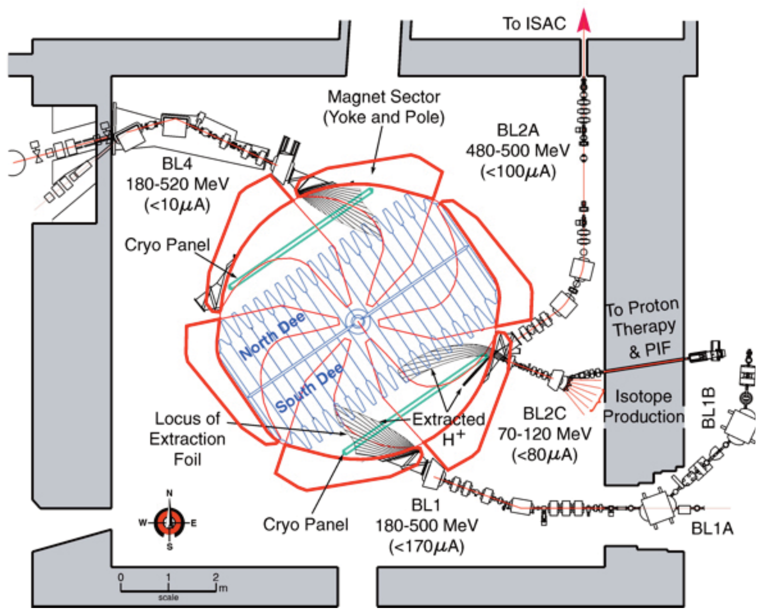


Figure 1: 500 MeV cyclotron and four primary proton beam lines: BL1, BL2A, BL2C, and BL4

The success of TRIUMF's programs depends on the ability to deliver protons from the cyclotron reliably. Typically the beam is delivered for about 5,000 hours per year with one major (three month) and one minor (one or two week) 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% (see Figure 2, 3 and 4). Replacement of the trim and harmonic coil power supplies was completed during shutdown 2012. Also, after 36 years of continuous service, the original vertical section of the injection line was decommissioned and replaced with a new one in April 2011.

Cyclotron Systems

The 4000-tonne magnet is composed of six separate sectors, radial near the centre, but increasingly spiralled at large radii to provide sufficient vertical focusing. The space between them is left free of iron to maximize the magnetic flutter. The magnet is excited by a pair of circular coils 19 m in diameter, each consisting of 15 vertical sheets of aluminium (45.7 cm x 2.5 cm) with internal water cooling channels, and weighing 77 t. The power supply provides 18,400 A at 75 V with stability 10^{-6}. The vacuum chamber is roughly circular (maximum diameter 17.9 m) and 46 cm in height, the lid being sealed by a pair of

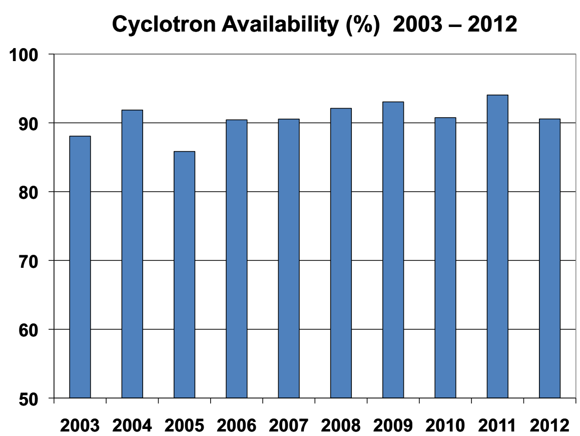


Figure 2: Cyclotron uptime as a percentage of scheduled operational hours per year.

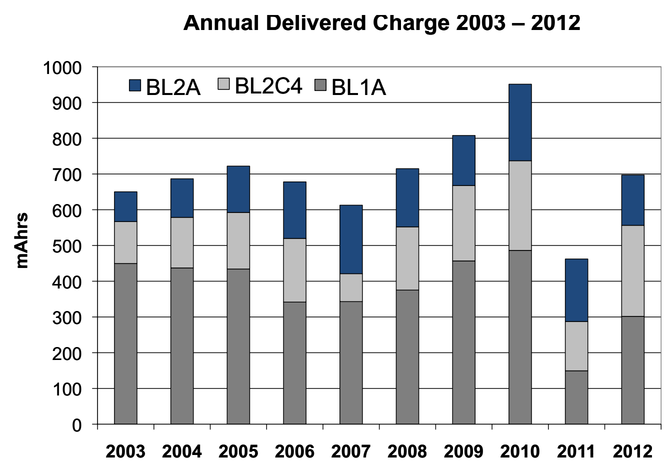


Figure 3: Total delivered charge per year from the main cyclotron over the past decade.

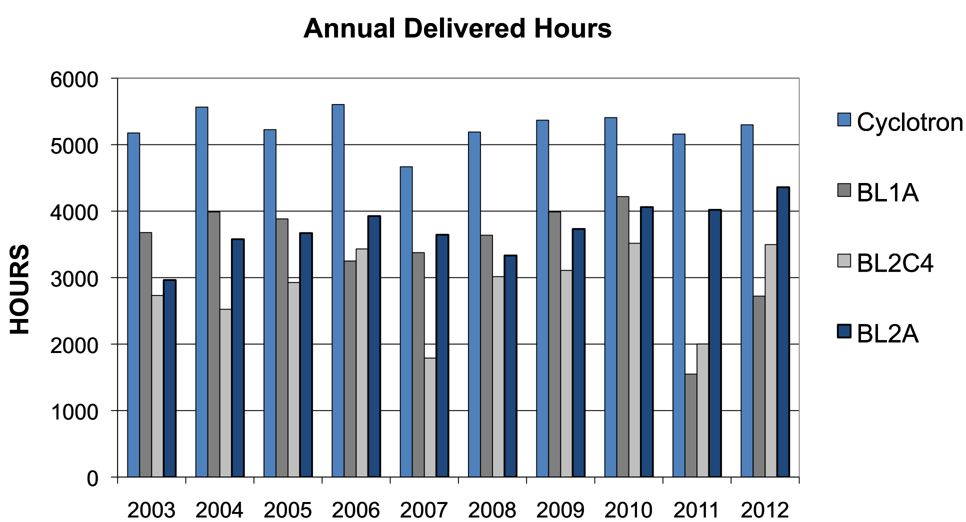


Figure 4: Total annual proton charge (mAh) delivered to three beam lines.

rubber O-rings. A vacuum better than 5 x 10^{-8} Torr is maintained by two long 4-K cryopanels and 6 cryopumps, backed up by turbopumps. Externally, the lid and base carry 54 circular and 78 harmonic trim coil pairs for fine adjustment of the magnetic field. The 2400-t atmospheric load on the base is supported by 332 steel tie rods anchored to the vault floor; that on the lid by another 332 tie rods bolted to a 109-t "spider" of steel I-beams above. The upper half of the magnet, the spider and the tank lid can all be raised 1.22 m by 12 electrically-driven jacks to permit maintenance work inside the tank. Much of this work can be carried out remotely (including replacement of the rf resonator sections) using a 9-m-long bridge that can be inserted and rotated about a central pivot.

H^- ions are produced in an external cusp source mounted in a Faraday cage raised to 300 kV by a Cockcroft-Walton set. The 300-keV ion beam is then transported horizontally over the cyclotron vault roof and bent 90° downwards for axial injection. Electrostatic focusing and steering is used throughout the 46-m-long injection beam line. An electrostatic spiral inflector and horizontal deflector are then used to steer the beam into the median plane of the cyclotron for acceleration by the dees.

Acceleration is by 5th harmonic rf (23.055 MHz), the two 180° dees each being composed of 40 half-wave resonators 75-cm-wide, 3-m-long, half mounted on the vacuum tank base and half on the lid. The system is powered by eight 250-kW Eimac tetrodes, producing a dee voltage of 95 kV (with 10^{-4} stability) and maximum energy gain/turn ΔE = 380 keV. There is also a 92-MHz booster cavity to increase ΔE by ≤ 200 keV above 450 MeV, significantly reducing the beam loss.

The primary beam diagnostic tools are two "low-energy" and three "high-energy" intercepting probes equipped with multi-finger heads that can be moved radially to cover the whole energy range. These provide data on total beam current, radial and vertical intensity distributions, and time of flight. Visual access is also available via periscope equipped with CCTV camera and rotatable mirrors.

Extraction systems are provided for four external beam lines (see Figure 1):

- **BL1:** ≤ 170 μA at 180-520 MeV for pion and muon production;
- **BL2A:** ≤ 100 μA at 472-500 MeV for radioactive ion production;
- **BL2C:** ≤ 100 μA at 70-120 MeV for radioisotope production, proton irradiations and cancer therapy; and
- **BL4:** ≤ 10 μA at 180-500 MeV (1975-2010); ≤ 200 μA at 470-500 MeV for radioactive ion production in the next five-year plan via the ARIEL project.

The stripping foils may be moved radially to change the extracted beam energy, and azimuthally to direct the beam to an external "combination" magnet that steers it down the beam line. Multiple foils are available in each extraction probe cartridge, and they may be changed remotely, either in case of damage, or when a different foil shape is required (as for the lower energy beams, where only a fraction, ranging from 1/50,000 to 100/1, is to be extracted). The extracted beams typically have an energy spread of 1 MeV, radial and vertical emittances $4e_{\mathrm{rms}}$ = 1 - 2 pmm, and a 4-ns, 23-MHz, bunch microstructure. A chopper in the injection line allows a pulse macrostructure with a duty cycle variable from 0.1% to 99% at 1 kHz repetition rate.

Operation and Performance

For decades the cyclotron operated in a fairly steady mode of 24/6 production with regular weekly 8- to 36-hour maintenance periods and two annual shutdowns: 7 days in September and 3-4 months in winter, depending on service and repair needs. Lately, aiming at higher scientific production and as a result of multiple machine upgrades, the number of maintenance days has been greatly reduced (by >30%).

Long maintenance periods are usually driven by ion-source filament replacements (every 3 weeks) and cryo-panel preventative defrosts (every 6 weeks). Over the last decade the machine has demonstrated reliable operation with annual availability around 90%.

Both peak and integrated beam production are driven by the beam delivery schedule determined by the users' needs. With the recent deployment of actinide targets in ISAC, beam demand down Beam Line 2A has dropped from 70-100 µA (high power targets) to 10 µA for a significant fraction of experiments. A histogram of beam charge delivered over the last decade is presented in Figure 3. The reduction in BL1 charge in 2011 and 2012 is associated with an extended shutdown of this beam line for installation of a new M20 secondary channel and repair of a vacuum leak at the T2 target extraction port; the reduction in BL2C4 charge in 2011 was due to an FDA investigation of an isotopes breach in the USA for a similar product and the subsequent interruption of Sr-82 production.

The most significant issues impeding operations and requiring extended effort during shutdowns are usually associated with water leaks (cyclotron resonator panels, Meson Hall magnets) or vacuum leaks (distorted joints and damaged seals in high radiation areas).

Under optimal conditions transmission up to 70% has been measured between injection and extraction to all beam lines. The extracted beams have small spot sizes (3-7 mm) at the targets and a 4-ns-long time structure.

Hardware Upgrades

Over last five years the cyclotron has received government funding for its refurbishing and upgrade of ~400 k$ annually. Within this program many subsystems and components have been upgraded:

RF System

Power amplifier (PA) resonators and filament power supplies upgrade, dee-voltage monitoring upgrade, rf coupler upgrade, new 12-kV AC switch gear.

Injection System

A new 12 metre long vertical section of the electrostatic beam line [1] employing low-maintenance reliable design dramatically extended the diagnostics and tuning capabilities, and supports high-intensity (up to 5 µA) beam transport (see Figure 5); an Alison-type emittance scanner has been installed downstream of the ion source, greatly expanding beam characterization and tuning capabilities; a new deflector was installed, that can provide, in addition to horizontal steering, some transverse focusing: this is achieved by an additional curvature of the deflector electrodes in vertical direction—new deflector allowed improvement of the cyclotron transmission by ~5%.

Figure 5: The installation of the vertical section of TRIUMF's new main injection line. The line is used to transport hydrogen ions from the ion source to the centre of the cyclotron.

Diagnostics and Probes

New non-intercepting beam position monitors have been installed in the beam lines, allowing on-line monitoring and tuning; old leak-prone devices in the central region were removed and a new vertical flag developed and installed; deployment of new highly oriented pyrolitic graphite material has dramatically improved the life time of the extraction foils (by a factor of 4).

DC Power Supplies

All of the 3-10 kW power supplies (120 units) feeding the cyclotron's trim and harmonic coils have been replaced with modern (switching mode) units.

Cyclotron Vault Cable Infrastructure

Wiring in the vault is exposed to harsh conditions of radiation, humidity, and temperature. This leads to premature failures and destructive damage. To address this issue TRIUMF has embarked on replacement of all the cables (~1500 units) ending in the cyclotron vault. A complementary parallel cable tray infrastructure has been created and more than half of the cables have been replaced.

Cyclotron Beam Development

Since 1995, when the ISAC project got under way, new requirements for beam quantity and quality have been established. First of all, the total beam intensity demand has grown from 200 to 300 μA. However, this growth in production had to be achieved without increasing facility activation due to beam loss. Also, due to the vulnerability of the ISAC targets and to the high sensitivity of their yields, stringent limits have had to be set on fluctuations in intensity and beam position on the BL2A target, setting high demands on machine stability and reproducibility. To address these issues a number of beam developments have taken place and several machine improvements have been implemented.

The cyclotron design does not support operation much beyond 520 MeV because above ~450 MeV there is a rapid rise in electromagnetic stripping losses (see Figure 6), due to the Lorentz force tearing one of the weakly coupled electrons off the hydrogen ion. In 2009, after careful evaluation of the impact on the experimental program, the extraction energy was reduced from 520 MeV to 480 MeV. This has led to ~30% reduction in both prompt and residual activation for the same beam intensity [2]. Alternatively, it allows an equivalent intensity boost within the traditional activation dose budget.

Several improvements were made to get the required higher stability for the ISAC primary beam. First, the BL2A beam intensity was stabilized to ±1% by introducing a feedback loop between the electron

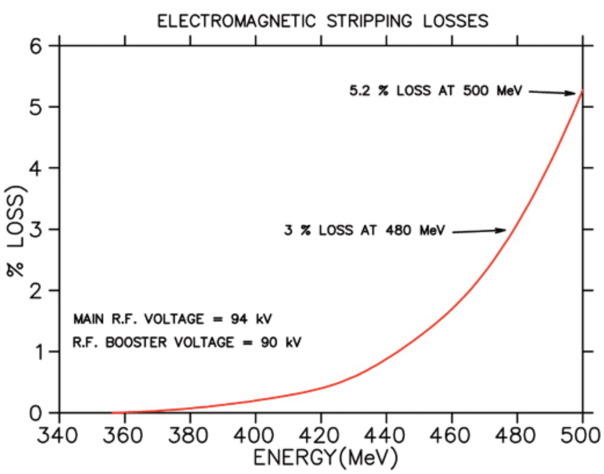


Figure 6: Electromagnetic stripping loss as a function of energy.

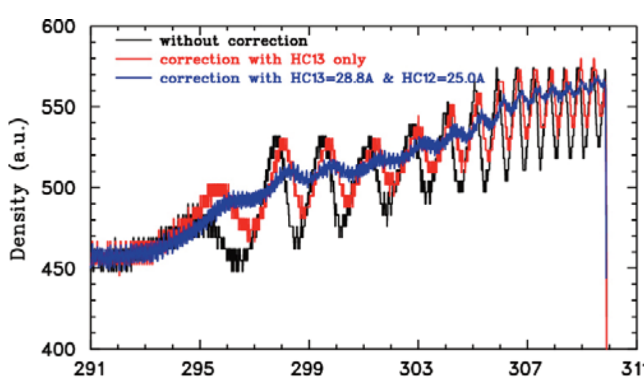


Figure 7: Suppression of the ν_r= 3/2 resonance. Current density around extraction with 0, 1 and 2 correction coils. Top: simulation; Bottom: experimental results.

current caught on the stripper and the pulser at injection, regulating the beam's duty cycle. Decreases in the stripper current are compensated by increases in duty cycle and vice versa [3]. Second, automatic beam steering was implemented to keep the beam centred on the production target. Thirdly, the beam line 2A tunes were developed to form an image at the target of the spot on the stripping foil, thereby minimizing the beam halo on the target. Automatic beam steering was also implemented for all targets in BL1A.

Stabilizing the BL2A intensity was found to produce a side effect—magnified intensity fluctuation in the other primary beam lines. The root cause of the instability was traced to the $\nu_r = 3/2$ resonance driven by field imperfection in the cyclotron, that causes radial beam intensity variation after resonance crossing, at energies above 450 MeV (see Figure 7) [4]. To suppress this resonance, a delicate machine tune was developed employing two independent sets of harmonic coils near the extraction radii (HC12 and HC13) energized in the third harmonic mode. This reduced the intensity instability in the unregulated beam lines (BL1A and BL2C) from ±10% to ±2%. To further diminish this source of current instability, we implemented an active feedback system. It regulates the amplitude of the first harmonic Bz produced by a set of harmonic coils (HC13). A proper choice of the phase of this first harmonic correction allows variation of the split ratio, without changing the energy of the extracted beams.

The ISAC production targets operate at extreme temperatures, very close to the material's destructive damage limit. Therefore, they are very vulnerable to abrupt thermal changes and thus sensitive to any beam interruptions, causing big changes in power deposition on the target. Instead of the full beam trip previously induced by an over-current or some other abnormal beam condition, a so-called "soft" beam trip was therefore implemented, where the beam intensity is dropped down to 80% without interruption, allowing the operator to address the anomaly and restore normal production. Also, slow ramping of the beam intensity (~1 minute, up or down), has been introduced to mitigate target thermo-cycling issues.

Also, we made important developments on the extraction probes and stripping foils. One of the issues was related to the beam spills. We can only tolerate beam losses of about 1nA/meter in the primary beam lines. This is 10^{-5} level at 100uA. Beam spills are primarily due to the large angle scattering from the stripper foil. For a 5mg/cm^2 foil, which is the usual thickness used in the past, 10^{-5} particles have an angle driving them into the 4-inch beam pipe. So, it was suggested that 2.5-5 times thinner foils be used to minimize the scattering. Another issue was that foils deformed or even cracked in the past. The cause was believed to be a temperature rise on the foil frame on the top. Concerning these two issues, improvements were made such that (1) highly orientated pyrolytic graphite foils, of thicknesses about 2mg/cm^2 are now used, and (2) a Tantalum frame, with a thin copper cushion, is now used in place of the previous stainless steel as Tantalum has better thermal conductivity. Also, additional heat relief features were introduced in the probe head mechanism. With these improvements, we have achieved 4 times longer lifetimes for the BL1 foils. As a result, the Be-7 contamination surveyed at the Ex1 probe has been reduced by a factor of 5 that is also attributed to foil vertical position optimization leading to lower foil temperature.

Primary Proton Beam Lines

TRIUMF has four independent extraction probes with various sizes of foils, providing the capability to deliver protons simultaneously to up to four beam lines. New foils, composed of highly oriented pyrolytic graphite, were employed, improving the quality of the extracted beam and decreasing the amount of foil changes, which in turn decreases the amount of possible problems associated with the foil change procedure. Because of the high energy of the proton beam, these beam lines use magnetic rather than electrostatic focusing and steering elements.

Beam Line 1A (BL1A) can deliver 180 to 500 MeV protons to two target systems, T1 and T2. The beam power ranges from 50 to 75 kW. The first target, T1, services three experimental channels, one of which is used as a detector test facility by multiple users. The second target, T2, services two μSR experimental channels. Downstream of T2 is the 500 MeV Irradiation Facility used to produce strontium isotopes for medical-imaging generators as well as the TRIUMF 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. The protons can be converted into neutrons for terrestrial electronic testing by companies, such as CISCO.

Beam Line 2A (BL2A) is capable of providing 475 to 500 MeV proton beams at up to 50 kW to the ISAC target facility, which 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). It is also used for 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 and these protons can be converted into neutrons for NIF users. The energy range for this line is 70 to 120 MeV. Recent foil improvements now allow high current running in BL2C4 when no other beam lines are available.

In the past, Beam Line 4 (BL4) could 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. Delivery to this line is on hold while it is under construction as part of the ARIEL project. Currently, only the vault section of the beam line remains since the Proton Hall was decommissioned during the 2011–2012 shutdown. An extension of this line, Beam Line 4 North (BL4N), will be used for the proposed ISAC expansion, to deliver protons to a target at the ARIEL facility.

Summary

The 520 MeV cyclotron delivers three simultaneous proton beams for both production and test purposes. The total mAh charge has generally increased 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.

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. This goal was reached in November 2010 when we ran for 12 days at 315 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.

IEEE RECOGNIZES TRIUMF'S MAIN CYCLOTRON

09 August 2010

The Institute of Electrical and Electronics Engineers (IEEE), the world's largest professional association for the advancement of technology, has recognized the extraction of the first high-energy proton beams from TRIUMF's main cyclotron on December 15, 1974 as an historic engineering milestone. A dedication ceremony was held at TRIUMF on the 36th anniversary of the event.

The main cyclotron at TRIUMF is the world's largest such device of it's kind, measuring 18 metres across and producing intense beams of protons at energies up to 520 Million electron-Volts (MeV). Since 1974, TRIUMF has used these proton beams (and secondary beams of pions, muons, neutrons, and rare isotopes produced in its experimental halls) to conduct pioneering studies that have advanced nuclear physics, particle physics, molecular and materials science, and nuclear medicine.

Prof. David G. Michelson, chair of IEEE Vancouver Section and a member of the Department of Electrical and Computer Engineering at the University of British Columbia, said, "The quality of the initial design and engineering of the TRIUMF 520 MeV cyclotron is underscored by the cyclotron's longevity. Thirty-five years after the first full energy proton beam was extracted, the cyclotron is still the main engine of TRIUMF's world-leading research program."

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5.4.2 ISAC TARGET AND ION SOURCES

TRIUMF's ISAC 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 nuclei 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 and extracted as ion beams that are mass separated so that pure beams of rare isotope can be delivered to the experimental facilities.

When the driver proton beam interacts with the target material a number of protons or neutrons can be ejected from the target nuclei, the nuclei can shed fragments or fission, so that a wide spectrum of isotopes are produced in the reaction – will all products being lighter than the original target nuclei. Hence the isotope production can be tailored only to some degree by the particular choice of target material. Ion sources then are selected primarily by their ability to ionize the isotope / element of interest to highest possible efficiency. Therefore a suite of different ion sources is required to deliver all isotopes of interest to the experimental program.

Initially when the ISAC project was funded, existing target designs could only accommodate up to 2 µA incident proton beam intensities. During the last five years we have developed techniques that allow us to operate special ISOL targets with up to 100 µA. Among the techniques that were developed was a high-power target equipped with radial fins that can dissipate up to 20 kW.

For the target material we used mainly refractory (high-temperature) foils—Ta, Nb, and carbide foils. The development of composite carbide target was a breakthrough that permits the ISAC facility to produce rare isotopes with a larger target material inventory, and this allows us to produce intense, rare isotope beams. At the time of writing, composite carbide targets operate routinely at an intensity of 70µA.

Because ISAC operates at very high proton intensity, the development of ion sources that can operate in such a high radiation environment is a challenge. Like the targets, a RIB ion source typically has to be replaced after an ion source run. Supplying currents, high voltage and cooling to the ion sources, typically operating at 20kV-60kV is an additional challenge. The hot surface ion source was the first ion source implemented at ISAC, and this was followed by an electron cyclotron resonance (ECR) ion source, a resonance ionization laser ion source (RILIS) and a forced electron beam ion arc discharge (FEBIAD) ion source. Currently an improved type of ECR ion source with improved electron confinement—and thus higher ionization efficiency—is under development. However, such an ECR would require a dedicated target module to be operational, where the current focus is on the refurbishment and replacement of the inventory of aging target modules in operation.

The TRIUMF RILIS delivered first beams on-line in 2004 and was the first all solid state laser based on-line laser ion source. TRIUMF pioneered this new development in order to minimize operations cost, yet benefitting from the unique feature of laser resonance ionization: element selectivity.

With a RILIS only the desired element is ionized–whereas all other isotopes remain in the target ion source, thus producing some of the cleanest beams of isotopes available. Still, some residual surface ions are created in the hot ionization cavity and heated transfer tube elements. The cost of implementing a state of the art, solid state laser based RILIS was that–element by element–new laser excitation schemes, suitable for the solid state lasers in use had to be developed. The development goal laid out was two new RILIS beams per year.

The priority of the last five-year plan was on the completion of the ISAC RIB production facility to its full specifications in order to improve the reliability of the target/ion source assemblies, the predictability of the produced RIB intensity, new rare-isotope beams, and sustainability of the ISAC production system.

ISAC Production Target/Ion Source: Improving Reliability

The major reliability issues encountered in ISAC were due to water leaks in the target heat shield cooling lines under vacuum. To provide context, the target ion sources used are mainly made of tantalum (Ta), a refractory material. The target/ion source operates at a high temperature—2200 ºC. At this temperature, tantalum glows white and is very sensitive to oxidation in contact with water molecules where the following reaction is very favorable:

$Ta + xH_2O \rightarrow TaO_x + H_2$.

Due to the long turnaround time of the target exchange process, the target/ion source must operate online for a period of four to five weeks. This means that even a tiny water leak will eventually damage or destroy the Ta in the target /ion source assembly. The techniques, skills, and experience used to produce the target ion sources assembly were lost in the machine shop due to a combination of staff turnover and retirements. It was not feasible to mitigate this through training of new people, and historical documentation was not sufficiently detailed to ensure proper quality assurance and resulted in several failures.

Once the diagnosis of the various failures pointed to water leaks, a failure mode and effects analysis (FMEA) was implemented. The analysis revealed that the design of the brazed water joints had to be changed. In addition, the original brazing alloy used for years had been changed to a less favorable alloy with a high cadmium content. In addition, the brazing techniques used in the production of the components that leaked were identified to cause premature failure.

The following measures have been implemented to improve the reliability: (1) a new protocol for brazing was developed, and the specification for the alloy was revised; (2) machine shop personnel have been trained to perform the required brazing (see Figure 1); (3) some of the joints were redesigned entirely to simplify the brazing; and, (4) an engineer specialized in product development and manufacturing has been hired to follow up the complete manufacturing process of the target ion source assemblies.

Now, new target ion sources are tested prior to installation. To achieve this objective, an existing ion source test stand was converted into a production test facility. Now each target and the ion source are tested prior to installation onto the target module. As a result, any problems identified during the testing can be corrected prior to the on-line production run.

For laser ion source laser ionization scheme development (laser spectroscopy) and ion source development a dedicated laser ion source test stand and laser system was completed in 2011 and has helped in the speedy development of new laser ionization schemes, laser system development and the prototyping and detailed testing of the radiation hard ion guide laser ion source prior to scheduling of the first on-line run with radioactive ion beams. TRILIS operation hours have more than doubled in the course of the running five-year plan.

As a result of these improvements in the targets and ion sources department in the past two years, a substantial increase in beam delivery reliability has been achieved with higher than 75-85% availability for accelerated and non-accelerated beams respectively.

Target Module Refurbishment

The ISAC Target Modules (four total) are used for transport of targets and contain the ion extraction system in a sub-assembly called the source tray. They have a finite operational life and eventually require refurbishment. During 2010/2011, several high-voltage problems during operation initiated a failure analysis and refurbishment of Target Module 1 (TM1). Due to the design of the module, and its radioactivity from operating under beam, it was only possible to replace the source tray sub-assembly.

A failure mode and effects analysis (FMEA) was performed on these items, leading to the redesign of certain components for improved durability and functionality. Drawings were updated to capture the changes, and replacement components were manufactured, cleaned, and assembled (see Figure 2). The rebuilt source tray was installed during summer 2011 in the ISAC South Hot Cell facility completely by tele-manipulator.

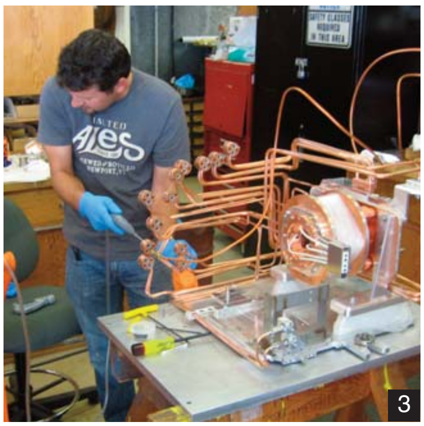
The replacement source tray was unable to resolve the high-voltage issues, but the refurbishment allowed the problem to be isolated to the module service chase, which is unfortunately inaccessible in this design. Target Module 1 is in service and reliable up to 20 kV for ISAC operations. This particular module is also limited as it can only accept certain types of target ion-source assemblies.

The refurbishment process for Target Module 3 (TM3) was formally initiated in spring 2013. Assembly and testing of the refurbished module is on-schedule for fall 2013 (see Figure 3). Lessons learned from previous refurbishments will be applied so that TM3 will be able to reliably operate all ISAC target designs up to the 60 kV design voltage. The refurbished TM3 will replace TM1 in the module rotation. Refurbishment of TM2 will begin immediately after. TM4 is currently operating reliably. The ISAC facility design requires two operational modules in the rotation to run at full capability. Having three modules (two primary and one spare) in rotation will vastly improve facility reliability and simplify operations.

ISAC Facility Upgrades

Other areas of improvement include both equipment and facilities required to generate a faster turnaround time for target exchanges. In order to accommodate the relatively long period of time required to change a target/ion source assembly (three to four weeks), it is necessary to run the same target/ion source assembly for at least four weeks. Most of the time, a significant degradation is observed in the yield after two weeks of continuous operation at an 80 μA proton beam on target. To reduce turnaround time for targets, three major upgrades are required for the ISAC facility. These are: (1) a Conditioning Station, which will allow off-line conditioning and testing of a target module equipped with a fresh target/ion source prior to installation on-line, (2) a second and dedicated North Hot Cell for target exchanges, which will reduce dependence on a single hot cell for both routine target exchanges and radioactive repair or refurbishment jobs, and (3) a Remote Quick Disconnect mechanism for the target and ion source services, which will eliminate the for long cool-down periods currently required before a technician can disconnect the service connections manually.

The combination of these three systems will allow us to reduce our target exchange cycle from weeks to days.



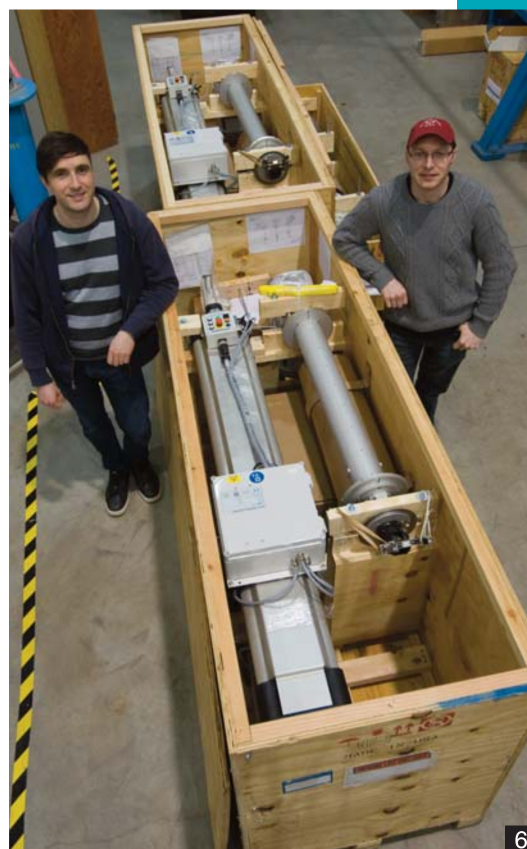


Figure 1: Inspection of brazing assemblies for target ion source heat shields.

Figure 2: An ion-source for ISAC is inspected in TRIUMF's clean room.

Figure 3: Elements of the target source tray are inspected during refurbishment.

Figure 4: ISAC Conditioning Station and members of the engineering team.

Figure 5: ISAC Conditioning Station with high-voltage terminal and chase.

Figure 6: Arrival of three-piece manipulators for North Hot Cell project.

The TRIUMF resonant ionization laser ion source (TRILIS) moved into a dedicated laser clean room laboratory in late 2008; in 2010 laser beam transport to the east target station was completed so that TRILIS achieved full scheduling flexibility. The number of isotopes from different elements increased from 6 elements in 2008 to 24 elements from which isotopes have been successfully delivered on-line. In 2013 the development of an ion-guide laser ion source target ion source module resulted in an unprecedented suppression of residual isobaric contamination from Na by a factor of 106. This ion guide laser ion source development has the potential to opening up experiments in mass regions that have traditionally been dominated by isobaric contamination – even when beams were ionized by use of the selective RILIS.

ACTINIDE TARGET DEVELOPMENT AT TRIUMF'S ISAC FACILITY

October 1, 2008

The first test of an actinide production target at TRIUMF's ISAC facility was carried out between August 29 and September 20, 2008. The use of actinide targets at ISAC is a key component of TRIUMF's Five-Year Plan.

Such targets are required for use by the proposed 50 MeV electron linac as a driver for rare isotope beam production by photo-fission. This approach will produce intense beams of isotopes with extreme neutron-to-proton ratios, including those sought by nuclear astrophysicists interested in the processes by which heavy elements are created. Simultaneously, a dedicated beam line has been proposed for use with actinide targets at higher proton currents than can be used with the existing Beam Line 2A target stations.

This will allow the production, primarily by spallation, of the Radon (Rn), Francium (Fr), and Astatine (At) isotopes of particular interest to those studying fundamental symmetries. This first test represents a significant milestone in TRIUMF's efforts to prepare for the next five years and beyond.

ISAC Conditioning Station

Preliminary concepts and design started in 2009, and the main structural elements, penetration coring, shielding, vacuum vessel and diagnostics were completed by autumn 2011. The high-voltage terminal and services, isolation transformer, power supplies, cooling water services, controls, and safety enclosures were installed throughout 2012. The first high-voltage bias test with a target module was done in February 2013 and full system commissioning is targeted for completion by end of spring 2013. Formal commissioning on a test target was successfully executed in March 2013. Several system faults and improvements have been identified, both during commissioning and also as a result of the first conditioning of a production target (Ta #40) in Target Module 4 during May 2013. Efforts are underway to document the results of commissioning, implement changes to address the improvements, and document the as-built system with updated drawings, schematics, and procedural manuals. The completed Conditioning Station and associated high-voltage services terminal are shown in Figures 4 and 5.

North Target Exchange Hot Cell

Preliminary specifications and design began in spring 2010. The CRL model N three-piece tele-manipulators were purchased in 2011 and received in February 2012 (see Figure 6). Design of the contamination enclosure, nuclear ventilation, shielding as well as services was delayed due to resource limitations but may commence again in 2014. Commissioned system completion is targeted for 2014. Departmental review of this project is underway to determine when resources will be available to work on it in conjunction with ARIEL Phase II.

ISAC Remote Quick Disconnect

Preliminary design concepts began in summer 2010. The manufacture of a mock-up target station to test concepts began in 2010 but was stopped. The project has been delayed due to resource limitations and cannot proceed until a dedicated project engineer and support staff can be hired. This project will resume as part of the upcoming designs for the ARIEL target stations. It is planned to modify the green field – remote quick disconnect design to be integrated into new ISAC target modules.

5.4.3 ISAC ACCELERATORS

TRIUMF's isotope facilities are presently based on proton beams extracted from the main cyclotron. The beams strike target materials, and exotic species of isotopes are extracted and distributed to experimental facilities for study. This complex is called ISAC—Isotope Separator and Accelerator. The experimental halls are called ISAC-I and ISAC-II.

In linear accelerators (linacs) such as those in ISAC, the accelerating fields are produced in a series of RF cavities through which the particles move and gain energy. One important parameter of such linacs is the gradient or energy gain per unit length measured in mega-electron volts per meter (MV/m). Superconducting radio frequency accelerating cavities are used in ISAC-II.

In the ISAC facility, 500 MeV protons from the cyclotron, with a maximum current of 100 μA, impinge on one of two production targets to produce radioactive isotopes. The isotopes are ionized, and the resulting beam is mass-separated and transported in the low-energy beam transport (LEBT) electrostatic beam line to either the low-energy experimental area or through two room temperature accelerating structures, a radio frequency quadruple (RFQ) and a drift tube linac (DTL), to the ISAC-I medium energy experimental area. The 35.4 MHz RFQ accelerates ions with $3 \leq A/q \leq 30$ from 2 keV/u to 150 keV/u, and the post-stripper (106.1 MHz) DTL accelerates ions with $A/q \leq 7$ to energies fully variable from 117 keV/u to 1.8 MeV/u. The accelerated beam can also be transported to the ISAC-II 40 MV superconducting linear accelerator (SC-linac) for acceleration above the Coulomb barrier and delivered to the ISAC-II high-energy area. The ISAC electron cyclotron resonance (ECR) charge breeder, CSB1, installed in the ISAC mass-separator room, is used to boost the charge state of masses with A>30 to allow acceleration in the RFQ. The accelerator chain is shown in Figure 1.

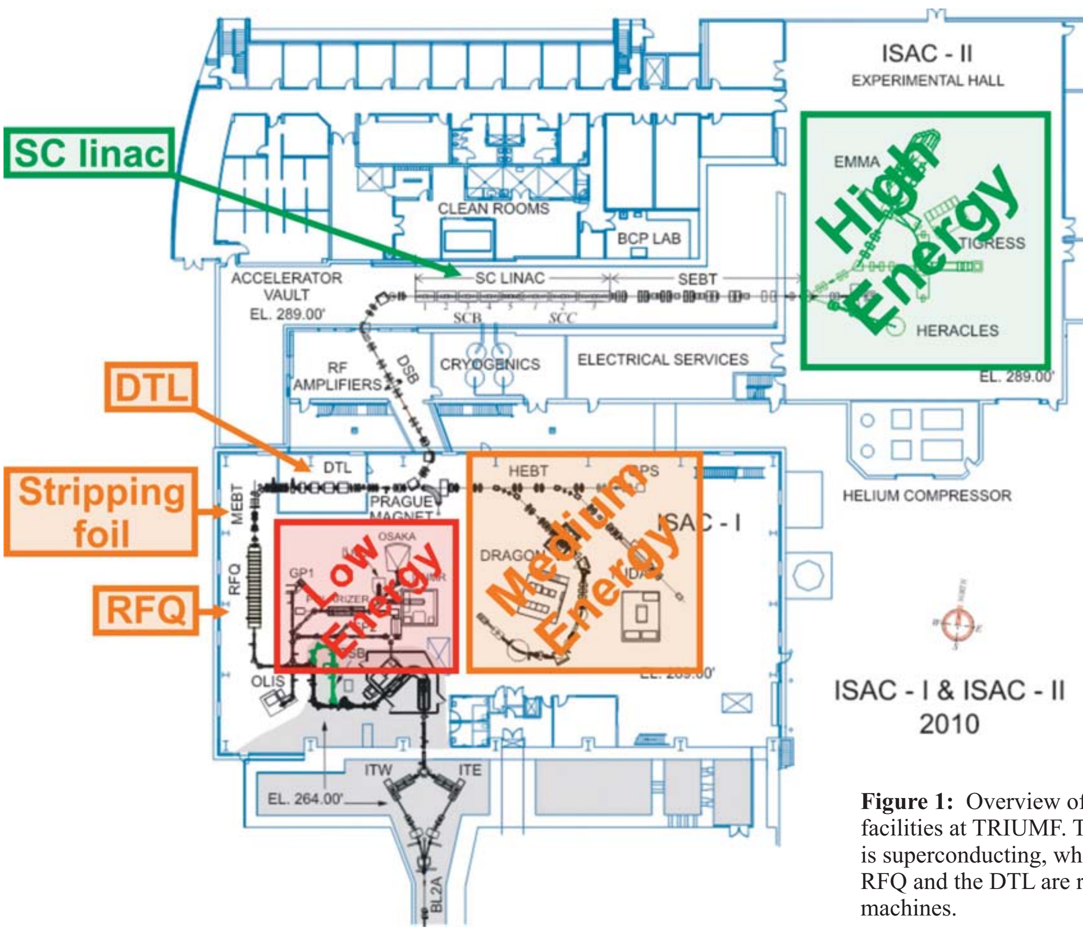


Figure 1: Overview of the ISAC facilities at TRIUMF. The ISAC-II linac is superconducting, while in ISAC-I the RFQ and the DTL are room temperature machines.

The eight meter long RFQ structure is composed of nineteen split rings supporting the electrodes. The RFQ itself doesn't have a bunching section; the beam is pre-bunched at the entrance with a three harmonics radio frequency buncher, the fundamental being 11.78 MHz. This configuration produces a high quality longitudinal emittance after the RFQ (0.5 π keV/uns) and a beam time structure convenient for experiments with a period of 85 ns. The RFQ accepts 80% of the beam with the rest of the beam unaccelerated and lost in collimators in the MEBT.

After the RFQ the ion charge state is increased by means of stripping through a thin carbon foil (4 $\mu g/cm^2$) with charge selection done in the MEBT dipoles. The dipoles accept ions with $A/q \leq 7$. The efficiency of the stripping foil depends on the mass of the stripped ions; in most of the cases it ranges between 30% to 50% for $A/q \leq 30$, with the most probable charge state given by $q \simeq 0.12A+1.5$.

The DTL is a variable energy machine covering the entire range of energies between 150 keV/u$\leq E \leq$1.5 MeV/u for $A/q=6$. The DTL maximal external energy is somewhat A/q dependent where the relation $E \simeq -0.074A/q+1.95$ MeV/u gives a reasonable fit with limits from $2 \leq A/q \leq 7$. As well, the lower limit can be decelerated to 117 keV/u. The DTL is a separated function machine composed of five IH inter-digital structure accelerating cavities and three split ring bunchers located between the first four cavities. This layout produces good beam quality at every energy in the range. Transverse focus through the linac is provided by quadrupole triplets between each cavity. The transmission through the linac is typically greater than 95%.

The SC-linac boosts the beam energy with an accelerating potential of up to 40 MV. It is composed of eight cryomodules; the first five cryomodules house four superconducting cavities and one superconducting solenoid (see Figure 2). The last three cryomodules house respectively six, six, and eight superconducting cavities, each with one superconducting solenoid (see Figure 3). The superconducting cavities are bulk niobium quarter-wave resonators at 106.08 MHz operating at 4K. The cavities are independently phased and have a broad velocity acceptance, and thus acceleration can be optimized for each ion with lighter ions able to reach energies of up to 16 MeV/u. The maximum final energy capability is roughly given by $E \simeq 1.5+35q/A$ MeV/u, so that all ISAC ions can be accelerated above the Coulomb barrier.

Figure 2: A ISAC cryomodule in the TRIUMF clean room.

The energy of the ISAC-II SC-linac was doubled with the completion of the Phase II upgrade. The ISAC-II facility acts as an energy booster to the radioactive ion beams produced in the ISAC facility, delivering rare isotopes to experiments such as TIGRESS and EMMA.

The superconductor of choice is ultra-pure niobium, fabricated into the correct shape and cooled in a bath of liquid helium. The challenge in superconducting cavity fabrication is to maintain the niobium in its ultra-pure state. Microparticles of other metals from machining, or absorbed gases during welding, can

Figure 3:A superconducting RF cavity manufactured by PAVAC for the ISAC-II accelerator.

contaminate the material and lead to a cavity that has sufficient imperfections to dramatically reduce its effectiveness in an accelerator. For this reason the niobium surface is chemically etched before each welding step and welding is done in a vacuum using an electron beam.

The accelerating modules consist of superconducting structures (cavities) that accelerate the beam using electromagnetic energy oscillating at 100 million times a second. The cavities are fabricated from highly refined niobium—a superconductor at temperatures less than 9K. Consequently, the cavities produce high field energy with almost no power loss.

The facility itself was installed in phases. The first phase, consisting of the addition of five cryomodules and twenty cavities, was commissioned in 2006. The second phase consisting of twenty more accelerating cavities housed in three cryomodules was completed on schedule and on budget to coincide with the end of TRIUMF's fiscal year 2010 (see Figure 3).

The first phase of linac installation utilized cavities fabricated in Italy. In the second phase, TRIUMF collaborated with a local company, PAVAC Industries Inc., of Richmond, BC to master the difficult technology.

PAVAC is the first Canadian company ever to produce bulk niobium superconducting cavities. This success is a first for Canada and registers the country in an exclusive group of only five in the world with this coveted capability.

The first experiment to use the new accelerating energy at TRIUMF was "Lifetime measurement of 6.791 state in 15O" where 10.8 MeV/u 16O5+ was delivered to the experiment. This is equivalent to E=6.5MeV/u for A/q=6 and matched the ISAC-II goal.

In the first half of 2010, two important milestones were met: hardware was on the floor before the end of March, and beam was accelerated before the April 25 start of the science program.

5.4.4 CMMS/UCN/SRF HELIUM LIQUEFIER FACILITY

TRIUMF'S Centre for Molecular and Materials Science (CMMS) facility at TRIUMF and its Superconducting Radio Frequency (SRF) program have historically utilized about 30,000 litres of liquid Helium (L-He) per annum for its operations (see Figure 1). Within two years the inauguration of new CMMS beam line infrastructure will increase this figure to ~35,000L/yr. Whereas L-He used to be "cheap," over the past decade its availability has been ever more restricted and, consequently, the price has more than doubled from ~$7/L to the current value of ~$15/L (see Figure 2). Compounding this fiscal impediment, in recent years, poor quality and supply restrictions (and sometimes even suspensions) have plagued TRIUMF to the point where these restrictions threaten to cripple, even suspend, the CMMS research program, which is so sensitively dependent on high quality L-He being readily available.

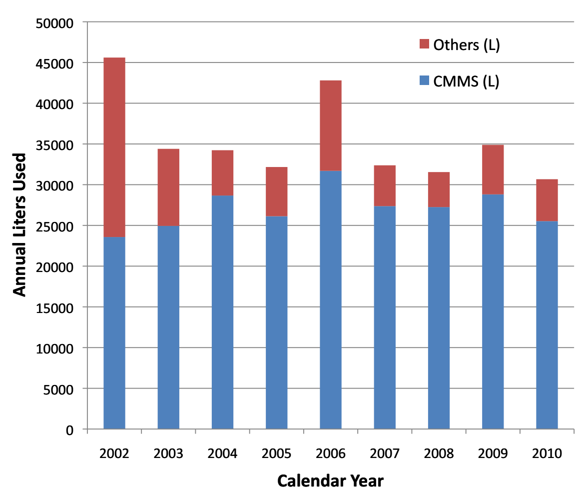


Figure 1: The historical usage of open-system liquid Helium at TRIUMF. A fully operational CMMS facility will use from 30–35,000 L/yr.

If TRIUMF continues its past policy—purchasing L-He— it would have to fund an ever-rising annual operating cost for the CMMS program; its current base cost is at a "crushing" level of $400,000/yr. Economically, a much better option is to purchase a Helium liquefier and gas recovery system (for a capital cost of ~$1,600,000) so that the TRIUMF can continuously re-supply itself with the L-He it requires to operate its programs. Indeed, the case for an in-house liquefier is further intensified by the knowledge that in 2016 the nascent ultra-cold neutron (UCN) Project will begin to require significant quantities of L-He, which ultimately will significantly eclipse the utilization of the CMMS. To these ends, TRIUMF has invested in a Helium liquefier system (HLS) which is being currently being installed. This system will serve the needs of the CMMS, the SRF program, and the initial phases of UCN. This installation has been planned so that a second liquefier can be added at a later time when the needs of UCN dictate that such an increase in liquefaction capacity is required.

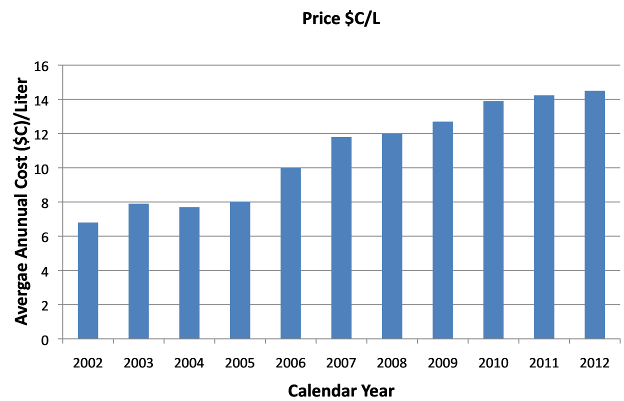


Figure 2: The cost of liquid Helium over a decade.

Description of Facility

There are three basic sections to the system (see Figure 3): the liquefier system on the right produces liquid into portable Dewars, which are then transported to various experimental stations/spectrometers, denoted by the area surrounded by the dashed dark blue lines on the left. Here the L-He is used to cool cryostats, magnets, and samples, and the resultant gas is exhausted into stainless steel recovery lines that travel back to the location of the liquefier. The return path is indicated within the dashed light blue lined box.

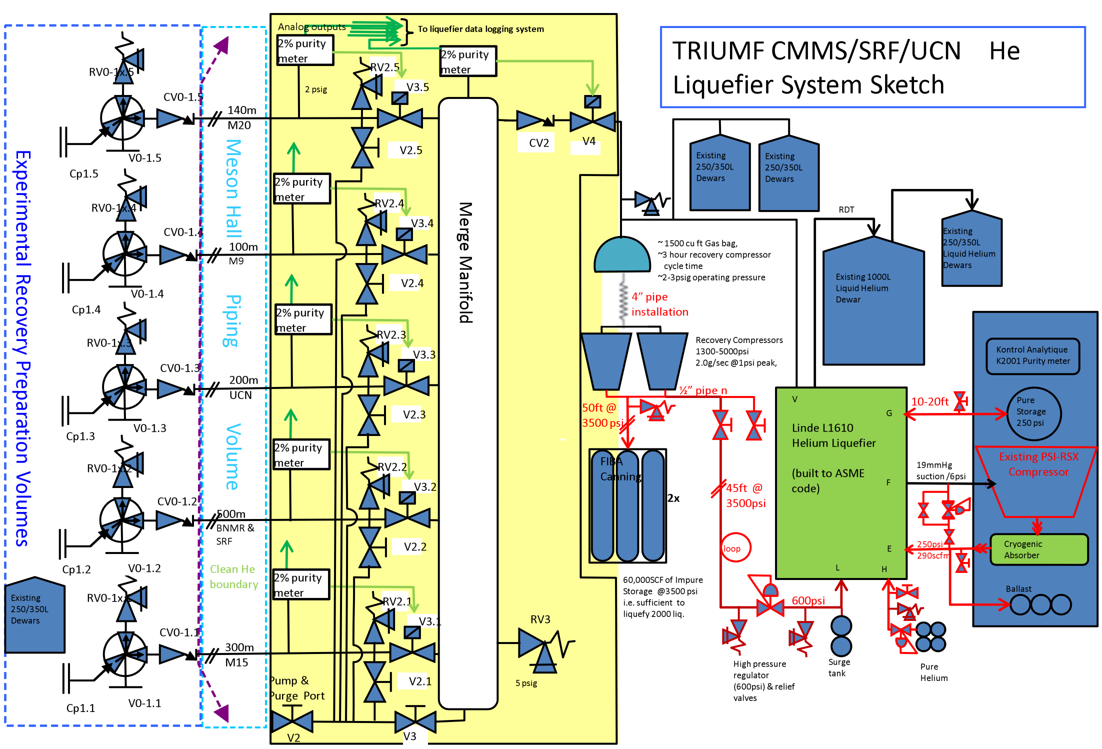


Figure 3: A schematic of the CMMS/UCN/SRF Helium liquefier system installed in 2013.

The returning gas is then monitored for purity, (which determines the ultimate efficiency of the liquefier), merged into a common volume, and then fed back into a high capacity high-pressure recovery volume from which it is destined to be re-liquefied as required.

Some features of this system are: (1) an all stainless steel recovery system and redundant He purity monitoring system, (2) sufficient high-pressure storage for 2000 L of L-He, (3) sufficient recovery speed to ensure that no He gas is lost due to the high rate of gas production from ongoing SRF tests, which the liquefier is designed to also support, and (4) sufficient liquefaction capacity (with LN2 pre-cooling) so the liquefier can support a nascent UCN operation in addition to CMMS and SRF needs, and (5) adequate piping infrastructure to enable the addition of a second liquefier for UCN, if required.

Recent Developments

The He recovery portions of this system are due to come online in October 2013 in order to be able to recover the L-He that is used in the final months of the year's experimental schedule. Operations of the liquefier itself will commence as soon as the system is tested and operating normally.

TRIUMF's Role

The $1.6M required funding for this system is being supplied by TRIUMF (with a contribution from KEK ($250k), a proponent of the UCN project, in recognition that it is the only financially sustainable means of meeting the laboratory's long-term requirements to programs that will depend on a secure and high-quality source of L-He.

5.5 EXPERIMENTAL FACILITIES AND INFRASTRUCTURE

While accelerators provide the beams, experimental detectors are needed to exploit them. TRIUMF has an array of state-of-the-art detectors to exploit the array of beams it produces. These detectors tend to be large multi-million dollar facilities with each facility devoted to one type of measurement. In some cases two or more detectors are used in combination. This is particularly true of the TIGRESS detector in the ISAC-II experimental hall which can use an array of auxiliary detectors.

TRIUMF has three large experimental areas in active use:

- **ISAC-I** for use of the low and intermediate energy rare-isotope beams
- **ISAC-II** for high-energy rare-isotope beams
- **Meson Hall** and associated annexes for molecular and materials science, ultra-cold neutron physics and in the recent past meson-decay studies.

In addition to the onsite facilities TRIUMF has collaborated on the construction of detectors located at other laboratories, notable in Ontario, Switzerland and Japan. These collaborations provide a two-way path for the propagation of expertise so that TRIUMF can stay current on detector technology while at the same time helping Canadian researchers working elsewhere. To this end, TRIUMF maintains detector development facilities.

In this section, we describe the on-site detector facilities, the offsite detectors TRIUMF has helped build and the on-site detector development facilities.

5.5.1 ISAC-I

ISAC-I is devoted to the use of low- and intermediate-energy beams from the ISAC facility. It has a large array of experimental facilities, each with different capabilities that can exploit the rare isotope beams in a number of different areas: nuclear structure, nuclear astrophysics, fundamental symmetries and material science. One of the detectors, the 8π, is being retired after over 25 years of service in a number of different laboratories and is being replaced by a new detector, GRIFFIN, with superior capabilities. Aside from the major facilities described in this section, special set-ups are being installed for specific experiments, such as the OSAKA experiment for decay spectroscopy of polarized ions, or the 3Hen neutron detector that will allow for the study of beta-delayed neutron emission.

5.5.1.1 THE DRAGON FACILITY

Our universe is filled with ordinary stars but also less understood objects and events, such as novae, supernovae, and X-ray bursts, in which 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 (see Figure 1), designed and built to measure just such nuclear reactions of importance in astrophysics — the nucleosynthesis reactions that occur in these exotic explosive stellar environments. The separator takes advantage of TRIUMF's intense beams of the kind of short-lived, rare isotopes that are involved in stellar burning and cataclysmic stellar explosions.

The first reaction ever measured by DRAGON was $^{21}Na(p,\gamma)^{22}Mg$ in 2001 and measurements continued until 2003. This was an especially important reaction to understand and calculate the processes occurring

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. Photograph courtesy of Craig Damlo.

in classical novae, a white dwarf star that 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. 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 studied 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 Na-21 nucleus, produced by ISAC-I, impinges on a proton in a hydrogen target. It is then absorbed forming Mg-22 and de-exciting, giving off a γ ray just as in the nova. 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 measured in a bismuth-germanate (BGO) crystal array that surrounds the thin-walled hydrogen gas target volume.

Using this technique as the yardstick, DRAGON has, over the last 12 years, waged successful campaigns to study some of the most important proton- and alpha-capture reactions to astrophysics, including the $^{21}Na(p,\gamma)^{22}Mg$, $^{12}C(\alpha,\gamma)^{16}O$, $^{26g}Al(p,\gamma)^{27}Si$, $^{40}Ca(\alpha,\gamma)^{44}Ti$, $^{23}Mg(p,\gamma)^{24}Al$ and $^{18}F(p,\gamma)^{19}Ne$ reactions.

Description of 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 0.15–1.8 MeV/nucleon provided by the ISAC-I accelerator, DRAGON studies the radiative (emits a γ ray) capture on hydrogen and helium relevant to nucleosynthesis on the neutron-deficient side of stability, for scenarios such as supernovae, classical novae, and type I X-ray bursts. The hydrogen or helium is circulated within a windowless gas target capable of holding up to 6×10^{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 a 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 dual micro-channel plate system, 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% [1]. The momentum and angle spread are induced by the range of momenta given to the recoil as the γ rays are emitted. This spread is thus dependent on the γ-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 $^{12}C(\alpha,\gamma)^{16}O$, 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 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 [2]. 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. More recently during tests for the $^3He(\alpha,\gamma)^7Be$ reaction, a record beam suppression factor of greater than 10^{14} was achieved [3]. The total background suppression capability of DRAGON, when combining γ-ray detection, recoil separation and particle identification is at minimum 10^{13}, and for certain cases as high as 10^{17}, making DRAGON sensitive to extremely small resonance strengths, with a strength of 13 μeV being the lowest measured so far.

In the past five years DRAGON has been using a local-time-of-flight system with time resolution Δt = 300-400 ps, providing an extra layer of background rejection and enabling the measurement of even more difficult measurements [4] This system has become a crucial advancement in the capabilities of the DRAGON.

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 4.2.2.4 highlight the important contributions of DRAGON to the field of nuclear astrophysics over the period of the last five-year plan. These include several radioactive beam reactions. To date, DRAGON is responsible for 63% of the world's measurements of radiative capture reactions in inverse kinematics using radioactive beams.

The DRAGON program has continually been re-funded by NSERC over the years 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 (2015–2020), DRAGON will continue to pursue the measurement of difficult and important astrophysical reactions with the development of novel radioactive beams. In addition, DRAGON has recently demonstrated the ability to successfully measure capture reactions with beams as heavy as A=58 (proton capture) and A=84 (alpha capture). This goes far beyond the design limit of the system, which was for A<30. This will enable opportunities in measuring reactions for more astrophysical scenarios, such as the 'p-process' present in core collapse supernovae.

Partners

In Canada: McMaster University, Simon Fraser University, University of Alberta, University of Guelph, University of Northern British Columbia, University of Prince Edward Island, Thompson Rivers University, University of Toronto, University of Victoria.
International Partners: Austria (1), Belgium (1), China (1), France (1), Germany (2), India (1), Israel (1), Spain (1), Switzerland (1), United Kingdom (3), United States (7).

TRIUMF's Role

TRIUMF's dedicated research scientists and technicians make up the core of the DRAGON Group, which is joined by a large number of Canadian and international academic collaborators in both experimental physics and astrophysics theory. In addition TRIUMF's support for the large infrastructure commitment to the DRAGON separator is crucial to the ongoing success of the facility.

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5.5.1.2 TRIUMF NEUTRAL ATOM TRAP FOR DECAY STUDIES: TRINAT

TRINAT uses laser trapping and cooling techniques to accurately study the decays of short-lived isotopes produced by ISAC, to search for physics beyond the Standard Model of particle physics. The pressure of laser light traps the atoms in a 1-mm-sized cloud in an excellent vacuum. The recoiling nucleus from each decay has very low kinetic energy, and would stop in ten atomic layers of material. But it freely escapes the shallow atom trap, and its momentum can be precisely measured. By also measuring the momentum of the emitted electron, the momentum of the (otherwise invisible) neutrino is deduced for each event. Unique experiments test predictions of the Standard Model for the average decay direction of the neutrinos with respect to the electrons and with respect to the spin direction of the nucleus, and deviations from these predictions would indicate the presence of new forces. The average decay direction tests whether the neutrino is always "left-handed," with spin oriented opposite its momentum.

Description of Apparatus

The complete two-trap system fits on a large tabletop. 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 (see Figure 1). The transfer time is about 40 ms, with more than 75% efficiency demonstrated; 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 uniform 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 beta 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 over 97% in unstable K-37 has been achieved in the previous geometry, with 99.5% achieved in stable test isotope K-41 in the new geometry. 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.

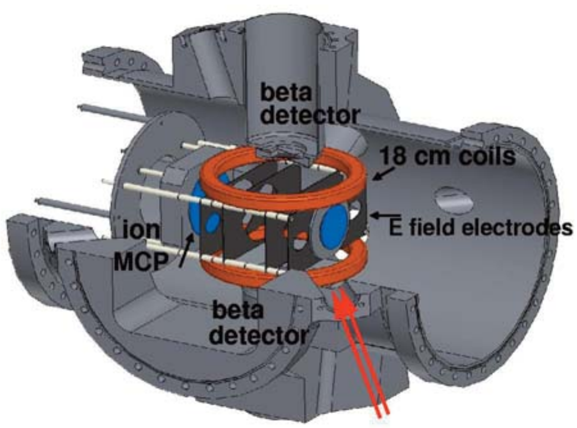

Figure 1: Cutaway view of upgraded chamber and ion detector geometry. One optical pumping beam is shown by the red arrows; the SiC mirror in front of the beta detector directs this beam downwards.

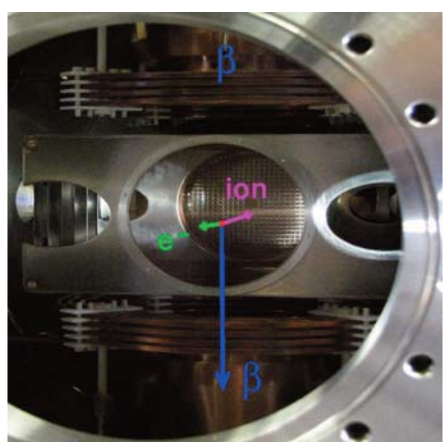

Figure 2: Magnetic field coils, electrodes, and ion microchannel plate of the new apparatus, before installation of the electron MCP in the 15 cm port.

A small percentage of the trapped atoms are 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).

The main collection trap laser is a tunable Ti:Sapph ring laser driven by an argon ion laser. The detection trap laser is a tapered amplifier semiconductor diode laser. A smaller diode laser is used for optical pumping. The material 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

The entire detection apparatus and optics have been upgraded to improve spin-polarized experiments. A larger vacuum chamber has materials that are less magnetic, with larger and more efficient beta detectors and recoil ion detectors. A new type of trap, an AC MOT with a sinusoidally varying magnetic quadrupole field, allows the trap magnetic field to be switched off to less than 1% of its value in 100 microseconds, four times faster than before. A new ion MCP readout design allows it to be floated to a higher voltage to increase uniformity of collection of all of the nuclear recoils. A more compact geometry that combines the same optical beam path for polarizing and trap lasers has better detection efficiency. A more powerful diode laser for optical pumping is now fiber-coupled for spatial beam quality and reproducibility. Optical pumping mirrors in the vacuum in front of the beta detectors now are 0.25 mm thick SiC, a stiffer material than the fused silica used before to preserve the spatial wavefronts. A new VME-based DAQ system digitizes the waveforms from a much larger number of silicon strip detector channels for the delta-E beta detectors.

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. The atomic electron provides a time-of-flight trigger for the recoil nuclei, so their momentum can be determined. This technique was used to set complementary limits on one type of short-range contact interaction (“tensor”) by measuring the recoil asymmetry with respect to the nuclear spin of Rb-80 [1]. It was also used to detect recoiling nuclei from the gamma decay of the Rb-86m isomer in a feasibility study concerning direct searches for emission of exotic massive particles by their missing momentum [2].

The new apparatus was used to measure the beta asymmetry with the respect to the spin of K-37 in December 2012, with statistical error of 1 to 2%, and systematics still being evaluated. The asymmetry of recoiling nuclei with respect to the nuclear spin was also measured. Goals for these observables of better than 0.2% would begin to be sensitive to new physics (e.g., radiative corrections from new particles in SUSY [3] still allowed by other experimental constraints).

Partners

In Canada: University of British Columbia, University of Manitoba.
International Partners: Israel (1), United States (1).

TRIUMF’s Role

TRIUMF supplies the short-lived isotopes via rare-isotope beams from ISAC-I, along with 1.2 FTE research scientists, and half-support for two undergrad co-op students per year. TRIUMF also provides technical support via the electronics, machine, and design shops, the detector facility, and the Data Acquisitions Group.

References

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[3] Profumo et al. PRD 75 075017)

5.5.1.3 8π, GRIFFIN, AND GPS

The 8π facility, and future GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei), facilities are microscopes into the structure of atomic nuclei. These facilities use the radioactive decay of exotic beams delivered from ISAC to access and probe nuclear excitations in the daughter nuclei through detection of the emitted radiations. Transition energies, decay branching ratios, and half-lives are measured and from these nuclear properties can be determined. The investigations made possible by decay spectroscopy forward our understanding in fundamental symmetries, nuclear structure, and astrophysical processes.

The 8π spectrometer was installed at ISAC in 2000 and with the addition of the ancillary detection systems described below was transformed into a world-unique facility for decay spectroscopy experiments. Operation of the 8π will come to an end in 2013 and will be followed by the installation of the GRIFFIN facility. GRIFFIN upgrades the hyper-pure germanium and data acquisition aspects of the facility. These upgrades dramatically improve the detection efficiency and count-rate capabilities that will enable full exploitation of all ISAC and ARIEL beams for the science program.

In addition to the 8π spectrometer, the GPS (General Purpose Station) Lifetime Facility is a moving tape collection system and 4π gas counter used for precision half-life measurements as part of the fundamental symmetries program.

Description of Apparatus

The primary feature of the 8π spectrometer is the 20 Compton-suppressed, hyper-pure germanium (HPGe) detectors. HPGe provides excellent energy resolution of around 0.15% for gamma-ray transitions emitted from decaying nuclei. This allows for accurate determination of excited level energies in nuclei. The detectors are arranged to fill the 20 hexagonal faces of a truncated icosahedron around the vacuum chamber with the central focus of all HPGe detectors coinciding with the beam implantation location (see Figure 1). The array provides a full photo-peak efficiency for single events of around 1% at 1.3 MeV.

The vacuum chamber is designed in a modular fashion such that any combination of in-vacuum ancillary detector subsystems can be utilized to meet the spectroscopic requirements of experiments. A central component of the facility, which is employed in every experiment, is a fast in-vacuum continuous-loop tape-moving system 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, at the central focus of all detectors. After a measurement period, 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 daughter nuclei or beam contaminants.

Figure 1: Photograph of the east hemisphere of the 8π spectrometer. Photo credit to Mikey Enriquez of the Global Photowalk 2010.

The vacuum chamber can also accommodate SCEPTAR (SCintilator Electron-Positron Tagging ARray). SCEPTAR, funded by NSERC, counts beta particles with 20 plastic scintillators covering 80% of the full 4p solid angle. SCEPTAR can be used simultaneously in a "singles" mode for normalizing of high-precision branching ratio measurements or high-precision half-life measurements [1] and for β-γ coincidence spectroscopy to eliminate the ~2000/s γ room background events from one to two decays per second of weakly produced, exotic beams [2]. The geometry is such that each HPGe views the sample through one, and only one, unique SCEPTAR element. Applying a veto to events with collinear SCEPTAR and HPGe detection reduces continuum bremsstrahlung background in the γ-ray spectra. The upstream and downstream hemispheres of SCEPTAR can be used together for maximum beta efficiency, or individually in combination with another ancillary detector type.

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 [3,4].This enables spectroscopy of internal conversion electrons, an alternative decay process to γ -ray emission for excited nuclear states. PACES occupies the upstream hemisphere with five Si(Li) detectors cooled to near liquid nitrogen temperature. The efficiency of PACES for conversion electrons is approximately 5%. Internal conversion electron emission is much more likely for heavy nuclei so conversion electron spectroscopy is an essential tool for studying the heavy beams produced from the ISAC actinide targets. In lighter nuclei certain nuclear structure phenomena generate intense internal conversion transitions, such is the case in nuclei displaying shape coexistence around shell closures. PACES was supported by the DOE and NSERC. The cryogenic cooling system and detector housing assembly were designed by LSU.

Another ancillary detector of the 8π is DANTE (Dipentagonal Array for Nuclear Timing Experiments), which is located outside of the vacuum chamber and fills the spaces in the support structure between HPGe detectors. Ten barium fluoride (BaF_2) counters provide relative timing information for detected γ-rays with a resolution two orders of magnitude superior to HPGe [5]. 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.

The data acquisition system of the 8π facility is arranged into four parallel FERA readout streams for each of the HPGe, plastic scintillator, Si(Li), and BaF_2 systems. The data acquisition infrastructure was funded by TRIUMF, NSERC, and the U.S. Lawrence Livermore National Laboratory.

High-precision β-decay half-life measurements have been carried out at ISAC since 1999 by direct beta counting using a technique that was first developed in Chalk River [6]. Although the measurements are simple in principle, great care must be taken to achieve the required precision (<0.05% for superallowed beta emitters whose half-lives range from 69 ms to 70 s). The low-energy (29 keV) radioactive ion beam from ISAC is implanted into a 25 mm wide 25 micron thick aluminized mylar tape of a fast tape transport system. After a collection period of roughly 4 half-lives, the ISAC beam is interrupted and the sample is moved out of the vacuum chamber through two stages of differential pumping and positioned in a 4π continuous-gas-flow proportional counter. After multiscaling the signals from the 4π counter for about 25 half-lives the data is stored and the cycle repeated continuously until sufficient statistical precision are accumulated. A 1 MHz ± 2 Hz laboratory clock is used to provide a time standard for the experiment which is controlled by a Jorway 221, twelve channel timing and sequence module. Sample purity is monitored using a HPGe detector located just outside the 4π β-counter or by delivering the beam of interest to the 8π which is a much more sensitive instrument to detect gamma-rays emitted by low intensity isobaric contaminants. Recently, the highest precision ever achieved in a single measurement for any superallowed beta emitter, 0.011%, was obtained using the GPS lifetime facility for Al-26m[7] and represents the experimental limit of this technique.

Recent Developments

With the development of actinide targets at ISAC, radioactive beams that undergo alpha decay can now be delivered to the 8π facility. In order to study the decay of these nuclei an upgrade to the electronic readout of the PACES lithium-drifted silicon detectors was necessary. The PACES detectors are sensitive to both the conversion electrons and the alpha particles seen in such decays, but the alpha particles produce much larger signals than conversion electrons, which would saturate the conversion electron readout channel. The addition of a parallel low-gain readout channel for each PACES detector allows for simultaneous observation of both conversion electrons (high-gain channel) and alpha particles (low-gain channel) in the same experiment. This capability was used in a preliminary search for decays of Astatine nuclei to access the excited states in neutron-rich Radon nuclei of interest for an atomic permanent electric dipole moment measurement.

The most recent development has been to replace seven of the ten barium fluoride detectors with lanthanum bromide ($LaBr_3$(Ce)) detectors, which offer a factor of three superior energy resolution. These detectors were funded by NSERC. This improved energy response dramatically improves coincidence-gated timing spectra and can therefore increase the sensitivity to weakly populated transitions.

In 2012 the GPS lifetime facility was moved to a new dedicated location in ISAC-I to make room for the new francium trap facility. At the same time, in collaboration with Louisiana State University, a new tape transport system was designed to use 50 micron mylar tape with a thick, 25 micron, aluminum layer on one side, to eliminate the problem of diffusion of gaseous isotopes of interest such as O-14 and Ne-18,19 encountered when these ions were implanted into the 25 micron aluminized mylar tape that must be used with the existing fast tape transport system. This upgraded GPS lifetime facility is now fully operational and the first high-precision lifetime measurement was carried out in summer 2013.

The final operation of the 8π facility will be in December 2013, at which time there will be a significant upgrade to the decay spectroscopy capabilities at ISAC with the installation of the GRIFFIN facility. GRIFFIN is supported through funding from the Canada Foundation for Innovation, TRIUMF, and a funding application led by the University of Guelph. With initial operation in the fall of 2014, GRIFFIN will be a major upgrade to the HPGe aspect of the 8π to an array of 16 large-volume HPGe clover detectors (see Figure 2). This will represent a factor of 17x increase in single gamma-ray efficiency, as well as close to 300-fold increase of gamma-gamma coincidence efficiency (see Figure 3) at 1.3 MeV. This upgrade of the HPGe aspect will be accompanied with the addition of a custom-designed, state-of-the-art digital electronics data acquisition system that will allow high counting rates and high accountability for precision measurements. GRIFFIN will be compatible with all existing ancillary detector systems of the 8π facility: the in-vacuum tape system, SCEPTAR, PACES, DANTE, as well as the new DESCANT array of deuterated scintillators for neutron-tagging, which has been developed

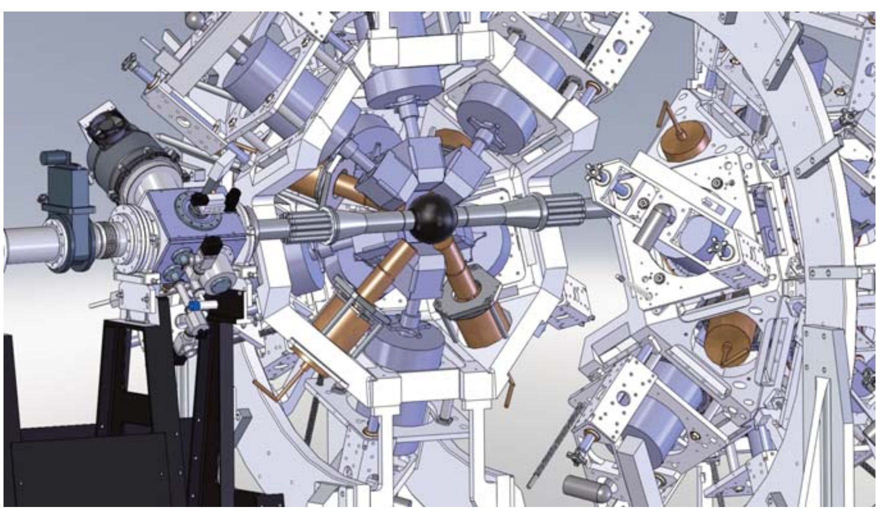

Figure 2: Schematic of 8π clover-detector arrays.

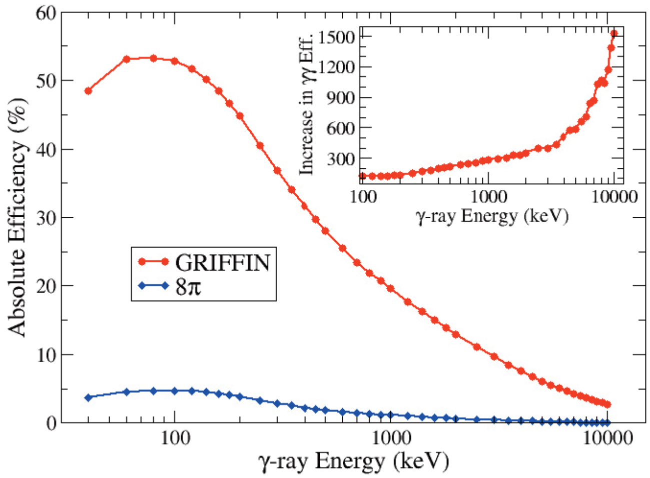

Figure 3: Gamma-gamma coincidence efficiency of 8π compared to GRIFFIN.

for use with TIGRESS in accelerated beam experiments. The support structure of DESCANT is fully compatible with GRIFFIN to enable the study of the beta-delayed neutron process in neutron-rich nuclei produced by ISAC and ARIEL.

Partners

In Canada: University of Guelph, McMaster University, l'Université de Montréal, University of Toronto, Saint Mary's University, Simon Fraser University, and Queen's University.
International Partners: Belgium (1), France (2), India (1), United Kingdom (1), United States (3).

TRIUMF's Role

The TRIUMF Gamma-ray Spectroscopy Group plays a lead role in the scientific program of these facilities. TRIUMF provides a dedicated technician for 8π, TIGRESS, and GPS. During the construction phase of GRIFFIN an additional dedicated technician will support the effort. One staff scientist manages the 8π and GPS programs as well as the GRIFFIN construction and installation project; 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, the stand for the tape system, target chambers for SCEPTAR and PACES, detector mounts for DANTE, cable trays, electrical service, and an enclosed, cooled enclosure for the electronics.

TRIUMF also provides front-end readout computers, back-end workstations, data acquisition software, networks, and mass data storage for the 8π that will continue for GRIFFIN.

TRIUMF also plays a major role in the design, fabrication and development of the custom-built digital data acquisition for the GRIFFIN spectrometer. The TRIUMF design office is designing all aspects of the GRIFFIN support structure, dedicated beam line and climate-controlled electronics enclosure. A large fraction of the mechanical components of the GRIFFIN mechanical support structure are being fabricated in the TRIUMF machine and scintillator workshops.

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5.5.1.4 TITAN

Understanding the interactions at play in atomic nuclei requires that precision data on the fundamental properties of nuclei be determined with accuracy. TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN) is currently one of the world's leading facilities for performing precision measurements using ion trap techniques. TITAN's goal is to perform these precision measurements on fundamental properties, such as the mass of atomic nuclei and the shape of nuclei via X-ray detection; however, it also serves as a one-of-a-kind system that prepare the exotic beam for other experiments, such as supplying cooled and bunched beams for laser spectroscopy. With ISAC, the source of some of the most exotic beams produced anywhere, and when connected in the future to ARIEL (please see Section 5.3), it makes for a unique and powerful combination.

Recent Developments

Precise mass measurements performed at TITAN have greatly impacted the knowledge of how nuclear structure evolves toward the neutron drip-line. These measurements have shown the importance of three-body forces in medium-mass nuclei. In addition, the recent installation of X-ray detectors in the electron-beam ion trap (EBIT) has allowed for proof of principle measurements of electron capture branching ratios. These ratios are important in determining matrix elements in double-β-decay experiments, which will be exceedingly important in determining the mass of a Majorana-neutrino, if, in fact, they do indeed exist. TITAN is the only Penning trap in the world that can perform measurements on very short-lived nuclei ($T_{1/2}$< 10ms), and developments are underway to go to even shorter lived nuclei (Be-14, $t_{1/2}$=4.5 ms). With all the recent developments in beam production at ISAC-I, we expect TITAN to break this record again (i.e. measure Be-14 with 4.5 ms), which is less than the half live of Li-11 with 8.6ms.

TITAN is based on atomic physics techniques adapted to the requirements of nuclear physics with short-lived radioactive beams. This is done by using well-established ion trapping techniques very similar to the techniques used in the work that received the 2013 Nobel Prize in Physics, i.e. the precise control and quantum manipulation of single ions. These single ions are stored using electric and magnetic fields, which provide well-defined environments, and which, in return, provide an ideal laboratory for performing precision measurements.

Description of Apparatus

The TITAN facility currently comprises three ion traps: a radio frequency quadrupole (RFQ) cooler and buncher for beam preparation, an electron beam ion trap (EBIT) for charge breeding, and a measurement Penning trap (MPET) for high-precision mass measurements on both singly and highly charged ions. The RFQ is used to cool and bunch the beams delivered from ISAC. The beam typically arrives with 20 keV of energy, where the RFQ then stops and captures the beam with only a few tens of eVs of energy. The cooling is provided by an inert buffer gas. Once the beam has reached thermal equilibrium and is accumulated in a defined trap region, this RFQ trap is opened and the ions are released as a bunch. TITAN's RFQ is noteworthy because it is the only RFQ that is capable of "forward" and "reverse" extraction. In forward extraction the beam is sent towards the other TITAN traps, for example the EBIT or MPET. Reverse extraction enables other ISAC experiments, such as the co-linear laser spectroscopy experiment, to use cooled and bunched beams.

The EBIT's predominant role is in charge breeding the singly charge ions (SCI) delivered from the RFQ. Charge breeding is important because the precision achievable in a mass measurement is directly proportional to the charge state of the ion. In the EBIT a beam of high-energy electrons is directed at the trapped cloud of SCIs. The charge state of the trapped ions is increased by subsequent impact ionization, and hence removal of electrons of the atomic shell. EBITs have been successfully used in Penning trap experiments with stable beam. Today, TITAN is the only Penning trap facility in the world that is able to perform measurements on highly charged rare isotopes. Since rare isotopes are typically short lived, and are produced in small quantities, a stringent requirement is that the charge breeding process be both fast and efficient. The EBIT is designed to have electron beam energies of up to tens of keV and currents of 0.5 A that will allow ions to be bred to high charge states extremely quickly. The EBIT is also equipped with 7 radial view ports, which allow for optical access to the trap centre. This access facilitates a different class of unique in-trap decay spectroscopy experiments such as the TITAN Electron Capture (EC) experiment.

The Cooler Penning trap (CPET), currently in development, is designed to prepare beams of HCIs for injection into MPET. CPET can originally utilize electrons to cool the HCIs; however, in the future, cooling with protons will be investigated as well. The cooling of antiprotons with electrons has already been shown, and simulations indicate that electron cooling of HCIs is possible, with high survival rates. Currently the major components of CPET have been assembled and offline testing has commenced.

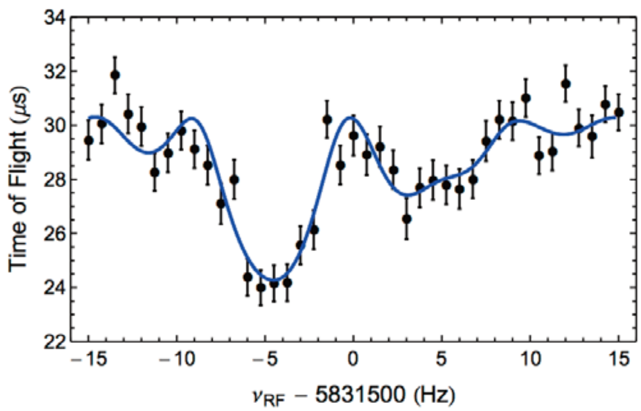
Bunches of either singly or highly charged ions are then sent to MPET for precision mass measurements. Penning traps provide an ideal environment to conduct precision experiments: A single ion is stored near rest in high vacuum (pressures approximately one trillion times smaller than atmosphere) and is subjected to well-defined electric and magnetic fields. The combination of a strong magnetic field and a weak electric field was used to confine ions both radially and axially, respectively. The motion of these trapped ions is well understood, which allows for a high-precision determination of the mass through a measurement of the cyclotron frequency. When an ion is placed in a magnetic field, it will begin to revolve at the cyclotron frequency $\nu_c = qB/(2\pi m)$. By exciting the ion's motion with this frequency it is possible to shorten the time-of-flight to a detector when the ion is extracted from the trap. By measuring this minimum time-of-flight, the cyclotron frequency can be extracted.

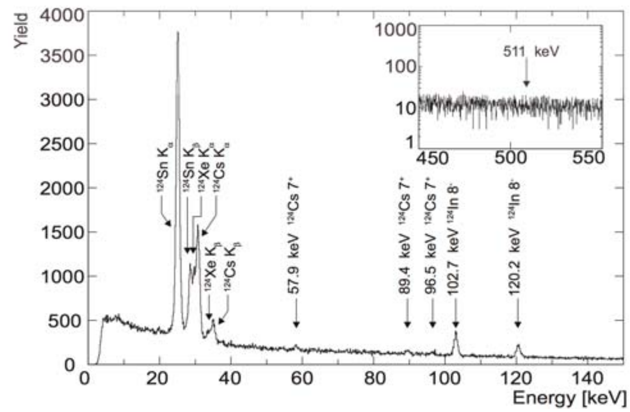
The in-trap experiments currently carried out include the above-mentioned TITAN-EC that aims to measure electron-capture branching ratios (ECBRs) of the intermediate nuclei in double-beta ($\beta\beta$) decays. Those ECBRs are important because they provide information about the ground-state properties of the nuclear wave function connected to the nuclear matrix elements involved in the $\beta\beta$ decay for both decay processes, the two-neutrino ($2\nu\beta\beta$) and the neutrino-less ($0\nu\beta\beta$) decay. The latter is particularly interesting since its detection would validate the Majorana character of neutrinos (i.e. whether the neutrino is its own anti-particle). The X-rays following the EC decay are detected by a set of detectors mounted in the view ports of the EBIT. The presence of the EBIT's magnetic field offers the additional advantage that electrons or positrons from the much more intense β^-/β^+ decays are directed on axis out of the trap and away from the detectors surrounding the EBIT. Hence there is no background created by β^- particles.

Recent Developments

TITAN has recently begun to harness the gain in precision made possible through the use of highly charged ions. The first measurement completed was of Rb-74, which is an important nuclide to test the Standard Model. A previous measurement of Rb-74 at ISOLTRAP achieved a precision of ~6 keV during a run time of ~60 hours. TITAN was able to reach a similar precision by using HCIs, and the measurement was completed in only 20 hours and with much less statistics required (see Figure 1). Next, it was demonstrated that HCIs could be used to resolve the mass difference between the ground state and low-lying isomeric states.

A Q-value measurement of Ge-71 and Ga-71 was completed using a novel threshold charge breeding technique. By tuning the EBIT to limit the maximum charge state that could be achieved, and combined with the increased yields from the TRILIS laser ionization source it was possible to produce beams of highly charged isobarically pure beams. The Q-value measured in this experiment was important to help clarify a long-standing discrepancy between the SAGE and GALLEX solar-neutrino experiments. With an accurate value for the Q-value, the uncertainties in the nuclear physics inputs have been removed, which may lead to new physics being the explanation for the observed difference between the two experiments.





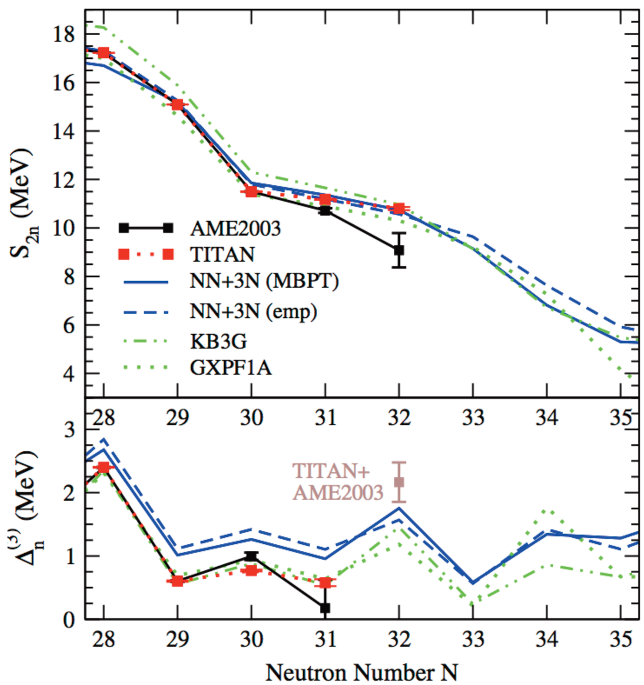


Figure 1: Highly charged resonance of Rb-78 showing the resolved ground (right dip) and isomeric (left dip) states.

Figure 2: Evolution of two-neutron separation energy, measured versus theory.

Figure 3: Electron-capture spectra. The lack of a 511keV line in the inset shows that background producing beta particles are guided away from the detectors.

Highly charged ions have also been used to explore how elements heavier than iron are created in core-collapse supernovae. The so-called *r*-process occurs during these supernovae, which are characterized by the rapid capture of neutrons. The exact path the *r*-process follows is not known due to a lack of knowledge of the basic nuclear properties of these nuclei. The masses of the neutron rich nuclei Rb-(94, 97, 98) and Sr-(94, 97, -99) were performed in a charge state of q=15+. In many cases, the uncertainty in the mass value was improved by over an order of magnitude and has eliminated any dependence on these masses in *r*-process model calculations.

TITAN has also recently investigated the evolution of nuclear shell structure near the limits of stability. Much theoretical and experimental work has been undertaken to explore the region near N=32 and 34. It has been predicted that new sub-shell closures should appear here, and while experiment and theory agree on the existence of the N=32 sub-shell closure, theory disagrees on the existence of the N=34 closure, while experiment has found no evidence. The TITAN mass measurements of Ca(51,52) and K(50,51) (N=31,32) show a much more flat behaviour in the mass surface than tabulated by the 2003 mass evaluation (see Figure 2). Large deviations of up to 1.7 MeV/c^2 in the mass were seen. This behaviour was predicted by new state-of-the-dart theory calculations that take into account the effects of three-body forces.

VANESSA SIMON RECOGNIZED AT 2011 WNPPC

07 March 2011

Vanessa Simon, a Ph.D. student from the University of Heidelberg and Max-Planck-Institut für Kernphysik (both in Germany) who is working here at TRIUMF was awarded 3rd prize for Best Student Presentation at the 2011 Winter Nuclear and Particle Physics Conference in Banff, Alberta. The conference focused on topics of research that are of great interest to the Canadian community. Geared towards junior researchers such as students and post doctorate students, it featured sessions focusing on areas of research such as nuclear astrophysics, anti-matter physics, and neutrino physics.

Simon's topic was the "TITAN Penning Trap for Cooling Highly-Charged Radioactive Ions at ISAC." In her 20-minute presentation to the audience of Canada's top researchers in nuclear and particle physics, she gave an overview of the TITAN experiment. She explained the development of the Electron Beam Ion Trap (EBIT), which helps prepare highly charged ions for improved precision in mass measurement.

"It feels quite good to be recognized." Ms. Simon said, "I appreciate the interest in my project and the recognition. It's an honour, and it motivates me to continue working hard."

The feasibility of the TITAN-EC set-up for measuring low branching ratios was proven by a test experiment on the isotope Cs-124 was performed in November 2012 (see Figure 3). A trapping time of up to 30s was demonstrated, which allows for half-life measurements in a region from seconds to minutes. These tests show that with further improvements, branching ratio measurements on the order of 10^{-3} are possible within the year.

Partners

In Canada: McGill University, University of Manitoba, University of Windsor, University of Calgary. International Partners: France (2), Germany (3), Switzerland (1), United States (5).

TRIUMF's Role

The scientific program and TITIAN collaboration are led by a TRIUMF staff scientist. TRIUMF provides a dedicated technician for the TITAN facility and delivers RIB beams to it. TRIUMF and NSERC invested approximately $3,500,000 into the TITAN facility.

5.5.1.5 LASER SPECTROSCOPY

An atom, by its very nature, consists of a nucleus surrounded by electrons. It therefore follows that one of the most sensitive probes of the nucleus are those electrons that are naturally interacting with it by matter of course. Laser spectroscopy makes use of this interaction by means of probing the electron's state in order to obtain detailed information on the shape and size of the nucleus. When implemented at a radioactive beam facility, where long chains of isotopes of the same chemical element are available, the evolution of nuclear structure can be probed from the relatively stable isotopes found in nature out to the extremes of nuclear structure. The techniques employed are almost universal across the chemical chart allowing information to be gained from the lightest Li and He isotopes out to francium, astatine, and beyond.

The basic technique of choice at ISAC has been collinear laser spectroscopy on beams prepared using TITAN's radio frequency (RF) buncher. This is a variant on the traditional collinear laser spectroscopy technique that was pioneered in Jyväskylä, Finland and is now in use at almost all radioactive beam facilities around the world where laser spectroscopy is performed. A schematic overview of the system is shown in Figure 1.

Description of Apparatus

The collinear, fast beam, laser spectroscopy facility utilizes the polarizer beam line as well as the radio-frequency quadrupole (RFQ) buncher that is the first trap in the TITAN mass trapping facility. A unique feature of the system at TRIUMF is that the RFQ is out of the plane of ion transport system. This allows the beam to either be directed into it, accumulated, and then ejected back into the beam line, or simply bypass the RFQ and proceed directly to the interaction region. Depending upon the details of the species to be studied, the ion beam can either be neutralized by passing through an alkali vapour cell or proceed purely as an ionic beam. In either case the beam is overlapped with a counter propagating laser and the laser frequency in the rest frame of the beam is scanned. When the laser is resonant with an atomic transition resonance, absorption occurs, resulting in spontaneous emission of light at the resonant wavelength. These resonantly scattered photons are detected by a photomultiplier tube mounted perpendicular to the direction of propagation of both radioactive and laser beams. Primary background suppression is achieved by means of a series of filters, often including a narrow bandwidth interference filter, placed in a parallel section of the light collection optics.

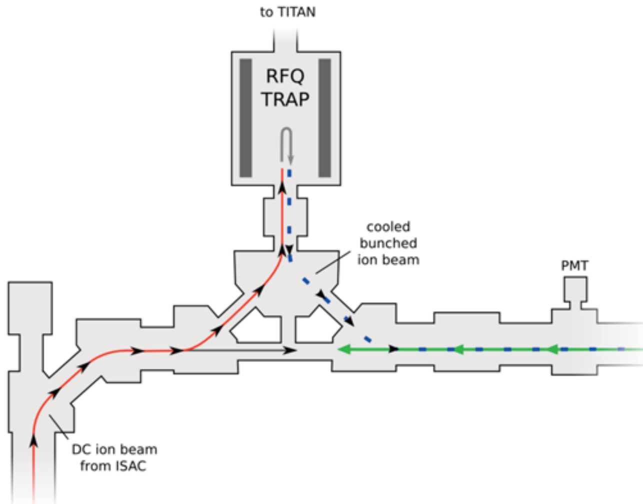


Figure 1: A schematic of the laser spectroscopy system.

Unique to the TRIUMF facility is a dedicated data-acquisition system designed around an FPGA-based multichannel scaler system. This system not only permits the usual scanning of beam energies and/or laser frequencies but also is completely time synchronized to the buncher injection and extraction timing. This permits for the time evolution of the expected signals to be mapped out and used not only for background reduction but also for investigations into any time dependant systematic effects. A typical spectrum is shown in Figure 2, with the raw two-dimensional data shown along with both time and energy projections.

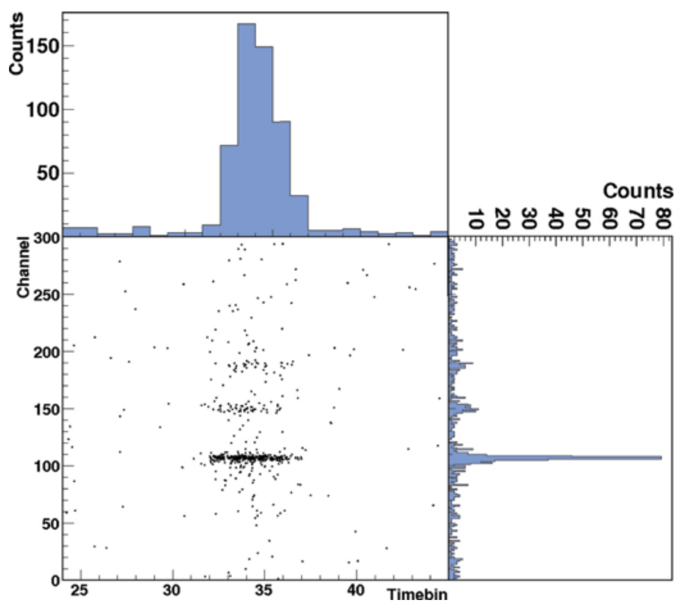


Figure 2: A typical 2D spectrum.

In addition to using the atomic electrons to probe the nucleus, the hyperfine interaction can be used in reverse. By manipulating the electrons it is possible to influence the nucleus. Most notably this method can be used in order to produce a polarized beam. Once again, unique to TRIUMF, is a pair of highly sensitive beta-detected nuclear magnetic resonance spectrometers. Whilst normally used for materials science work, these spectrometers have also been utilized for nuclear physics purposes. The dual spectrometer system at TRIUMF allows nuclei to be probed in both high (several Tesla) and low (down to zero) magnetic environments. This unique ability allows the magnetic and electric moments to be decoupled from each other and probed independently, resulting in significant improvements in sensitivity over other systems.

Recent Developments

Over the last five years this project has gone from starting out to being operational. The major developments include a new dedicated laser laboratory. Housing narrow line width ring dye and Titanium Sapphire lasers pumped with traditional Argon ion lasers along with frequency doubling capabilities, it is possible to access virtually all wavelengths that can be fibre coupled to the beam line. In the near future it is envisioned that this laboratory will be coupled to others around the ISAC Hall to allow for the sharing of laser light between projects ensuring the most efficient use of equipment. Currently, long-term laser stabilization is achieved by using a reference cavity stabilized to a commercial frequency standard, currently a polarisation stabilized Helium Neon laser.

Major developments have included not only the data-acquisition system but also the development of radio-frequency (RF) techniques to manipulate the laser light in order to make better use of the available atoms. Basic techniques have been developed to prevent atoms being pumped from one atomic hyperfine state to another in the region between charge exchange and observation. This involves switching the narrow linewidth, continuous wave laser beam via an electro-optic modulator such that each atom is only able to interact with a single, approximately two atomic lifetimes wide pulse of light. This allows the light, when present, to be of significantly higher intensity, resulting in higher probabilities of excitation in the region of interest. This technique was first demonstrated on neutron deficient Francium atoms and later used with great affect on the neutron rich Rb-98m and 99.

Runs over the past five years include B-NQR on Li8, 9 and 11 (S1155) as well as collinear spectroscopy on neutron-deficient Francium atoms (Francium 208,206,206m, 205,204,204m,204m’) and neutron-rich Rb isotopes (92,98,98m,99). This data is in the process of being analyzed and published.

Partners

In Canada: McGill University.
International Partners: Finland (1), Japan (1), United Kingdom (1), United States (1).

TRIUMF’s Role

TRIUMF leads the laser spectroscopy program with a staff scientist and provides ongoing support for the polarizer beam line and data acquisition as well as providing beams. Over the past five years, TRIUMF has also provided and funded the renovation of space to enable a dedicated laser laboratory to be established. TRIUMF has invested approximately $70,000 in this program, along with an NSERC investment of approximately $500,000, with a replacement cost of all equipment ~$1,500,000

5.5.1.6 FRANCIUM TRAPPING FACILITY

Francium is the heaviest known alkali element. Its high nuclear charge, large mass, and relatively simple atomic and nuclear structure make it an ideal laboratory for the study of many fundamental properties. These range from basic nuclear and atomic structure measurements, both of which enhance the knowledge of this region of the nuclear chart and also provide stringent tests of theoretical models, to high-precision tests of the Standard Model via the weak interaction. However, along with the many advantages of using Francium for this purpose comes a drawback: francium is the least stable of the first 103 elements on the periodic chart. With no stable isotope, and an estimated worldwide inventory of 20 g at any one time, these studies are required to be carried out at radioactive beam facilities. Facilities such as ISAC at TRIUMF do not naturally provide the required controlled environment to permit such high-precision studies to be performed.

To this end the Francium Parity Non-Conservation (FrPNC) collaboration has constructed and commissioned a Francium trapping facility within the ISAC experimental hall, supplied with radioactive beams from ISAC (and, in the future, from ARIEL, please see Section 5.3). This facility consists of a fully enclosed Faraday cage with independent climate control into which the francium is brought as an ionic beam. The ions are then neutralized and injected first into a magneto optical trap (MOT) where the atoms are cooled and trapped using laser beams. From here they can either be probed directly in order to obtain atomic hyperfine structure information or transferred to a second, more specialized trapping system where high precision, weak interaction studies can be performed. The trap system allows for high precision measurements, which can probe the very basics of fundamental forces because the environment in which the atoms are held is highly controllable.

Description of the Facility

The facility consists of a commercially purchased Faraday enclosure with a shielding factor in excess of 100 dB between 14 kHz and 1 GHz. This is sufficient to totally remove any measurable electrical noise from the ISAC hall, including leakage from the nearby accelerators. In addition to providing RF shielding, the entire enclosure is electrically isolated from the ISAC hall, permitting a single point earth to be established, significantly reducing any electrical noise. The enclosure also permits the environment within to be controlled independently of the environment in the surrounding ISAC hall. This enables temperature and humidity control consistent with the requirements for delicate measurements of the weak interaction to be achieved. All penetrations into the room, which provide compressed air, HVAC, cooling water, telephones, Ethernet, and most importantly the ISAC beam, have been engineered so as to not break either the earth isolation or the RF shielding.

The enclosure houses all the elements required to load incident alkali ions from ISAC into a magneto optical trap and from there into more specialized trapping systems. This includes the laser systems that are mainly Titanium Sapphire ring lasers frequency stabilized by transferring the stability of a commercial, polarization stabilized Helium Neon laser using a scanning Fabre Perot cavity [1]. The use of tunable ring lasers affords the versatility to change the alkali element being trapped whilst using the same laser systems.

A new development to decouple the light production from the trapping system is a fully fiber coupled trap. All of the laser light required for trapping, manipulation of the trapped atoms, and any measurements made, is fiber coupled across to the trap using single mode fiber combiners and splitters. Not only does this significantly reduce the complexity of optics around the trap region but also eliminates the dependence of the trap alignment on the laser's output direction as well as preventing high-powered, free laser beams from crisscrossing the enclosure.

Francium (or other alkali) beams enter the enclosure through a differentially pumped vacuum system that transitions from the usual ISAC beam line vacuum (~1e-5Pa) to the ultra-high vacuum required for a trap (~10-8Pa) where it impinges upon an yttrium foil. Based upon a concept developed at Stony Brook [2], the MOT is loaded in a pulsed mode. The yttrium foil is normally in the *down* position whereby the ion beam is in incident upon it, and accumulated on it. Once saturated with activity, the foil assembly is flipped into the *up* position whereby it closes the input to the trapping glass cell. The foil is rapidly, resistively heated for approximately one second, releasing the surface francium predominantly in atomic form. This vapour is then trapped in the MOT and either ready for measurements or, in the future, ready to be transferred to a second, science chamber located below the capture trap and optimized for the measurement to be performed rather than for the accumulation of atoms. A drawing of the assembly with the foil in both *up* and *down* positions is shown in Figure 1.

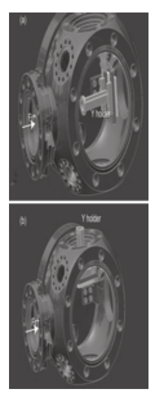


Figure 1: Neutralizer chamber with the neutralizer holder in the catching down position (a). Neutralizer chamber with the neutralizer holder in the delivery up position (b).

In addition to using the online beam directly a method of collecting a long-lived, albeit somewhat smaller, sample of Fr-221 has been developed. By utilizing the availability of long-lived Ac-225 (t-1/2=10.5d) beams after protons have stopped irradiating an ISAC target, a source can be collected that releases a small amount of Fr-221 over the half-life of the Ac. This has successfully been used to investigate systematic effects within the trapping system. It is envisioned that in the near future this system will allow for technical developments to take place over a period of a couple of weeks following an actinide target run at ISAC, irrespective of what is happening elsewhere within the hall.

Recent Developments

To date several isotopes have successfully been trapped, namely Fr-206,207,209,213. For each of these the atomic $P_{1/2}$ state hyperfine splitting has been successfully measured using a technique of rapidly sweeping a pair of sidebands using microwave-scanning techniques. In a technique developed at TRIUMF by the collaboration, the probe laser light is passed through a high bandwidth (20 GHz) fibre modulator. To this microwaves are applied at a frequency similar to that of the required hyperfine splitting. By rapidly sweeping the microwave frequency, one sweeps the frequency of these sidebands relative to the stabilized laser. With the carrier placed approximately central, with respect to the atomic hyperfine states of interest, a modest size scan (~few hundred MHz) can result in a statistically, high precision measurement of the state splitting. A typical spectrum for Fr-206 is shown in Figure 2. The rapid (a full scan taking ~20 ms) microwave scanning almost eliminates the systematic errors due to the long-term laser frequency shifts

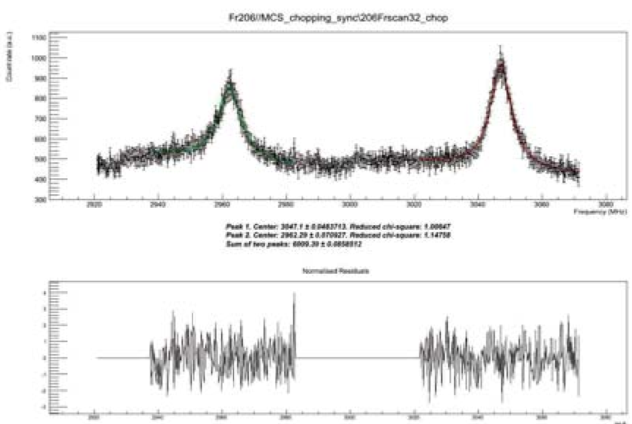


Figure 2: A typical spectrum Fr-206. The rapid (full scan taking ~20ms) microwave scanning almost eliminates the systematic errors due to the long-term laser frequency shifts.

Partners

In Canada: TRIUMF, University of Manitoba.
International Partners: Australia (1), China (1), Mexico (1), United States (3).

TRIUMF's Role

TRIUMF has a leading involvement in the FrPNC program through two staff scientists. Over the past few years TRIUMF has not only provided space in the ISAC Hall but also relocated the two running experiments that used to operate in that space. TRIUMF has also provided the beams required for experiments to take place as well as a custom, high vacuum to ultra-high vacuum transitional beam line and significant amounts of technical expertise in building, controlling, and running the required systems. In addition to this over the past two years TRIUMF has hosted two sabbatical visitors dedicated to this project. In terms of money, TRIUMF has invested approximately $100,000. In addition, the U.S. Department of Energy has provided approximately $900,000. The entire replacement value would be approximately $1,500,000

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5.5.1.7 MTV: TEST OF TIME REVERSAL SYMMETRY USING POLARIZED UNSTABLE NUCLEI

Time reversal symmetry is one of the most fundamental symmetries of physics. It is equivalent to symmetry between matter and antimatter. In order to explain why our universe is dominated by ordinary matter, unknown interactions that violate time reversal symmetry are required to exist. The MTV (Mott polarimetry for T-Violation) experiment searches with the highest precision for violation of time reversal symmetry, which is predicted by models of physics beyond the Standard Model, in the nuclear beta-decay of the radioisotope Li-8 using a new type of particle position detection device. Following first tests at TRIUMF in 2009 the first physics data taking was performed in 2010, achieving the finest statistical precision. A next-generation device was developed in 2011, tested in 2012 and will begin taking data in 2013. This experiment will produce the most precise result on this particular test of time reversal symmetry.

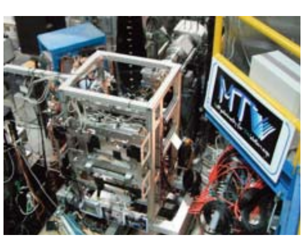
Description of the Apparatus

The MTV experiment was originally performed at KEK in Japan where a 10% precision was achieved [1] using a newly developed particle detector that could precisely measure the polarization of electrons emitted in the beta decay of polarized Li-8 nuclei.

Existence of electron polarization perpendicular to its momentum direction is the signal for the violation of time reversal symmetry. In a first stage, a planar multi-wire drift chamber (MWDC) is applied as the polarimeter to detect the position of the electron path with hundreds of thin wires in a gas-filled chamber. In 2009 this setup was placed at a low-energy polarized beam line at ISAC (see Figure 1) and a first test experiment was performed with polarized Li-8 beam from ISAC with up to 107 particles per second and around 80% polarization. These numbers were compared with 105 particles per second and 8% polarization at KEK.

In addition, the performance of the MTV detectors was tested with the high beam intensity, which is a hundred times larger than at KEK. The tests confirmed that a statistical precision of at least 0.1% could be achieved with this set-up [2-3]. After improving the detector and electronics performances a first physics run was performed in November 2010, and this run yielded sufficient statistics to achieve the expected precision. In order to further improve the experimental precision, the original MWDC was replaced by a cylindrical drift chamber (CDC), which was developed in Japan in 2011. By utilizing the cylindrical symmetry of the CDC, the experimental precision could be improved by cancelling undesired systematic effects, which limited the final precision achievable with the MWDC. The CDC was commissioned in November 2011, and final tests of the full detector setup were carried out in 2012 (see Figure 2). The physics data taking with the new CDC setup will start in 2013.

The Standard Model of particle physics predicts negligible signals for the MTV experiment. Therefore, it can be said that this experiment is sensitive to the signals of new physics by suppressing the Standard Model background. Expected precision of 0.01% with the CDC promises to explore such new physics signals.



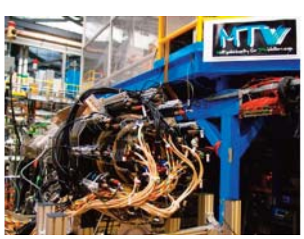


Figure 1: The MTV setup with the MWDC at ISAC in 2010.

Figure 2: The MTV setup with the CDC at ISAC in 2012.

Partners

International Partner: Japan (4).

TRIUMF's Role

TRIUMF delivered the world highest intensity and polarization Li-8 beam to the experiment, operated the collinear laser facility to produce the polarized beam, provided ongoing detector maintenance.

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5.5.1.8 β-NMR FACILITY

The beta-detected nuclear magnetic resonance (β-NMR) facility at ISAC is constructed specifically for using radioisotopes for experimental studies in materials science, utilizing a probe beam of spin-polarized radioactive ions such as Li-8$^+$ (half-life = 848 ms) to monitor the local electromagnetic properties of the host material sensed at the atomic scale. A crucial capability of this technique is control of the average implantation depth of the probe, thus obtaining *depth resolution* on an interesting length scale (5–200 nanometers).

The β-NMR facility at TRIUMF is unique in the world. Similar to the low-energy muon facility at PSI in Switzerland (using polarized μ^+ as probes) it applies a low-energy spin-polarized probe to studying magnetic and related phenomena on nanoscale depths into materials. However, β-NMR is sensitive to much longer timescales than low-energy muons. These local probe techniques provide important complementary tools to reciprocal space methods like polarized neutron reflectometry (PNR) and synchrotron techniques such as resonant inelastic X-ray scattering (RIXS)—that also study depth-dependent electromagnetic properties of materials. As with conventional NMR, the nuclear spin senses its local environment, specifically the local magnetic field (which is determined by the surrounding electronic structure of the host), and the electric field gradient via the quadrupolar coupling, as well as fluctuations of these quantities that result in relaxation of the probe nuclear spins.

The β-NMR facility is used for a number of experiments in magnetism and superconductivity as well as on novel ultra-thin heterostructures exhibiting properties that cannot occur in bulk materials. Recently the scope of research using this facility has expanded into soft condensed matter and ionic conductivity. The science program is described elsewhere in this Plan. Here we give a technical description of the facility, its operation, and TRIUMF's role.

Description of Facility

The facility consists of a polarizer and a suite of spectrometers.

Polarizer. The polarizer does the essential step: the alignment of the probe ion beam's nuclear spins. To do this, it uses circularly polarized laser light whose wavelength is tuned to an atomic transition of the probe. The layout of the polarizer and two spectrometers is illustrated in Figure 1. The polarizer consists of a section of low-energy beam line situated 6 m upstream from the experiments and associated laser facilities. In detail, the polarizer functions as follows. A 20–30 keV incident Li-8$^+$ beam is partially neutralized with ~50% efficiency in a Na vapour charge-exchange cell (CEC). Unneutralized ions exiting the CEC are removed from the beam by electrostatic deflection plates. The fast atomic Li-8 beam is nuclear-spin polarized in flight via collinear laser optical pumping with circularly polarized light on the D_1 electronic transition at 671 nm. Polarization as high as 80% can be achieved. In principle, ion beams of many chemical elements can be polarized through optical pumping. The alkali metals are the most straightforward, with high polarization achieved by pumping with visible wavelength lasers on the $^2S_{1/2}$ - $^2P_{1/2}$ or $^2S_{1/2}$ -$^2P_{3/2}$ atomic ground state transitions. Most sodium and lithium isotopes have been polarized in this facility, which also serves other experimental groups besides condensed matter physics.

The polarized beam is re-ionized through impact ionization in a windowless, cooled helium gas cell with over 60% efficiency. Re-ionizing the beam has several advantages: (1) The ion beam can be directed by electrostatic elements to different experimental stations. (2) Two experiments can share the same beam, through the use of a kicker. (3) The experimental target is not exposed to laser light. (4) The absolute polarization direction, initially longitudinal with respect to the beam motion, is unchanged by electrostatic elements. Therefore the beam polarization can be transformed from longitudinal to transverse simply by steering the beam through a net angle of 90 degrees, with no loss of polarization. (5) The beam energy at the target, and hence implantation depth, can be adjusted by applying a variable potential to the target. All of these features have been used to advantage at ISAC.

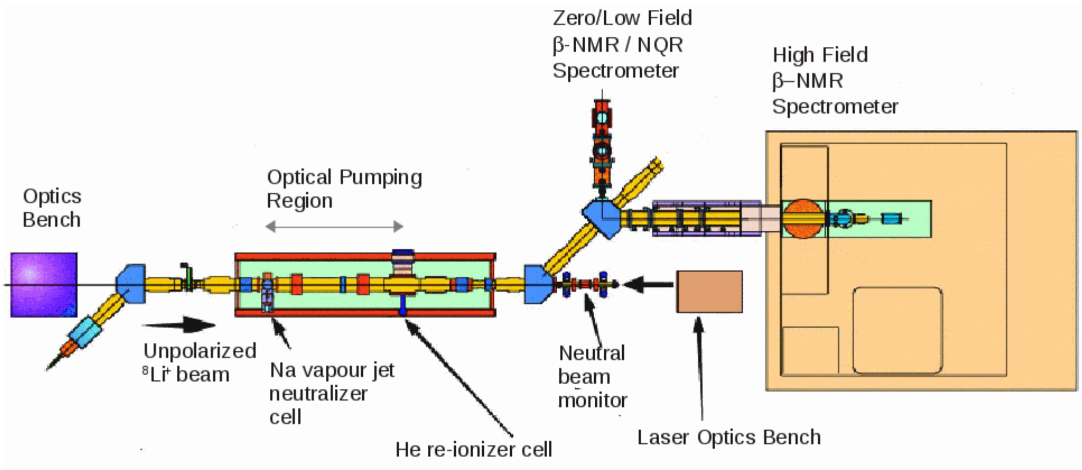

Figure 1: General layout of the in-flight polarizer and high- and low-field spectrometers. Beam (from the left) is longitudinally polarized while in-flight by counter-propagating circularly polarized laser light, then steered electrostatically to one of the two spectrometers.

Spectrometers. Two spectrometers have been constructed to cover different ranges of applied magnetic fields. Their purpose is to measure the spin polarization of the implanted Li-8^+. Two basic types of experiments can be performed with either spectrometer. Time-differential spin relaxation experiments, performed with pulsed beam, measure the rate at which the initial spin polarization is lost due to dynamic processes, usually as a function of temperature and/or applied DC magnetic field. In the frequency domain, by applying a weak radio frequency (RF) magnetic field and scanning over a range of frequencies, the resonance lineshape can be recorded, which measures the distribution of magnetic fields at the site(s) occupied by the probe Li-8 within the material being studied. Each spectrometer is equipped with a helium flow cryostat that provides stabilized sample temperatures in the range of 3–325 K. In order to reduce the accumulation of residual vacuum gases on the sample surface at cryogenic temperatures, spectrometers operate under ultra-high vacuum (UHV) conditions in the 10^{-10} Torr range. Samples are mounted to and removed from each of the cryostats via vacuum load-lock chambers, which can be isolated, vented, accessed, and pumped independently of the main vacuum system, thereby preserving the spectrometer UHV. When both spectrometers are running experiments that require pulsed beam, the beam can be kicked alternately to both spectrometers. In this mode of operation beam pulses typically 1 to 4 s long are sent to both spectrometers every 10 to 20 s, making the best use of beam time with no overhead. Each spectrometer is mounted on an electrically isolated platform that may be biased to a high electrostatic retarding potential. Simple electrostatic optics are used to decelerate the ions in the last few cm before impacting the sample surface. Deceleration close to the sample minimizes the lateral spread of the beam on arrival at the sample. Due to the very small energy spread of the beam and its small transverse momentum, well-focused beam spots, with energies down to a few hundred eV and stopping range of about 5 nm, are possible. Typically the beam lands within a ~2 mm diameter spot on the sample without the use of beam collimation at the spectrometer. At single-counter event rates of about 10^6/s, each resonance or spin relaxation run typically requires 20–40 minutes to accumulate. A temperature scan on one sample, at one implantation energy, can be completed in a day.

High Magnetic Field Spectrometer. The high field spectrometer (see Figure 2) uses a 9 T superconducting solenoid with field oriented along the incoming beam momentum. The implanted beam has nuclear polarization normal to the sample surface. Two detectors are situated along the direction of initial polarization to count the decay betas —one inside the cryostat 10 cm in the forward direction with respect to the sample position and one annular detector upstream of the magnet 75 cm in the backward direction. Although they are very different in physical dimensions, focusing of the decay electrons in high magnetic field results in nearly equivalent effective solid angles. The RF magnetic field is generated with a non-resonant helical transmission line having a flat 50 Ohm impedance and frequency response up to 45 MHz. The RF synthesizer, under control of the data acquisition system, can be programmed to generate continuous wave (CW) or complex-modulated pulsed RF excitation for various types of resonance experiments.

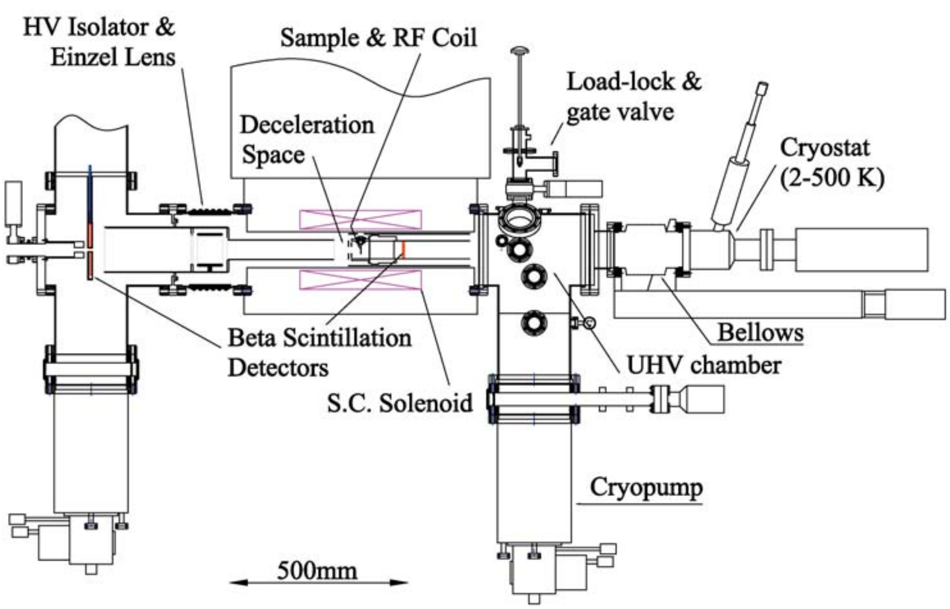

Figure 2: Schematic side view of the high-field β-NMR spectrometer. A polarized beam of Li-8+ ions enters from the left and comes to rest in a sample held in the cryostat at the magnet's center. The entire experiment may be raised to a high positive potential, creating a retarding electric field between the grounded end of the beam line and the front of the cryostat, thereby controlling the ion energy and implantation depth. Beta-decay events are counted by one detector located downstream of the sample within the cryostat, and another annular backward detector situated outside the magnet.

Zero- and Low-Field Spectrometer. Being optimized for low magnetic fields (0–24~mT), the low field spectrometer (see Figure 3) differs from the high field spectrometer in several fundamental ways. Due to the use of electrostatic dipoles in the low-energy beam line, the orientation of spins of the positive Li-8 ions exiting the polarizer is preserved while the beam momentum is bent through 90 degrees. Polarized $^8Li^+$ ions therefore arrive at the low field spectrometer with spin polarization transverse to their momentum and in the plane of the face of the sample. Two pairs of scintillation detectors and phototubes are situated outside the vacuum chamber on the left and right sides, arrayed along the initial polarization. A small coil generates an RF magnetic field perpendicular to H_0, in the plane of the sample surface. The RF system is capable of CW and complex-modulated pulsed-mode operation over a frequency range of 0–2 MHz. The external DC magnetic field H_0, if applied, is parallel to the initial polarization and therefore also in the plane of the sample face, an arrangement suitable for measuring the depth dependence of magnetic field in the Meissner state of superconductors. Trim coils can be employed to permit zeroing of the ambient magnetic field to within 1 μT. Therefore, in zero field, this spectrometer can perform nuclear electric quadrupole resonance (NQR) experiments. Samples are mounted into the low field spectrometer on a four-stage multiple sample ladder via a vacuum load-lock. The use of a ladder enables rapid changes among the loaded samples and beam spot imaging scintillator.

Recent Developments

In 2012, TRIUMF committed to providing at least five weeks of beam time per year for β-NMR experiments. Prior to this, the available beam time was substantially less and would fluctuate from year to year. Sufficient beam time with a predictable schedule was crucial to the viability of the program. Even with this increase, it will be difficult to compete with the PSI LEμSR facility that has much more available beam time and a much higher level of support in terms of facility manpower. With such restricted availability, it will be difficult to grow the user base. The ARIEL facility, which will start its science program with the delivery of Li-8 for β-NMR offers the prospect of alleviating this shortage in beam time. In the meantime, there are have been several developments specific to both spectrometers and the polarizer.

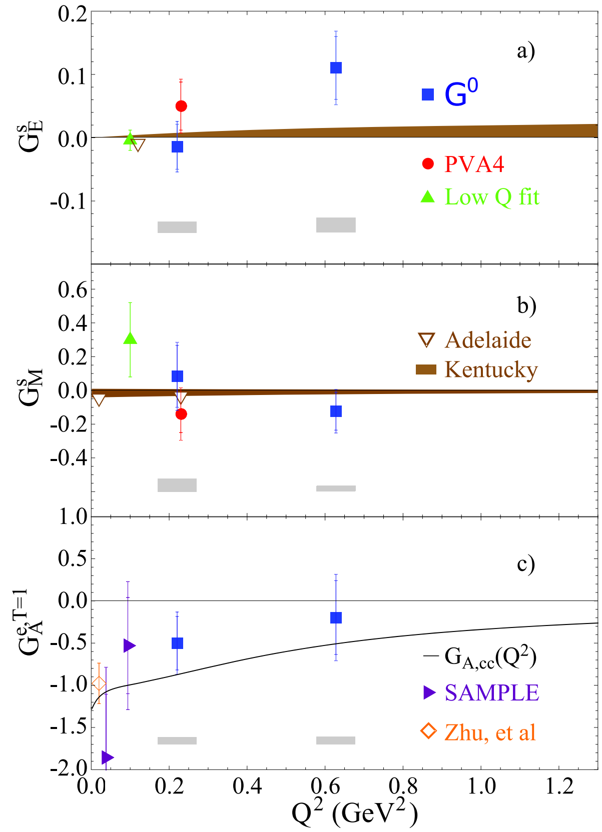

Figure 3: Schematic view of the zero-/ low-field β-NMR spectrometer from above. Unlike the high field apparatus in Figure 2, the initial polarization and applied magnetic field are in the plane of the sample face. Beta detectors are situated on either side, outside the vacuum vessel. Particularly when operated at zero magnetic field, this spectrometer also performs beta-detected nuclear quadrupole resonance (β-NQR) experiments, yielding information about the electric field gradient and crystallography symmetry at the site of the probe Li-8.

Modifications that allow electrical contact to the sample during the measurement have been commissioned. These modifications will allow a new set of experiments in which an applied current or voltage is an important independent parameter, like controlling the magnetic properties of the electrons of a material via current or voltage, or causing ionic diffusion as in an operating lithium ion battery. Electrical connections to sample holders in the high field apparatus have been added to permit current injection through magnet/semiconductor interfaces. A similar capability is under development for the low field sample holder to apply potential gradients across interfaces, thereby generating very high electric fields within the thin interfacial region.

Efforts in data acquisition control software is aimed at improving immunity to beam rate instabilities that introduce spurious signals into the data, and data analysis software is under constant development, and all of the effort to develop analysis tools is provided by the experimenters.

The possibility of polarizing spin-1/2 $Be\text{-}11^{+}$ was tested. The required modifications were: (1) Magnetic coils were added to the beam line for transporting paramagnetic ions without loss of polarization, (2) A frequency doubler was purchased for generating ultraviolet light, and (3) A system of biased collinear tubes, which spread the beam energy over a range of a few eV in discrete steps, was invented as a way to cover the Doppler width of the ion beam with a fixed frequency laser. The usual method of broadening the laser with electro-optic modulators was not available due to the cost of EOMs in the ultraviolet.

It was found that the Be-11 effective asymmetry parameter is too low for β-NMR studies without energy discrimination because the two main beta transitions have opposite sign asymmetry parameters that nearly cancel.

The TITAN RF cooler was built and can be used to cool and bunch an incoming ion beam and direct it towards the polarizer beam line. This has been used to increase the signal to noise ratio in laser spectroscopy measurements of Rb isotopes.

A second charge exchange cell has been built to allow quick changes between Na and Rb vapour cells. A Rb vapour cell is more efficient for neutralizing elements such as Rb and Fr, which have low ionization potentials.

Partners

In Canada: Simon Fraser University, TRIUMF, the University of Alberta, the University of British Columbia, University of Waterloo.
International Partners: Australia (1), German (2), Japan (3), Switzerland, (1) United Kingdom (1), United States (3).

TRIUMF's Role

TRIUMF has supported the costs of maintaining, repairing and operating the polarizer and associated laser systems. It has also paid for developing the new charge exchange cell and the costs of polarized Be-11^{+} development.

TRIUMF contributed the design and construction effort of the beam lines and ~2/3 of the initial instrument development costs. TRIUMF funds on-going maintenance costs (~$15k/y) of the core facility equipment and related beam lines, vacuum and controls systems. TRIUMF also provides manpower. Additional support is provided by the TRIUMF CMMS technical and scientific staff, and data acquisition groups.

During experiments, TRIUMF is responsible for delivering the probe ion beam to the experimental stations at the end of the beam line. This includes operating the cyclotron that provides the primary driver beam (500 MeV proton at 30 to 100μA) transported down Beam Line 2A to the ISAC production target. TRIUMF designs, fabricates and operates the targets that convert the primary proton beam into secondary radioactive ion beams, such as Li-8^{+}. High yields of Li-8^{+} are produced by surface ionization targets made of Tantalum or Niobium. TRIUMF is responsible for delivering well-tuned high-flux beams with stable rates and beam spots to the experimental spectrometers. This involves sophisticated design and fabrication of the target, beam transport and tuning, and depends upon the ISAC operations, beam delivery and targets groups.

A significant amount of beam time is still being used in the tuning process (at least 10%). TRIUMF is making a continuing effort to reduce this fraction, making tune-ups more systematic, reproducible and expeditious, so that more beams—of higher quality—is available for science.

Monetary Investment

Polarizer: $535k in parts, including lasers, optics, beam line, vacuum, controls, and supporting infrastructure.
Spectrometers: high field $555k; low field $315k in parts including beam lines, vacuum system, control system, high voltage and platforms, detectors, data acquisition, RF systems, magnets and cryogenics. Approximately $250k of this was obtained via NSERC equipment grants.

Additionally, approximately 33 person-years of combined effort from TRIUMF scientists, technicians, and engineers, plus university faculty, graduate, undergraduate students, and post-docs has been spent developing the facility and conducting experiments to date.

5.5.1.9 RADONEDM

The RadonEDM experiment is an online, precision measurement of the NMR precession frequency of 20–30 minute half-life nuclei in combined electric and magnetic fields, with an anticipated total running time of about 100 days over several years. A change in the precession frequency correlated with the relative orientation of the magnetic and high-voltage electric fields (parallel or antiparallel) is the signal of an EDM (electric dipole moment) (i.e. proportional to the EDM); however, because the magnetic moment of the nucleus couples to the magnetic field, it is essential to minimize and monitor changes of the magnetic field correlated with the electric field

Description of the Facility

The facility for the RadonEDM experiment has several requirements: online beam position to which low-energy radioactive beams will be delivered with maximum efficiency coupled to the gas-transfer system for the experiment; the gas-transfer system similar to the one developed at TRIUMF in 2004 [1], including radioactive-gas exhaust; active and passive magnetic shielding and magnetic field coils surrounding the EDM cell and EMI shielding; magnetometers incorporated into the active shielding and within the passive shield for magnetic-field monitoring (magnetometry); laser safety and optic components for noble-gas (Xe and Rn) polarization; EDM cells; and high-voltage systems. Each component is described in more detail below in Recent Developments.

The desired low-energy isotope beam is implanted in a metal foil (e.g., zirconium) for about two half-lives. After implantation, the foil is heated, driving the activity off into a sealed chamber with a LN_2-cooled trap located near the EDM cell. After quickly warming the trap to free the sample into the gas phase, a piston of N_2 gas pushes the sample into the EDM-measurement cell. The first version of the collection-and-transfer apparatus, reported in Nuss-Warren [2] provided a transfer efficiency of 40%. This was improved to approximately 100% by improving the cold-trap and the rates of warming and cooling. The apparatus, consists of the foil, heating, remote-actuated valves, vacuum pumps and the cold-trap and control system.

Magnetic shielding reduces the effects of static and time-dependent external fields and is provided by the combination of active and passive shielding. Active shielding is effected by feedback to a set of magnet coils, a combination of magnetic field measurements in the vicinity of the experiment. Changes of up to a few hundred µT (a few Gauss) are accommodated by measurements with an array of flux-gate magnetometers, and the coil system has outer dimensions of 3-4 m in all three dimensions. Detailed

FIRST ACCELERATION OF CHARGE-BRED RIB AT ISAC

12 November 2008

On November 11, 2008, a team of scientists led by Dr. Friedhelm Ames successfully accelerated a beam of positively charged Rubidium isotope ($^{80}Rb^{14+}$) ions at TRIUMF's ISAC facility. This represents the first accelerated, charge-bred rare isotope beam (RIB) at ISAC, making ISAC one of only three facilities in the world with this capability and signaling the beginning of a new program of nuclear physics at TRIUMF.

Until now, the heaviest RIB accelerated at ISAC had been. To achieve higher charge states for accelerating ions heavier than 30 atomic mass units, a new Charge State Booster (CSB) was designed and installed. In the case of Rb-80, beam was extracted with the rubidium atom's full complement of 37 electrons removed. The team then confirmed its acceleration using a gamma ray detector to detect the decay signature associated with Rb-80.

This milestone marks the culmination of five years of development by ion source physicists and technical teams. There is significant experimental interest in accelerated rare isotope beams with atomic masses greater than 30. Having the CSB available will greatly extend ISAC's capabilities at TRIUMF, strengthening its position as one of the world's premier Rare Isotope Beam facilities.

designing of the active shield requires knowing the magnetic field environment in the final position of the experiment, with the expectation that the field will be quieted to the μT level. Within the active shield, passive shielding made up of 3-4 mu-metal enclosures is expected to have axial and transverse shielding factors much greater than 10^3 and 10^5, respectively, for cylindrical shields. The optimal shape and size of the final mu-metal shields depends on the free-precession detection technique; however the principles and design procedures for both active and passive shielding are well established and proven, for example by the system developed for the Munich neutron EDM experiment which has achieved these specifications.

Within the shields, a small uniform magnetic field, e.g., 1 μT, is maintained by a set of coils and stabilized with signals from a set of optical magnetometers, e.g., Cs magnetometers [2] will complement the field measurement provided by the co-magnetometer within the EDM cell. A co-magnetometer is provided by a second species that has a similar magnetic-moment interaction, but an intrinsically much smaller electric-dipole moment interaction. For example, for the Xe-129 EDM measurement, the co-magnetometer was He-3, which was chosen due to the Z^2 dependence of the atomic EDM in diamagnetic atoms [3]. For the Radon-EDM measurement, possible co-magnetometer species include xenon isotopes and non-octupole enhanced radon isotopes, e.g., Rn-209, which will also be polarized by spin-exchange optical pumping.

Narrowed diode lasers for spin-exchange optical pumping of Rb, providing 20–50 watts, have been developed and are inexpensive, stable, and easy to operate. Laser safety, including containment and procedures, are based on standard operating protocols that have been implemented at several facilities, including the Radon-EDM test beam. Optics are standard, off-the shelf items.

EDM cells for noble gases are continually developing. In the current design, the cylindrical cells consist of a fused silica body with conductive silicon endcap electrodes. These are commercially manufactured to our specifications. The cell materials are compatible with producing the electric field with minimized leakage current at temperatures of 50–100°C, low spin relaxation of polarized noble gases. An automated Teflon valve has been tested and it will close the cell after transfer of the gases.

Electric fields of 10 kV/cm, applied across the EDM cell, require high voltage of 20–25 kV, depending on the final cell dimensions. The polarity on each electrode is reversible.

Recent Developments

It is crucial to establish the experimental as well as theoretical basis for octupole enhancement of Schiff moments in specific systems, i.e. radon and radium. There has been significant theoretical effort on estimating the sensitivity of the Schiff moment to the isospin 0,1,2 components of a CP-violating pion-nucleon coupling, with the most specific quantitative work in Hg-199, and Ra-225. The isotope Ra-225 is particularly interesting because it is relatively long lived (14 d) and its nuclear structure has been well studied. By contrast, there is little data on levels of the odd-A radon isotopes, specifically Rn(221/223). We have therefore set out to collaborate with experts in several approaches to the needed measurements at TRIUMF, NSCL, and ISOLDE. We have played a major role in motivating and extracting science from these efforts.

The use of actinide targets at TRIUMF-ISOLDE has allowed development work that will lead to beams to populate excited states of Rn for identification of spin and parities. A new efficient 3-step laser ionization process was developed by the TRILIS group starting with At-199 and moving up to neutron-rich At-219. The 8π spectrometer was used to identify the isotopes. One problem is contamination from easily ionized Fr isotopes, but for short-lived alpha emitters this is manageable. In contrast, longer lived Fr and Ac isotopes with lifetimes > 1 m led to a large-surface ionized contamination of the beam that completely dominated the much less intense laser-ionized At isobars. TRIUMF has assigned Beam Development Priority 1 to the At-221 beam for S929, and a major effort to suppress surface-ionized beam contamination by combining the TRILIS ion source with a new RFQ system has since been made, with plans to test a TRILIS+RFQ .

Noble gas polarization by spin-exchange has been studied most extensively for Xe-129 and He-3, motivated in part by applications to medical imaging, EDMs, polarized targets, and neutron polarization. Our earlier work with Rn-209 at Stony Brook (and much earlier work with Rn-209 and Rn-223 at ISOLDE) show that spin-exchange will provide significant polarization (>10%) for an EDM experiment [5]. We have recently developed a 50-watt, narrowed laser source for Rb optical pumping, with 0.11 nm linewidth. This is being tested in a new-generation Xe-129 EDM set-up that uses He-3 as a co-magnetometer. Improvements to Rn polarization are also expected and can be tested at ISAC.

We have developed a new method of detecting the NMR-precession of noble gases, specifically Xe-129 using a 2-photon transition. This will be directly applicable to a RadonEDM experiment and will provide the most sensitive possible measurement—more sensitive than the previously proposed methods observing nuclear decays. This work has been motivated most directly by the ideas for a Xe-129 co-magnetometer for neutron-EDM measurements (the Xe-129 would take the place of Hg-199 used in the ILL experiment [6]). Conventional 1-photon magnetometers are not practical for the 147 nm transition; however, two-256 nm photons will populate the triplet-D state from the ground state. In our scheme, the two photons are circularly polarized, and will thus effect only Dm=2 transitions serving to probe the ground state polarization. Precession of the nuclear spin will lead to modulation of the fluorescence, absorption, or optical rotation at the Larmor frequency. We have been working on a model-experiment in Yb, which is a 2-electron atom with atomic structure similar to xenon, and we will test the scheme with xenon in collaboration with E. Babcock and P. Fieleringer groups at Munich, who have appropriate lasers for both Xe-129 polarization and 2-photon magnetometry.

Partners

In Canada: Simon Fraser University, TRIUMF, University of Guelph.
International Partners: Switzerland (2), United Kingdom (1), United States (3).

TRIUMF's Role

TRIUMF has provided the Radon-EDM test facility and beam line at ISAC from 2008–2013 and is involved through a staff scientist. Improvements to the radioactive noble-gas collection and transfer apparatus, as well as extensive optical pumping studies, were completed with this set-up. TRIUMF has provided radioactive Xe-120 and Xe-121 for development and has developed the actinide targets and relevant yield measurements and will provide the Ac-221 beam for Rn-221 structure studies in December 2013.

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5.5.2 ISAC-II

ISAC-II is the newest and highest energy of the rare-isotope areas at TRIUMF. It has a number of advanced detector facilities each optimized for a different purpose: TIGRESS for gamma rays, EMMA for recoil mass spectrometry, HÉRACLES for multi-particle detection, IRIS and TUDA for charged particle reaction studies, and so on. The large detector TIGRESS is movable so that it can be used with EMMA when needed. Smaller detector set-ups can be installed for specific programs, such as the fusion reaction studies with halo nuclei. HÉRACLES is the senior detector having been used at Chalk River and Texas

A&M before moving to TRIUMF in 2003. It is used to studying heavy ion reaction mechanisms in particular related to the nuclear equation of state. The other detectors are used for the study of nuclear structure including halo nuclei, direct nuclear reactions and nuclear astrophysics.

5.5.2.1 THE TIGRESS FACILITY AND ITS AUXILIARY DETECTORS

Some of the most exciting recent results in nuclear structure are associated with the evolution of novel nuclear behaviour at the extremes of nuclear existence, including (but not limited to) halo nuclei [1,2], dissolution of the classical shell gaps [3,4], emergence of new magic numbers with special stability [3], and proton-neutron pairing [5]. These manifest themselves as excitation properties of exotic nuclei, for example, through in-beam γ-ray spectroscopy with accelerated exotic radioactive ion beams (RIBs). Heavy-ion collisions near the Coulomb barrier with RIBs, directed upon stationary targets, can lead to a wide range of reaction channels and excitation modes. Nuclei excited in the collision process will then emit one to ~40 γ rays, with typical energies from ~50 keV to ~8 MeV. These emitting nuclei will be fast-moving sources ($v/c \sim 0.03$ to 0.10), so the detected photons will be Doppler-shifted in the laboratory frame. These features generally point towards a need for high purity germanium (HPGe) gamma-ray detectors with anti-Compton shields and high accuracy in γ-ray vector determination. In RIB experiments, beam intensity is limited by RIB production technology and cannot be easily increased so high total γ-ray detection efficiency is essential. The most sensitive experiments require the use of additional sophisticated radiation detectors; one must take due care in the mechanical layout of the γ-ray detectors to accommodate these. Finally, to maximize the physics output of a RIB facility, the experimental end-stations must allow for rapid reconfiguration; beam scheduling is driven more by production targets than experimental setups [6,7].

Description of Facility

The TRIUMF-ISAC Gamma Ray Escape Suppressed Spectrometer, TIGRESS, is used at the ISAC-II facility primarily for RIB experiments. It consists of up to 16 units of so-called clover HPGe multi-crystal detectors and scintillator suppressor shields, with waveform sampling digitizers. TIGRESS has operated with arrays of highly segmented silicon detectors for charged-particle detection, BAMBINO and SHARC, and will also be used with a plunger and CsI(Tl) detector (TIP), electron conversion spectrometer SPICE, and neutron detector DESCANT, as well as recoil separators.

The 16 high-energy-resolution γ-ray spectrometers in TIGRESS consist of four HPGe n-type bulleted-coaxial detectors in a single cryostat. The crystals are nominally 60 mm in diameter and 90 mm long before they are machined and tapered. Each crystal has a photopeak efficiency of ≥38%. The cryostat is also tapered. This allows for close packing of the detectors in a truncated cube. The inner-core coaxial contact holds positive bias and collects charge from the full volume of the crystal. The outer surface of the detector has eight electrically isolated contacts, with four quadrants around the axis of the core contact and a lateral segmentation 30 mm from the front of the crystal. The centre contact is instrumented with a cold FET and feedback front-end network within the cyrostat volume, while for the outer contacts the network is at room temperature. All contacts are instrumented with charge-sensitive preamplifiers.

In multi-crystal detectors such as the TIGRESS detectors, γ rays that enter one crystal and escape have a high probability of striking another crystal. The incident photon energy can be measured by adding the energy deposition in two (or more) neighbouring crystals. This add-back results in a relative efficiency for a full TIGRESS clover detector of between 215% and 220%.

Each clover is outfitted with a set of escape suppression scintillators to detect and veto escaping photons. Backplug and sidecatcher suppressors detect small-angle scattering out of the back and flat side of the cryostat, and are bolted directly to the HPGe assembly. Trapezoidal front suppressors fit around the front, tapered part of the clover cryostat for large-angle Compton scattering, especially from the front of the HPGe volume. In the high-ε (efficiency) configuration, the front shields are withdrawn and the clovers are inserted within 2 mm of each other for maximum photopeak efficiency. Alternatively the clovers may be withdrawn, and the front suppressors inserted between them to afford the maximum coverage for large-angle Compton scattering; this is the high-P/T (peak-to-total) mode. In both configurations a full 22.0 cm diameter inner sphere is available for vacuum and auxiliary detectors, and the entry and exit ports for beam are identical.

The mechanical support structure holds eight clover and suppressor units on a central corona perpendicular to the beam axis. To this main frame, lampshade frames may be fastened to hold up to eight more clover and suppressor units, four at 45º and four at 135º to the beam axis. The lampshades and their clovers may be removed to accommodate auxiliary detectors.

It is possible to change between the high-P/T and high-ε modes in under a day. During the 2010 experimental campaign, TIGRESS comprised ten clover units (including suppressors) on the central corona and backward lampshades. It was operated in both modes, and for the high-P/T mode an absolute photopeak efficiency of 4.7% was measured, including add back. In the high-ε mode the absolute photopeak efficiency was 7.4%. This included add back within a clover unit but not between neighbouring cryostats.

The data acquisition system [8] uses a hierarchal, scalable multi-level triggering system and digital waveform sampling. Signals from the HPGe and suppressor charge-sensitive preamplifiers are digitized by VXI-C modules consisting of ten channels of 100 MHz 14-bit flash ADCs called TIG-10s. The waveforms are continuously sampled. Contemporaneously, a large FPGA on each channel evaluates features of the waveform in real time. The hierarchical trigger consists of a Level 0 per-channel pretrigger, Level 1 triggers on each TIG-10 card, and a Level 2 trigger implemented in TIG-C VME collector cards that provide master triggers for up to 12 lower level digitizer cards. After trigger validation the digitized signal trace and evaluated features (energy and time) are read out over the VME backplane into a front-end computer.

TIGRESS: Recent Developments

The most significant upgrade of TIGRESS itself in the period 2008–2013 was the integration of the TIG-64 high-density digitizers into the data acquisition system. This upgrade project, led by Saint Mary's University, commissioned the University of Montreal to develop 12-bit, 50 MHz waveform digitizers suitable for the less restrictive requirements of large arrays of Si or CsI(Tl) detectors. These have been used in experimental campaigns in 2010 and 2012. Although TIGRESS was only funded for 12 detectors, cost savings during construction and additional funding through partners have allowed us to procure a total of 16 TIGRESS-compatible clovers. Otherwise, TIGRESS has been operational since 2008, in configurations with up to 14 operational clovers, limited only by the needs of the auxiliary detector required for the experiment(s).

BAMBINO

The BAMBINO facility, optimized for detection of inelastically scattered heavy ions (for example, Coulomb excitation), was used in the first TIGRESS experiments (see Figure 1). BAMBINO consists of up to two, so-called S2 or S3 CD-style segmented annular silicon detectors from Micron Semiconductor, a spherical scattering chamber, and feedthroughs. The two CDs may be arranged as a dE-E telescope or may be placed on either side (upstream and downstream) of the target ladder, which holds up to five targets or apertures and which can be biased to suppress delta electrons. The nominal position places an S3 detector 30 mm either

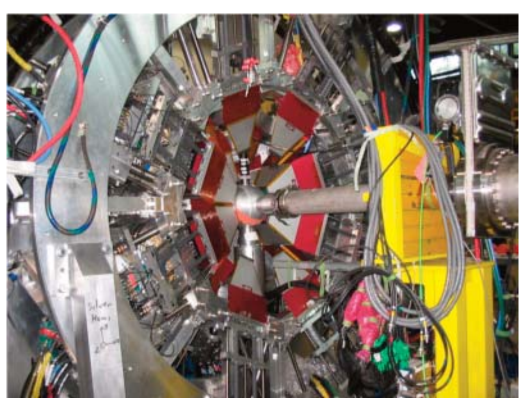


Figure 1: Photograph of TIGRESS with BAMBINO.

upstream or downstream of the target ladder. At this position, two S3 detectors will span laboratory-frame polar scattering angles from 20˚ to 49.4˚ at forward angles and the back-angle supplements, for a total angular coverage of 3.63 Sr, or 29% of a full sphere, with rings subtending $\Delta\theta \approx 0.8˚$ to 1.7˚ and $\Delta\varphi \approx 11.2˚$. The aluminum target chamber vacuum vessel has an outer radius of 102 mm (diameter 8”) and thickness of 1.5 mm (0.06”). The S3 holder is designed so that, with appropriate standoffs, the S3 may be placed anywhere from ~3 mm to 70 mm from the target. The Si signals are processed through charge-sensing amplifiers, and the rise and decay times of the signals are sufficiently similar to HPGe signals so that they may be digitized for energy, time, and trigger evaluation with TIG-10 modules [2,9,10,11].

Recent Development. Bambino was used in the first experiments at TIGRESS and has been used without modification since 2006. Bambino has become the *de facto* standard upon which all other TIGRESS scattering detectors are based.

SHARC

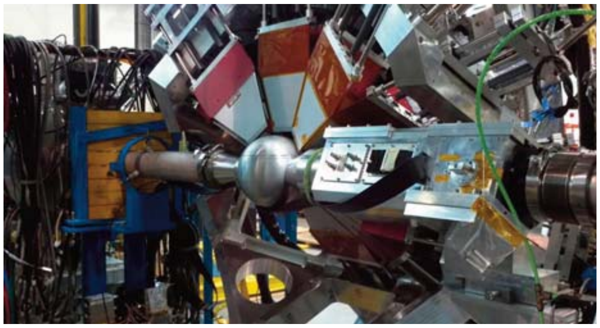
The combination of γ-ray spectroscopy and charged particle spectroscopy is a powerful tool for the study of nuclear reactions with beams of nuclei far from stability. SHARC [12], the Silicon Highly-segmented Array for Reactions and Coulex, is a new silicon-detector array designed for use in reactions with radioactive ion beams in conjunction with the TIGRESS γ-ray spectrometer. SHARC is built from custom Si-strip detectors, utilizing the fully digital TIGRESS readout (TIG-64 modules) (see Figure 2). SHARC has more than 50% overall efficiency and approximately 1000-strip segmentation yielding angular resolutions of $\Delta\theta \approx 1.3$ deg. and $\Delta\varphi \approx 3.5$ deg. Preamplifiers custom-built at TRIUMF provide four gain ranges nominally from 15 MeV, suitable for protons or dE detectors, to 600 MeV for beam-like heavy ions. Furthermore, 25-30 keV energy resolution, and thresholds of 200 keV for up to 25 MeV particles have been achieved.

Figure 2: Photograph of TIGRESS with SHARC.

Recent Developments. SHARC was first used for experiments in 2009. A major upgrade in 2011 saw the introduction of selectable-gain preamps spanning nominal ranges from 15 to 600 MeV, i.e. suitable for low-energy light-charged particles through to beam-like heavy ions. SHARC collaborators also provided a thin-film scintillating heavy-ion detector called a Trifoil, which, despite using fast-readout phototubes and NIM coincidence electronics, was seamlessly integrated into the data stream as a fusion-evaporation veto counter [13].

The TIGRESS Integrated Plunger (TIP)

TIP was developed by collaboration between Simon Fraser University, Saint Mary’s University, and TRIUMF for recoil distance method (RDM) lifetime measurements of short-lived excited states in exotic isotopes using TIGRESS. It was designed to provide precise (submicron) control of distance shifts between thin target and stopper/retardation foils while maintaining parallel alignment between the two to achieve picosecond-order lifetime sensitivity. TIP offers a high degree of versatility for lifetime measurements, employing a variety of reaction mechanisms and several particle-tagging techniques. It can run in stand-alone mode with TIGRESS, or in tandem with an extensive suite of auxiliary charged particle detector systems (see Figures 3). For Coulomb excitation reactions, a highly segmented annular silicon detector and modular PIN diode array have been implemented for precise kinematic reconstruction of inelastic scattering events in coincidence with gamma-ray detection in TIGRESS. A compact 3π CsI(Tl) scintillator ball is being developed for lifetime measurements of exotic nuclei along the N=Z line produced by fusion-evaporation reactions. The identification of evaporated charged particles via digital pulse-shape analysis will enhance the experimental sensitivity through reaction channel discrimination. TIP is also designed to be coupled with DESCANT, SHARC, and the electromagnetic spectrometer EMMA.



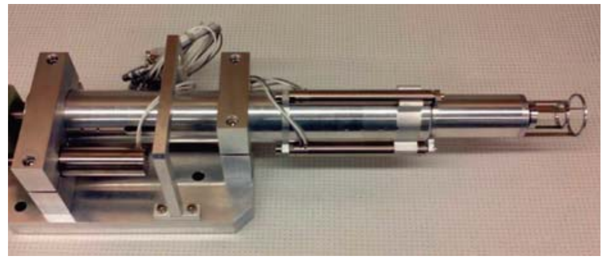


Figure 3: Photographs of TIP: a) plunger b) vacuum chamber installed on TIGRESS.

Recent Developments. The TIP alternate target system and several of its ancillary charged-particle detector arrays were first used in late 2011 and early 2012. The beam times were devoted to various tests of the TIP target and detector systems; at the same time, high-statistics lifetime and Coulomb excitation data were collected for Ar-36.

The most recent developments involve the construction of a CsI(Tl) wall as a precursor to the 3π ball. Twenty-four detectors coupled to Hamamatsu silicon PIN diodes are under construction at SFU. Using SFU custom-built 8 channel charge-sensitive preamplifiers, typical resolutions for the 5.5 MeV alpha particle from Am-241 have been below 275 keV. An in-beam demonstration of reaction-channel selectivity following fusion-evaporation reactions using CsI pulse shape analysis was performed in spring 2013. Significant effort on the control system for precision target-stopper alignment is also ongoing at SFU.

SPICE

SPICE (SPectrometer for Internal Conversion Electrons), currently underway at TRIUMF, is a project to design and build an in-beam electron spectrometer ancillary detector for the TIGRESS array (see Figures 4). SPICE will have a particular sensitivity to higher energy electrons in the energy range 100 keV to 4000 keV which is required for the study of shape-coexistence in nuclei. In-beam electron spectrometers operating today are limited to below about 500 keV electron energies. Electrons emitted from the reaction target of TIGRESS following a nuclear reaction will be collected by a rare earth permanent magnetic lens and directed around a photon shield into a 6.1 mm thick lithium-drifted silicon electron detector. Coincident gamma rays will be detected in the TIGRESS clover detectors.

Recent Development. Since 2010, a full GEANT4 simulation of SPICE has been developed and used to optimize the detailed design of the components of the spectrometer. The fabrication of the spectrometer has been completed. A first in-beam test of SPICE coupled to TIGRESS will take place in fall 2013, followed by the first physics experiment in 2014.

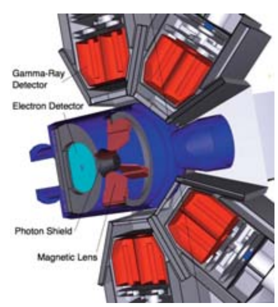


Figure 4: (a) Model of SPICE with TIGRESS and (b) a photograph of assembled magnetic lens.

DESCANT

The DESCANT spectrometer is designed to be coupled with both the TIGRESS, (see Figure 5), and the future GRIFFIN spectrometer. It will replace the forward "lampshade" of four clover-type HPGe detectors (with their BGO suppression shields), and will occupy a solid angle of 1.08π sr with the maximum angle of 65.5 degrees with respect to the initial beam direction. The target-to-detector distance is 50 cm, and the individual detector cans are 15 cm thick. When fully loaded, DESCANT contains 70 individual neutron detectors. DESCANT is designed so that the inner and adjacent ring of detectors surrounding the beam line can be removed to facilitate larger forward detector systems that may be placed downstream of the target. The detector units contain liquid deuterated scintillator, BC537, and were fabricated by the Bicron division of Saint-Gobain. Signals from the DESCANT detectors will be digitized by custom-built 1 GHz waveform digitizers manufactured by Instrumentation Services of the University of Montreal. Onboard digital signal processing will integrate the pulse to yield the total charge, determine the event time via a constant-fraction algorithm, and perform neutron-γ discrimination.

Figure 5: Photograph of DESCANT.

Recent Developments. During the 2008–2013 period, the DESCANT detectors were delivered and tested, the support structure was designed and built, and the first prototype of the electronics was tested. Testing of the second TIG-4G prototype is nearing completion with production to commence immediately thereafter. The components are on track for commissioning in-beam experiment in fall 2013.

Partners

In Canada: Saint Mary's University, l'Université de Montréal, University of Toronto, McMaster University, University of Guelph, Simon Fraser University.
International Partners: France (1), Italy (1), Spain (2), United Kingdom (3), United States (4).

TRIUMF's Role

Two TRIUMF research scientists and one emeritus work on TIGRESS; one of these is responsible for all aspects of TIGRESS on-site management, operation, maintenance, planning, coordination, and safety. TRIUMF provides one technician in support of the gamma-ray and GPS tape-station facilities; approximately 1/3 of his effort is devoted to TIGRESS. TRIUMF provides support for data acquisition including firmware development and long-term data storage. The TIGRESS detector facility provided conceptual design for TIP, SPICE, and the SHARC preamplifiers, and manufacture of the SPICE magnetic lenses. The TRIUMF Engineering Division provided detailed mechanical design, engineering analysis, and machining of the DESCANT superstructure and some TIP components. The TRIUMF electronics shop fabricated and modified, as needed, the SHARC preamplifiers and all cables.

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ISAC ACHIEVES ACCELERATED, "SCRUBBED" BEAMS OF HEAVY ISOTOPES

31 July 2013

Providing pure beams of short-lived isotopes for precision science experiments is a challenging endeavour. Studies of such rare isotopes are carried out at different energies, depending if ground state or decay properties are studied or the aim is to carry out nuclear reactions. At TRIUMF's ISAC facility, a variety of rare isotopes are produced in the target when struck by the proton beam from the main cyclotron. A series of sophisticated online systems ionize, separate out and select the singly charged isotopes of interest for the downstream science experiments. The mass and ionization properties (largely dictated by the electron structure around the nucleus but subtly influenced by the nucleus, too) are used in concert to manipulate, electrically charge, purify, and control the beam. To accelerate heavy beams (more than 29 nucleons) for nuclear reaction experiments at ISAC it is necessary to ionize them to higher charge states by removing more electrons in a so-called charge state booster, in TRIUMF's case an electron cyclotron resonance source. However, the charge breeding process introduces new contaminations into the beam, rendering it potentially useless for the experiments.

Over the past week at ISAC, a combined team of accelerator, target, and nuclear physicists demonstrated a breakthrough in providing an intense beam of Sr-94 to the ISAC-II accelerators for use in the TIGRESS germanium gamma-ray spectrometer augmented by the SHARC silicon detector array for charged particle detection. The experiment aimed to study the nuclear structure of the neutron-rich isotope Sr-95 via a one-neutron transfer reaction. Beams of this isotope are subject to contamination with various stable isotopes from the charge state booster, a feature that prevented this research for some time. This was the first high-mass experiment with accelerated rare isotope beam at ISAC.

By using a combination of cleaning techniques and beam identification tools developed by TRIUMF's "High Mass Task Force," the team was able to separate out the desired Sr-94 isotopes with an intensity of up to 300,000 particles per second enabling a successful experiment! The techniques combine careful optimization of the charge-state booster and the network of subsequent accelerators and collimators to deliver a clean, pure beam of energetic Sr-94 isotopes. With the available simulation tools and cleaning procedure the way for numerous high-mass accelerated beams has now been prepared and many exciting experiments will follow.

Congratulations to the ISAC and TIGRESS teams!

This photo shows as substantial part of the collaboration and High Mass Task Force that is currently successfully running experiment S1389 with charge-bred Sr-94 beam to TIGRESS in ISAC-II.

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5.5.2.2 EMMA: ELECTROMAGNETIC MASS ANALYZER

The superconducting ISAC-II linear accelerator has enabled the delivery of intense, high-quality beams of radioactive ions with masses up to 150 u and maximum energies of at least 6.5 A MeV. These beams will allow the study of the single-particle structure of exotic nuclei, the evolution of nuclear structure and shapes far from stability and at high spin, and nuclear astrophysics. Fusion-evaporation and transfer reactions initiated by radioactive ions in inverse kinematics promise to yield invaluable information about these subjects that cannot be obtained by other means. The study of many of these reactions will require detection and identification of the heavy recoil nucleus, in addition to light charged particles, neutrons, and γ rays. The ElectroMagnetic Mass Analyzer (EMMA) was designed to be ideally suited to study the products of fusion-evaporation reactions induced by the heavy radioactive beams of ISAC-II because its large acceptance implies high transmission efficiency and its high mass resolving power provides high selectivity and excellent beam rejection capability.

Description of Apparatus

EMMA is a recoil mass spectrometer designed to separate the recoils of nuclear reactions from the beam and to disperse them in a focal plane according to their mass-to-charge ratio (m/q). Measurements of position, energy loss, residual energy, and time-of-flight are expected to uniquely identify the transmitted recoils. In addition to having a large solid angle of 20 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 monoenergetic ions of a single mass within the spectrometer are calculated to be isochronous within 0.1%, allowing high-resolution time-of-flight measurements and large real-to-random ratios in coincidence experiments. These properties are anticipated to make EMMA a recoil mass spectrometer of very high quality that will enable previously impossible experiments with ISAC-II

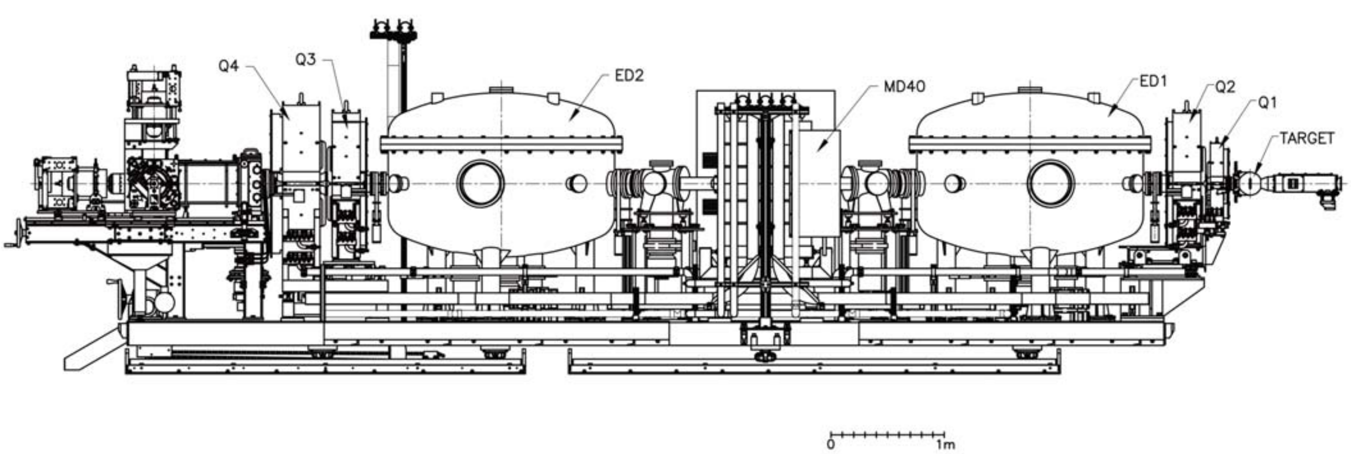


Figure 1: Schematic view of EMMA showing the two large electric dipoles on either side of the central magnetic dipole. Magnetic quadrupole doublets at the front and back serve to spatially focus the recoiling nuclei and allow for variable mass dispersion.

beams. 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 radioactive 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 multiwire 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 are likely to make EMMA an exceptional instrument for nuclear physics research. When coupled with the unique radioactive ion beams from ISAC-II and the advanced γ-ray spectrometer TIGRESS, EMMA will position TRIUMF as a world leader in the field. EMMA is schematically depicted in Figure 1.

One area of research in which EMMA is expected to make an important contribution is the production and study of nuclei far from stability under extreme conditions, such as high excitation energy or angular momentum. This will be accomplished through the study of weak, otherwise inaccessible reaction channels by using EMMA as a mass filter in coincidence experiments. For example, in the study of high-spin states, events in TIGRESS detectors positioned around the target will be gated by signals from a particular nucleus in the focal plane detectors of EMMA. This technique permits the low background study of weak reaction channels without the concomitant large loss of efficiency normally encountered when these measurements are carried out with small-acceptance detectors. Without the recoil detection and identification, the weakest channels, which are often the most interesting, would be totally obscured by the large number of γ rays from more copiously produced nuclei. The large energy, mass, and angular acceptances of EMMA will be crucial in these experiments, and will provide high sensitivity by allowing triple coincidence measurements in which two γ rays are detected in coincidence with the recoil.

While being well suited to the detection of recoil nuclei from fusion-evaporation reactions, EMMA will also be able to detect the projectile-like recoils of transfer reactions in inverse kinematics with high efficiency and good beam rejection capability. In one- and two-nucleon transfer reactions induced by heavy projectiles on light targets such as (d,p), (p,^{3}He), and (d,t), the recoil nuclei are strongly forward focused and have relatively small energy spreads. They can therefore be detected with geometric efficiencies near unity. The detection of recoils from these transfer reactions will represent one of the important uses of the spectrometer. In studies of both fusion-evaporation and transfer reactions, EMMA will be used in conjunction with TIGRESS. We anticipate that between 1/2 and 2/3 of TIGRESS experiments will require EMMA, which has led to detailed considerations of how EMMA can be designed to take full advantage of it.

Recent Developments

In 2006, EMMA was funded by a C$2M NSERC Subatomic Physics Research Tools and Instruments award, with the understanding that TRIUMF would furnish the additional C$1M required to complete the spectrometer. Following the initial award, a dedicated effort was required to precisely specify the electromagnetic and mechanical properties of the spectrometer components that are 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.

In 2007, after a tendering process, a contract to build the two electric dipoles, the dipole magnet, and four quadrupole magnets was awarded to Bruker BioSpin GmbH of Germany. The fabrication of the electromagnetic components was considerably more challenging than originally anticipated by the manufacturer, resulting in long delivery delays. All of the magnets were delivered in 2012. Figure 2 shows them on the common support structure. Three positive and three negative high voltage power supplies capable of providing 350 kV were built and tested at TRIUMF. High voltage testing at the Bruker factory revealed a number of design and manufacturing flaws in the electric dipole components. After remediation of these flaws, the electric dipoles were shipped to TRIUMF in 2013.

Partners

In Canada: University of Guelph, McMaster University, Saint Mary's University, and Simon Fraser University.
International Partners: Germany (1), Italy (1), Japan (1), United Kingdom (3), United States (5).

TRIUMF's Role

TRIUMF has made major contributions to the design of EMMA and the fabrication and installation of its components. The ion optical design was done by a TRIUMF research scientist who also is the EMMA project leader. All of the design effort for the EMMA mechanical support structure, the target chamber, and the focal plane box is being carried out by TRIUMF. TRIUMF designed and built the high voltage power supplies for the electric dipoles of EMMA. The TRIUMF Detector Group is constructing and testing the position-sensitive multi-wire gas detectors and the ionization chamber for the focal plane.

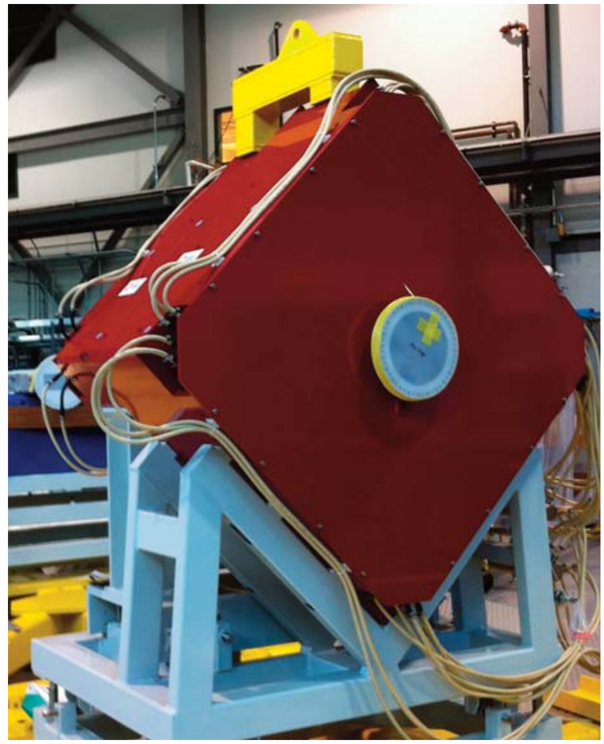


Figure 2: Photograph of the EMMA platform showing the red quadrupole doublets and the bottom half of the dipole magnet with its vacuum chamber.

5.5.2.3 IRIS: THE ISAC CHARGED PARTICLE REACTION SPECTROSCOPY STATION

The charged particle spectroscopy in direct reactions of rare isotopes is one of the most effective ways to unveil new features in the proton- and neutron-rich nuclei. These exotic forms of rare isotopes exhibit unusual ordering of nuclear orbitals. The low-energy reaccelerated beams can allow precision studies to find which orbitals the valence neutrons/protons occupy, how the neutrons in the neutron-rich surface are correlated, and whether new facets of pairing surface in such regions.

These questions are addressed using the newly built ISAC Charged Particle Reaction Spectroscopy Station (IRIS) through nucleon transfer reactions and inelastic scattering. One-nucleon transfer reactions provide angular momentum selectivity to decisively determine the unknown spin of energy levels in the exotic nuclei. The orbital occupied by the valence nucleons is reflected in the shape of the angular distribution. Reactions of interest in the IRIS facility are those using hydrogen isotopes as target, such as, (p,d), (d,p), (d,^{3}He). Contrary to reactions using stable isotopes, due to the short lifetime of the unstable nuclei, the targets in these reactions are the light hydrogen isotopes, and the projectile is the heavy unstable isotope. IRIS is particularly well suited for experiments with very low intensity RIBs ($\sim\geq 10^2$ /sec) and low-energy level density in the residual nucleus (light nuclei and heavy nuclei near shell closures). As such it complements reaction studies with TIGRESS that can resolve close-lying energy levels via gamma-ray spectroscopy but needs RIB intensities in excess of 10^5/sec.

The (p,d) and (d,^{3}He) reactions, where one neutron from the unstable projectile nucleus is transferred to the target, provide information on the configuration mixing in the ground state of the unstable nucleus of interest with mass number A. They also serve as the tool to determine the spin and excitation energy of the nucleus A-1.

The (d,p) and (d,n) reactions are those where the unstable projectile nucleus picks up a nucleon from the target, thereby producing a more neutron-rich or more proton-rich nucleus, respectively. These reactions can also serve as alternate ways to understand the neutron capture (n,γ) and proton-capture (p,γ) reactions relevant to the nucleosynthesis reaction networks for the rapid-neutron and rapid-proton capture processes.

The two-nucleon transfer reactions of the type (p,t), (p,^{3}He) and their inverses are important ways to learn about pairing correlation in the exotic isotopes.

Description of the Facility

The IRIS facility is designed to study the reactions in the energy range from ~ 3-15*A* MeV. The layout of the facility and schematic detector arrangement are shown in Figure 1. The rare-isotope beams can be tagged for isobaric contaminants as they lose energy in passing through a low-pressure ionization chamber before interacting with the reaction target. A compact ionization chamber of 16 cm x 5 cm x 5 cm with a coplanar anode configuration was constructed. The chamber is segmented into 16 anodes which can be combined together in sections to optimize for desired energy loss, depending on each case. The ionization chamber is designed to operate with isobutane at 10–25 mbar. Thin silicon nitride (50 nm) or mylar (900 nm) windows with a dimension of 10mm x 10mm are used to separate the gas volume from the vacuum.

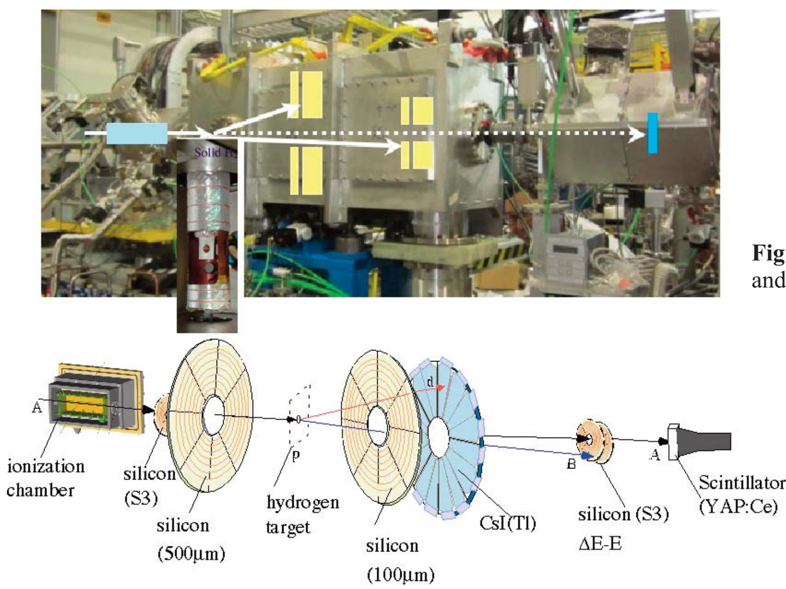


Figure 1: Snapshot of the IRIS beam line (top) and schematic layout of the detectors (below).

The novel feature of IRIS is the development of a thin solid hydrogen target. The solid hydrogen target cell is backed by a thin silver foil. The target cell with the foil is cooled by a Sumitomo cryocooler with a helium compressor to a temperature of ~ 4K. The hydrogen gas is then sprayed through a diffuser onto the silver foil to form a solid hydrogen target. By controlling the gas volume, the desired target thickness can be achieved. Typical thicknesses range from ~ 50–150 μm. The target assembly is surrounded by a copper cylinder whose temperature is around 30K. This acts as a heat shield to restrict heating of the target from the ambient temperature. The reaction products from the target are emitted through an opening in the heat shield. IRIS is also designed to have the possibility of using thin polyethylene foils $(CH_2)_n$ and $(CD_2)_n$ as targets. Tritium implanted foils for use as triton target are also planned.

The main focus of the IRIS facility is to detect the charged particle reaction products following reactions with isotopes of hydrogen as targets. Therefore, the detection system is designed to detect both the light target-like reaction ejectiles as well as the heavy beam-like reaction residues. The light particles that are emitted at backward angles in the laboratory frame usually have rather small energies ~ less than 1 MeV. Therefore, these reaction channels are identified using the energy-angle kinematic correlation. This involves detecting the particles using an annular array of 500 μm thick segmented silicon detectors. The forward scattered particles have higher energy, which allows identifying them through a ΔE-E correlation. This is achieved using a detector telescope with a 100 μm thick segmented silicon detector layer followed by a 12 mm thick annular CsI(Tl) array that matches the silicon array in overall configuration. The CsI(Tl) detectors form an array of 16 individual crystals each of which are read out using silicon photodiodes. The annular silicon detector array for both upstream and downstream have 8 independent azimuthal detector sectors. Each sector is segmented into 16 rings which provides the scattering angle information. Figure 2 shows the particle identification spectrum from reactions of O-18 with the solid hydrogen target.

In the upstream direction, a smaller silicon array of 500 μm thick MICRON Semiconductor-S3 type detector provides additional smaller scattering angle coverage for particles that pass through the hole of the larger YY1 array. Further downstream to the YY1-CsI(Tl) telescope, is a detector telescope that is made up of a 60 μm thick layer of S3-type silicon followed by a 500 μm thick silicon of same type. This allows a ΔE-E identification of the heavy reaction residue. The detector arrays can be placed at any distance from the target ranging from 7 cm to 75 cm, the choice of which will be optimized for the specific reaction to be studied.

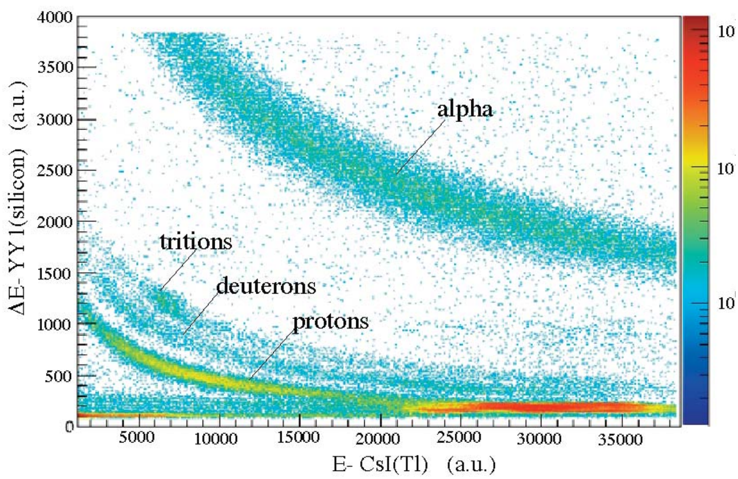


Figure 2: Particle identification spectrum using ΔE-E correlation of the downstream YY1-CsI(Tl) detector telescope from reactions of O-18 on a 100 μm solid hydrogen target.

The unreacted beam passes through the hole in all the detectors and is eventually stopped and counted using a radiation hard YAP:Ce inorganic scintillator readout by a photomultiplier tube which is placed in the last vacuum chamber.

Recent Developments

The IRIS facility was successfully commissioned in 2012 and has started full-fledged operation with radioactive beams from 2013.

Partners

In Canada: TRIUMF and Saint Mary's University.
International Partner: Japan (3).

TRIUMF's Role

The TRIUMF Detector Group has been intensely involved in the project and has designed and fabricated the IRIS ionization chamber. They have also laid out the conceptual design of the IRIS scattering chamber that was detailed by the TRIUMF Design Office. All components were fabricated at the TRIUMF Machine Shop. The Beam Lines Group installed all the components, with the Vacuum Group, Electrical Group and Controls Group taking responsibility for implementing the relevant components of the beam line. Several TRIUMF research scientists are a part of the IRIS collaboration.

5.5.2.4 TRIUMF UK DETECTOR ARRAY: TUDA

The TRIUMF nuclear astrophysics program is carried out at a set of complementary facilities in the ISAC post accelerator areas: the two key detectors are: (1) a large-suppression recoil spectrometer system called DRAGON, and (2) 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 type I X-ray bursts, i.e. events that create the heavy elements of our universe and provide spectacular light shows in the skies over the millennia. 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 gaseous 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 Li-11 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 Apparatus

Presently located at ISAC-II, the TUDA facility was built to be interchangeable between ISAC-II and ISAC-I to enable different types of measurements: the direct measurements in the lower energy ISAC-I area, and indirect studies in the higher energy ISAC-II area. Radioactive ion beams 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, and can accommodate a variety of detector mounts, target ladders/structures, and diagnostic instruments.

The LEDA detector is mounted on long poles attached to the downstream flange. The structure behind the LEDA houses the electronics. The detector shown is composed of 8 azimuthal sectors (only 4 are installed in the picture), each having 16 individual concentric silicon strip detectors, 0.3 mm thick. Thus, each detector array has 128 individual independent channels. When one of the individual strip detectors detects a particle, the energy and position are measured. The hole in the centre of the array allows the unscattered beam to pass through. It is possible to stack several detector arrays 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 silicon detectors such as CDs and S2s. The 512 channels of high-quality analog electronics, as well as electrical isolation for noise suppression, enables the TUDA facility to operate at extremely high sensitivities and energy resolutions, making it not only a versatile facility, but a precision one.

Recent Developments

During the present five-year plan period, experiments at TUDA have been shared between experimenters with nuclear astrophysics aims and those with nuclear structure aims. Much work has been done to exploit radioactive F-18 beams, when TUDA was stationed at ISAC-I. In particular, an experiment was performed to simultaneously measure the ^{18}F(p,p)^{18}F and ^{18}F(p,α)^{15}O reactions using solid targets. This successful experiment paved the way for more studies and was the first time an R-Matrix fit to (p,p)/(p,α) channels was performed in a RIB experiment. Later, a direct measurement of ^{18}F(p,α)^{15}O was done at the lowest energy ever for that reaction, right in the astrophysically relevant region. Further direct measurements are planned.

When TUDA then moved to ISAC-II, several measurements were performed. For nuclear astrophysics, a determination of the ^{18}Ne(α,p$_0$)^{21}Na reaction was performed via a measurement of the inverse reaction, ^{21}Na(p,α)^{18}Ne with radioactive beam (see Figure 2). Also, a determination of the ^{18}F(α,p)^{21}Ne reaction rate was performed by filling the entire TUDA chamber with He gas, enabling high efficiency and a wide

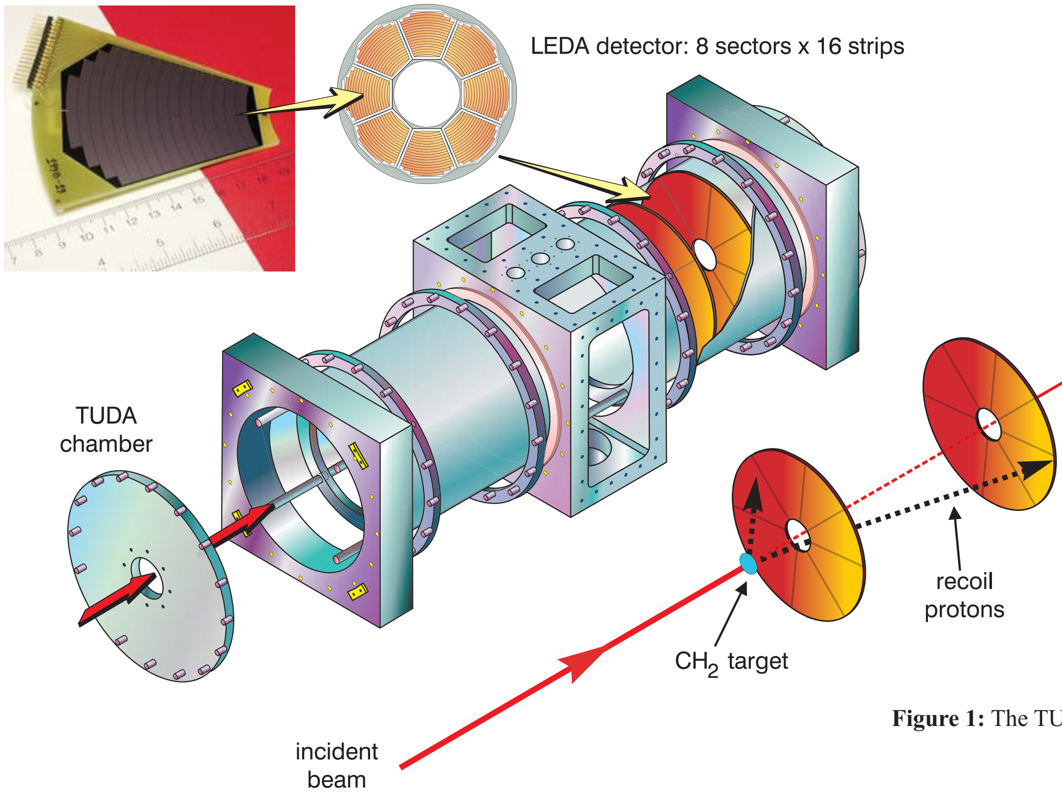


Figure 1: The TUDA chamber.

excitation function to be measured. Also for astrophysics, measurements of $^{7}Li(^{8}Li,^{7}Li)^{8}Li$ and $^{12}C(^{8}Li,^{8}Li)^{12}C$ cross-sections were performed using radioactive Li-8 beams. Nuclear structure studies were performed with Li-8 and Li-11 beams on a variety of targets. A wide variety of silicon detector array types were used in these experiments, as well as gas and solid targets, showing the versatility of the TUDA facility.

Partners

In Canada: McMaster University, Saint Mary's University, Simon Fraser University, University of British Columbia, TRIUMF.
International partners: Belgium (1), Spain (1), Switzerland (1), United Kingdom (2).

TRIUMF's Role

TRIUMF provided the electronic housing environment for the TUDA electronics and continues to provide annual maintenance support for the facility. This provides access to the design office and the electronics and machine shops. Three TRIUMF research scientists contribute significantly to the experimental collaboration.

5.5.2.5 DSL

The mean lifetimes of excited nuclear states are of considerable interest in nuclear structure and nuclear astrophysics research. Motivated primarily by the latter, the Doppler Shift Lifetimes (DSL) facility is a scattering chamber designed to provide a clean environment conducive to detecting the γ-ray emission from excited nuclear states populated in heavy ion-induced transfer reactions in inverse kinematics, in particular on He-3,4 targets. To carry out such experiments, the use of actively cooled He-implanted foil is essential in order not to evaporate the He and keep the target surface free from contamination that would limit the precision of line shape analyses of transitions from excited states with fs lifetimes. With this infrastructure the DSL facility complements the TIGRESS gamma-ray spectrometer.

Description of Apparatus

The DSL scattering chamber is made from thin Al and contains provisions for mounting cooled He-3-implanted target foils along with a Si surface barrier detector telescope at 0°. A schematic view of the DSL facility is shown in Figure 1. The scattering chamber was designed with a cold trap to ensure a clean target surface and also to prevent losses of the implanted He-3. This was achieved using a narrow differential pumping aperture followed by a copper cylinder enclosing the path of the beam to the target. The copper cylinder is cooled using liquid nitrogen. To avoid any condensation of impurities on the surface of the target, the copper cylinder is not in direct contact with the target ladder. Indirect contact of the cold copper cylinder with the copper target ladder is achieved using BeCu fingers mounted on a boron nitride plate, which provides electrical isolation as well. This arrangement maintains a temperature difference between the copper cylinder and the target ladder. In this way the target can be cooled below room temperature to ensure that He-3 does not diffuse out when heated by bombardment with a beam power of up to 300 mW. Moreover, the colder surfaces surrounding the target foil and the beam path in front of it reduce the buildup of carbon and other contaminants on the target itself during the experiment.

In all DSL measurements to date the target foils were prepared at l'Université de Montréal by implanting 30 keV He-3 ions into Au and Zr foils, yielding an areal He-3 number density of 6×10^{17} cm^{-2}. The concentration of He-3 in the foil is monitored via yields of elastically scattered He-3 during bombardment.

Recent Developments

As described in the nuclear astrophysics science highlights (Section 4.2.2.4) the lifetime of the 6.79 MeV state in O-15 is one of the dominant uncertainties in determining the rate of the $^{14}N(p,\gamma)^{15}O$ reaction, on which the estimated ages of the oldest stars in the Milky Way Galaxy strongly depend. After its initial use in ISAC-I, the DSL facility was moved to ISAC-II, where it has been used with a TIGRESS γ-ray detector to measure the mean lifetime of this state using a 50 MeV O-16 beam. This measurement was performed using the ISAC-II accelerator in order to reach a bombarding energy at which the state of interest was known to be populated; a TIGRESS n-type γ-ray detector was employed due to its resistance to fast neutrons, which are copiously produced at these energies. In 2012 the DSL facility was used to

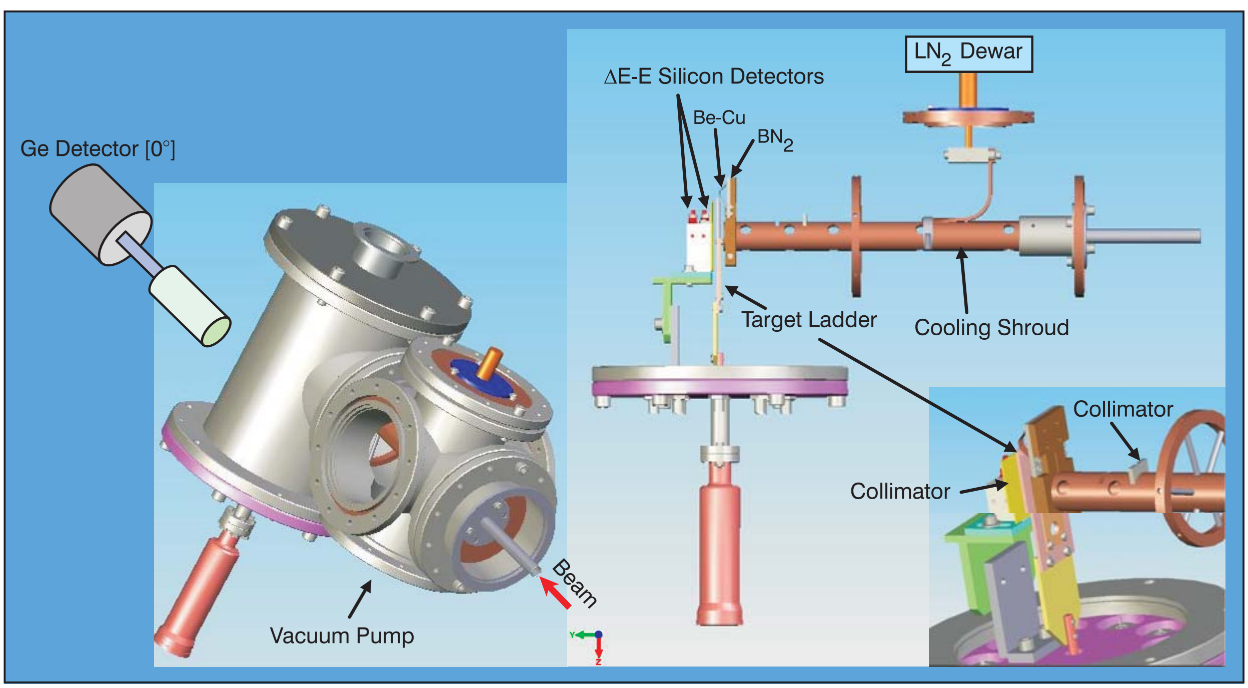


Figure 1: TRIUMF's DSL facility, showing the liquid nitrogen-cooled shroud along the beam axis, the target ladder, the Si detector telescope, and the high-purity germanium detector used to measure Doppler-shifted γ rays.

measure the lifetimes of states in Mg-23 that serve as resonances for the $^{22}Na(p,\gamma)^{23}Mg$ reaction via $^{3}He(^{24}Mg,^{4}He)^{23}Mg$. A spectrum of γ rays detected at 0° in coincidence with α particles emitted during the bombardment of a He-3-implanted Au foil by a 75 MeV Mg-24 beam in ISAC-II is shown in Figure 2.

Partners

In Canada: Saint Mary's University, l'Université de Montréal, Queen's University, Simon Fraser University, University of Guelph.
International Partners: United States (2).

TRIUMF's Role

TRIUMF was solely responsible for the design and fabrication of the DSL facility. It was conceived by two TRIUMF research scientists and implemented with the help of students and postdoctoral fellows.

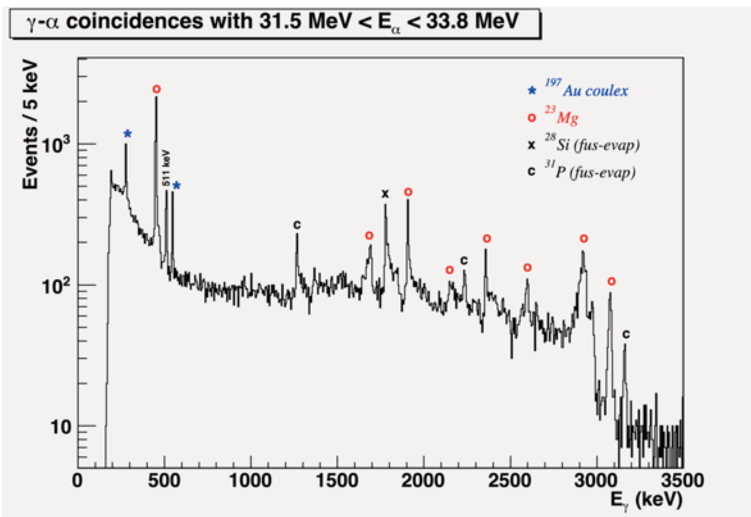


Figure 2: Spectrum of γ rays detected at 0° in coincidence with α particles of energy between 31.5 and 33.8 MeV emitted during the bombardment of a He-3-implanted Au foil by a 75 MeV Mg-24 beam. Observed transitions from excited states in various nuclei are indicated.

5.5.3 MESON HALL

TRIUMF's Meson Hall (see Figure 1) is one of the oldest parts of the laboratory site but it still supports a variety of important activities. The central feature is Beam Line 1A (BL1A) that carries 500 MeV protons from the main cyclotron to two meson production targets through an irradiation facility, followed by the beam dump. The first target station produces muons for the M15 beam line, pions for the M13, which was used for the PiENu experiment but will be phased out to make way for the ultra-cold neutron facility, and both muons and pions for M11.

M11 is a unique facility that provides low-energy beams of pions and muons for detector testing. The second target station is used to produce muons for the M9 and M20 beam lines. These two beam lines, along with M15, provide the muons for TRIUMF MuSR program (see Figure 2). The 500 MeV irradiation facility at the end of BL1A produces strontium for Nordion, Inc., along with other isotopes. BL1A beam dump produces neutrons that are then used at the TNF for neutron irradiation facility (NIF). Also coming off BL1 is BL1B used for both the proton irradiation facility (PIF) and NIF. PIF & NIF are used primarily for testing the effects of radiation on electronics. The meson hall also houses the proton therapy facility used for treating ocular melanomas.

In this section we describe the primary beam line BL1 (Section 5.5.3.1), the muon beam lines (Section 5.5.3.2) and the ultra-cold neutron facility (Section 5.5.3.3) being built at the current location of M13.

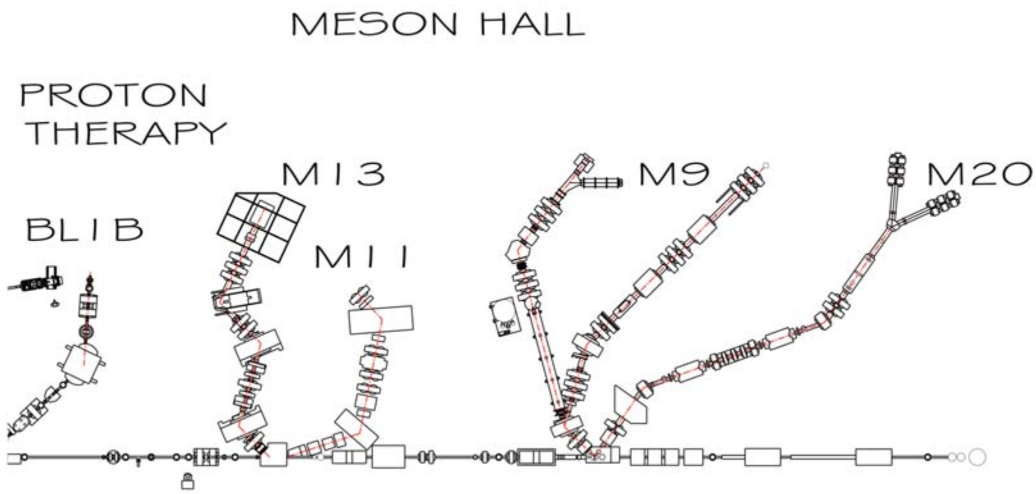


Figure 2: The current Meson Hall secondary beam lines: M15 comes off the first target opposite, and M11 and is located in a Meson Hall Annex.

5.5.3.1 MuSR BEAM LINES AND SPECTROMETERS

TRIUMF provides intense beams of spin-polarized positive and negative muons and radioactive ions for Canadian and international researchers to probe materials at the molecular level. Material properties are determined using a set of magnetic resonance techniques known as μSR (muon spin rotation, relaxation, and resonance) and β-NMR (beta-detected nuclear magnetic resonance). These techniques are used to study a wide range of inter-disciplinary and multi-disciplinary topics in condensed-matter physics (such as magnetism, superconductivity, and defects in semiconductors) and chemistry (including radical kinetics and the structure and dynamics of free radicals).

These capabilities at TRIUMF are managed through the Centre for Molecular and Materials Science (CMMS), established in 1990 and supported by several funding sources. Operated as a user facility, CMMS collects proposals from scientists around the world twice a year, and with the advice of an international, independent review panel screens, prioritizes, and schedules the high-priority proposals. Scientific results obtained from the beam time at TRIUMF have been published by visiting scientists and students with the support of their home institutions.

Muons are present in cosmic radiation but high-intensity beams of spin-polarized muons required for spectroscopic studies are only available at TRIUMF's CMMS facility and three other facilities throughout the world (Paul Scherrer Institute, Switzerland; ISIS, UK; J-PARC, Japan).

TRIUMF also manages a Proton Irradiation and Neutron Irradiation Facility (PIF & NIF) that is used for academic research and industrial testing of electronics performance during and after irradiation. Although PIF & NIF is primarily operated as a stand-alone facility, its focus on radiation effects in matter overlaps with the molecular and materials science focus of the CMMS.

Description of Facility

The CMMS facility has two surface muon beam lines (M15 and M20) with a third (M9A) nearing completion. These transport μ^+ with a nominal momentum of 28 MeV/c, having selected muons coming only from the decay of pions that are at rest on the surface of the production target. Surface muon beams are essentially 100% spin polarized and are also largely monochromatic, with a nominal kinetic energy of 4.1 MeV and a stopping range of ~0.15 g/cm^3, which corresponds to a penetration depth of about 0.2 mm in copper, 1.5 mm in water, or 1 m in He gas at STP. This type of beam is very important in the study of thin samples or in gases at low pressures.

The CMMS has a fourth beam line, M9B, which is used to study thick target samples or high-pressure environments, where more penetrating muons are required, or when a μ^- beam is required. The muons in the M9B "decay channel" are collected from the decay of π^+ or π^- in flight. Both the pion and muon momenta are selected by bending magnets, with muon momenta that can be tuned down to as low as 40 MeV/c, but are more typically in the range 60 to 120 MeV/c. The polarization is lower than from a surface (μ^+) beam, but nevertheless can be as high as 80%. The corresponding particle energy is about 40 MeV, and the stopping range in matter is about 8 g/cm^2, which means decay muons have sufficient energy to penetrate a thick sample or container, such as a pressure cell. The penetration depth is about 1 cm in Cu and 1 m in He gas at 500 bar and 300 K. The CMMS facility at TRIUMF is unique in that all of its beam lines can provide beams with the muon spin either transverse or longitudinal to the momentum.

M9A, M20C, M20D are all surface muon beam lines that are ideal for MuSR studies on materials that do not require confinement in enclosures that support high pressures. M9B services the latter environments where higher energy muons are required to penetrate respective enclosures before encountering the sample under study.

The major new μSR beam line infrastructures implemented at TRIUMF within the 2010–2015 year plan are represented by the total redevelopment of the previous M20 beam line into a dual channel and the addition of a new M9A channel (see Table 1). Both of these beam lines are outfitted with modern achromatic high transmission Wien filter/spin rotators which act to both remove contaminants in the beam and allow the muon spin to be rotated up to 90 degrees as the beam traverses the device. Additionally, both beam lines have ultra-fast electrostatic kickers, which enable a "Muons on Request" (MORE) feature. This mode of operations ensures that one and only one muon is allowed into the sample by rapidly switching the electric field in the device after muon detection and thereby diverting the trajectory of any subsequent muon. Ensuring only one muon has entered the sample allows one to reduce the random background to a level that permits the μSR measurement to extend much farther out in time. Figure 2 illustrates by the inset, in which the muon signal oscillations in the spectra endure for a much longer time with the MORE mode active. The dual channel M20 is in fact designed to accept the kicked beam into the second leg to accommodate a simultaneous conventional MuSR experiment that is running there. The combined capabilities of these beam lines, i.e. 90 degree spin rotation + MORE, are unique in the world's muon facilities.

Beam Line		Characteristic				Flux	Beam	MORE
		MeV/c	Δp/p%	Spin Rotation	Polarization	10^6	h x v	y/n
M15	μ^+	29.5	2-10	0-90°	>98%	2	1.2 x 1.6	n
M9B	μ^+	<70	11	0°	>90%	3	10 x 10	n
	μ^+	>70	11	0-90°	70-90%	2-.5	7 x 7	
	μ^-	30-80	11	untested	>90%	1.4	10 x 10	
M20C, D	μ^+	29.5	2-10	0-90°	>98%	1.5	1.5 x 1.5	y
M9A	μ^+	29.5	2-10	0-90°	>98%	2	1.5 x 1.5	y

Table 1. TRIUMF's four main beam lines and their characteristics.

Another one of a kind capability also resides in the M9B beam line, which is the world's sole provider of spin-rotated high-momentum muons. This feature (i.e. spin rotation) is essential for high magnetic field transverse field MuSR, and the Helios spectrometer (see below) has been used extensively on this beam line for such experiments.

The array of MμSR spectrometers provides a variety of experimental configurations, some of which are tailored to very specific requirements. For example the DR (Dilution Refrigerator) is an instrument designed to achieve very low (15×10^{-3} Kelvin < -273° C) temperatures, where the random thermal motion of the atoms and electrons is suppressed compared to higher temperature environments. For experiments in very high transverse magnetic fields (up to 7 Tesla or 70,000 Gauss) the HiTime spectrometer, with its 180×10^{-12} sec timing resolution, has dominated this experimental space for the last decade. The use of this spectrometer has heralded many breakthrough scientific results in the field of superconductivity, and specifically, the elusive underlying mechanisms of high-temperature superconductivity. Also of note is the development of a super-conducting general purpose spectrometer for the new M9A beam line, which, coupled to the capabilities of the M9A beam line, promises to be the most flexible and general purpose µSR spectrometer in existence.

Associated with the spectrometers is a significant array of supporting equipment including cryostats, temperature/flow/vacuum/magnetic field controllers, pressure cells, electric field devices, and highly specialized data acquisition electronics/computers.

The scientific support, which the facility extends to its user base, can be categorized into four categories: (1) the setting up of an experiment, i.e. preparing the beam line and spectrometer so that a user can quickly embark on the experimental program when beam is delivered; (2) assisting the users with the execution of their experiments, both technically (data acquisition) and scientifically (data analysis); (3) supporting an active outreach program, the goals of which are to educate new users and to introduce the technique to those research institutions that would benefit from it; and (4) the development of new research capabilities (i.e. advanced spectrometers and beam lines) so that cutting-edge research continues to be available to the TRIUMF CMMS user community.

User access to CMMS is managed by TRIUMF's Science Division with the advice of the Molecular and Materials Science Experiment Evaluation Committee (MMS EEC). During the 2008–2013 performance period, the EEC met at least once a year and approved hundreds of shifts per year. Subject to scheduling and backlog, CMMS provided users with nearly 3,600 shifts of beam time (see Table 2).

	2008			2009			2010		
	Requested	Approved	Delivered	Requested	Approved	Delivered	Requested	Approved	Delivered
MMS1	408	328		485	314		695	269	
MMS2	567	445		697	459		106	24	
Total	975	773	956	1182	773	1147	801	293	506

	2011			2012		
	Requested	Approved	Delivered	Requested	Approved	Delivered
MMS1	520	362		411	284	
MMS2		(EEC met only once)			(EEC met only once)	
Total	520	362	163	411	284	825

Table 2. Beam time requested and delivered 2008–2013.

Access to PIF & NIF for academic research is managed in a similar manner to the CMMS facility; industrial or commercial access is managed by TRIUMF's senior management to balance revenue-generating activities with the core science program. From 2008 to 2013, non-commercial use of PIF & NIF for basic research was (please see Section 4.4 for commercial usage):

2008	214 hours
2009	150 hours
2010	172 hours
2011	184 hours
2012	240 hours

Recent Developments

The major developments relate to M20 and M9A above, as both of these were rebuilt during 2011–2013 into the advanced capability μSR beam lines they now are. The M20 project received support from the Canada Foundation for Innovation (40%), British Columbia Knowledge Development Fund (40%) and TRIUMF/National Research Council (NRC) (20%), whereas the M9A project was funded solely by TRIUMF/NRC.

For many years, PIF & NIF has been using the Monte Carlo simulation code FLUKA to model its facilities to help better characterize its beam lines and to provide input to potential upgrades. In 2011, a student project was used to create a model of the low-energy BL2C facility that was then enhanced in 2012 to design a double-scattering system. From the FLUKA modeling, this new device was able to be quickly built and implemented and allows a larger, homogenous area of electronics or materials to be irradiated at a higher rate. It has increased PIF & NIF capabilities and has already been used by several commercial customers.

FLUKA modeling was used to both design and characterize the BL1B upgrade with support from Cisco Systems, Inc. The necessary infrastructure was installed during the Spring 2013 Shutdown period and first beams have already been generated to verify diagnostics, controls, shielding, and beam characteristics. It is anticipated that this upgrade will be embraced by both industry and research groups worldwide.

Partners

International partners: Japan (1), Switzerland (1), United Kingdom (1).

TRIUMF's Role

Although for M20 the majority of capital funding came from external sources, provision of the intellectual, technical, and administrative human resources required for the successful completion of these beam lines was almost entirely provided by TRIUMF. It is estimated that 12 man-years of effort was devoted to these beam lines and included substantial technical innovation in the design and implementation of the high-voltage Wien filters.

With respect to personnel, the eight dedicated individuals that comprise the CMMS facility staff consist of five facility scientists and three technicians; the majority of these are supported by a renewed major research support grant via NSERC. The scientists are the facility manager, deputy manager, operations manager, IT/DAQ support, and outreach Liaison/EEC secretary. In addition to the duties implied by their titles, they provide general experimental user support and have collective expertise in semiconductor, surface, and theoretical physics, as well as that in reaction kinetics and physical chemistry, inclusive of soft materials. The CMMS technical staff members also have individual specializations including high vacuum expertise, design technologies, and millwright/mechanical fabrications.

5.5.3.2 ULTRA-COLD NEUTRONS

Ultra-cold neutrons (UCN) are neutrons of such remarkably low energies that they are totally reflected from the surfaces of a variety of materials. UCN can therefore be stored in magnetic bottles for long periods of time. Typically, UCN have kinetic energies that are less than 300 meV. Correspondingly, UCN may also be trapped by the Earth's gravitational field, and by magnetic bottles. Since UCN can be stored in such a fashion, it makes them the perfect laboratory to study the fundamental properties of the neutron.

TRIUMF has seized upon a window of opportunity to capitalize on the successes of our Japanese collaborators in developing new technology to produce UCN. This collaboration will allow the Canadian project to surpass other proposed sources. The UCN source will be located at TRIUMF, which is ideal because of the high-intensity high-energy proton beam that is used to drive the UCN source. The high UCN density that will be obtained at TRIUMF will allow a class of precision measurements of the fundamental properties of the neutron to be conducted with significantly higher precision than ever before. A description of the science program for the UCN source is presented in Section 4.2.1.3.

Description of Facility

The UCN facility planned for TRIUMF is shown schematically in Figure 1. It is comprised of a fast kicker magnet, septum magnet, beam line, spallation target, and associated shielding. Above the spallation target, and within the shield package, will be located the UCN production volume containing superfluid helium. (The UCN source cryostats have been constructed and are being tested by the Japanese branch of the collaboration.) UCN will diffuse out of the source to experiments. The goal UCN density is 1300 polarized UCN/cm^3, to be delivered to the EDM measurement cell. This value can be compared with typically ~ 1 UCN/cm^3, used for the previous best experiment.

This goal is also comparable to the goals of other UCN facilities elsewhere. The chief difference in our strategy is the use of a spallation-driven UCN source, where the UCN converter is superfluid helium. An advantage of this type of source over spallation-driven solid deuterium sources (at e.g., LANL and PSI) is that the lifetime of UCN in the superfluid helium is much longer. This means that a longer pulse structure can be used to accumulate density over hundreds of seconds, resulting in competitive densities with smaller instantaneous beam power. The challenge in our case is the cryogenic issue of placing a 0.8 K bath close to the spallation target, whereas the solid deuterium need only be >5 K. We believe that the cryogenic issues can be dealt with, at least at TRIUMF beam intensities, and therefore that, ultimately, our technology will be successful for the present generation of UCN sources.

Figure 1: Location of the UCN facility in the Meson Hall.

Recent Developments

The UCN facility was funded by the Canada Foundation for Innovation (New Opportunities Fund, 2009), with partner contributions from the Japan Society for the Promotion of Science (JSPS), TRIUMF, KEK, RCNP Osaka, Acsion Industries (Pinawa), and the Government of Manitoba.

In September 2010 the project successfully underwent a review by an international expert panel commissioned jointly by KEK, RCNP, and TRIUMF.

A memorandum of understanding (MOU) between KEK, RCNP, TRIUMF, and the University of Winnipeg was completed in January 2011 for the UCN source and EDM Experiment. Canadian funds for the project were released in April 2011. The project has been supported by NSERC since April 2010 and now supports 14 eligible signatories over three separate subatomic project grants. Renewal of this support with three new cosignatories is being sought this year.

Support for the EDM experiment itself is through NSERC, and we have received two RTI grants for related work. The project has been supported by separate CFI grants to its members at the Manitoba universities, the most recent being the CFI Learning Opportunities Fund to Martin and Bidinosti to support a Xe lab for fundamental physics related to comagnetometer development. As a part of the MOU, JSPS and internal support from both KEK and RCNP Osaka have been committed. The internal support from the laboratories is particularly important; it supports beam line components and cryogenic equipment destined for TRIUMF, as well as EDM equipment crucial for completing experiments at RCNP Osaka.

The project underwent another successful review by an international expert panel in December 2012, this one commissioned by KEK's Institute for Particle and Nuclear Science (IPNS). As a result of this review, the TRIUMF project was selected (over another neutron EDM project at J-PARC) for additional KEK support (beyond the support specified in our MOU) for 2013 and beyond.

Technical Status

The prototype UCN source at RCNP Osaka delivered a UCN density of 20 UCN/cm^3 to a detector located outside the shield package [9], a second-generation source being developed at this time (see Figure 2). The new source features improvements to the geometry, production volume, storage lifetime, transport efficiency, and higher energy transported UCN, which are anticipated to result in higher UCN density.

Figure 2: Left Top: Photo of Helium-II cryostat. The pumping for the He-3 and natural He (1 K) pots may be seen projecting out towards the viewer. Right: High voltage prototype of the storage cell for the measurement of the neutron electric dipole moment at TRIUMF. Left Bottom: Photo of cryostat. The long horizontal section that would connect the two cryostats is also shown.

The new UCN source cryostats, which contain the superfluid helium UCN conversion volume, and the cold moderator materials are under development at RCNP Osaka. Figure 2 shows photos of both cryostats. The superfluid helium cryostat will undergo cold tests throughout 2013. The UCN source will be available for experimentation at RCNP with lower intensity proton beam until 2015, when relevant parts of the apparatus will be moved to TRIUMF for installation.

Substantial progress has been made on the major subsystems of the TRIUMF facility: The bender magnet was completed in fiscal year 2011–2012 by KEK. The kicker and septum magnets underwent internal review at TRIUMF in March 2012. The kicker magnet and its associated power supply entered the bidding process at TRIUMF in early 2013. At time of writing, detailed drawings for the septum magnet are being completed. The proton spallation target will be water-cooled tungsten, and this has been studied in detail using MCNPX and ANSYS CFX simulations. Conceptual designs of the target and remote handling systems have been completed. Basic radiation shielding concept drawings have been studied and simulations of the radiation shield package are ongoing. Space has been reserved for the neutron electric dipole moment experimental area.

Facility Status

The UCN facility at TRIUMF began construction in early 2013, with the first step being general area clean up and a few modifications to quadrupole magnets in the existing Meson Hall beam line. A detailed plan for successful completion has been formulated, taking into account availability of TRIUMF resources as appropriate. A project manager and a project engineer at TRIUMF have begun work on the project. Monthly meetings are being held with the relevant TRIUMF division heads to ensure open lines of communication and to monitor progress.

Partners

In Canada: University of British Columbia, University of Manitoba,
University of Northern British Columbia, University of Winnipeg.
International partners: Japan (4), Switzerland (1), United States (1).

TRIUMF's Role

Through this project, TRIUMF has developed a new discipline of research in subatomic physics in Canada: the field of fundamental physics using UCN. TRIUMF scientists have taken on leadership roles for several key parts of the nEDM experiment: magnetic environment, high-voltage, UCN detectors, cold neutron moderator design, and studies of heat transport through superfluid helium. In addition, TRIUMF provides the expertise to develop the new proton beam line and associated spallation target, shielding, and cryogenics for the UCN facility. [8,4,5].

CANADIAN MILESTONE IN JAPAN-BASED EXPERIMENT

08 October 2009

The Canadian group associated with the T2K (Tokai to Kamioka) neutrino experiment in Japan achieved a major milestone in October 2009, with the installation of two fine-grained detectors (FGDs).

Neutrinos are nearly massless subatomic particles that interact very weakly with matter. There are three types (or flavours) of neutrinos, and as shown by the Sudbury Neutrino Observatory, they can oscillate from one flavour to another. The T2K experiment will study these oscillations in unprecedented detail.

Operational tests of the FGDs will now be conducted making use of cosmic rays. The experiment is scheduled to start taking data in December 2009.

T2K Canada consists of groups at TRIUMF, Victoria, UBC, Alberta, Regina, York, and Toronto and is the largest group of collaborators outside of Japan. The entire T2K collaboration includes groups from Japan, Canada, the US, Europe, and Russia.

5.5.4 DETECTOR DEVELOPMENT AND FABRICATION FACILITY

All experiments in particle and nuclear physics, as well as condensed matter experiments at TRIUMF, require instruments to detect energetic subatomic particles. 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. New scientific opportunities arise from advances in detector capabilities, such as enhanced precision in kinematic properties; the rate at which particles may be detected, which leads to improved statistical precision; and in reduced costs, which make possible larger systems with greater sensitivity to rare processes.

Over the last several decades, TRIUMF's Detector Group (DG) has established a strong international reputation for developing, designing, and constructing state-of-the-art detectors, as well as developing new detector technologies. A steady progression of new instruments has been successfully deployed in measurements at TRIUMF and in collaborative projects elsewhere in Canada and abroad. As was typical in previous years, every detector or detector element produced by the DG during 2008–2013 has performed as required, with no disappointments. These successes are noted in the corresponding descriptions of those experimental activities in the scientific section of this document.

Detectors exploit various special technologies. One example is scintillating materials, which emit a flash of optical light when stimulated by impact or passage of an energetic particle. The intensity of light is typically proportional to the energy that the particle deposited in the material, thereby leading to arrays of such scintillators being known as calorimeters. The light can, in turn, be collected and detected by a variety of devices, which themselves are a topic of recent advances. The scintillator material, which can be organic or inorganic, a solid, liquid or gas, is chosen from a set 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. The most prominent example of scintillator construction during 2008–2009 was a close collaboration with the T2K collaboration in the construction of two large fine-grained plastic scintillator arrays for the T2K neutrino experiment in Japan, as described in Section 5.5.5.3. This project was large and ambitious, successfully employed, for the first time, a new photo-sensor technology on a large scale. The DG also provided the design concepts and construction techniques for a potentially commercial application of scintillator technology on a substantial scale to the identification of subterranean ore bodies through the detection of cosmic-ray muons by scintillator assemblies deployed underground.

Another widely used detector technology exploits the trail of ions and free electrons produced in the track of a charged particle, which typically passes through gases but also through certain liquids, to determine the spatial location of that track to a precision that may be as small as the thickness 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 the 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 the magnetic field of a large magnet in which the tracks of charged particles are curved to a degree related to their momenta. Measuring a track's curvature thus determines the particle's momenta. In addition, the density of the ionization along the track can be recorded and used to identify the type of charged particle.

The largest gas detectors constructed during 2008–2009 were three large time-projection chambers (TPCs) for precisely tracking charged particles produced by neutrino interactions in the T2K Experiment, as described in Section 5.5.5.3. This was the first large-scale application to TPCs of a recently developed technology for sensing clouds of electrons drifting in the gas. The mechanical design of these and most other detectors produced by the DG depends on the inventive and tireless efforts of Robert Henderson. The Group also has strong skills and experience, and an impressive track record, in the design and production of the complex systems for circulating, re-purifying, and precisely controlling the pressure of the special gases for this type of detector.

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 analogue technology as well as in the digital processing devices and techniques, have played crucial roles in rapid enhancements in the capabilities of detector systems. The Group's success in this area flows from the experience and insight of Leonid Kurchaninov.

The investigation and application of new detector technologies is a principle interest of Fabrice Retière. He led the application of the new optical sensors to the T2K project, as well as the design and construction of the signal processing and digitization electronic system. Overall leadership of the Group is provided by Andy Miller, which brings the total number of Ph.D. scientists to four. There are eleven other designers and technicians in the Group, many of them in the later stages of their careers. Their collective seniority has major advantages concerning the wealth of experience in the Group but it will require a concerted effort to maintain the Group's capabilities over the period of succession that looms ahead of us.

Description of Facilities

The facilities for detector construction occupy four substantial areas on the TRIUMF site.
The Scintillator Shop is equipped with:

- a Haas VF-5/40XT CNC vertical milling center with a 5-axis spindle and 2-axis rotary table yielding a precision of ± 5 µm over a working volume of 1.5 m × 0.66 m × 0.64 m (see Figure 5.5.4-1)
- a Haas TL-3 CNC lathe with a maximum cutting diameter of 0.5 m and a maximum cutting length of 1.5 m (see Figure 5.5.4-2)
- a Manfred manual 3-axis precision turret mill and a manual lathe, both with about 4' travel
- a Band-saw, pneumatic press-brake, and pneumatic shear
- a temperature controlled oil bath for shaping plastic scintillators and light-guides, often into exotic shapes to fit into the complex geometries of experimental instruments

In another building is a large tent housing a Multicam CNC router with a precision of ±100 µm over a working volume of 3 m × 3 m × 0.4 m (see Figure 5.5.4-3). Linear encoders within its ball rails enhance its precision for static operations such as hole drilling to ±25 µm. Furthermore, its spindle has an angle encoder in a spindle-rotation servo loop for "rigid tapping" (synchronized rotation and thrust) of hole threads. Finally, its spindle carriage can be equipped with a CCD camera for coordinate measurements, or a surface scanning probe to precisely map the varying height of the surface of a work-piece before machining accordingly. All of these machine tools are housed in temperature-controlled areas with internal 5t crane coverage and dust extraction systems suitable for machining the composite materials that play a major role in the fabrication of modern instruments. This facility also machines such materials for other TRIUMF Divisions. Any machining of metals is done with only slight lubrication to avoid subsequent contamination of plastic work-pieces that can result in cracking and other degradation.
The machine tools are operated by a journeyman machinist and two other technicians, all with many years of experience with CNC equipment. They are also particularly well suited to interact effectively with the scientific clients in developing practical solutions for the varied requirements.

The Group also has three temperature-controlled class-1000 clean rooms, with volumes 7.8 m × 11.5 m × 5 m, 8 m × 10 m × 2.4 m, and 8 m × 9 m × 2.8 m, for assembling instruments of all sizes. The largest such room has full coverage by an internal 5t crane, and can house a 3 m × 2.4 m and/or a 1.2 m × 4.3 m precision-ground granite slab with pneumatic or hydraulic presses (see Figure 5.5.4-4). Finally, there is a 10 m × 27 m detector development area with 2t crane coverage, equipped with several high-purity gas mixture manifolds. This area is serviced with a stainless steel gas distribution and return system from an adjacent gas mixing shack, and typically hosts half a dozen separate activities involving assembly and testing of detectors and related equipment. In this area the Group also has a QMS gas analysis system. The replacement value of the entire infrastructure of the detector facility for construction is about C$1M.

Figure 1: The Haas VF-5/40XT CNC vertical milling center. **Figure 2:** The Haas TL-3 CNC lathe. **Figure 3:** The Multicam CNC router. **Figure 4:** The 3 m × 2.4 m precision-ground granite slab in the 7.8 m × 11.5 m × 5 m clean room.

The Detector Electronics subgroup has an 8.4 m × 12 m space for design and development of electronic systems for precisely sensing and processing the tiny signals typically produced by detectors. This laboratory is well equipped with modern test equipment. An experienced designer combines his broad knowledge of the great array of applicable electronic component technologies with advanced skills in both 3D mechanical and multi-layer printed-circuit board design tools to produce integrated detector solutions. A more junior technician in this group combines appropriate capabilities for such design with cryogenic and vacuum experience, skills in constructing prototypes, repairing production instruments, and coding of instrumental firmware and software. This subgroup undertakes not only detector instrumentation projects, but also some design and development work for the TRIUMF Accelerator Division.

Partners

The Detector Group has collaborated with many experiments, local, national and international to design and produce instruments essential for their success.

TRIUMF's Role

The Detector Group is a major component of the TRIUMF Science Division. All of the personnel are permanent TRIUMF staff. Only machining and assembly work done in the Scintillator Shop is charged to the clients on an hourly basis.

5.5.5 TRIUMF CONTRIBUTIONS TO OFF-SITE INFRASTRUCTURE

TRIUMF expertise in detector development is sought out by foreign collaborators and TRIUMF has made significant contributions to a number of offsite experiments: ATLAS (Switzerland), T2K (Japan), ALPHA (Switzerland) and four at SNOLAB (Ontario). These contributions to the detectors facilitates TRIUMF staff and other Canadian scientist involvement in these experiments.

5.5.5.2 ATLAS UPGRADES

The ATLAS detector at the CERN Large Hadron Collider (LHC) has been running with proton-proton collisions since the autumn of 2009. In total, about 25 fb^{-1} of data with centre-of-mass energies of 7-8 TeV have been analyzed by ATLAS scientists, with leading roles by Canadians in many physics areas. In 2012, ATLAS announced the discovery of a particle consistent with the Standard Model Higgs boson, a discovery enabled by Canadian-built detectors, computing systems, data analyzers, and analysis reviewers.
In summer of 2013, the LHC entered a two-year shutdown period in order to consolidate and upgrade the facility to allow higher intensities and to nearly double the beam energies. At the time of writing, ATLAS is undergoing a detector upgrade program to enable full exploitation of this future running. Canadians are fully engaged in the ATLAS upgrade program, including significant efforts since 2008 involving TRIUMF facilities and personnel. Further details of the scientific program at ATLAS can be found in Section 4.2.1.1.

The ATLAS Detector

A full description of the ATLAS detector [3] is beyond the scope of this document. ATLAS is a multipurpose particle physics apparatus with forward-backward symmetric cylindrical geometry.
The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a straw-tube transition radiation tracker. The ID is surrounded by a thin superconducting solenoid which provides a 2~T magnetic field, and by high-granularity liquid-argon (LAr) sampling electromagnetic calorimetry. The electromagnetic calorimeter is divided into a central barrel and end-cap regions on either end of the detector. An iron-scintillator/tile calorimeter gives hadronic coverage in the central rapidity range, while a LAr hadronic end-cap calorimeter (HEC) provides coverage in the forward regions. The HEC was designed at TRIUMF, and half its modules were built in Canada and assembled at TRIUMF. The final assembly at CERN was directed and overseen by TRIUMF personnel. The regions closest to the beampipe are instrumented with LAr calorimeters for both electromagnetic and hadronic measurements. The hadronic forward calorimeters were built in Canada with the participation of TRIUMF staff.
The muon spectrometer surrounds the calorimeters and consists of three large air-core superconducting magnets providing a toroidal field, each with eight coils, a system of precision tracking chambers, and fast detectors for triggering. The combination of all these systems provides charged particle measurements together with efficient and precise lepton and photon measurements.

The data from ATLAS are selected with a three-level triggering system to which Canada contributed significantly. After initial processing at CERN, the data are distributed to ten Tier-1 Data Centres around the world. TRIUMF hosts Canada's ATLAS Tier-1 Data Centre (please see Section 5.8.1).

ATLAS performance has been exceptionally good, with 93.5% of delivered data being recorded with sufficient quality to use for physics analysis. The LAr calorimeters were over 99% efficient in 2012, when the bulk of the data were taken.

Description of Facilities

ATLAS has made use of several TRIUMF facilities for upgrade studies since 2008.
Neutral Beam Irradiation Facility (NBIF)

The TRIUMF neutral beam irradiation facility (NBIF) is located in the cyclotron vault near the beam line 1 and beam line 4 extraction points, taking advantage of the neutral hydrogen beams that result from the stripping of a single electron from the H- ions by the magnetic fields at the outer orbit. The neutral hydrogen leaves the magnetic field region in a planar beam, which is fully stripped as it leaves the vacuum region, exiting as a proton beam at nearly full energy (500 MeV). Each NBIF station has an ion chamber which tracks the relative local beam intensity, and users calibrate the dose received during irradiation using thin aluminum foils which are analyzed after irradiation runs. ATLAS has used the NBIF for several tests of polycrystalline chemical vapour deposition diamond detectors, and plans further tests of new electronics technologies in the future. Total fluences of 5 x 10^{16} protons cm^{-2} were reached in the current tests. The NBIF facility is shown in Figure 1.

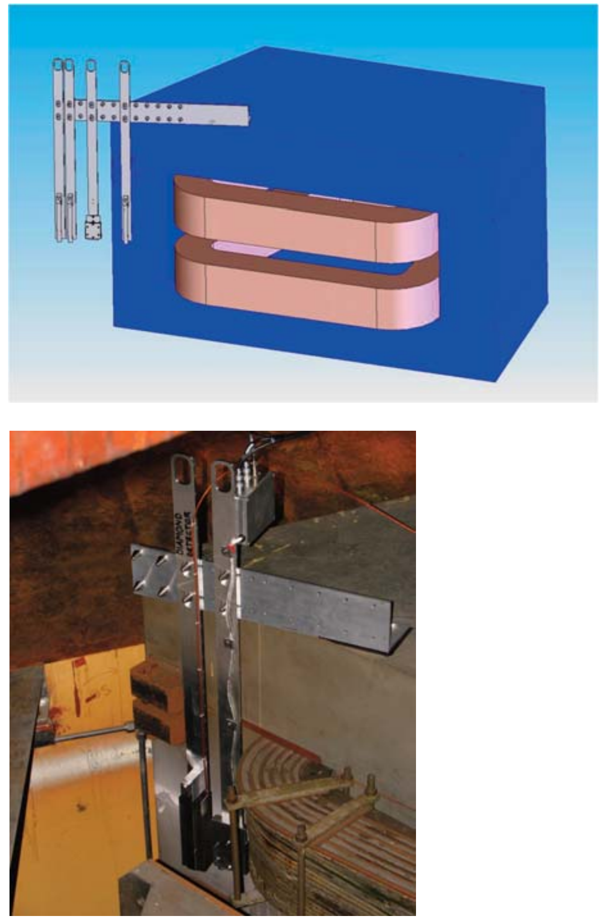


Figure 1: Neutral beam irradiation facility. The left-hand diagram shows a schematic of the NBIF, and the right-hand photo shows an ATLAS sample installed to the left of the NBIF ionization chamber.

Beam Line 1A (BL1A)

The NBIF irradiation fluences are insufficient to reach the levels expected in the ATLAS forward calorimeter region in ten years of upgraded LHC operation when the required safety factors are included. Installing samples directly into TRIUMF Beam Line 1A makes it possible to

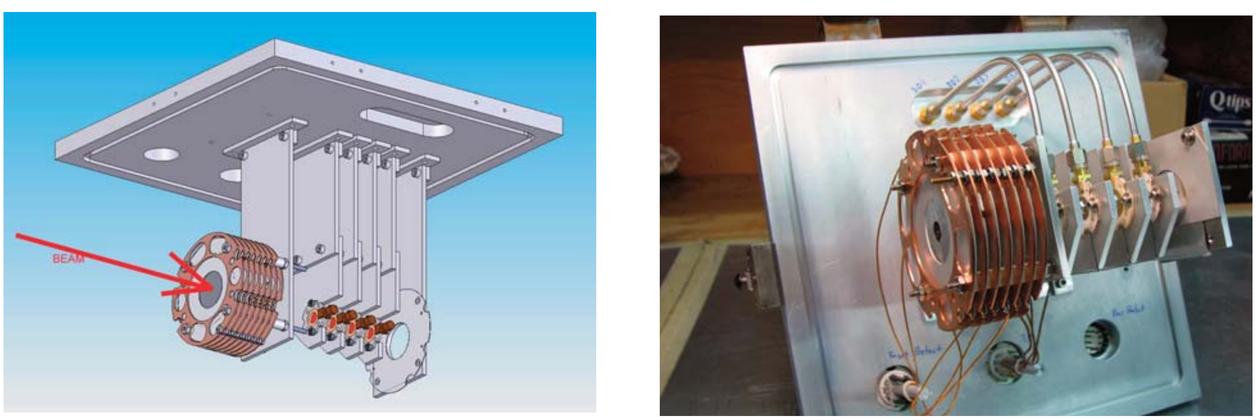


Figure 2: Beam Line 1A high intensity ATLAS irradiation tests. The schematic on the left shows the beam impinging upon a diagnostics system, with four pCVD diamond detectors mounted downstream. The photo on the right shows the same setup. The detectors are mounted on an aluminum plate, which is then mounted as the lid of a standard beam line "diagnostics box," and then installed directly into Beam Line 1A.

achieve the desired dose in about two weeks of low-intensity operation. ATLAS has used BL1A for high intensity irradiation tests, reaching fluences of 2.5 x 10^{17} protons cm^{-2}. The BL1A irradiation setup used for high intensity ATLAS pCVD diamond tests is shown in Figure 2.

M11 Beam Line

TRIUMF beam line M11 is a secondary muon and pion beam line running at low intensity. ATLAS has used M11 as a precision muon source for measuring the response of particle detectors. ATLAS used M11 muon beams to characterize the uniformity of pCVD diamond detectors. A sketch of the ATLAS tests in M11 is shown in Figure 3.

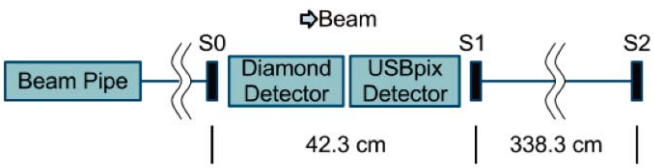


Figure 3: Diagram of the ATLAS detector tests in the M11 beam line, where the beam exit is labeled "Beam Pipe." S0, S1, and S2 are scintillators used to trigger muons that have passed through the entire detector. The diamond detectors and precision pixel tracking detectors (USBPix) are located between two of the trigger scintillators.

TRIUMF Engineering Division Personnel and Facilities

Members of the TRIUMF engineering division led the planning of ATLAS end-cap calorimeter upgrade scenarios, including designing both new detector elements and the tooling required to carry out the installation of new detectors, and handling of the existing activated detectors in the ATLAS experimental area. These TRIUMF staff members have experience working with ATLAS technical coordination and radiation safety groups at CERN, including TRIUMF members who led the installation of the current ATLAS endcap calorimeters in cryostats and the transport and installation of the 250-ton assemblies in the ATLAS detector.

TRIUMF Detector Group Facilities

The TRIUMF Detector Electronics Group plays a critical role in ATLAS upgrade activities, both on- and off-site. This group also designed and deployed the readout electronics and data acquisition systems for the irradiation and uniformity tests described in this section and also assisted in data taking. NIM modules, crates, oscilloscopes and other equipment from the detector group are used throughout our program. Detector group members also designed and constructed electronics used for ATLAS high-rate calorimetry tests at IHEP/Protvino, Russia and neutron irradiation tests at the IBR reactor facility in JINR, Russia.

TRIUMF Diagnostics Group Facilities

The TRIUMF diagnostics group designed, built, and installed the NBIF facility and also packaged the ATLAS components for use in the NBIF and BL1A tests. They constructed all of the beam instrumentation and assisted in cabling both the NBIF detectors in the cyclotron vault and the BL1A pCVD diamond detectors with cable runs from the beam line to a data acquisition platform in the TRIUMF Meson Hall.

Recent Developments

ATLAS has seen many developments since 2008.

Tooling for Endcap Calorimeter

ATLAS is exploring two options for the forward calorimeter, the complete replacement of the current system with a "super Forward Calorimeter" (sFCal) or the less expensive option of installing a smaller, high-rate calorimeter (MiniFCal), which shields and protects the existing detectors while maintaining precise energy measurements.

TRIUMF's engineers and designers were critical to the overall design of the current ATLAS LAr end-cap calorimeters and supervised the assembly and installation of the detectors at CERN. If the FCal is replaced with an sFCal, significant tooling will need to be installed in the ATLAS pit to handle the highly activated, massive detectors. The installation of the MiniFCal would be simpler and less risky than the full replacement option but would still involve working in a challenging environment with radiation-shielding issues. TRIUMF engineers and designers have led the effort to design the full set of tooling needed for handling the forward calorimeters for ATLAS upgrades, whether we need to replace the

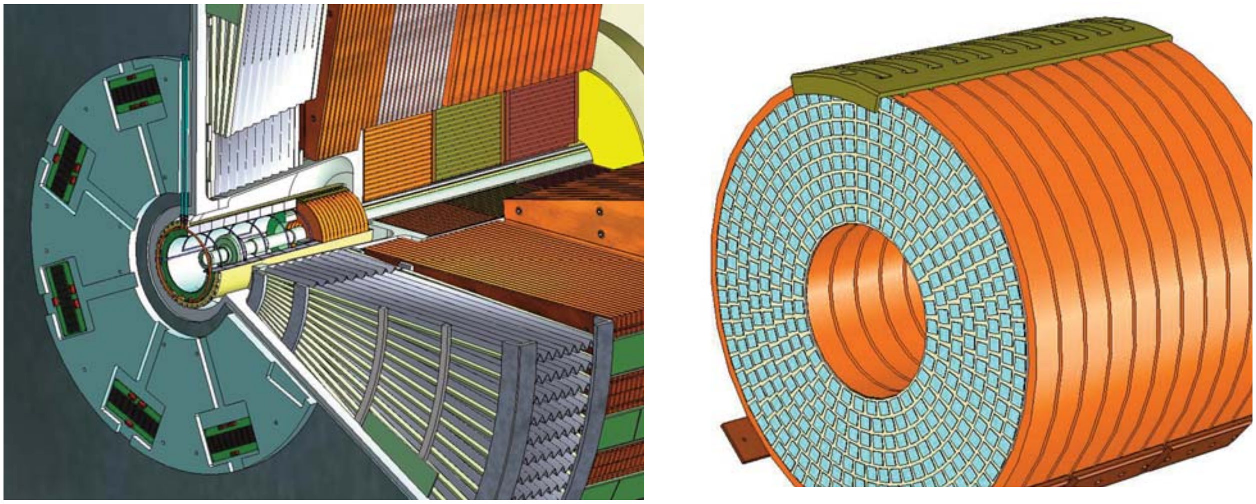


Figure 4: On the left is a SolidWorks design by Roy Langstaff showing the installation of a MiniFCal, shown on the right, in ATLAS. Langstaff and Lenckowski have developed complete installation scenarios for both the MiniFCal, and complete FCal replacement, options, as well as designed tooling for handling the HEC calorimeter required for replacement of electronics mounted on the edges of the detector.

complete forward calorimeter system or just to install the MiniFCal. They have also completed designs of tooling required to remove the hadronic end-cap calorimeters (HEC) for replacement of the electronics mounted on the detectors should that be required. A sketch of the MiniFCal option is shown in Figure 4, developed by members of the TRIUMF engineering division based at the University of Victoria.

Radiation Hardness of Polycrystalline Chemical Vapour Deposit (pCVD) Diamond Detectors
Developing an active detector able to handle the high rates and radiation fluxes near the ATLAS beam pipe is essential for the MiniFCal. Diamond technology promises very fast response from radiation hard

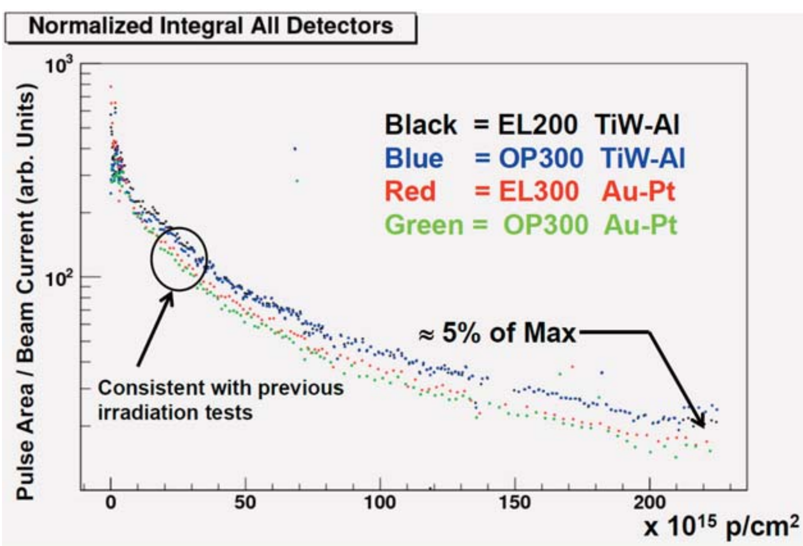


Figure 5: Normalized response of four different detectors irradiated in TRIUMF Beam Line 1A. These tests extend the levels of previous measurements by about an order of magnitude. "EL" and "OP" refer to the grades of the pCVD diamonds (high quality electronics grade and medium quality optical grade), "200" and "300" refer to the detector thicknesses in microns, while the chemical symbols refer to the composition of the electrodes coating the pCVD diamond surfaces.

detectors, but pCVD diamonds had only been tested to fluences of 10^{16} particles/cm^2, about an order of magnitude less than that expected in the ATLAS FCal region over 10 years of running at the upgraded LHC. In a set of continuing irradiation tests at TRIUMF, we have tested different grades and thicknesses of pCVD diamond detectors above 2.5 x 10^{17} particles/cm^2, the level required for use in ATLAS forward calorimetry. We have performed tests in both the "NBIF" facility in the TRIUMF cyclotron vault and using TRIUMF Beam Line 1A. The highest fluence results, from tests in TRIUMF Beam Line 1A, were published in [1]. The normalized detector response is shown in Figure 5 for the Beam Line 1A tests.

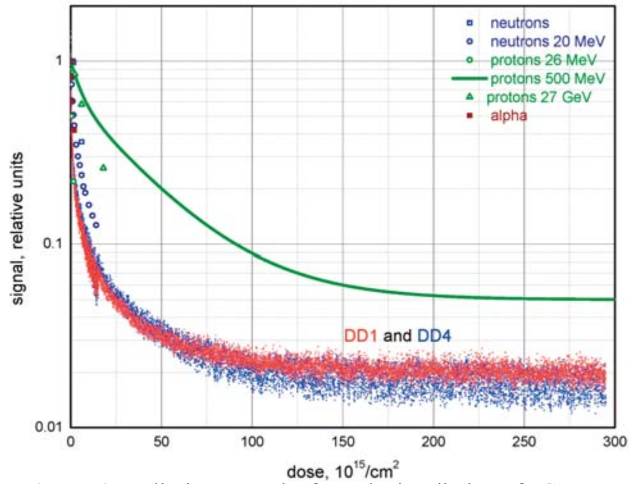


Figure 6: Preliminary results from the irradiation of pCVD diamond detectors with neutrons. Also overlaid are our results with proton beams at TRIUMF, which seem to cause less damage than the neutrons. Calibration of the neutron fluxes is pending, and the results are subject to change.

The irradiation tests performed at TRIUMF on pCVD detectors used protons, while the ATLAS calorimeters predominantly see neutron fluxes. The TRIUMF ATLAS group, along with members of the TRIUMF Detector Group, led Canadian participation in neutron irradiation tests of pCVD diamond detector at the IBR reactor at JINR/Russia. Preliminary results of the neutron irradiation test are shown in Figure 6.

Spatial Uniformity of pCVD Diamond Detectors

For use in a calorimeter, the active detector elements must also be uniform since their signals are summed prior to digitization. Using muons in TRIUMF beam line M11, we studied the response uniformity of pCVD diamond detectors to single particles. The analysis from those studies is completed, and the paper submitted to JINST (preprint number JINST_002P_0712). Figure 7 shows the spatial uniformity results from the detector tested in M11.

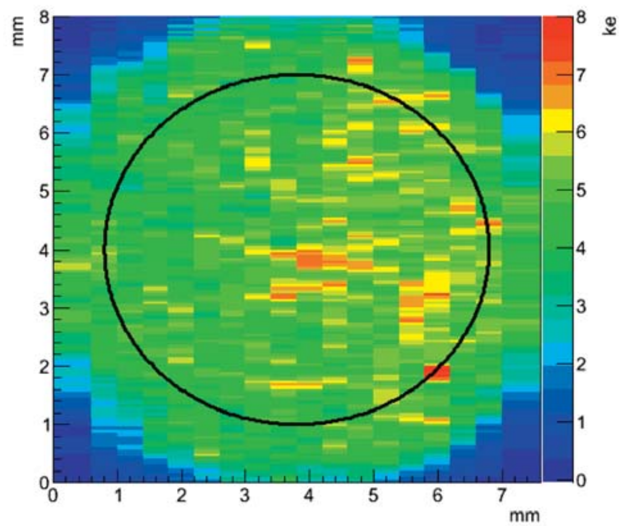


Figure 7: Response uniformity of a diamond detector tested in Beam Line M11 at TRIUMF. The plot shows the results for negative bias voltages on the pCVD diamond detectors. The uniformity varies by nearly a factor of two across the detector surface, which is problematic for use in a precision calorimeter.

High Rate Liquid Argon Calorimeters

Several of the technology options being considered for ATLAS calorimeter upgrades requires the construction of Liquid Argon calorimeters that operate at higher rates than the current ATLAS forward calorimeters. These options include the possible replacement of the current ATLAS forward calorimeters by similar devices with smaller liquid argon gaps, or a possible MiniFCal using liquid argon technology. Canadians proposed high rate calorimeter tests at the IHEP/Protvino facility in Russia, and members of the TRIUMF ATLAS and detector groups continue to play critical roles in those tests (see Figure 8). A critical result of these test, published in, is that a liquid argon calorimeter with a viable gap size of 119 microns can be constructed which has good linearity at any possible upgraded LHC beam intensity.

Partners

In Canada: Carleton University, McGill University, Simon Fraser University, TRIUMF, University of Alberta, University of British Columbia, l'Université de Montrèal, University of Toronto, University of Victoria, York University. ATLAS also has many partners associated with computing and networking, including Compute Canada and CANARIE.
International Partners: 156 in 38 countries.

TRIUMF's Role

TRIUMF has roles across all aspects of the ATLAS program, including faculty, graduate students, undergraduate students, engineers, designers and technicians. TRIUMF faculty members conceived several of the possible ATLAS calorimeter upgrade possibilities, initiated detector design concepts, and advocated for both high rate and high particle fluence tests of new technologies. Planning of ATLAS endcap calorimeter upgrades, including the design of the massive tooling required in the ATLAS detector cavern, is led by TRIUMF engineers and designers. Members of the TRIUMF ATLAS and detector groups designed and assembled the electronics for irradiation, uniformity and high-rate studies new detector technologies for ATLAS upgrade R&D.

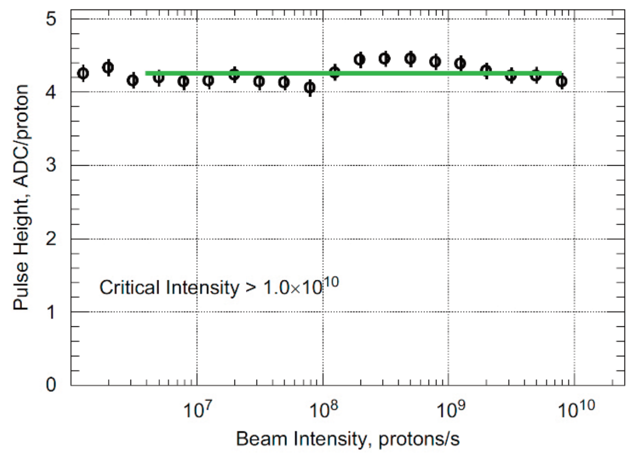


Figure 8: Pulse height response as a function of beam intensity for a liquid argon calorimeter with a gap of 119 microns in the tests at IHEP/Protvino. The highest intensities exceed those in the ATLAS forward calorimeter region at the upgrade LHC. The results indicate that it is possible to build a liquid argon forward calorimeter for ATLAS that will function at the highest LHC intensities.

TRIUMF managed the entire Canadian in-kind contribution to the LHC accelerator project, valued at $41.5M over the course of the 1995–2000 and 2000–2005 Five-Year Plans. TRIUMF provided resources for design and construction of two of the four hadronic endcap (HEC) wheels of the ATLAS liquid argon calorimeter, including machining the copper plates in Alberta, and participated in the design and engineering of the liquid argon cryostat feedthrough project at Victoria. TRIUMF personnel helped design and build the forward calorimeter modules at Carleton University and the University of Toronto. TRIUMF personnel played several key roles in ATLAS data quality assessment and assurance, both for the liquid argon calorimeters, and for the "global" ATLAS data quality.

TRIUMF'S SIMON VIEL IS 2011 VANIER SCHOLAR

03 August 2011

Simon Viel, a UBC physics graduate student under the joint guidance of TRIUMF's Oliver Stelzer-Chilton and UBC Professor Colin Gay, was selected as a recipient of the prestigious Vanier Canada Graduate Scholarships, which is valued at $50,000.

Working with ATLAS, Viel analyzes data to observe the pair production of muons, in order to determine if there is any excess signal that could lead towards a new discovery. The Standard Model successfully combines together three of the forces we know: electromagnetism, and the strong and weak nuclear forces (leaving aside gravity) – but there is strong theoretical and experimental evidence hinting that this description is incomplete, fueling speculation as to models with new forces. Viel's aim is to aid the search for new force-carrying particles. The discovery of a new force would greatly enhance our understanding of the fundamentals of our universe

TRIUMF PRODUCES AND DELIVERS MAGNETS FOR CERN'S LHC

08 May 2008

The end of the winter season marked another assembly milestone of the Large Hadron Collider (LHC) at CERN. A total of 154 'warm' magnets arrived from around the world, and TRIUMF oversaw the contribution of 52 (48 plus 4 spares) units to the project.

The TRIUMF-designed warm magnets are called warm because they are normal conductors (as opposed to superconductors). These twin-aperture quadrupole magnets were fabricated from TRIUMF designs by ALSTOM in Tracy, Quebec. TRIUMF supplied the contract management, design, and quality assurance, while ALSTOM completed the physical production. The first prototype was completed in 1996, the order was delivered in 2003, and installation completed in February 2008.

Although the LHC is famous for its use of superconducting cold magnets, warm magnets are essential to directing the proton beam along the path of the world's most powerful particle accelerator.

The magnets represent one of the many ways in which TRIUMF has contributed to cutting-edge particle physics at CERN. TRIUMF is also home to Canada's Tier-1 Data Centre for the ATLAS detector as well as being a contributor to the detector.

TRIUMF scientists hold or have held a number of key roles in the management of ATLAS and in the coordination of ATLAS physics and performance groups. TRIUMF hosts the Canadian ATLAS Tier-1 Data Centre, a roughly $20M project initially funded by Canada Foundation for Innovation, with matching funds from the British Columbia Knowledge Development Fund and computing hardware vendors, which hosts 5% (currently 10%) of the ATLAS RAW data, and are one of the ten international computing centres responsible for hosting and distributing ATLAS data and Monte Carlo samples.

TRIUMF research scientists, TRIUMF-paid faculty members at ATLAS-Canada universities, and their students and post-doctoral fellows participated actively in most of the search examples described in this section.

References

[1] D. Axen et al., "Diamond detector irradiation tests at TRIUMF", JINST vol 6 no. 05, P05011, 2011.
[2] A. Glatte et al., "Liquid argon calorimeter performance at high rates", Nucl.Inst.Meth. A669 (2012) 47-65
[3] G. Aad et al., JINST 3 (2008) S08003.

5.5.5.3 T2K

The T2K long-baseline neutrino experiment uses an intense muon neutrino beam produced at the J-PARC (Japan Proton Accelerator Research Complex) proton accelerator in Tokai, Japan to study neutrino oscillations. The primary goals of the experiment are to carry out precise and highly sensitive measurements of muon neutrinos oscillating to electron or tau neutrinos. As elementary particles, whose properties profoundly impact, the evolution of the universe, T2K follows Theme 1 "Understanding the building blocks of the Universe and how they fit together." A detailed description of the science of the T2K project is presented in Section 4.2.1.2.

T2K uses a magnetized near detector, with key components built at TRIUMF, to study the properties of the neutrinos prior to neutrino oscillation effects, and the existing Super-Kamiokande detector, located 295 km west of Tokai, a distance optimized to coincide with the first maximum from neutrino oscillations. TRIUMF has made significant contributions to both the beam line and near detector facilities. In Canada, TRIUMF provides facilities for analysis (T2K Tier-1 centre) and detector R&D and calibration.

Description of Facilities

The T2K experiment consists of the beam line, near detector, and selected facilities at TRIUMF.

T2K Beam Line

The Canadian group contributed to the T2K beam line from inception, introducing the idea of producing a neutrino beam with a narrow energy spectrum peaked at the neutrino oscillation maximum by placing the detector slightly off-axis, as well as the design of the FODO lattice using combined bending and focusing magnets for the proton beam transport.

With up to a megawatt of proton beam power hitting the target, devices in the target station, such as the target and horn magnet, can only be serviced by a full remote handling mechanism. The remote handling system in the T2K target station is based on the TRIUMF ISAC Target Hall design: the horn and target hang under tall shielded modules with service connections at the top where human access is possible when the beam is off. Servicing the horn and target is done by moving the module to the hot cell.

TRIUMF's remote handling group built a beam monitor station for the final focus beam section upstream of the T2K target, along with a hot cell handling facility for remotely exchanging the target in the horn magnet. A novel design approach that allows insertion of the manipulator from the top was developed for this.

The Canadian group also built an optical transition radiation detector (OTR), which monitors the profile of the primary proton beam right at the target in an extreme radiation environment. The optical transition radiation image on a Ti-alloy foil is transported using four parabolic mirrors through the target-shielding module to a radiation-hard camera. Monitoring of the beam position and profile is critical to the operation of the beam line: the magnetic horn provides point-to-parallel focus, which translates the proton beam position at the target into the neutrino beam axis. The neutrino beam axis, in turn, determines the peak energy of neutrinos incident towards Super-Kamiokande. The beam line was successfully commissioned in 2009 with the OTR monitor.

The large earthquake that hit the east coast of Japan on March 11, 2011 significantly damaged the J-PARC facility. Buildings and roads were damaged, and realignment of the accelerator and beam line components was necessary. The beam line equipment built by the Canadian group played a key role in the damage assessment and subsequent realignment of components. In the target station, displacements of the order of 1 cm were observed in the horn modules, leading one to suspect damage. As a result, one of the horn modules was moved to the hot cell (using the remote handling system for examination), and found to be

TRIUMF SHIPS T2K EXPERIMENT PARTS TO JAPAN

22 July 2008

Six hundred thousand dollars worth of equipment from TRIUMF was recently shipped on a vessel from Vancouver bound for Tokai, Japan. Members of TRIUMF's Remote Handling group packaged and sent an important contribution to the T2K (Tokai to Kamioka) Neutrino Oscillation experiment at the J-PARC facility. The 4m-tall focus-monitor stack was designed and built at TRIUMF. The stack will control the position and intensity of the neutrino beam, as well as guide the beam to the target.

In addition to the focus monitor, the design for the experiment's hot cell was influenced by a collaboration of TRIUMF remote-handling specialists and researchers from the UK's Rutherford Appleton Laboratory.

"Many of the remote handling techniques used in this target hall are modeled after TRIUMF's ISAC and Meson Hall target area experience," says Ewart Blackmore, Coordinator for TRIUMF's J-PARC contribution. "The Remote Handling group at TRIUMF has made an important contribution to the design of the neutrino target station at J-PARC."

undamaged. The OTR, which is attached to the target plate, provided re-calibration of the target position when the beam came back on in December 2011.

Near Detector

The T2K off-axis near detector complex (ND280) measures neutrino interactions prior to oscillation effects, with the goal of constraining large systematic uncertainties in neutrino flux and cross-sections and predicting the far detector neutrino interaction rates and spectrum with minimal systematic uncertainty. In addition, the near detector studies neutrino-nucleus interactions with the goal of fundamentally improving our understanding of these interactions.

ND280 is a magnetized spectrometer located 280m from the production target, which consists of a central tracker formed from three large-volume time projection chambers (TPCs) alternating with two fine-grained detectors (FGDs) made from polystyrene scintillator bars. The TPCs and FGDs sit inside a magnet, which produces a 0.2T horizontal field, and are surrounded by an electromagnetic calorimeter. The FGDs provide target mass for the neutrino interactions, and they track particles emerging from the neutrino interaction vertex, while the TPCs provide sign/momentum information from the curvature of the track in the magnetic field and particle identification through the ionization yield in the gas. The magnet also contains a p^0 detector (P0D) and side muon range detectors embedded within the magnet yolk.

The TPCs and FGDs were designed and built at TRIUMF. The TPCs are large rectangular structures, with parallel horizontal electric and magnetic fields, an Ar:CF4:isobutane gas mix, and micromegas pad readout on both sides. TRIUMF also designed, and maintains, the accompanying TPC gas systems.

The FGDs use 1 cm x 1 cm x 200 cm square extruded polystyrene scintillators with wavelength-shifting fibre readout attached to Hamamatsu Multi-Pixel Photon Counters (MPPCs). Thin passive water layers in the second FGD provide a means of measuring neutrino interactions on a water target. T2K is the first experiment to use MPPCs (or so-called silicon PM) on a large scale, and the muSR group at TRIUMF recently adopted this equipment.

In 2008 and 2009, the Canadian T2K group tested the detectors in TRIUMF's M11 beam line, and the detectors were shipped to Japan in summer 2009, reassembled and tested in Tokai, and then installed inside the magnet. These detectors have operated reliably with little downtime since their installation and have provided the primary input for the T2K neutrino oscillation analyses from the ND280.

In addition to these tracker detectors, TRIUMF also provided the global slow controls system for ND280, which monitors the status of all detector elements. TRIUMF also provided several pieces of common ND280 infrastructure, such as the detector electronics cooling system, which uses chilled water at sub-atmospheric pressure to avoid water leak, a dry air system, and scaffolding and mezzanines used to access the inside of the magnet during installation or repairs.

T2K Facility at TRIUMF

TRIUMF hosts one of the two T2K Tier-1 data storage facilities (the other being at Rutherford Appleton Laboratory in the UK). It also hosts the slow control database and the T2K collaboration web page (t2k.org). A large fraction of the T2K-Canada collaboration (approximately six graduate students, five post docs and a few undergraduates, along with TRIUMF and UBC staff/faculty) is hosted at TRIUMF, forming one of the largest analysis groups in the collaboration and the only one that spans across the beam, near detector, and far detector. Apart from the critical mass afforded by the concentration of people and expertise, nearly all of the post docs and faculty/staff have held formal convener positions in the T2K collaboration, making TRIUMF an intellectual centre for T2K analysis activity.

A miniature version of the FGDs, called HARPSICHORD, was built at TRIUMF and operated in the M11 beam in the 2010–2012 period. Together with an all-scintillating fiber tracker detector built by Kyoto University, this detector has primarily been used to study the tracking and particle identification performance of the detector and to measure the scattering and absorption of pions in scintillator, which is an important systematic uncertainty for understanding neutrino interactions in the near detector. It has also served as a testing facility for firmware and software updates for the FGD, allowing TRIUMF DAQ experts to work and validate updates locally before performing the updates on the FGDs at J-PARC.

A new PMT test facility is being prepared in 2012–2013 to calibrate the PMTs for the far detector and to develop new photosensors for the future detector, Hyper-Kamiokande. The facility provides a magnetically shielded water tank with a movable laser and monitor system to study the PMT response and passive optical properties (reflectivity, etc.) in water.

TRIUMF's Role

TRIUMF provided key elements of the neutrino beam line for T2K and the design and construction of the fine grained detectors and time projection chambers that form the core tracking system for the near detector (ND280). TRIUMF has also provided essential support in the data acquisition, slow control monitoring, computing and services for the entire near detector complex. Currently, TRIUMF hosts one of the largest T2K analysis communities, with leading roles on all aspects of the experiment. It hosts the T2K website (t2k.org) as well as one of two major data servers for the experiment.

Partners

In Canada: TRIUMF, University of Alberta, University of British Columbia, University of Regina, University of Toronto, University of Victoria, University of Winnipeg, York University.
International Partners: Japan (8), France (4), Germany (1), Italy (4), Korea (3), Poland (6), Russia (1), Spain (2), Switzerland (3), United Kingdom (9), United States (10).

5.5.5.4 ALPHA: CASTING LIGHT ON ANTIHYDROGEN

ALPHA (Antihydrogen Laser Physics Apparatus) at CERN aims at producing and trapping antihydrogen atoms to carry out microwave and laser spectroscopy to test a fundamental symmetry, CPT, between matter and antimatter at the highest possible precision, and violation which is a possible explanation for the observation that our universe is composed entirely of matter.

Atomic hydrogen is one of the best-studied systems in all of physics, and seminal discoveries such as the Bohr atom and Lamb shift underlie the basis of modern quantum physics. A comparison of properties of hydrogen and its antimatter counterpart, antihydrogen (Hbar), belongs to this class of fundamental experiments. It is designed to address the validity of CPT that occurs in quantum field theories that are relativistic, local, and unitary. More details on CPT symmetry can be found in Section 4.2.1.3.

After the design, construction, commissioning, and development over several years, first antihydrogen trapping has been demonstrated in 2010 [1]. In 2011, confinement of antihydrogen for as long as 1000 seconds have been reported [2], an extension by more than a factor of 5000 from the initial confinement time. In fall 2011, the first spectroscopic measurement on antihydrogen was performed, leading to the announcement in March 2012 [3].

Description of Facilities

The central part of the ALPHA antihydrogen trap is shown schematically in Figure 1, where the Hbars are synthesized by mixing of antiproton (pbar) and positron (e^+) plasmas, and then trapped. The experiment was approved in 2005, and within a short period of time, the main parts of the trap apparatus [4] had been constructed and commissioned [5]. Antiprotons from the Antiproton Decelerator, caught in the catching trap, and the e^+ obtained from the positron accumulator, are transferred into the central region for mixing. These charged particles are confined and controlled by an arrangement of 34 cylindrical electrodes which are contained in the innermost ultra-high vacuum (UHV) region. The magnetic trap, consisting of

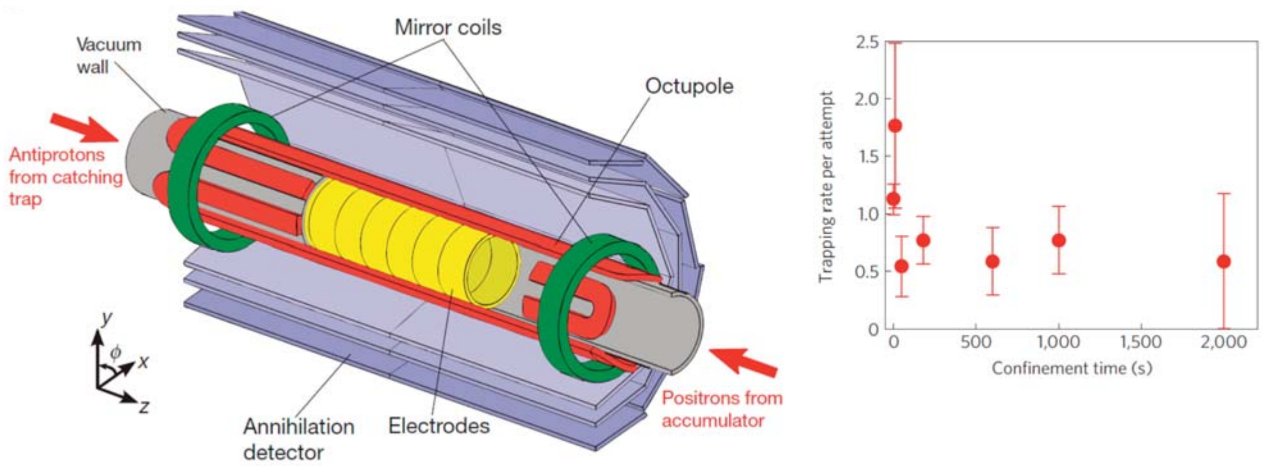


Figure 1: (Left) The ALPHA-1 central apparatus. (Right) Antihydrogen trapping rate as function of confinement time.

state-of-the-art superconducting octupole and mirror coils, has a depth of 50 μeV, while the e^+ and antiproton plasmas have space-charge potentials of up to 10V. The difference in these characteristic energy scales necessitates precise control of plasma processes in order to produce cold enough antihydrogen that can be trapped.

Around the magnetic trap lies a cylindrically symmetric silicon strip annihilation vertex detector that was fully deployed in 2009 after three years in construction. Trapping of antihydrogen atoms is detected by observing their annihilations upon release from the trap. The basic performance parameters obtained were a 7 mm position resolution for the annihilation vertices and an overall efficiency for detecting annihilations of 58% [17]. Cosmic rays were eliminated with an efficiency of 99.5% by topology cuts; later a multivariate analysis technique was developed that reduced the cosmic background by an additional order-of-magnitude [3].

Microwave spectroscopy techniques have been developed at UBC/SFU since 2005 [5]. In 2010 a microwave injection system was deployed and microwaves were first introduced into the atom trap to enable microwave probing of cold plasma via a study of plasma modes. In 2011 high-power microwaves were introduced into the trap via an internal horn in order to perform the first spectroscopy on an anti-atom via the positron spin resonance transitions at 28 GHz.

Following the success in initial microwave spectroscopy, the collaboration has taken on a major upgrade project: ALPHA-2. Prime motivations for ALPHA-2 are to allow laser access to trapped antihydrogen, and to provide improved and more flexible magnetic field configuration for microwave spectroscopy and anti-atom manipulations. By the end of 2012 major components for ALPHA-2 were mounted on the floor at CERN and successfully commissioned with antiproton (see Figure 2). These include: a new “catching” trap dedicated to efficiently capturing antiproton, a new atom trap with laser access with a Canadian designed and built cryostat hosting eight custom-made superconducting magnets, an augmented Si detector appropriate to the larger trap with an improved data acquisition system, and a new external solenoid.

In order to perform laser spectroscopy on anithydrogen, powerful laser sources that are not commercially available need to be developed. In 2012, a Lyman-alpha laser (122 nm) was demonstrated at the University of British Columbia. It had sufficient power to allow initial laser measurement on antihydrogen. Other laser developments, as well as microwave resonator developments, are currently being actively.

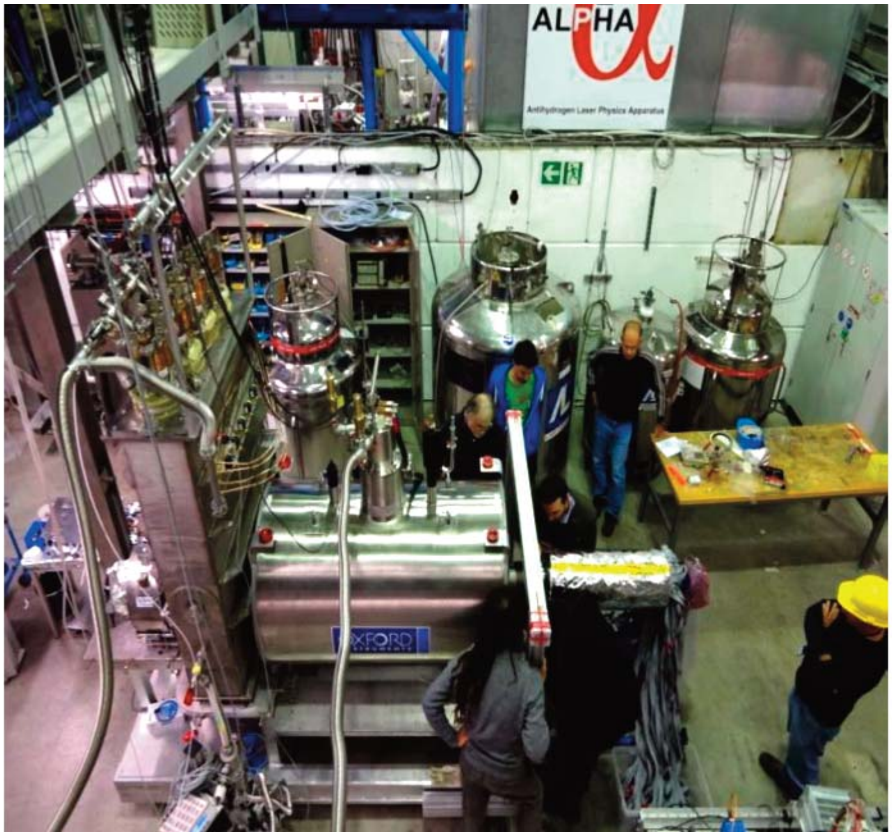


Figure 2: Construction of the ALPHA-2 apparatus and the Canadian-built cryostat.

Partners

In Canada: University of British Columbia, University of Calgary, Simon Fraser University, and York University.
International Partners: Brazil (1), Denmark (1), Israel (1), Sweden (1), Switzerland (1), United Kingdom (3), United States (2).

TRIUMF's Role

TRIUMF is the lead institution for ALPHA-Canada, and its leadership allowed Canadian university-based researchers to make significant impacts on the international project. TRIUMF and York University collaborators were responsible for the readout, data acquisition, software, and analysis for the Si vertex detector. Ancillary detectors, such as scintillator paddles, were built by TRIUMF and operated by ALPHA-Canada students. ALPHA-Canada scientists have developed techniques and equipment for microwave spectroscopy and are now developing lasers for antihydrogen spectroscopy, with significant intellectual and infrastructure support by TRIUMF.

In the area of trap/plasma physics, ALPHA-Canada has introduced techniques for microwave probing and manipulations of cold plasmas. A major TRIUMF and University of Calgary contribution is the engineering design and fabrication of the cryostat for the atom trap that will be the core of the new ALPHA-2 apparatus.

TRIUMF also contributed in the electronics for the particle traps in ALPHA, as well as in the expansion of the Si detector system for ALPHA-2. Canadians were lead authors on two major publications, and four ALPHA-Canada scientists served as run coordinators leading the experimental efforts

5.5.5.5 SNOLAB

SNOLAB is located two kilometers below the surface in the Vale Creighton Mine located near Sudbury. It has 5,000 m^2 of clean space underground for experiments and the supporting infrastructure. It offers a very low radiation environment for experiments that require very low background. These are typically related to the detection of neutrinos or dark matter. TRIUMF was involved in the original SNO experiment and has continued that involvement with SNOLAB.

TRIUMF provided critical infrastructure support to SNO during the construction phase. The ten rope equalizers from which the acrylic vessel (AV) holding the heavy water is hung were fabricated in the Machine Shop, as were the seals that prevent water from passing through the rope penetrations in the phototube sphere. The Universal Interface, which provides access to the interior of the AV for insertion of calibration sources, was both designed and fabricated at TRIUMF. The mechanism used to store the umbilical carrying services to calibration sources while they were deployed inside the vessel was designed in the Design Office. All of the data acquisition electronics were tested at TRIUMF before seeing service in the experiment. In addition, several other components of the electronics chain were fabricated in the Electronics Shop. Finally, the TRIUMF Data Acquisitions Group provided considerable assistance to the SNO DAQ group in preparation for the turn on of the experiment.

TRIUMF is expected to play a major role in the design, construction and operation of the next generation of the Enriched Xenon Observatory (nEXO). The nEXO experiment is designed to achieve unprecedented sensitivity to the possible neutrinoless double beta decays of Xe-136 that would show that neutrinos are their own antiparticle, violate lepton number conservation and allow us to determine the absolute neutrino mass. TRIUMF will play a leading role in designing, prototyping and fabricating the scintillation light detection system that is one of the key elements that must be optimized to achieve the required energy resolution. TRIUMF will also be a major player in the development of the barium ion trapping system that will allow ultimate background rejection. By contributing to nEXO and T2K in the next five years, TRIUMF scientists will contribute to pinning down the properties of neutrinos, one of the most elusive and unusual particles.

SNO+ Universal Interface

SNO+ is a new experiment that will take place in the SNO cavity at SNOLAB in Sudbury, Ontario. The acrylic vessel (AV) that held the heavy water in SNO will be reused with the water replaced by a liquid scintillator linear alkyl benzene. The higher light output of the scintillator will allow SNO+ to search for neutrinoless double beta-decay, measure the fluxes of pep, CNO, and B-8 solar neutrinos and and the fluxes of geoneutrinos and, neutrino oscillations from several nearby reactors, as well as to search for neutrinos from supernovae. The neutrino is a fundamental particle that had a profound influence on the nuclear processes that played a part in on the evolution of the universe and fuel stars like the sun. For the science of SNO+ please see Section 4.2.1.2.

Besides the AV, much of the equipment originally used in SNO will be reused in SNO+. One item that cannot be reused is the universal interface (UI) that provides access to the inside of the AV from the outside world.

Description of Apparatus

The UI has an upper and a lower part. Liquid for filling the AV passes through the lower part while ports in the upper part permit the introduction of calibration sources and various monitoring devices. Because the radioactivity requirements of SNO+ are about one hundred times more stringent than in SNO, it is essential that mine air, heavily laden with radioactive radon gas, be prevented from entering the AV. Thus the UI must be sealed directly to the AV.

This task is accomplished by a double O-ring seal with pump/purge capability of the space between the O-rings. In addition, the seal between the two halves, and the seals between each piece of apparatus that attaches to a port, must also be robust against mine air penetration. Each of these seals consists of either a double O-ring seal similar to the one between the UI and AV, or a conflat seal. Thus there is a minimal chance of mine air reaching the inside of the UI and AV, and this will allow the exacting experimental program to be carried out.

Ropes for manipulating the position of calibration sources inside the AV also pass through the UI (see Figure 1). Apparatuses for changing the lengths and tensions in these ropes are attached to the UI and are an essential part of its design. Again, the design of the boxes containing this equipment is such as designed to prevent any incursion of mine air.

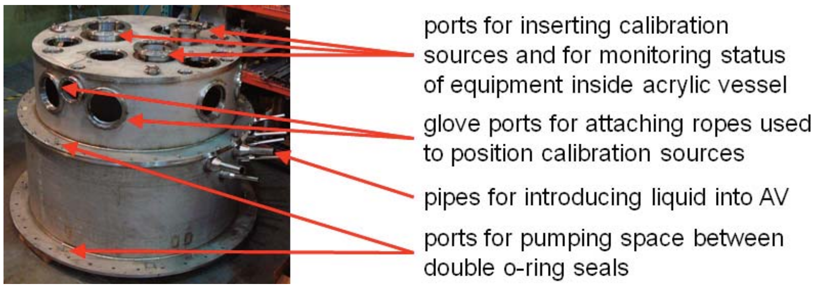


Figure 1: Photo of the UI while various vacuum and fitting tests of apparatus were being carried out at TRIUMF.

Recent Developments

The design of the UI was completed in 2010 and fabrication was complete in December 2011. The lower half of the UI was shipped to SNOLAB in December 2012. It is scheduled to be installed in March 2013, at which time filling of the AV can commence. In the meantime, design of the rope boxes was completed in November 2012 and fabrication is underway. The complete upper half is scheduled to be installed at SNOLAB in June 2013.

Partners

In Canada: Laurentian University, University of Alberta, University of Toronto, and Queen’s University. International Partners: Germany (1), Portugal (1), United Kingdom (6), United States (8).

TRIUMF’s Role
The design of the UI as described above was carried out in the TRIUMF Design Office. Fabrication of all the small components was done by the TRIUMF Machine Shop. Larger components, such as the barrels of the UI, were fabricated in an outside shop. Labour charges for the DO and MS were waived by TRIUMF. One TRIUMF Emeritus Researcher is member of the SNO+ collaboration.

HALO

The Helium and Lead Observatory (HALO) is a dedicated supernova neutrino detector located 2 km underground in SNOLAB. It is almost unique in that it is primarily sensitive to electron neutrinos, and is thus complementary to the water Cherenkov and liquid scintillation detectors that are mainly sensitive to electron anti-neutrinos. When fully commissioned, HALO will be sensitive to neutrinos from a core-collapse supernova anywhere in our galaxy and will be a member of the international SuperNova Early Warning System (SNEWS). A comparison of the data from neutrino detectors of different flavour sensitivities will allow understanding of the neutrino flavour transitions that occur in the core of the supernova, with important consequences for supernova explosion dynamics and for R-process nucleosynthesis. More details on the supernova dynamics can be found in Section 4.2.2.4.

Description of Facility

HALO is a "detector of opportunity," constructed largely from surplus equipment, namely: (1) 79 tonnes of lead blocks from a decommissioned cosmic ray station, worth $1M, (2) the He-3 neutron detectors from the third phase of the SNO experiment, worth $6M, and (3) the SNO electronics. The 869 annular lead blocks are stacked into a matrix measuring roughly 2.5 m wide x 2 m high x 3 m deep. The cylindrical He-3 neutron detectors are located inside the cylindrical voids in the lead matrix. A 30-cm thick layer of water and polystyrene shields the detector from neutrons emitted from the rock walls of the cavity.

Neutrinos from a supernova would undergo charged (neutral) current interactions with the lead nuclei and produce bismuth (lead) nuclei in excited states that decay by emitting one or two neutrons, which would thermalize and be captured by the He-3 neutron detectors. Monte-Carlo simulations indicate that the overall neutron detection efficiency will be around 43%, but this will be measured by placing a Cf-252 neutron source of known strength inside the lead matrix. A canonical supernova at the galactic centre with temperature T=8 MeV is anticipated to result in about 40 detected neutrons; a closer supernova at Eta Carinae or Betelguese, both of which are known to be unstable, would result in several hundreds to tens of thousands of neutrons. Because lead has a large cross-section for neutrino interactions, the 79-tonne mass of HALO will yield about the same number of interactions as the only other detector primarily sensitive to ν_e, namely the 600-tonne ICARUS liquid argon detector at the Gran Sasso laboratory in Italy. A rough statistical measure of the neutrino energy will be given by the ratio of 1-neutron to 2-neutron emission events.

Construction began in summer 2009 with the cleaning and painting of the lead blocks, which were then moved into the underground clean-room environment of SNOLAB and stacked, starting in March 2010. The He-3 neutron detectors, which had been welded together in long strings for the SNO experiment, had to be carefully cut apart into their constituent modules, refurbished with new endcaps, and individually tested. HALO began data taking in May 2012 with a full set of 128 He-3 neutron detectors. The activities still underway include calibration of the neutron detectors, and replacement of the legacy electronics and data acquisition system with a modern system that has built-in redundancy to ensure that no single-point failure will cause HALO to miss the ~20 second long neutrino burst from the next galactic supernova. Figure 2 shows a view of HALO, with the front shielding wall not yet installed.

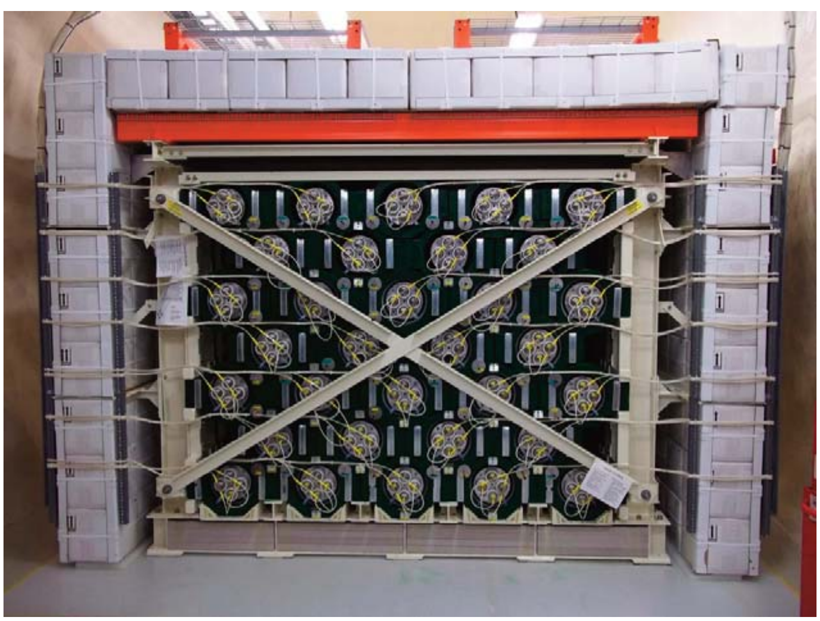


Figure 2: HALO, front shielding wall not yet installed.

Partners

In Canada: Laurentian University.
International Partners: Germany (1), United States (5).

TRIUMF's Role

TRIUMF has played several important roles in the development of HALO: defining the physics potential of HALO to elucidate neutrino flavour transitions in supernovae designing and assembling the detector, fabricating the high-voltage and signal cables and the test stand for testing the neutron counters before installation, and the ongoing operation and upgrades to HALO.

References

M. Schumacher et al. [HALO collaboration] Data Acquisition for the Helium and Lead Observatory, IEEE Conference Record 2010 Nuclear Science Symposium, paper ID N65-3.

SuperCDMS

Numerous astrophysical and cosmological observations indicate that nearly a quarter of the energy content of the universe is in the form of a non-luminous matter that cannot be explained by known particles. This so-called "dark matter" problem is one of the most pressing issues in physics today. The most compelling explanation consistent with the observations is that dark matter is composed of heretofore-unidentified weakly interacting massive particles (WIMPs) produced in the Big Bang.

The SuperCDMS-SNOLAB experiment is the next step in a series of very successful dark matter experiments that use superconducting transition edge sensors to detect the phonons from nuclear recoils produced by interactions of WIMPs in germanium and silicon crystals. The ionization is also collected and measured, providing discrimination against background. By employing larger, improved detectors at SNOLab, where cosmogenic backgrounds will be greatly reduced, SuperCDMS-SNOLab aims to have nearly two orders of magnitude more sensitivity to WIMPs than current experiments.

Description of Facility

CDMS (cryogenic dark matter search) technology detects WIMPs by measuring the ionization and phonons produced in WIMP-nucleus interactions in germanium and silicon crystals. The ionization and phonon information provides a powerful means to detect and reject backgrounds caused by contaminants on the surface of the detector. Results from this method have been at the forefront of the direct dark matter detection field for many years. It has also weighed in on a purported claim of evidence for direct dark matter detection, in particular low-mass signals reported by the DAMA, CoGeNT and CRESST experiments, rejecting most of the allowed region of WIMP mass and cross-section inferred from these claims. This technology is generally considered the most proven in terms of background rejection among dark matter experiments and can obtain lower thresholds and sensitivity to lower-mass WIMPs than most competitors.

Recent Developments

Recent R&D efforts have led to a new detector configuration ("iZIP") (see Figure 3) in which interlaced electrodes on both sides of the detector provide a large improvement in discrimination against surface contamination, as well as larger detectors that provide more detector mass (hence sensitivity) and further reduce the impact of surface contamination. The proposed SuperCDMS-SNOLAB experiment will place these new detectors in SNOLab, where the backgrounds from cosmogenic sources will be greatly reduced. The combination of these improvements will result in sensitivity to WIMP-nucleon cross-sections of $\sim 10^{-46}$ cm^2, comparable to the projected sensitivity from experiments using other methods, and cover a large fraction of WIMP masses and cross-section predicted by extensions to the Standard Model.
The total project cost for SuperCDMS is $29M.

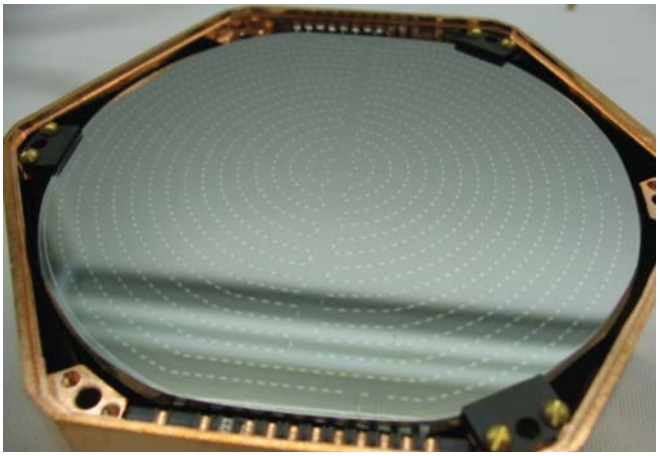


Figure 3: An interlaced z-dependent ionization and phonon detector ("iZIP") for SuperCDMS.

While CDMS detectors have been in operation for some time, the SuperCDMS-SNOLab project is in the R&D phase. In 2012, SuperCDMS-SNOLab responded to a solicitation from US funding agencies for one-year R&D proposals for "second generation" direct dark matter experiments. The outcome of this competition is expected soon. This will be followed in approximately one year by an additional competition to select a few projects for construction.

In Canada, SNOLab has responded positively to hosting SuperCDMS. A request to the Canada Foundation for Innovation Leading Edge Fund for $4.2M to provide the cryogenic and shielding infrastructure for the project was successful, contingent on the US selection process. The University of British Columbia (UBC) joined collaborators at Queen's University to enlarge the Canadian component. In 2012, a proposal to develop a MIDAS-based DAQ system for the experiment was accepted.

Partners

In Canada: Carleton University, Laurentian University, Queen's University, TRIUMF, University of Alberta, University of British Columbia, University of Guelph.
International Partners: Spain (3), United States (75).

TRIUMF's Role

Canadian collaborators at UBC, with technical support from experts in the TRIUMF DAQ Group, have recently taken a leadership role in the development of a MIDAS-based data acquisition system for SCDMS. Continued expert support from the DAQ group is needed to finish the development program and to maintain the system once the experiment is in operation. TRIUMF also provided a MIDAS-based DAQ for the DEAP (please see Section 5.5.5.5) experiment, creating synergy, allowing the sharing of expertise between the two experiments, and creating the possibility that MIDAS will become the preferred in-house DAQ solution at SNOLab as it is at TRIUMF.

DEAP

The Dark Matter Search Experiment with Liquid Argon Pulse Shape Discrimination (DEAP) was constructed 2009–2013 at SNOLAB in Sudbury, Ontario, roughly 2 km underground. The aim of the experiment is to detect weakly interacting massive particles (WIMPs) interacting in 1 ton of liquid argon.

While dark matter nicely explains a number of astronomical and cosmological data, its nature is not known. WIMPs are compelling dark matter candidates, but they have not been detected unambiguously, either directly, or at the Large Hadron Collider through their production in p-p collisions. DEAP's aim is to achieve a sensitivity to the WIMP interaction cross-section of 10^{-46} cm^2 for WIMP mass of 100 GeV, which is about a factor of 10 better than the best existing large underground xenon (LUX) dark matter experiment in South Dakota. DEAP is expected to start taking physics data in 2014.

Description of Apparatus

The core of the DEAP experiment is 3.6 tons of liquid Argon enclosed in an acrylic vessel (see Figure 4). WIMPs are expected to interact elastically in liquid argon, bouncing on Argon nuclei that subsequently recoil, producing scintillation light. The scintillation photons are detected by 255 8" diameter photo multiplier tubes (PMTs) that surround the acrylic vessel. The PMTs are attached to 20 cm long acrylic light guides bounded onto the acrylic vessel. The light guides absorb the neutrons emitted by radioactive material inside the PMTs and bring the temperature from 100°K at the acrylic vessel surface to about 250°K at the PMT front face, which simplify their operation. The whole detector is enclosed in a steel shell, itself immersed in a water tank. The water tank is instrumented with 48 PMTs in order to detect and veto residual cosmic muon interaction.

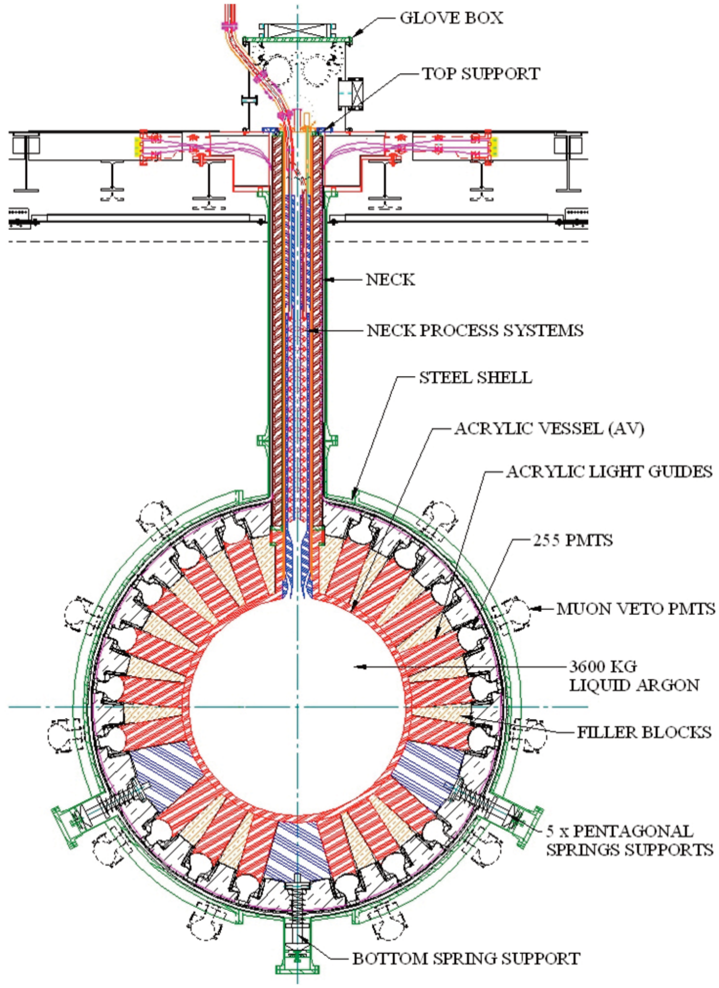


Figure 4: Schematics of the DEAP experiment.

The vast majority of the interactions in liquid argon are due to the beta decay of the Ar-39 isotope. It occurs at a rate of about 3.6 kHz, while the WIMP interaction rate will be, at best, µHz. Hence, reliable Ar-39 background rejection is critical to the success of the experiment. It is achieved by measuring the fraction of scintillation light emitted by Argon atoms in the singlet and triplet excited states that decay in 7 ns and 1.6 µs, respectively. Electron recoils from beta decay or gamma-ray interactions yield a much larger fraction of atoms in the triplet state than nuclear recoils (from WIMP and neutron interactions) do. The pulse shape discrimination technique relies on measuring the number of prompt photons (i.e. coming from the de-excitation of atoms in the singlet state) over the total number of photons. One of the main experimental challenges of DEAP will be to achieve an electron recoil leakage in the nuclear recoil sample of 10^{-10}. The electronics readout system was designed to allow counting every single scintillation photon detected by PMTs in order to optimize the background rejection.

Recent Developments

The DEAP experiment construction spans the entire time between 2009 and 2013. Figure 5 shows the acrylic vessel as of February 2013. Machining of the acrylic vessel was completed in June 2013 and the light guide bounding is proceeding with completion expected by October 2013. The steel shell, the process system, the calibration systems, and the electronics are being constructed in parallel. The acrylic vessel is expected to be ready for filling with liquid argon by April 2014. Detector commissioning will start in January 2014 using calibration light sources.

Partners

In Canada: Carleton University, Laurentian University, Queen's University, TRIUMF, SNOLab, University of Alberta.
International Partners: United Kingdom (3).

TRIUMF's Role

TRIUMF's contribution to the experiment includes engineering support for the design of the steel shell, the fabrication of the acrylic light guides, and the design, construction and commissioning of the complete electronics readout system. 265 optical quality light guides were machined and polished from raw square blocks in TRIUMF's scintillator shop from February 2012 to April 2013.

TRIUMF has complete responsibility for the readout electronics system. The electronics hardware fabrication and installation was completed in April 2013. Data acquisition and trigger software development will be completed by early 2014. The optimization of the trigger system is likely to be an active field of research in 2014.

Figure 5: Acrylic vessel, underground at SNOLab.

5.6 NUCLEAR MEDICINE INFRASTRUCTURE

TRIUMF's expertise in the production and handling of rare isotopes has given it the opportunity to expand beyond the physical sciences to the biological sciences and nuclear medicine. The use ranges from proton therapy to treat ocular melanoma to the production of rare isotopes for medical imaging. Each requires its own specialized facilities. The isotopes are used for diagnoses or treatment related to human subjects; the requirements are even more stringent than for normal science.

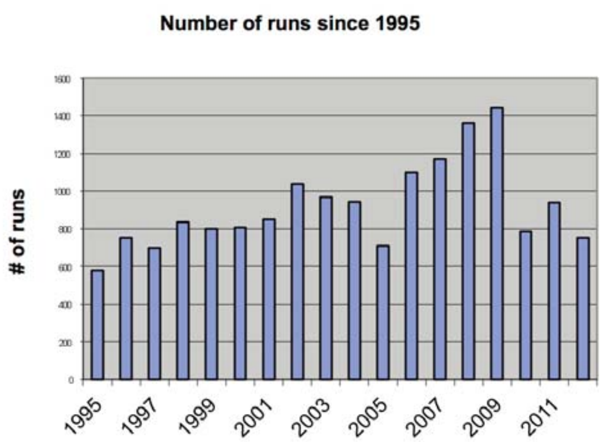
5.6.1 TR-13 CYCLOTRON

The TR-13 is the smallest cyclotron at TRIUMF, accelerating H^- ions to 13 MeV. It is located in the Meson Hall extension and produces isotopes that are primarily used for the production of carbon-11 (C-11) and fluorine-18 (F-18) containing radiopharmaceuticals. The main programs supported are the Pacific Parkinson's Research Centre (PPRC) and the BC Cancer Agency (BCCA).

Description of Facility

From 2008–2012, the TR-13 operations group delivered 49,948.7 μA-hrs in 5,282 separate runs with a very good reliability of 98.7% (see table below and Figure 1) The following isotopes were produced: N-13, F-18 (as F^- ion and F_2 gas), C-11 (as CH_4 and CO_2), Co-56, Co-55, Tc-94m, Mn-52, Sc-44, and Ga-68. Currently, there are eight targets mounted at two target stations, three water targets, four gas targets and one solid foil target.

Year	Number of runs	Number Lost runs	Reliability	Delivered beam
				(μA-hrs)
2008	1361	9	99.3%	14151.0
2009	1445	5	99.7%	13947.1
2010	784	12	98.5%	8960.5
2011	939	25	97.4%	6533.3
2012	753	17	97.8%	6356.8
Total	5282	68	98.7	49948.7



Until 2010, F-18 was produced twice daily for the FDG production needed by the BC Cancer Agency. Since then the BCCA has been operating their own cyclotron, and TRIUMF only delivers F-18 to them during their maintenance periods.

Recent Developments

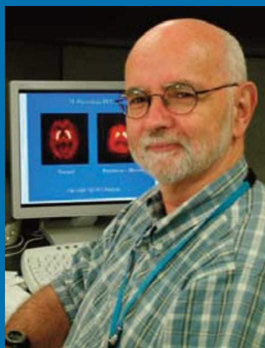
In 2011, the aging cyclotron control system was upgraded to EPICS, the TRIUMF site standard. The hardware for the target control was upgraded and expanded to deliver different isotopes to five different hot cells in three different locations. Several new targets were introduced for production of [C-11]CO_2, Tc-94m, Sc-44, and Ga-68 (please see section 4.2.3.3). A total of 11.3 % of all runs were classified as development runs to improve existing targets or to investigate new targets or isotopes. Five undergraduate students were trained during the course of these projects.

Partners

In Canada: BC Cancer Agency, Pacific Parkinson's Research Centre, University of British Columbia.

TRIUMF's Role

TRIUMF's TR-13 cyclotron and the operations team have been essential for the production and study of novel isotopes.



TOM RUTH WINS THE MICHAEL J. WELCH AWARD

11 April 2011

TRIUMF's Dr. Tom Ruth was awarded the 2011 Michael J. Welch Award of the Radiopharmaceutical Sciences Council, which is given to individuals who have made a significant contribution to the field of radiopharmaceutical sciences.

"It is an honour to receive this award, however this award really reflects on the great people with whom I have had the opportunity to work," said Dr. Ruth who is a research scientist at TRIUMF and a jointly appointed BC Cancer Agency senior researcher. This award is significant as it indicates North American recognition of Dr. Ruth's work.

Dr. Ruth was recruited as a Research Scientist by TRIUMF in 1980 to help develop the UBC PET (Positron Emission Tomography) group, which he lead as associate director from 1989 to 2008. During that time he oversaw the installation of 4 PET scanners and the TR-13 cyclotron, which is specially designed for producing medical isotopes and lead to the local manufacturing of low energy TR series of cyclotrons by ACSI in Richmond, BC. Dr. Ruth also collaborated with Dr. John Vincent at TRIUMF to develop techniques to generate Rb-82, which are now used by the Ottawa Heart Institute for heart imaging on a daily basis.

5.6.2 LABS AND FACILITIES FOR NUCLEAR MEDICINE INFRASTRUCTURE

TRIUMF has undertaken steady, incremental renovations of its nuclear medicine laboratory space to provide modern facilities that meet established standards for preparation of preclinical and clinical pharmaceuticals.

Description of Facilities

The nuclear medicine laboratories include the GMP lab and the Meson Hall Extension Service Annex (MHESA) laboratory.

Recently a new good manufacturing practice (GMP) lab (see Figures 2, 3), containing three new hot cells for the production of radiopharmaceuticals for human use was completed in the lower level of the Chemistry Annex at TRIUMF. Western Economic Diversification Canada provided nearly \$1M of capital assistance for this project.

This lab is designed with a clean air room area surrounding the hot cells so that the production of radiopharmaceuticals can be prepared in a controlled air environment. The hot cells also have air filtration that increases the clean room level inside the hot cells where the processes are carried out. The lab is equipped with surfaces that can easily be cleaned and sterilized. It also has an area outside of the clean room where quality

Figure 2: GMP labs at TRIUMF.
Figure 3: Chemistry synthesis unit at GMP labs.

control analysis, shipping, and workflow conform to the regulatory criteria defined by Health Canada. This lab also has restricted access to authorized personnel only. It is expected that all of the current PET radiopharmaceuticals, such as C-11 methyphenidate, raclopride dihyrotetrabenzine, DASB, MRB, yohimbine, and fallypride as well as F-18 dopa will all be prepared in this new GMP lab space in 2013. These are agents currently being use in the Pacific Parkinson's Research Centre's research program, funded by a Canadian Institutes of Health Research team grant.

A new joint TRIUMF/Nordion in the MHESA basement contains 4 new hot cells for research radiochemistry and became operational in April 2013. The lab is equipped with a state-of-the-art ventilation system and control systems to meet current regulatory requirements. This new ventilation system will allow us to do research on a wide variety of radioisotopes in a safe manner. It is intended that research will be conducted on collaborative projects between Nordion and TRIUMF researchers.

Five projects have been identified for 2014, with particular emphasis on the interaction between TRIUMF and Nordion on the production of Tc-99m using cyclotrons.

Figure 4: Hot cell robotic arms at the MHESA Lab.

TRIUMF JOINS CUTTING-EDGE ALZHEIMER'S STUDY

26 August 2009

The University of British Columbia (UBC) and TRIUMF Positron Emission Tomography (PET) group is playing a major role in a groundbreaking new study that could significantly advance the understanding and management of Alzheimer's disease. The much larger Alzheimer's disease Neuroimaging Initiative (ADNI) is being supplemented by a new subset of studies involving 16 North American PET centres, including the UBC and TRIUMF PET group. These sub-studies will image extracellular deposits of protein aggregates on the brain (called amyloid plaques) using PET scanners and [C-11] Pittsburgh Compound B (PIB) in a subset of study participants who are scheduled to receive normal PET scans.

"Originally, researchers could not demonstrate the presence of these telltale amyloid plaques, which would definitively diagnose a patient with Alzheimer's, until the time of autopsy," explained Dr. Tom Ruth, Senior Research Scientist participating in the project at UBC and TRIUMF.

The development of biomarker and imaging studies that track the development and progress of Alzheimer's may lead to a predictive test or better treatments for the disease. According to Dr. Ruth, if pharmaceuticals to remove amyloid plaque are developed from the research being conducted worldwide, scientists may be able to intervene at an earlier stage and slow or even halt the progression of Alzheimer's disease.

With one new laboratory nearly complete, future expansion has begun on renovations in two additional labs to serve as an intermediate-level nuclear medicine/ radiochemistry facility with shielded fume hoods, as well as a new target manufacturing facility.

Installation of a new CFI-funded trimodal PET/SPECT/CT pre-clinical imaging camera was completed in the fall of 2012 in the new Centre for Comparative Medicine (CCM) building across Wesbrook Mall from TRIUMF. Work on a pneumatic transfer line for subterranean transport of radiotracers is slated began in August 2013.

Partners

BC Cancer Agency, Hevesy Laboratory (Denmark), Nordion, Inc., University of British Columbia, General Electric, Pacific Parkinson's Research Centre, and Simon Fraser University

TRIUMF's Role

TRIUMF's TR-13 medical cyclotron where much of this work took place under the supervision and guidance of researchers in the Nuclear Medicine Division. TRIUMF's lead radiochemists have led several of these research efforts and collaborate closely with researchers at the Pacific Parkinson's Research Centre and the BC Cancer Agency. In addition, TRIUMF's Paul Schaffer leads the Genome BC effort and the collaboration with General Electric.

5.6.3 PROTON THERAPY FACILITY

TRIUMF provides radiotherapy in collaboration with the BC Cancer Agency and the UBC Eye Care Centre by operating Canada's only Proton Therapy Facility.

Since 1995, patients with ocular melanomas have come to TRIUMF to receive treatment, achieving a local tumour control of 91%. Between April 1, 2008 and April 1, 2013, 40 patients were treated with protons during five scheduled treatment sessions each year. This brings the total number of patients treated with protons at TRIUMF since the start of the program to 170, with an average per year of 9.4 (see Figure 4).

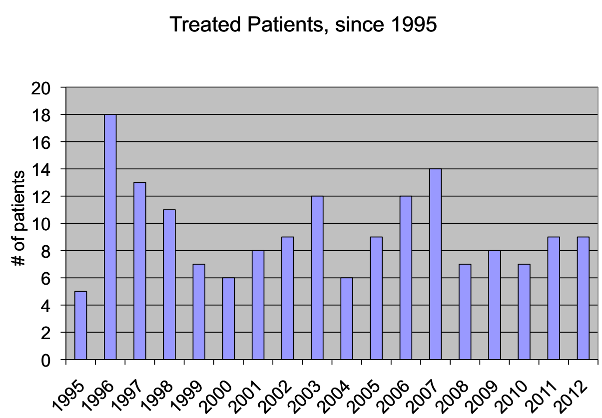


Figure 4: Patients since beginning treatment in 1995.

Description of Facility

Treatment is carried out using a modulated beam of 74 MeV protons at Beam Line 2C1 with the dose delivered over 4 daily fractions, each taking about 90 seconds. The alignment of the tumour to the proton beam is made by taking X-rays of tantalum marker clips that are placed around the tumour by the ophthalmologist in a surgical procedure a week or so before treatment (see Figure 5). These clip positions are then compared to the desired locations determined by the treatment-planning program. The patient chair is then moved to correct for any errors.

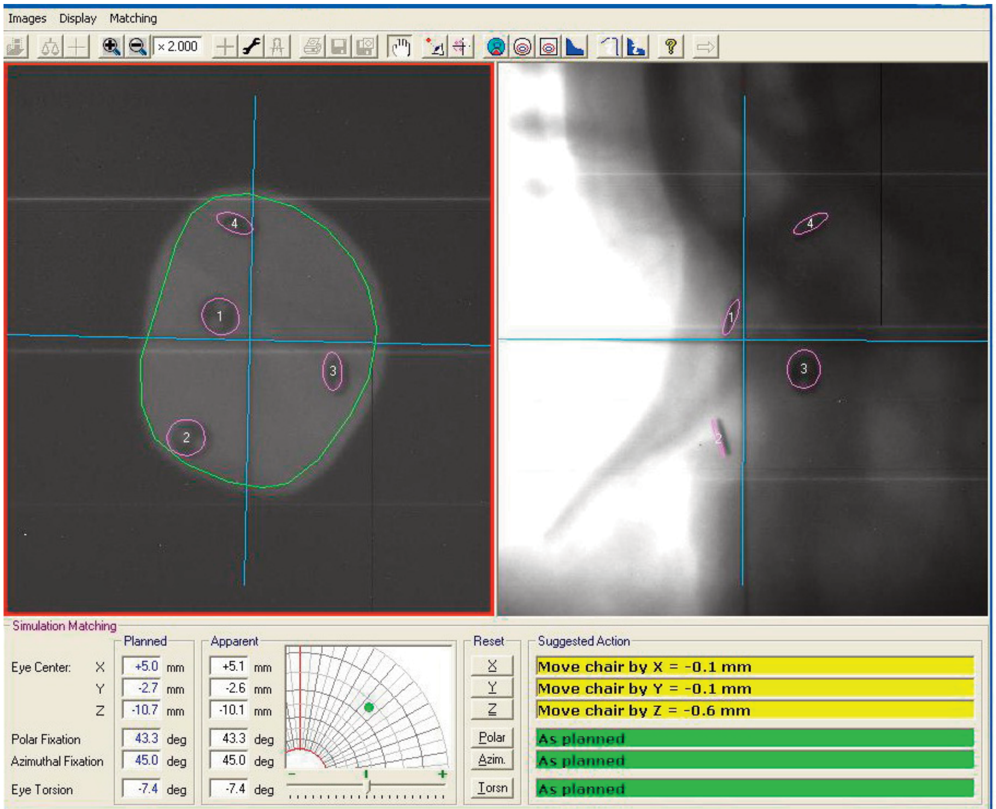


Figure 5: Digital X-ray image, lateral and axial. This patient had four metal clips inserted around the tumour. The software is used to match the expected position of the clips (purple circles) with the actual clip position in the X-ray image, thus aligning the patient.

Recent Developments

Since the beginning of TRIUMF treatments, X-rays have been imaged using a Lanex intensifying screen and Polaroid film. As the type of Polaroid film used is no longer being manufactured, alternative methods for imaging X-rays have been tested over the past years. The solution that has been selected is a digital X-ray camera based on a CMOS image sensor manufactured by the Rad-icon Imaging Corporation. This camera has an active area of 5 cm x 5 cm with 1024 x 1000 pixels. X-ray tests have shown the desired sensitivity and, in 2009, the images were integrated into the Eye Plan Treatment Program to provide rapid patient position information. It was successfully introduced to align patients in December 2009 and has been in use ever since.

In 2012, the waiting room and patient washroom were renovated to maintain a pleasant and welcoming environment for patients and their accompanying families. The waiting room received new flooring, ceiling, paint, and some new furniture. The washroom was updated with new fixtures, tiles, and paint.

Partners

BCCA, University of British Columbia's Eye Care Centre, University of British Columbia PET Centre.

TRIUMF's Role

TRIUMF has taken the lead in exploring PET after PT, as well as the modelling of the local treatment facility. In both cases, the local FLUKA expertise has been used. A Ph.D. student has been recruited to continue this work.

5.7 THEORY TOOLBOX

The TRIUMF Theory Group pursues a broad research program in the areas of low-energy nuclear physics, hadronic physics, and high-energy particle physics.

5.7.1 NUCLEAR PHYSICS

Atomic nuclei are made of nucleons, protons, and neutrons that themselves are composite particles made of quarks and gluons. The fundamental theory of the strong interaction, the quantum chromodynamics (QCD), is, however, non-perturbative at the low-energy regime relevant for nuclear physics. At present we are not able to calculate nuclear properties directly from the QCD or even to derive exactly the nucleon-nucleon interaction from the QCD. Currently, the most promising bridge between the QCD and the low-energy nuclear physics is the chiral effective field theory (EFT), allowing for derivations of nucleon-nucleon and three-nucleon forces consistent with the underlying QCD symmetries. Such forces then serve as a starting point for various many-body techniques that can be applied to solve the quantum-mechanical nuclear many-nucleon problem.

We have developed the capability to describe light nuclei as systems of nucleons interacting by realistic inter-nucleon forces, i.e. forces derived from the QCD by means of the chiral EFT that accurately fit nucleon-nucleon and three-nucleon data. At TRIUMF we concentrate on studying nuclear structure and reactions with *ab initio* approaches, which allow us to address a variety of observables.

Weakly bound or even unbound exotic nuclei produced at TRIUMF experiments cannot be understood using only bound-state techniques. Our *ab initio* many-body approach, no-core shell model with continuum (NCSMC) focuses on a unified description of both bound and unbound states. Within such an approach, we can simultaneously investigate the structure of nuclei as well as their reactions. The method combines a square-integrable harmonic-oscillator basis accounting for the short- and medium-range many-nucleon correlations with a continuous basis accounting for long-range correlations between clusters of nucleons. With this technique, we can predict the ground- and excited-state energies of light nuclei (p-shell, $A \leq 16$) as well as their electromagnetic moments and transitions, including weak transitions. Furthermore, we can investigate properties of resonances and calculate characteristics of binary nuclear reactions, i.e. cross-sections, analyzing powers etc.

Recent applications of our *ab initio* techniques included an investigation of the unbound He-7 [1], calculations of the ^{3}H(d,n)^{4}He and ^{3}He(d,p)^{4}He fusion (see Figure 1) [2], the calculation of the ^{7}Be(p,γ)^{8}B radiative capture [3] important for the Standard Solar Model and the neutrino physics (see Figure 2). Our calculations also supported the TRIUMF experiment to determine the sign of the quadrupole moment of the first excited state in Be-10 [4]. We were also able to demonstrate a unique role of the chiral three-nucleon interaction in the origin of the anomalously long half-life of C-14 used for archaeological dating [5].

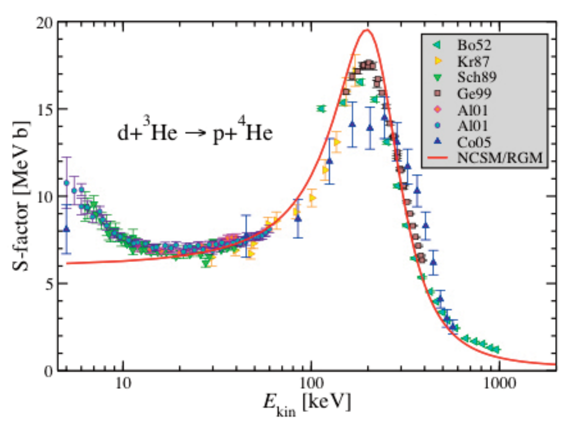
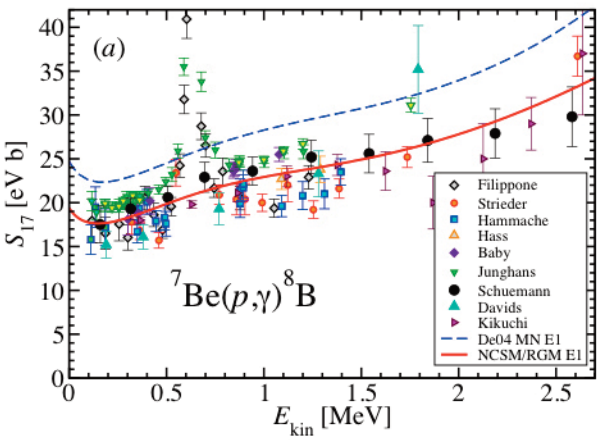


Figure 1: Experimental results for S-factor of ^{3}He(d,p)^{4}He reaction from beam-target measurements. The full line represents the *ab initio* calculation. No low-energy enhancement is present in the theoretical results, contrary to the laboratory beam-target data.



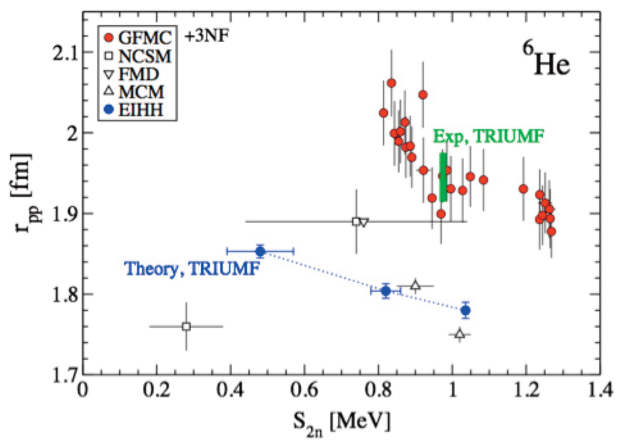


Figure 2: The *ab initio* calculated $^{7}Be(p, \gamma)^{8}B$ S-factor (full line) compared to experimental data and the calculation used in the latest evaluation (dashed line).

Figure 3: Correlation plot of the He-6 point-proton radius r_{pp} versus the two-neutron separation energy S_{2n}. The experimental range is compared to theory based on different *ab initio* methods. All calculations, but the red circles, omit three-nucleon forces. The fact that they do not go through the experimental band points towards the importance of three-nucleon forces in nuclear physics.

Our *ab initio* approach can be extended to reach *sd*-shell and medium-mass nuclei by employing various techniques of basis reduction such as the importance-truncated no-core shell model or the coupled-cluster method. These approaches were recently successfully applied to carbon, oxygen, and calcium isotopes [6,7]. We also work on a three-cluster extension of the method to describe, e.g., the Borromean nuclei such as He-6 and Li-11. Finally, we are implementing the capability to study reactions of nuclei with electroweak probes with the possibility to calculate, e.g., neutrino cross-sections on light nuclei.

An alternative method to calculate ground-state properties of light nuclei is to use hyperspherical harmonics (HH) expansions. They are typically employed in few-body physics to study nuclei with mass number A=3 and 4, but can be extended to larger mass number like A=6,7 and 8. The HH approach has the advantage that an exponential fall-off of the wave function is implemented, which accelerates the convergence of the expansion.

At TRIUMF we recently used this method to calculate the two-neutron separation energy and the point-proton radius for the He-6 halo nucleus from low-momentum chiral forces (see Figure 3). Theoretical results were published together with experimental data obtained at the TRIUMF TITAN Penning trap [8,9]. TRIUMF is a unique place to merge theory and experiment concerning the physics of halo nuclei.

One can use bound state techniques like HH even to calculate break-up reactions induced by perturbative probes, like photons, electrons, or neutrinos. This is achieved using the Lorentz Integral Transform (LIT) method, in which the continuum problem is reduced to the solution of a bound state–like equation.

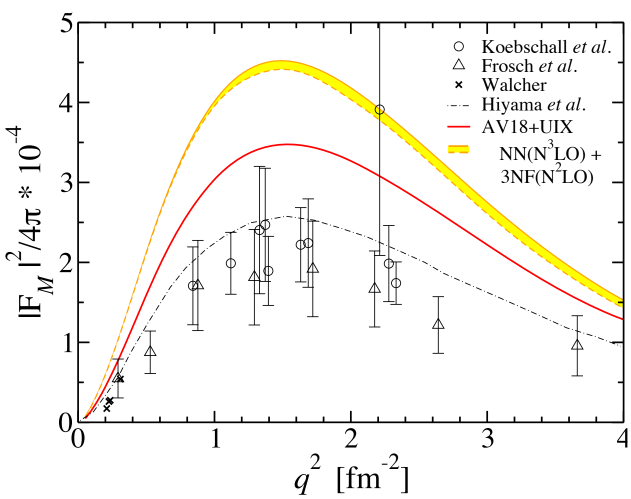


Figure 4: Theoretical He-4 transition form factor $0^+1 \rightarrow 0^+2$ as a function of the squared momentum transfer q^2 calculated with various Hamiltonians, which all include three nucleon forces, in comparison to the available experimental data from electron scattering off He-4.

One of our recent case studies with the LIT method is the monopole transition form factor from the ground state 0^+_1 to the first 0^+_2 excited state in He-4 [10], which can be extracted from electron scattering data. We have used several different nuclear Hamiltonians, which include three-nucleon forces as the sole input of our calculations. Such Hamiltonians lead to the correct experimental binding energy of He-4. Interestingly, we observed a very strong dependence of the theoretical results on the input Hamiltonian (see Figure 4), which makes this observable extremely interesting. We have also calculated the nuclear dipole polarizability of the halo He-6 nucleus [11] with simple two-nucleon potentials and found out that theory under-predicts experimental data.

For the future, we plan on using the LIT method in conjunction with other bound state techniques, like coupled cluster theory, which will allow us to extend the present limits on mass number. We aim at studying, for example, giant dipole and quadrupole resonances in medium mass nuclei from first principles.

5.7.2 HADRONIC PHYSICS

Quantum chromodynamics (QCD) is the theory of the strong force. At high energies, the relevant degrees of freedom are quarks and gluons, while at lower energies the coupling among these states becomes so strong that they confine into colour-neutral hadrons. It is not known how to compute analytically the properties of hadrons from the underlying theory of quarks and gluons, so other methods must be used.

TRIUMF's Theory Group has the capability to study low-energy QCD and many different kinds of hadronic systems using the methods of lattice field theory. All aspects of numerical simulation of lattice field theory can be dealt with including Hybrid Monte Carlo for generation of field configurations, conjugate gradient methods for the calculation of fermion propagators, and advanced analysis methods such as constrained fitting for extraction of excited hadronic states. At present it may be optimal to use different methods in different quark mass sectors. The Group can handle simulations over the whole quark mass range from light to bottom using clover, highly improved staggered, or non-relativistic, fermions as appropriate.

Recent applications of these methods include a study of D meson resonances [1], and the calculation of radiative decay amplitudes for excited bottomonium states [2]. More details may be found in Section 4.2.2.1. These methods for studying QCD have also be applied to other field theories such as the lattice Higgs model or the Higgs-Yukawa model, as well as to other gauge theories which may be relevant beyond the Standard Model [3].

Partners

In Canada: Simon Fraser University, York University
International Partners: Austria (1), Germany (1), Slovenia (1), United States (1).

TRIUMF's Role

The work described here was led by a research scientitst and/or a post-doctoral research fellow in the TRIUMF Theory Group with participation of Canadian and international collaborators. Some calculations were carried out using the TRIUMF Theory Group computer cluster.

5.7.3 HIGH-ENERGY PARTICLE PHYSICS

The primary research focus of the Theory Group in high-energy particle physics is the search for new particles and forces. Our current understanding of elementary particles is given by the Standard Model (SM). While the SM is able to explain the results of a broad range of experiments, there are many key questions the theory is not able to answer. Most important among these are the mechanism of electroweak symmetry breaking that separates the weak from the electromagnetic force, the cosmological puzzles of dark matter, the excess of matter over antimatter, and the origin of neutrino masses.

In the SM, electroweak symmetry breaking is induced by the Higgs field. A recent major advance in this direction has been the discovery of a new particle at the CERN LHC with the right properties to be the corresponding Higgs boson. The Theory Group has extensive expertise in Higgs physics and has the capability to predict the rates of Higgs boson production and to simulate the signals these processes would generate in collider detectors for both the Higgs of the SM and in more complicated extensions. The Group has used this expertise to interpret the new experimental data and to apply it to test whether the newly discovered particle is the Higgs boson predicted by the SM or something more exotic [0a, 0b].

The strong sensitivity of the SM electroweak sector to quantum corrections suggests that there exist new particles and forces with masses just above the weak scale, a range that is currently being probed by the CERN LHC. Members of the Theory Group have contributed significantly to the development of consistent theories for what this new physics might be [1]. They are also able to apply Monte Carlo simulation tools to model how such new phenomena would appear in high-energy colliders and estimate the discovery prospects [2,3]. Having such theories in hand has helped the LHC experimenters to focus their searches in the most promising directions. The experience of the Theory Group in developing new theories also places them in a competitive position to interpret any new discoveries or deviations from the SM at the LHC and other experiments [4].

The SM also fails to account for the observed cosmology. In particular, it is unable to explain the origin of dark matter (DM) or why there is more visible matter than antimatter. Theory Group members have proposed novel candidates for DM [5], and they have developed new mechanisms to account for the asymmetry of matter [6a, 6b]. The group has the capability to compute the signal rates of DM candidates in deep underground direct-search experiments, cosmic-ray telescopes, astrophysical systems, and at particle colliders [6a,6b, 7]. This is essential for testing whether a DM candidate is consistent with current experimental data and it helps to guide future searches for that candidate.

A second area of expertise of the Theory Group is in developing and investigating mechanisms to explain the asymmetry of matter relative to antimatter. A process for creating both the DM density and the matter asymmetry was proposed where the DM consists of hidden antibaryons [6a,6b]. An implication of this mechanism is that DM can scatter inelastically with a nucleon to create a meson and an anti-DM particle. The resulting signal mimics nucleon decay and can be searched for in nucleon-decay experiments. Figure 5 shows the cross-section for such a scattering process, with the grey shaded regions illustrating where the scenario is constrained by existing SuperKamiokande data. The Theory Group has also studied the implications of recent Higgs data at the LHC for mechanisms of baryon creation during cosmological electroweak symmetry in the early Universe [8]. This broad research focus allows the group to connect the results of many different types of experiments to each other, allowing for a maximal usage of the experimental data.

A further shortcoming of the SM is that it does not explain the origin of the broad range of particle masses that have been observed, from the very heavy top quark to the very light neutrinos. While the masses of the charged fermions can arise in a simple way from the Higgs field, neutrino masses are more puzzling. To explore the origin of neutrino masses, the Theory Group constructs models for how these masses can arise [9]. Such models can potentially be tested in neutrino experiments such as T2K (please see Section 4.2.1.2).

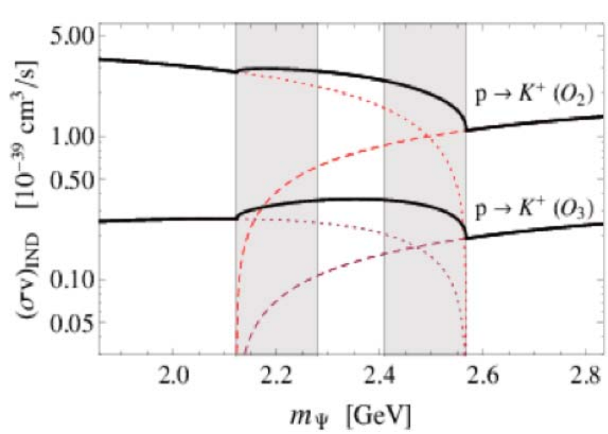


Figure 5: Cross-sections for nucleon destruction by hidden antibaryonic DM scattering.

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5.8 SCIENTIFIC COMPUTING

There are two aspects to computing at a laboratory like TRIUMF. One is the cutting edge computing, data collection and storage required for scientific research. This is typified by the ATLAS TIER-1 Data Centre and the light pipe connecting it to CERN in Switzerland. The other aspect is the computing requirements of any modern enterprise: internet connections, office software, e-mail etc. These do not exist as separate entities, but are connected by a common infrastructure like network switches and shared physical spaces. TRIUMF only runs smoothly, with the needs of both scientists and general users being met, when the various parts of the system work harmoniously together.

5.8.1 CANADIAN ATLAS TIER-1 DATA CENTRE

Computing resources play a critical role in extracting the science from the ATLAS experiment. The Large Hadron Collider (LHC) has been in full operation since 2010 and an enormous amount of data has been produced since then. The ATLAS experiment is collecting close to 3 Petabytes of raw data each year and producing several derived and simulated datasets that are of similar sizes. The data is stored and analyzed on an international network of high-performance computing centres that are linked together by high-speed networks and Grid tools: the Worldwide LHC Computing Grid infrastructure (WLCG). Part of this infrastructure, the Canadian Tier-1 Data Centre at TRIUMF is a key player and has been ramped up to full production at nominal capacities for data storage and processing. There are ten Tier-1 centres around the world and they are primarily responsible for storing and processing the raw data and to produce various derived datasets to be distributed to the worldwide ATLAS community in a timely fashion.

Description of Facility

The Tier-1 centre is a large-scale data-intensive facility that is maintained and operated 24 x 7 in full compliance with the WLCG Memorandum of Understanding (MOU). The Canadian Tier-1 is a leader in the field by being consistently at the top, or near the top, in terms of availability, reliability, and efficiency when compared to other sites in the world. The Tier-1 centre provides the dedicated resources necessary for the storage of the raw and secondary datasets, as well as compute nodes for data processing, simulation, and physics group activities in a secure environment. For the successful operation and exploitation of ATLAS, the Tier-1 centre is presently providing 10% of the required Tier-1 resources worldwide.

SFU/TRIUMF PHYSICIST SELECTED FOR ATLAS LEADERSHIP ROLE

23 January 2012

Effective this March, Project leader for the ATLAS Canadian Tier-1 Data Centre, Michel Vetterli (TRIUMF scientist and SFU physics professor), has been appointed deputy chair of the ATLAS Publications Committee (PubCom).

Vetterli will take over as chair of the ATLAS PubCom in March 2013 and move to Geneva for a year to be near the ATLAS particle detector at the CERN Large Hadron Collider. The PubCom is responsible for reviewing all papers and scientific notes published by ATLAS, an international collaboration of nearly 3,000 physicists and engineers.

"It's like being on a thesis supervisory committee, but you're interacting with more senior people so it's more challenging," says Vetterli of his new role. "As part of the executive board, you're in on many high-level discussions and you get to express your opinions."

The Tier-1 centre also plays a central role for the Canadian Tier-2 centres that are located at the Compute Canada shared facilities. Today, the Tier-1 centre consists of 7.2 Petabytes of usable disk storage, 5.5 Petabytes of tape storage, 4830 processor cores and 90 servers. Figure 1 shows the Tier-1 centre architectural diagram. As part of WLCG and ATLAS distributed computing operations, several critical services are being provided: a set of Compute Elements that act as gateways for ATLAS Grid jobs; a Storage Resource Manager layer to store and access the data; a top- and site-level Berkeley Database Information Index (BDII) to publish Grid resources and services access points; a Grid accounting service to collect and publish usage information; Squid proxy servers for caching database information and ATLAS software; a Frontier service to provide access to Oracle database information related to detector conditions; an Oracle database repository of meta data information related to the properties of ATLAS collision events (used for event and file selections); and, finally, a File Transfer Service (FTS) that is used for file movements between Grid sites and data replication. In terms of connectivity, the Tier-1 centre has dedicated network links to CERN (Tier-0), BNL (U.S. Tier-1), SARA (Netherlands Tier-1), and to the Tier 2 centres. The networking infrastructure was put into place in collaboration with and with support from CANARIE, BCNet and HEPNet-Canada. The network topology is shown in Figure 2. With respect to the Tier-1 operations and user support staff consists of 10 people (9.5 FTE), the smallest of any of the LHC Tier-1 centres. To date, the total project costs are close to $26.5M.

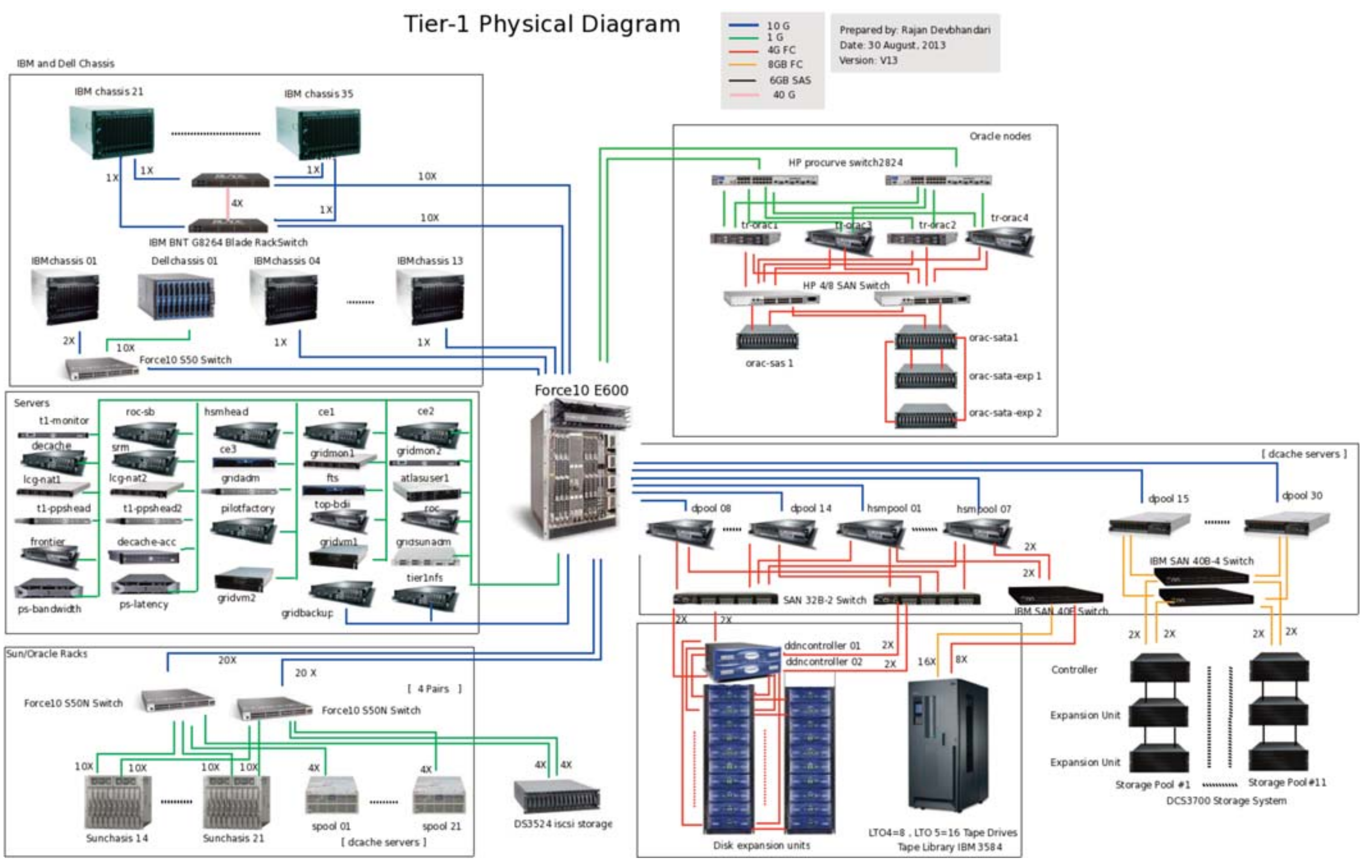


Figure 1: ATLAS Tier-1 architectural diagram.

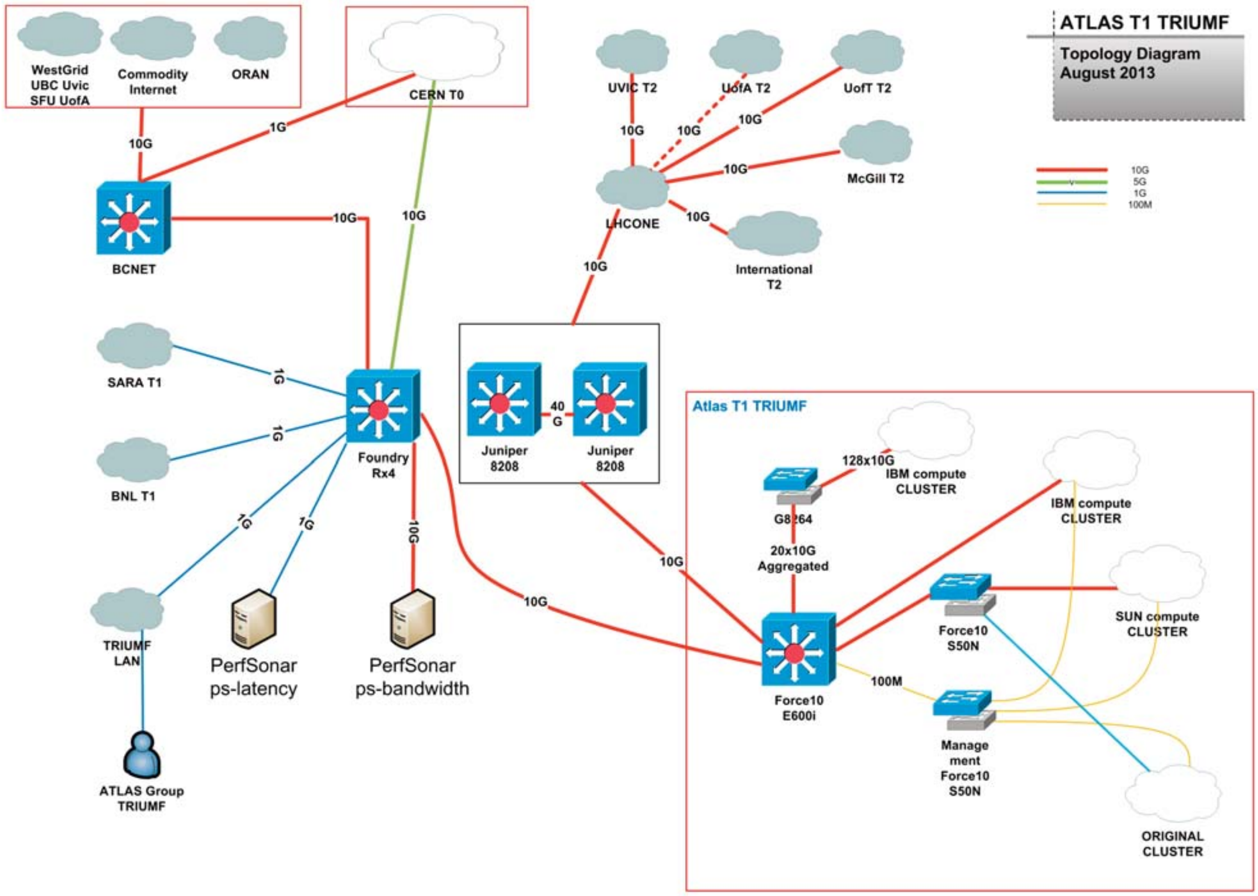


Figure 2: ATLAS Tier-1 network topology diagram.

Recent Developments

The ATLAS computing model has matured and evolved in order to adapt to real operating conditions with respect to data distribution and analysis on a global scale. At TRIUMF, the Tier-1 resources expanded by a factor of ten from the initial deployment of the facility back in 2007. Two large systems acquisitions were completed in the fall of 2009 and in late 2011, bringing the Tier-1 capacity to what it is today. In 2011, ATLAS-Canada submitted another proposal to CFI and was successful in securing $3.3M to cover the operating costs for the period 2012–2015. In 2012, another successful CFI proposal secured capital money for the replacement of computing equipment purchased in 2007 and 2009 ($2.5M as a total project cost with $1M from CFI).

The ATLAS Tier-1 is a centre of excellence, where highly qualified personnel and co-op students are trained using the best known practices with respect to data centre design, applications development, and systems administration for mission critical operations. A solid base of expertise has been assembled over the years while deploying large-scale storage systems, databases, complex clusters and network topologies, and Grid technologies. TRIUMF runs also the Canadian Regional Grid Operation Centre (ROC Canada) to oversee several Grid sites as part of the overall WLCG operations.

The ATLAS Tier-1 centre at TRIUMF also played an important role in the Higgs boson discovery that was announced in July 2012; it produced several simulation samples that were urgently needed in order to complete the analysis in time. During the last five years, nearly 20M Grid jobs have been processed and 60M hours of computing time have been utilized at TRIUMF; these resources were necessary to produce numerous ATLAS results.

Partners

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

TRIUMF's Role

TRIUMF provided contributions to several key areas: electrical and mechanical engineering, wide area networking infrastructure and expertise, and logistics with respect to shipping and receiving. TRIUMF scientists have played a leading role for the project as a whole since its inception.

5.8.2 COMPUTING FOR SCIENCE AND DATA ACQUISITION

Four computing groups provide computing and networking services at TRIUMF.

- **CCN -** Core-Computing and Networking, 8 FTE's provide the central computing and networking services for the site. Principal responsibilities include centralized email, printing, file and web servers, site backups, PC desktop support, networking and security.
- **MIS -** Management and Information Systems, 3 FTE's provide the computing support for the business and administration services, finance, human resources and supply chain management. It is also responsible for the development and support of custom applications to meet the unique requirements of TRIUMF.
- **DAQ -** Data Acquisition - 4.3 FTE's provide computing support to the TRIUMF experimental program. This small group is responsible for maintaining and supporting approximately thirty active experiments both locally and internationally. It is one of the key developers and maintainers of the MIDAS data acquisition system used by experiments at research facilities worldwide.
- **ATLAS Tier 1**, 9.5 FTE provides 24/7 operational support of the Canadian ATLAS Tier-1 Data centre. The TRIUMF Tier-1 is presently hosting ~5000 processor cores, 7 PB of disk storage and 5.5 PB of tape storage. It is the number one rated ATLAS Tier-1 site for availability and is providing 10% of the ATLAS LHC data to the international ATLAS community.

All four groups provide critical and in many cases unique IT services to TRIUMF staff and research scientists. The last five years have seen several significant developments. In 2009 an external international review committee was convened to examine the resources, services, organizational structure and prioritizing procedures of TRIUMF Computing groups. This resulted in several organizational changes. All four computing groups report to one computing group leader. The computing group leader was appointed to the senior management group. The CCN computing group has assumed responsibility for core services that were common amongst the other computing groups, reducing duplication of effort. The computing groups were also encouraged to take advantage of outsourcing various commodity IT services were feasible and to focus internal IT support in those areas unique to TRIUMF. TRIUMF is following this recommendation and is in the process of replacing the 30-year-old in-house custom developed ERP system with a modern commercial ERP (Enterprise Resource Planning) application. Commercial email and calendaring services are also being pursued. Software development is being limited to those applications that have unique TRIUMF requirements.

The following summarizes achievements specific to each of the TRIUMF computing groups.

CCN

The primary role of the Core-Computing and Network Group (CCN) is to provide a highly available, reliable and secure computing and networking infrastructure for the TRIUMF laboratory and staff. Its secondary role is to provide advice and expertise on a wide range of IT issues that assist laboratory staff and research scientists.

Traditionally the CCN Group provided scientific computing support for the TRIUMF research community. Over the last decade the focus has transitioned and broadened from scientific computing to all aspects of computing and networking services. This has become necessary in order to adapt to the widespread use and demands for computing by all staff, where previously the demand was driven by the research scientists.

To meet the demands of TRIUMF's research programs external networking requirements have been increased substantially. TRIUMF's 1GbE connection to the Canadian and international research networks was upgraded to 10GbE in 2010. TRIUMF in collaboration with BCNet and CANARIE have establish a high-speed, dedicated 10GbE network, connecting the Canadian eastern and western ATLAS Tier-2 sites to the Canadian Tier-1 centre and ATLAS sites internationally. In late 2011, an RFP was issued to replace aging 1GbE internal network core with 10GbE. The RFP was awarded to Juniper Networks in 2012. Full deployment is anticipated by the end of the summer of 2013. The new network core has been designed to meet TRIUMF's requirements for the next 7–10 years and will support the 100GbE, a requirement of the TRIUMF ATLAS Tier-1 by 2016/17.

TRIUMF IT has embraced the benefits of virtualization over the past few years. In 2012, CCN deployed both a virtualized storage and virtualized server environments based on the Red Hat Enterprise Virtualization (RHEV) and Nexenta virtualized storage. This has allowed CCN to operate a highly performant and reliable data centre with minimal staffing and infrastructure resources. In 2013, the virtualization will be extended to blade-based infrastructure, reducing further the resources needed for space and management.

CCN have adopted TRIUMF's strong and increasing commitment to documentation and monitoring. In the last five years it has incorporated new revision control procedures and enhanced existing monitoring systems for documenting, maintaining and monitoring configuration changes and availability of its IT services. This has improved significantly its ability to quickly deploy new, failed or failing services and to track and maintain a history of system changes.

MIS

Since the start of the current Five-Year Plan, the MIS Group has developed three new JavaEE applications: Human Resources (put into production use early 2010, but developed the previous year), Identity Management, and the Work-Request System. In addition, the transition of the Science Application from PHP prototype to JavaEE was completed when the Experiments Database component was re-written (the Beam Schedule and Beam Request components had been done prior to the Five-Year Plan). These applications continue to be updated, with the most notable enhancements being access-group maintenance and distributed identity management (both for IM) and the Experimenter's Dashboard (for Science).

Preparatory work to integrate TRIUMF applications with the new Agresso ERP has also been done. Agresso logins are now created and managed by the Identity Management application, and cost centre work orders are being propagated to the Agresso database. Further development in the integration of account validation and financial transaction postings are underway and will be completed before Agresso is "live."

The TRIUMF website was converted to a Drupal framework to coincide with the start of the previous Five-Year Plan. Since then, the most notable improvements have been automatic personal profile maintenance (integrated with the Identity Management application) and enabling group pages that allows groups to maintain their own portions of the public website.

DAQ

Over the past five years the small but productive DAQ group have supported and deployed real-time computing systems for an increasing number of successful TRIUMF experiments. This is a direct result of the recent success of CFI funded experiments over the last several years. The following is a condensed list of the groups' achievements over the past few years:

ALPHA : Electronics, Firmware, Full DAQ (2009–2011)

The DAQ system developed and maintained by the TRIUMF DAQ Group has been key to the successful science results obtained by the ALPHA collaboration in 2011. As for most major experiments, our involvement started from the beginning of the project.

Geotomo: VME-Based DAQ (2009–2010)

The first Geotomo detector based on standard VME boards required a fair amount of time for testing the VF48 waveform digitizers and reliability of the overall system, including the satellite communication.

AAPS/Geotomo/Cript: New DAQ Architecture (2011–2012)

For the next version of the Geotomo detector, we suggested designing the DAQ with custom hardware boards to make the system more flexible and more reliable. Its realization has been a great success, with the DAQ Group involved mostly for concept and problem solving and acting as consultant.

T2K-FGD: Electronics Development and Acquisition (2009–2011)

We developed custom hardware for the FGD, test bench for other sub-detectors DAQ, and successfully helped the T2K-UK group to take DAQ responsibility using MIDAS as their main DAQ.

TIGRESS: (2011–2012)

We improved time and energy resolution using dedicated firmware in the digitizers as well as completed the firmware for the TIG64 board (64ch. 50Msps) used for the TIGRESS auxiliary detectors.

GRIFFIN: (2011–2012)

We revised the design of the overall DAQ, designed a new digitizer (100Msps), and associated trigger module in collaboration with the Electronics Development Group.

DESCANT: (2012)

We developed firmware for the 1Gsps digitizer.

DEAP-3600: DAQ Architecture, Implementation, and Infrastructure (2010–2012)

Presently in full testing phase, the DAQ required the use of new commercial Waveform Digitizers and precise timing sychronization of all the acquisition boards. The large number of channels and the anticipated event rate required special front-end applications (multi-threaded) and in-line data filtering (event builder) in order to reduce the overall data collection to the experimental goal.

TRINAT: Successful DAQ Migration (2012)

TRINAT has been converted and is running VME modules. In particular, the use of the VMEIO custom trigger circuit has been extremely powerful.

IRIS: Successful DAQ Implementation (2012)

This experiment required multiple acquisition processors to ensure proper data synchronization, which has been achieved with the VMENIMIO32.

VF48 Firmware Development for LiXe, PiENu, TACTIC (2009–2011)

The VF48 have been used in several experiments but required a lot of firmware development to accommodate the different experimental requirements.

New DAQ Hardware Development: VMENIMIO32, VMEPPG32, MSCB (2010–2012)

These main VME units have been designed and programmed by the DAQ group with realization by the Electronics Group. So far, several units have been placed in experimental setup and are found to be very useful as custom trigger circuitry or as default standard DAQ functions (Scaler, Time Stamp, TDC). These boards can replace a good section of NIM modules and therefore address the aging state of the unmaintained NIM electronics.

5.9 LABORATORY ORGANIZATION

In addition to the physical plant, the productivity and performance of TRIUMF is determined by its administrative structures and the accumulated knowledge about how to operate and manage a laboratory effectively. TRIUMF has evolved a management structure and process that allows setting priorities and implementing them in a timely manner. In its December 2012 report to the NRC President, the Advisory Committee on TRIUMF noted:

The Committee finds that TRIUMF is performing its mission very well across the full spectrum of operating programs and future projects. The Director and the Heads of the Science, Accelerator, Nuclear Medicine, and Engineering Divisions work coherently as a team and provide outstanding leadership for the scientific and technical staff. Particularly notable is the coherence of the priorities and goals enunciated by the senior management team.

In this section we outline the laboratory management structure and give insights into how the laboratory is run. Over the last five years a number of improvements have been made to TRIUMF management and operating procedures (see Sidebar: Continuous Improvement).

5.9.1 LABORATORY OVERVIEW

The Government of Canada funds TRIUMF's core operations; however, the laboratory is owned and operated as a joint venture by a consortium of Canadian universities. This unique governance structure has been and continues to be a very successful model for operating a national facility. The Joint Venture Agreement establishes TRIUMF's Board of Management to operate, supervise, and control the laboratory.

Over the past five years membership in the joint venture has grown reflecting TRIUMF's increased value to the Canadian university research community. The University of Manitoba (in 2009), Guelph University (in 2009), Queen's University (in 2009), and York University (in 2008) all became full members of the joint venture. The University of Calgary (in 2009), McGill University (in 2013), the University of Northern British Columbia (in 2011) and the University of Winnipeg (in 2012) received associate membership in the joint venture, a prelude to applying for full membership.

TRIUMF is headed by a laboratory director who reports to the Board of Management and is normally appointed to five-year terms. The laboratory staff are organized into five distinct divisions: Accelerator, Business and Administration, Engineering, Nuclear Medicine, and Science (see Figure 1). The Director's Office includes an executive assistant and the chief accountability holders: the five division heads; the head of strategic planning and communication; the manager of environment, health, and safety; the project-management coordinator, and the chief financial officer.

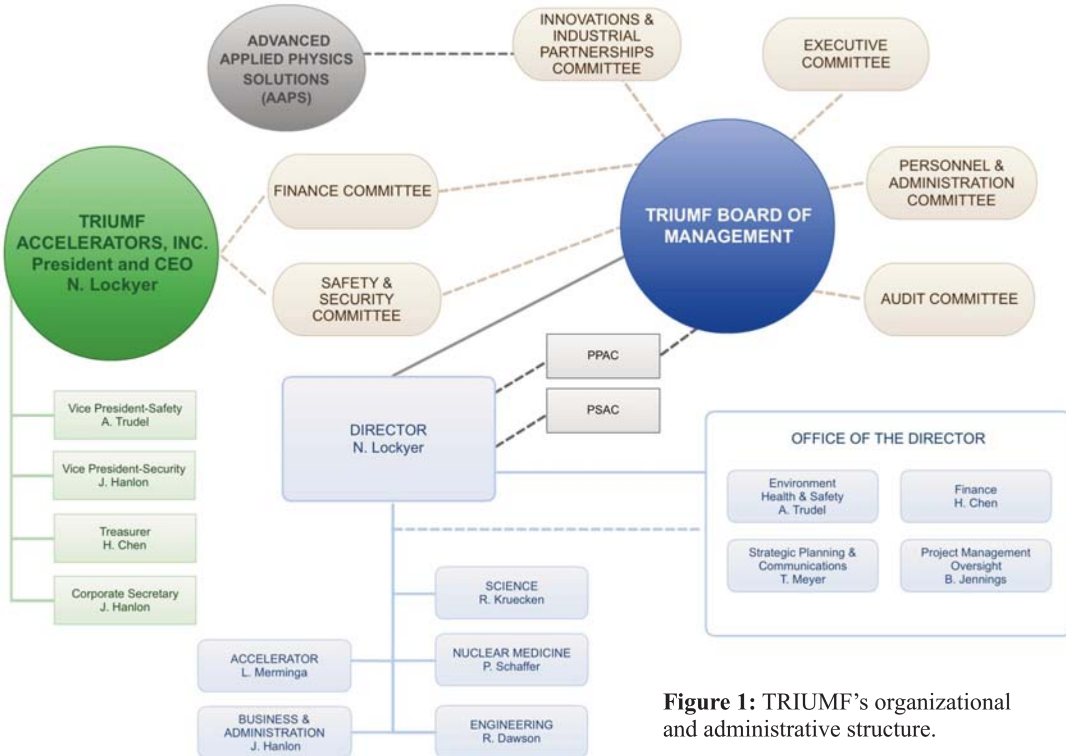


Figure 1: TRIUMF's organizational and administrative structure.

5.9.2 ACCOUNTABILITY

TRIUMF's Board of Management is made up of two voting representatives from each full member university, one non-voting member from each associate member and two voting private sector representatives nominated and appointed by the Board of Management. It is expected the private sector members will bring a unique expertise to the Board, particularly in assisting TRIUMF to evaluate its commercial activities and opportunities. The TRIUMF Board of Management meets twice a year and is responsible for the financial and administrative affairs of TRIUMF. The executive committee of the Board of Management has six members including the chairman of the Board. It normally meets in between Board meetings on an "as needed" basis.

Funding from the Government of Canada flows to TRIUMF through a "Contribution Agreement" between the National Research Council of Canada (NRC) and the full members of the TRIUMF Joint Venture. NRC provides the federal government oversight and accountability for the funding on the basis of Five-Year Plans prepared by TRIUMF. The Contribution Agreement defines the terms and conditions under which TRIUMF receives funding for the Five-Year Plan and defines a "Statement of Work," the work that TRIUMF must complete during the five years and upon which TRIUMF's success will be evaluated.

In addition to the NRC contribution, TRIUMF receives funds from a number of other sources, either directly or through collaborations with its university partners, from a number of other sources: The Natural Sciences and Engineering Research Council (NSERC), the Canadian Institutes for Health Research (CIHR), Natural Resources Canada, Western Economic Diversification, the Canada Foundation for Innovation (CFI), the British Columbia Knowledge Development Fund (BCKDF), commercial partners and affiliated institutions. For TRIUMF's funding, ending March 31, 2010, see Table 2. TRIUMF's buildings have been funded by the Province of British Columbia and are owned by the University of British Columbia.

Monitoring the laboratory's performance is a joint responsibility of the Agency Committee on TRIUMF (ACT), represented by Industry Canada, NSERC, and the NRC, who normally meet semi-annually to oversee the Government of Canada's investment in TRIUMF and the economic benefits accruing to Canada from that investment. ACT has a particular focus on financial and commercialization matters. In addition, the Advisory Committee on TRIUMF (ACOT), a panel of internationally recognized scientists, monitors the scientific performance of the laboratory and commercial activities through semi-annual meetings held at TRIUMF. Once during each five-year funding period, NRC appoints an International Peer Review Committee (IPRC) to review TRIUMF's scientific performance and evaluate its proposals for the next Five-Year Plan. The last one was in 2008. CFI and CIHR are invited to attend.

The organizational and administrative structure of TRIUMF is shown in Figure 1. Under the Board of Management are TRIUMF Accelerators Inc. (TAI) and TRIUMF proper. TAI is an incorporated non-profit company that holds the operating license from the Canadian Nuclear Safety Commission (CNSC) for TRIUMF's accelerators and is a party the land lease between UBC and the full members of the Joint Venture.

TRIUMF proper is divided into five divisions and the Office of the Director. The Office of the Director contains the Heads of essential administrative services groups. They are the CFO, the Safety Officer, Head of Environment, Health and Safety, Head of Strategic Planning and Communication, and the Project Management Office. The five divisions are: Accelerator, Business and Administration, Engineering, Nuclear Medicine, and Science. They reflect the top-level work breakdown structure for the laboratory.

Experiment Evaluation Committees advise the Division Heads about which experiments to run on TRIUMF beam lines. There are three such committees: Subatomic Physics Experimental Evaluation Committee (SAP-EEC), Molecular and Materials Science Experiment Evaluation Committee (MMS-EEC), and Life Sciences Projects Evaulation Committee (LSPEC). For general policy issues, the Director is advised by the Policy and Planning Advisory Committee (PPAC), which is made up of members chosen from Canadian Universities.

Insurance

TRIUMF carries a $50M Nuclear Energy Liability policy from the Nuclear Insurance Association of Canada (NIAC) that complements other Commercial General Liability coverage of $50M and coverage for Directors and Officers of $10M. In addition TRIUMF is a "named insured" on the University of Victoria's Property Insurance policy through the Canadian University Reciprocal Insurance Exchange program (CURIE).

Site Security

The Head of the Business and Administration Division is responsible for day-to-day site security and works closely with the Manager, Environment, Health and Safety to ensure that Canadian Nuclear Safety Commission, CNSC, is made aware of any security enhancements or breaches. The Manager, Environment, Health and Safety is responsible for day to day communication with CNSC on physical security matters. All activities regulated by CNSC are within a fenced compound area. This fenced compound area is randomly patrolled in the off-hours and weekends by a contract security guard.

CNSC staff perform ongoing compliance monitoring activities in the area of security to verify that the TRIUMF security program, including its implementation, continues to meet regulatory requirements for a Class 1B nuclear facility. TRIUMF is in compliance with all aspects of its security operations. Concurrent with the ARIEL construction project, a new badge room was built to allow access to the controlled area that has optical turnstiles designed to eliminate tailgating and improve secure access to the site.

TRIUMF has a Main Control Room that is staffed 24/7 – 365 days per year. Video surveillance cameras monitor the main access gates. Any security breaches are reported to Main Control Room personnel, who then contact the appropriate authority.

Security and site access as identified in TRIUMF Standard Operating Procedure 10 is included in the employee orientation Program and the Basic Safety Orientation Training. All staff and visitors are required to have a security access card and access cards will not be issued without the appropriate authorization.

CNSC staff continues ongoing compliance monitoring activities in the area of security to verify that the TRIUMF security program, including its implementation, continues to meet regulatory requirements.

All employees and long-term visitors are required to wear a photo ID security access card. All short-term visitors, those visitors of less than three weeks, are required to wear a visitor badge.

Human Resources

TRIUMF has a dynamic and diverse workforce of highly skilled people working together to deliver excellent service and support. Our resource planning initiatives have allowed us to proactively manage our human resources to meet current and future workforce needs through succession planning, demographic analysis, and staff redeployment based on cross departmental and divisional cooperation. The introduction of an online orientation program in 2011 has strengthened our onboarding process, and reference guides for new employees and supervisors have been introduced to better acquaint new hires with TRIUMF's policies, practices, and procedures.

With respect to employee health benefits, a comprehensive market survey analysis was undertaken to determine the financial impact of introducing a harmonized and improved health benefit plan for all employee groups. The results of this analysis indicated that the current TRIUMF employee benefit plans are cost effective and competitive, and supported no change at this time.

Our current strategic HR priorities include strengthening leadership training and development, performance management, and position classification and compensation practices. Our performance-based compensation program supports fiscally responsible budget planning, and the current project of introducing job families and salary scales includes the review of positions and salaries across the organization. The ability to differentiate the pay of one occupational group from another is central to the benefits of TRIUMF's job family implementation project that has a number of goals, including increasing retention of competent employees and improving attraction of new employees. In 2009, a market salary review was conducted for all technicial positions, and six job families were introduced as a result. At present we are conducting a compensation market review for all administrative, professional, and supervisory positions at TRIUMF with the goal of introducing relevant job families and corresponding pay ranges for all employee groups.

TRIUMF has performance based pay philosophy and merit is awarded to those employees who demonstrate strong performance during a given performance review period. For approximately 350 employees paid from operating funds, performance is reviewed on an annual basis and merit is awarded in the form of an increase or honoraria, as allocated in the annual budget. While those employees whose salaries are supported through sponsored research are subject to the administrative policies of the institution, salary administration may be dictated by the availability of funds allocated to salaries in the applicable research grant.

TRIUMF has a very strong undergraduate student program and hires some 70 summer students per year in addition to approximately 10 university co-op students each term. In addition there are around 35 graduate students and 45 post-doctoral research fellows at TRIUMF.

TRIUMF has established an on-line office where users and visitors can contact the Visitor Services Coordinator who assists with sign-in procedures and facilitates the issuance of security access cards, radiation badges, computer accounts, and safety training. The Coordinator also provides experimenters with basic information about TRIUMF and directs them to appropriate TRIUMF contacts, such as the Scientific Liaison for experimental facilities.

Finance, Procurement, and Logistics

The Finance Office is responsible for those activities associated with Treasury, Accounting, Procurement, and Logistics. Managing the financial risks and supporting the laboratory's goals and ongoing reviews of TRIUMF's business practices in order to maximize the efficiency and effective use of resources are the objectives of this group. In the current five-year cycle, several initiatives were undertaken to support the group's objectives:

Agresso: A New Enterprise Resource Planning (ERP) System

In September 2009, TRIUMF held an external review of its core computing facilities, including its Management Information System. In its recommendation, the review committee stated that TRIUMF requires a flexible and responsive information system to comply with the changing and increasingly stringent regulatory demands, and to provide reliable management reporting. Subsequently, the TRIUMF Board of Management approved the purchase and implementation of a new ERP System called Agresso Business World.

Since the Board's approval, a project team was formed in 2011 and the process of discovery to implementation began. The project has proven to be more challenging than originally envisioned. The new system, while less flexible than the current highly customized system, still requires complex configuration to meet TRIUMF's needs. The start of commissioning will occur in the 4th quarter of 2013.

The new system offers many advantages. The procurement process, from requisition to accounts payable, is becoming paperless, with electronic approval replacing signatures on paper. This change precludes processing gridlock associated with a paper based system. It allows for on-line approval of requisitions from anywhere, providing there is access to the Internet. Stores purchases and travel approval are integrated into the same procurement process. The laboratory Work Breakdown Structure (WBS) is being fully incorporated into the accounting architecture for consistency in tracking expenditures and as an aide to project management. The flexible reporting capabilities of the new system make information far more accessible then with the present system and will give account holders and TRIUMF senior management direct access to information that at the present time requires involvement of Management Information System (MIS) staff. This will facilitate corrective actions and increase responsiveness to issues as they arise.

Preliminary Decommissioning Plan: Financial Guarantee

One of the requirements of TRIUMF's Accelerator Operating Licence is the Preliminary Decommissioning Plan (PDP). The main objective of the plan is to ensure that the site is brought to a safe state of closure in the event of decommissioning. The Financial Guarantee, a significant component of the plan, demonstrates the funding measures and provides assurance that adequate resources will be available to fund decommissioning activities. TRIUMF has conducted an extensive review and updated the PDP and the Financial Guarantee in late 2011. The cost study was prepared in accordance with generally accepted accounting and quantity surveying methods and procedures by an independent quantity surveyor firm.

The decommissioning fund, a restricted fund governed by an escrow agreement had a balance of $10.4M at the end of Fiscal Year March 31, 2013. The Escrow Agent (The Royal Bank of Canada) commented on the state of the PDP and Financial Guarantee: "…escrow account is in a solid position to fund the activities of decommissioning…".

Finance

As a result of a review of its cash management practices, and with the cooperation by funders, TRIUMF has minimized its cash flow concerns for funding operations and large-scale projects.

Cash transfers from funders are timed to occur before or at the time TRIUMF disburses funds for expenditures. This adjustment relieved prior practice whereby expenses were incurred and TRIUMF would wait for reimbursement from funders after a monthly billing cycle. This change enhances TRIUMF cash flow and coupled with an improved process to obtain competitive interest rates means that TRIUMF has systemically increased its ability to generate higher investment income on available cash balances.

In August 2011, Elections BC announced that the Harmonized Sales Tax (HST-12%), which came into effect on July 1, 2010, had officially been repealed by a majority vote of 55% to eliminate the tax. This tax change took effect April 1, 2013.

As a registered charity, TRIUMF was adversely impacted by this change when a portion of rebates claimable on taxes paid were also eliminated. The value of lost rebates cost TRIUMF $1.2M per year from its program. TRIUMF has fully reviewed the tax changes and systems and procedures have been modified accordingly. Over the months leading up to April 1, 2013, coordinated efforts in expediting and advancing purchases in order to claim rebates before they became unavailable resulted in tax savings of $0.1M.

TRIUMF employs in excess of 500 employees (350 paid from operating funds and 150 funded through grants or affiliated institutions). Given the diversity of its labour pool, and the demarcation required between personal activities and work activities, the Director instructed TRIUMF's administration team to develop a Political Activity Policy. The coordinated efforts between Human Resources, Strategic Planning and Communication, and Finance resulted in a Political Activity Policy and with assistance of legal counsel, a policy was created that gives employees clear direction when interacting with politicians and/or volunteering in partisan political activities. This was passed by the board on November 16, 2012.

TRIUMF consumes roughly 30kL of liquid helium (LHe) annually to support its material sciences and SRF research programs. Full helium recovery systems are in place or the ISAC-II superconducting linear accelerator and the new electron linear accelerator (e-linac) so they consume much less. LHe is used as a cooling agent in scientific experiments and superconducting equipment. The annualized cost to purchase LHe is in excess of $0.4M and the cost/litre has been steadily rising in excess of inflation. Therefore, the reliability of supply in both quantity and quality has become a recurring issue.

Starting in 2016 (plan), the Ultra-Cold Neutron (UCN) Project is forecasted to require 50kL, rising to 150kL per year by 2018. If LHe requirements continue to be purchased on the open market (assuming its availability), TRIUMF's annual cost would swell to $2.8M at today's prices.

Over the past few years, TRIUMF's Centre for Molecular and Materials Science (CMMS) group has been studying alternatives to recover LHe during consumption, and after an extensive review, they developed a solution described in detail in section 5.4.4. In October 2012, a Gate Review Committee concluded its review and recommended the proposed solution be accepted. Shortly after, the Senior Management group convened to review the recommendation, and the solution was accepted along with the funding plan. The cost of the project is $1.6M, and the payback of the capital cost will occur after four operating years, based on current consumption. Furthermore, the value of the investment is compounded significantly when considering the cost avoidance in future years due to the LHe required for the UCN project.

Procurement

After exporting the final goods and securing materials for the T2K project in Japan, Procurement began establishing the purchasing requirements for the Advanced Rare Isotope Laboratory (ARIEL) at TRIUMF. This included preparing and managing the tender documents for the Architectural and Engineering Services for the infrastructure, participating in the tendering processes for the construction of the new Stores building, the Badge Room, and the main construction of the ARIEL infrastructure, including excavation and site preparation.

After the main construction was started, Procurement focused on purchases of specialized components and items related to the electron linear accelerator (e-linac), while maintaining a high level of customer service to the rest of the laboratory. During this time, TRIUMF's purchasing policies and procedures were reviewed and updated in 2012. The result is a continued support of the objective of utilizing resources in the most efficient and effective manner.

Logistics

The Stores facility was relocated in 2011 because of the demolition required to clear the ARIEL construction site and build the northern annex ("RIB building") of the ARIEL facility. The move of Stores to its new location was completed with minimal impact on service to the TRIUMF site.

The introduction of a "virtual" inventory system enabled the efficient and cost-effective distribution of non-stock inventory items like helium dewars and office supplies. This system follows a "Just In Time" concept of inventory management.

In addition, the Logistics Group facilitated an effort to create usable storage space in an area of the Proton Hall. The effort resulted in an increase of usable storage space and a systematic process for the storage or disposal of unusable items.

TRIUMF House

Ensuring the comfort of visiting scientists staying at TRIUMF House is paramount to its operations. In 2011, TRIUMF House achieved a "perfect score" when reviewed by Tourism BC in their annual assessment visit. This rating reflects the cleanliness and state of repair, two important guest services factors in the accommodation industry. Several relationships outside of the scientific community were cultivated as a revenue source for those periods when TRIUMF House is not required by TRIUMF users.

CONTINUOUS IMPROVEMENT

Over the last five years, TRIUMF has systematically reviewed it procedures and made changes to increase productivity and reduce risk. The changes are spread widely across the laboratory and affect all areas of operation. The new procedures are process driven and stress documentation and site-wide standards.

Three examples typify the changes: the Document Type Index, the Commitment List and improved training (a comprehensive list is given below). With the emphasis on documentation, a plan for identifying and managing documents in different fashions based on their use is needed. The Document Type Index fulfills this need and also provides a pointer to where each type of document is stored. The main document repository is a backed-up web-based system with access controlled by specially trained documents controllers. Included among the controlled documents are the TRIUMF Standard Operating Procedure documents, the risk registry, and training plans.

In addition to the traditional organization chart maintained by Human Resources, there is a hierarchical arrangement of TRIUMF's program of work. This hierarchy is the work breakdown structure (WBS). The WBS, documented in the Commitment List, has all TRIUMF's activities, both operational and projects, organized into a logical hierarchical structure. The Commitment List provides the framework to monitor resource usage. It also has each activity ranked by its importance to the TRIUMF program. Each project on the commitment list undergoes a series of gate reviews as it progresses from conception to completion. The combination of the importance rating and gate reviews are used to set site-wide priorities and monitor and document the progress of projects.

With the highly specialized activities that take place at TRIUMF, it is important not only that processes are documented but also that staff are trained to carry out the processes. While generic training is all that is required for some tasks, much that goes on at TRIUMF requires specialized knowledge. TRIUMF is working to improve its training, starting at the top with supervisors and extending to individual groups who are developing training programs suited to their individual needs.

To indicate the wide spread nature of the changes, here is comprehensive list of changes to process:

Accelerator Division

- Weekly shutdowns replaced by shutdowns on demand.
- Increased engineering oversight of ISAC target production
- Systematic Approach to Shutdown
- Installation, commissioning, and operation of conditioning station, north hot cell for ISAC target conditioning
- Combining accelerator control rooms (in study stage)
- Controls (standardize on one system, EPICS)
- Cyclotron uptime
- Target reliability
- Increased beam to ISAC

Science Division

- Modified EEC process to better manage backlogs for experimenter requests for beam time
- Increased publications
- LHe Recovery

Quality Management System

- Work request system
- Training program – group specific
- Document control
- Group manuals
- Calibration and inspection index
- Uniformity in reporting non-conformities
- 10 year license
- Environmental protection program
- Safety program

Project Management

- Commitment list developed to provide an overview of all activities at TRIUMF
- Importance rating of each commitment to set relative priorities between tasks
- Gate Reviews to define transitions between project phases by gathering information and subjecting to expert review before resources are made available
- Expanded time sheets to better track all work on all activities

Finance, Procurement, and Logistics

- New Enterprise Resource Planning system (Agresso)
- Developed a sustainable financial plan for Decommissioning
- Overhauled TRIUMF's methods of accounting, reporting and budgeting
- Enhancements to the NRC/TRIUMF Contribution Agreement
- Re-engineered cash management and treasury processes
- Updated procurement policies (RFP/Tendering)
- Inventory management improvements (virtual inventory)

Human Resources

- Old pay-grid model of compensation replaced with pay ranges, job families and pay for performance
- Improved onboarding process to include online orientation prior to commencing employment
- 90 day new employee surveys for critical feedback
- Introduction of new employee handbook and supervisors handbook
- Formal supervisor training for new supervisors
- Phase 1 of Succession Planning, identifying the critical positions and identifying future turnover

Engineering Division

- Risk registry
- Neighbourhood District Energy Program

Business and Administration

- Partnering with like-minded organizations for community and outreach events to share costs and increase impact: Science World for public science lectures, University Neighbourhoods Association for open houses, Perimeter Institute for Theoretical Physics and SNOLAB for national high-school teaching awards.
- Reduced meetings and travel costs

5.9.3 EH&S, QMS, AND LICENSING

Operation of TRIUMF's accelerator facilities is regulated under the terms of a Class IB Accelerator Operating Licence issued by the Canadian Nuclear Safety Commission to TRIUMF Accelerators Inc. The terms of the licence mandate a suite of regulatory programs in different safety and control areas that include all aspects of personnel and environment health and safety, as well as a quality management system. The suite of regulatory programs are managed and administered by the Environment, Health, and Safety (EH&S) group that consists of a team of physicists, engineers and technicians with expertise in radiation safety systems, radiation protection, safety analysis and shielding design, as well as occupational health. Over the reporting period 2008–2012 TRIUMF devoted significant effort and resources to upgrading its regulatory programs with the goal of improving the laboratory safety record.

TRIUMF began to develop a Quality Assurance (QA) Program in 2002 to meet CNSC requirements. In 2006, the CNSC conducted an audit of TRIUMF QA. In response to directives and a recommendation, TRIUMF's director created the Quality Management System Implementation Panel, which was chaired by the Head of the Engineering Division with strong guidance from the QA Manager. Panel members included senior staff from all divisions who had the broadest and deepest knowledge of TRIUMF activities. The panel was charged with ensuring that documentation was up-to-date and that staff was properly trained and followed TRIUMF Standard Operating Procedures (TSOPs).

Over this reporting period 2008–2013, Quality Management System TSOPs have become well established in TRUMF's everyday processes and activities. The QA Manager, responsible for the day-to-day operation of the Quality Management System, also manages the auditing of the system procedures and regular reporting of progress to the senior management team. In addition, the QA Manager provides on-going assistance with implementation across the site, sets the schedule of internal assessments, and selects assessment teams with the appropriate independence to perform the assigned assessments.

The TRIUMF Quality Manual, 14 TRIUMF Standard Operating Procedures (TSOPs), the TRIUMF Document Manual, and a collection of Group Manuals now define the laboratory's operating processes and cover everything from access to the TRIUMF restricted site to project management.

Some of the tools put in place to facilitate implementation of a Quality Management System at TRIUMF are:

- A QMS leaders panel to promote communication and provide opportunities for continuing QMS education;
- Site-wide performance metrics and annual assessments at the Quarterly Safety Management Meeting;
- A site-wide database for nonconformity reporting and corrective action resolution to allow better tracking and opportunities for analysis of operational experience;
- A trained team of experts in incident investigation to identify root causes associated with nonconformities;
- A QMS newsletter to assist with dissemination of information during the implementation phase of the program;
- A TSOP for project management with well-identified gate reviews to provide oversight and regular reporting for projects;
- An enterprise resource package to allow better tracking of resources;
- An annual schedule of internal audits and assessments that is one of the processes in the Quality Program TSOP;
- A document-type index to systematically categorize QMS document types and their associated workflows;
- A calibration and inspection index to facilitate tracking of inspections and calibrations for instrumentation and equipment across the site; and,
- A site-wide work request system to provide a single entry point for all groups on site and to facilitate tracking.

The resources required for both the implementation and sustainability of the QA program was, and continues to be, reviewed at the Quarterly Safety Management Meeting, thus ensuring that TRIUMF has a QMS system that both works for the laboratory and demonstrates to its stakeholders, staff, and visitors, as well as its regulators—the Canadian Nuclear Safety Commission (federally) and the Worker's Compensation Board of BC (provincially), that TRIUMF is a safe, efficient, and productive research environment.

Following on the success of the QMS Implementation Panel, TRIUMF addressed deficiencies in its training program with the creation of the Training Implementation Panel. Led by head of the Science Division, the Panel's mandate was to oversee the work of the Training Task Force and ensure a timely implementation of training requirements for all groups on site.

The Task Force assessed the training requirements for all positions where performance could affect the operation of beam delivery facilities, or where incorrect performance could result in injury, downtime, expense, or radiation dose. It also identified and prioritized these positions, completed the task analysis for the more critical positions, and is now in the final stages of completing the process of design, development, and implementation of training for all positions by September 2013.

TRIUMF's suite of EH&S programs were also revised and upgraded to remain compliant with regulations and standards in the nuclear industry. A summary of the programs that received significant upgrades from 2008–2013 are included below.

Personnel Safety Systems. Maintaining the high level of reliability and performance of TRIUMF's personnel protection radiation safety systems continued to be a focus. The main cyclotron central safety system and radiation monitoring system microprocessors were upgraded to newer technology. In addition, the January 2012 shutdown saw the culmination of a five-year long project to replace all Access Control System Area Safety Units microprocessors for the main cyclotron.

Fire Protection Program. Documents were revised, approved and released in October 2010. These included procedures for inspection, testing, and maintenance of fire protection systems, thereby bringing all of these activities into compliance with he latest versions of regulatory codes and standards.

Emissions and Environmental Monitoring Programs. A review of stack calibrations was undertaken as part of the continual improvement process for the Emissions and Environmental Monitoring Program. In addition, in the context of upgrading ISAC operations for higher mass targets, a safety analysis showed the need for increased engineering controls for the Target Hall nuclear ventilation system to ensure that doses to personnel, members of the public, and the environment remained below regulatory limits. These upgrades were completed in time for the amended operating license in October 2011.

Radioactive Waste Management Program. Documents were revised to comply with the new regulatory clearance levels for defining waste as nonradioactive. In-house upgrades to the instrumentation used for monitoring radioactive waste were also completed to meet the new clearance level criteria. With these changes the Radiation Protection Group was able to put into place a comprehensive program to address the safe disposal of a significant fraction of its low-level radioactive waste and leave TRIUMF in a position to better manage, at lower costs, the low-level waste generated from ongoing projects involving refurbishment of beam lines.

OH&S Programs. All workplace occupational health and safety (OH&S) programs, mandated under the provincial occupational health and safety board WorkSafe BC, were reviewed and updated. These programs include safety training in ten distinct areas ranging from laboratory chemical safety to rigging and crane operator training. The training programs are either developed by the OH&S coordinator or a third-party contractor, and are administered by the training program coordinator.

Flexibility in regulatory licensing for a facility such as TRIUMF is crucial to maintaining a vibrant research program. By dedicating resources to its regulatory programs, TRIUMF demonstrates its due diligence in matters of environment health and safety and facilitates the regulatory process for new projects that require changes to the Operating Licence. Several licence amendments have been required since April 2010: (1) an upgrade to the energy and beam current for the ISAC II rare isotope beam accelerator; (2) changes to the ISAC irradiation facility to include target materials heavier than lead; (3) increases in beam current, energy and target thickness for the Solid Target Facility; and (4) site preparation for construction of the ARIEL facility.

At the time of writing this report, TRIUMF has received a construction licence for ARIEL and has just applied for a separate operating licence for the electron gun and injector cryomodule portion of the e-linac.

In addition to the above operating licence amendments, TRIUMF's Accelerator Operating Licence was successfully renewed in June 2012 for a ten-year term. Licenses are usually renewed for a five-year term, but given TRIUMF's safety record and strong regulatory program performance, a renewal for a 10-year term was requested and granted.

TRIUMF's operating performance for environment, health, and safety (EH&S) metrics continued to do well between 2008–2013. The average total personnel radiation dose decreased over the previous five-year average by ~15%, or 50 person-mSv.

Environmental releases continued to remain well below the regulatory limit of 0.05mSv/year. TRIUMF annual airborne releases were just below 0.01mSv/yr and sump effluent releases at less than 10-6/yr for this period. Steps were taken to reduce airborne emissions by decreasing the maximum acceleration energy in the cyclotron. This reduction will allow for future cyclotron beam increases while still keeping emissions below 0.01mSv/yr.

TRIUMF's average lost-time injuries during the reporting period was 12.5 days/100 person-years and continued to be better than that for BC Universities (16.2 d/100p-y), the WorkSafe BC equivalent industry group. TRIUMF had one significant lost-time injury on the beam line shielding blocks during this time. A full incident investigation was carried out and corrective measures identified, including the implementation of fall protection equipment for rigging work together with procedures and training for all workers working on the shielding blocks.

QMS metrics were used to assess performance with respect to EH&S goals for this operating period. Goals were largely met and, in a few areas where performance was not fully met, EH&S group identified corrective actions with the aim of continual improvement.

5.9.4 PROJECT MANAGEMENT AND COORDINATION

The successful running of a laboratory depends on understanding what resources are available, and on what time scale, so that management can schedule current projects and plan for future ones. In the last five years, TRIUMF has made major improvements to how it tracks resource usage and projects future requirements. It has, in fact, migrated to an explicit matrix organization structure that consists of two parts: the organization chart, which is the human resources record of who reports to whom and the work breakdown structure (WBS), which breaks up the work at the laboratory into its logical structure. The matrix structure facilities the sharing of resources across organizational units to maximize resource usage and allow expertise residing in one area of the organization chart to be available to all projects.

As part of this matrix organization structure, TRIUMF has established a Project Oriented Management System. In this system, the allocation of any TRIUMF resource is keyed to a specific project—or commitment—on an official Commitments List approved by Senior Management and the Director. This commitment is the third level in the WBS. The four commonly used levels are shown in Figure 1. The top level is the Division and corresponds to the divisions on the organization chart. The next level is the program and would correspond, for example, to nuclear physics or accelerator MRO. The individual projects or commitments are then assigned to their programs. For example, the commitment TITAN is part of nuclear physics.

Each commitment is given an importance rating that is used in conjunction with the project schedule to assign priority in accessing TRIUMF resources. If a resource is needed in a time-critical manner for a commitment rated "crucial," like the e-linac, then it takes precedence over all other demands for that resource. The importance rating is set by a committee including the director, division heads, and the head of the Program and Policies Advisory Committee. The list of commitments, each with its own importance rating, is available to all TRIUMF staff members.

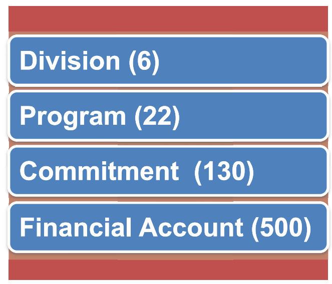


Figure 1: The top four levels of the work break structure.

All TRIUMF employees, except students, fill out timesheets, recording their time against individual commitments. Entries in the Commitment List fall into two broad categories: operations and projects. Operations are commitments that are ongoing and roughly the same from year to year. Timesheets from past years can be used to estimate requirements for future years and to help pinpoint where additional operational efficiencies can be found.

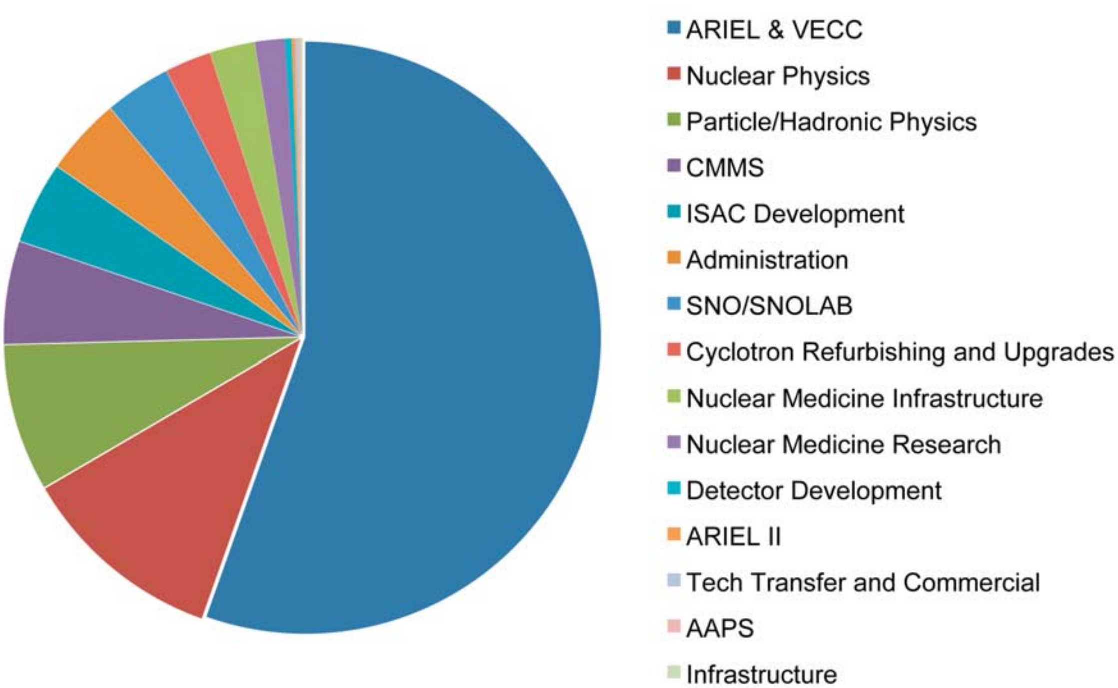


Figure 2: A pie chart for manpower usage by project for fiscal year 2012.

Projects have finite lifetimes and are managed based on the phase of the project. There are a series of gate reviews that each project must pass before it can proceed from one stage to the next. The first gate review is used to decide if the project can be added to the commitment list or must be abandoned; these are normally held before requests are made to external funding agencies. The remaining gate reviews determine if the project is progressing according to schedule, or if it must be reassessed. The entire process is described in the TRIUMF Standard Operating Procedure document TSOP-15.

As an example of the information that can be extracted from the time sheets using the WBS, Figure 2 below shows the relative resources usage for projects in the fiscal year 2012. From it, we can see that the ARIEL collection of commitments uses over half of all the human resources devoted to projects, with the total for all projects being 86 full time equivalents (FTEs). The lowest level shown for the WBS is the Financial Account. This level ties accounting information directly into the project management system.

This complete integration will only be available when the new enterprise resource planning (ERP) software goes live in 2013. TRIUMF will then have the unprecedented ability to track financial and human resources in a uniform manner.

5.10 INNOVATION AND INDUSTRIAL PARTNERSHIPS

TRIUMF has developed a significant portfolio of specialized knowledge, skills, and abilities through its cutting-edge research in particle physics, nuclear physics, nuclear medicine, materials science, and accelerator physics and through its interactions with Canadian universities and international researchers. In academic arenas, TRIUMF freely shares this expertise in collaborations intended for mutual benefit, as time and energy allow. In some cases, this expertise has potential commercial value or relevance to industry. The challenge is to discriminate wisely between academic relevance and business relevance while maintaining integrity, using public funds responsibly, and encouraging Canadian success.

The following discussion outlines the overall framework that TRIUMF uses to be effective in addresses the "create societal and economic growth" element of its mission. (Section 4.4 summarizes accomplishments in this area over the past five years.) The source of value creation is fundamentally intellectual property in the form of know-how, invention, disclosures, or patents. A five-year business development plan (prepared separately) assists TRIUMF in forecasting emerging opportunities and tracking new developments. TRIUMF has several vehicles to exploit intellectual property; the primary agent is Advanced Applied Physics Solutions, Inc. (AAPS) a stand-alone non-profit company that collaborates closely with the laboratory for market analysis, product development, and commercialization. Finally, success cannot occur in a vacuum: TRIUMF's network of partners, typically scoped and shaped by formal agreements, provide resources, markets, and contacts.

Although knowledge development, transfer, and commercialization is not a linear, one-way process, Figure 1 illustrates the basic relationships. In this simplified model, TRIUMF conducts basic research and develops knowledge and platform technologies (in the Technology Readiness Level (TRL) scheme, these outcomes would be at TRL 1-4). In turn, AAPS is guided by interactions with industry and analyzing the market. When AAPS sights a potential match between a platform technology and a market opportunity, it identifies an industrial partner and conducts product development (TRL 5-8) and commercialization (TRL 9) to generate business. The outcome of these efforts would normally be a spin-off venture that takes the product to market. Finally, the activities of TRIUMF (and its network of research partners) are generally guided by interactions with the marketplace (typically via industrial partners) to identify opportunities for developing potential technologies.

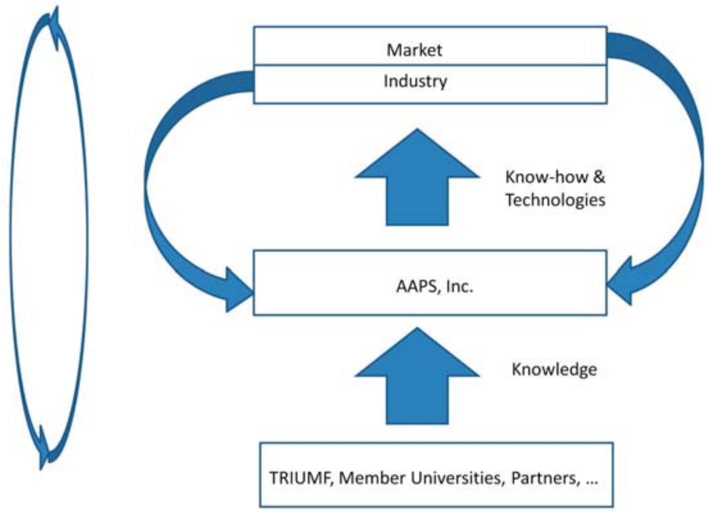


Figure 1: Positioning diagram of TRIUMF and AAPS Inc. relative to developing and exploiting techniques for commericialization.

As an example, consider the superconducting electron linear accelerator (e-linac) being constructed at TRIUMF as the heart of the ARIEL project. The e-linac uses superconducting radio-frequency (SRF) cavities as the core technology for accelerating an intense beam of electrons. When generalized from the specific application of 10 MeV/m, 1.3 GHz cavities for electron acceleration, SRF cavities represent a platform technology developed at TRIUMF. AAPS surveyed the world market along with TRIUMF and industrial vendor PAVAC Industries, Inc., and an opportunity was identified for widespread commercial use of SRF accelerating cavities. Moreover, the "cryomodule" technology that modularizes the SRF cavity and its life-support systems was identified as a more advantageous business opportunity because it is higher up the value chain. AAPS is now facilitating a technology-transfer agreement with PAVAC for TRIUMF. As part of a work package between TRIUMF and India, PAVAC will manufacture and deliver its first cryomodule product to India using TRIUMF technology. Subsequent to this demonstration deliverable, PAVAC will manufacture and sell cryomodules to other customers under a licensing arrangement.

5.10.1 KNOW-HOW AND INTELLECTUAL PROPERTY

To fulfill its research objectives, TRIUMF maintains a broad portfolio of technical and engineering capabilities. Several of these have immediate relevance to the commercial sector and are summarized below. Innovation and industrial partnership activities are managed through the Business and Administration Division at TRIUMF.

Irradiation and Radiation Effects in Materials

TRIUMF's Proton Irradiation Facility (PIF) and Neutron Irradiation Facility (NIF) regularly make use of three beam lines and provide testing facilities for aerospace and high-performance computing vendors. TRIUMF's expertise in radiation effects in materials is well recognized. In 2011, Ewart Blackmore, the chief scientist for PIF & NIF, was asked by the Canadian Space Agency to provide expert support to a technology assessment related to radiation prediction, monitoring, and protection technologies for future space missions. (See Section 4.4 for a discussion of performance over the 2008–2013 period.)

In a related topic, TRIUMF's expertise in environment, health, and safety especially with regard to radiation and radioactivity is regularly tapped by industrial partners. Ranging from consultations to assist the Chief Medical Officer of British Columbia during the Fukushima crisis of March 2011 to assistance with development of precautions for neutron exposure at one company's product-development laboratory and particle flux calculations to validate designs for shielding around medical equipment, TRIUMF's Radiation Protection Group and Manager of Environment Health and Safety are often in demand by external organizations.

Isotope Production and Chemistry

TRIUMF is expert in the physics and chemistry of isotopes and plays a crucial role in their biological applications, in particular, medical diagnosis and treatment. The nuclear medicine team has mastered the chemistry needed to isolate, purify, and combine the isotopes with biologically active target molecules for use by TRIUMF and its partners. As a particle-accelerator laboratory, TRIUMF's expertise in cyclotron design, engineering, and operation has led to the development of a variety of novel targets that enable the production of selected isotopes in relatively high yields.

TRIUMF's operational expertise in cyclotron production of medical isotopes is embodied in the Applied Technology Group, a team of about 30 scientists, technicians, and engineers that operate Nordion's on-site cyclotrons. This group is increasingly in demand by external organizations for technical consultations or project-management advice.

Other Technologies

Additionally, TRIUMF has established technical prowess in the following areas:

- Ion beam dynamics;
- Mechanical design, engineering, and fabrication;
- Advanced electronics: digital and analog;
- Advanced computing for scientific and facility control;
- Particle and radiation detection, modeling, and shielding;
- Radio-frequency (RF) technology including low-level RF and high-power RF;
- Precision magnet design, engineering, and measurement;
- Vacuum technology; and
- Cryogenic technology.

For instance, TRIUMF's expertise in cryogenic systems in vacuum environments was tapped by Westport Innovations, Inc., to discuss optimizing certain aspects of a product line they are developing that deals with pressurized natural gas.

Intellectual Property Management

The laboratory has a standard set of invention-disclosure requirements and policies that apply to all staff. TRIUMF reserves the right to protect (or not to protect) each invention with a patent or other type of arrangement.

In general terms, any invention created or discovered in whole or in part by any member of the TRIUMF staff is owned by the inventor. If it is determined that this invention has potential commercial opportunities then all rights would be assigned to TRIUMF for commercial exploitation unless TRIUMF makes a written agreement to the contrary with that member of the TRIUMF staff. The staff member would be entitled to royalties from the invention.

Income derived from the sale or licencing by TRIUMF of inventions or discoveries will be distributed such that the inventor(s) will receive 50% of the net revenues and TRIUMF will retain 50% of the net revenues. Net Revenues means royalty, licensing and other income received from the assignment or licensing of the rights to an Invention, less legal and other fees and expenses incurred directly in the process of establishing and maintaining the legal protection of those rights.

In conjunction with AAPS, TRIUMF manages a modest portfolio of registered intellectual property. TRIUMF surplused its historical patent holdings to AAPS in 2009; the portfolio is presented in Appendix 7.3.11.

"The FY 2011 survey of U.S. university licensing activity conducted by the Association of University Technology Managers (AUTM) reports a total of 38,600 active licenses and options, with 591 commercial products introduced."

FY2011 Survey, prepared by the Association of University Technology Managers (AUTM).

5.10.2 ADVANCED APPLIED PHYSICS SOLUTIONS, INC.

The physical sciences continue to be a rich source of inspiration, invention, and innovation that drive new technologies and products into the marketplace. Increasingly, however, the development of physics-derived technologies into real-world products and services requires substantial technical and financial resources. Canada is ripe with opportunities in this sector, from medical isotopes and particle accelerators to radiation detection and control at TRIUMF to faculty and student discoveries and innovations at the universities and academic laboratories. AAPS was established to capitalize on these opportunities and be the sector's business-development and commercialization resource for all of Canada.

AAPS is a federally funded Centre of Excellence for Commercialization and Research (CECR), launched in 2008 based on a proposal filed by TRIUMF. AAPS is fulfilling its goal of leading national efforts to commercialize physics-derived technologies, driven by seasoned business professionals and young entrepreneurs within a well-established governance structure. By end of 2012, AAPS had spent or encumbered about $10M of the original CECR funding and engaged another $9.5M (including cash and in-kind) from other sources.

The relationship between TRIUMF and AAPS is structured in a manner that respects TRIUMF's status as a charity and the need for AAPS to be a separate non-profit corporation. As availability allows, TRIUMF resources are made available to AAPS at standard charge-out rates with a premium for priority access.

The mission of AAPS is to develop and commercialize advanced physics technologies for the social and economic well-being of Canadians and for the benefit of people around the world. To accomplish this mission, AAPS works to create new commercial opportunities by leveraging disclosures generated from local entrepreneurs, expanding projects with private sector partners, or commercializing projects with TRIUMF and its network of partners. Since inception in 2008, AAPS' deal flow has come from all three sources, in part because of pent-up demand for a robust and capable commercialization vehicle.

The three commercial spaces in which AAPS is focusing are: natural resources (mining exploration), health and life sciences (medical isotopes and imaging radiation), and national security (detection of nuclear materials). Since Canada is a small market, international relevance is stressed. AAPS will normally not get involved in a project unless there is a commercial partner.

The AAPS Board of Directors is composed of primarily business and financial leaders. The business experience of the Board has been crucial to not only running the company, but also to steering the process towards greater and greater business best practices. The AAPS governance model is successful and remains unchanged after nearly five years (see Figure 1). The Board membership has been adjusted to include TRIUMF member universities and key entrepreneurs in the high-tech physics sector. The AAPS organization supports about 8 FTEs at present.

Leveraging its network of partners, including governments, universities, national laboratories, and industry, AAPS fulfills the following strategic goals:

- Identify research outcomes that can be moved rapidly to commercialization in partnership with the private sector to generate profitable income streams within a reasonable time-period;
- Develop and maintain a portfolio of activities that generate revenue sufficient to support operations and selected investments;
- Provide increased opportunities for science, technology, and engineering personnel to work at the R&D interface, helping train the entrepreneurs of tomorrow; and
- Serve as a strategic advisor and resource for innovation and commercialization activities to increase opportunities for Canadian companies in the areas of natural resources, health, environment, and information and communications technologies.

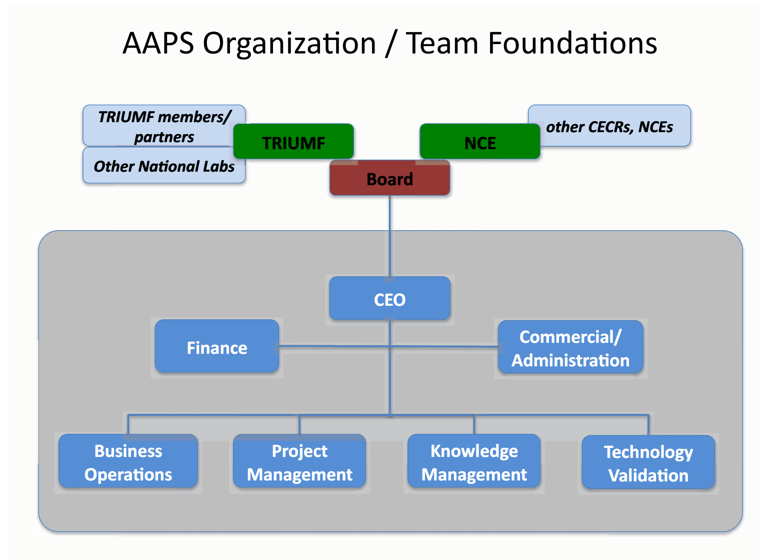


Figure 1: The AAPS governance model.

The AAPS business strategy uses a four-stage flow to manage technology development and commercialization.

- Applied Research. AAPS is involved in monitoring in this stage, but does not provide resources or investment. Applied research includes both technology-push (development on the bench) and technology-pull (market formulation and preliminary evaluation) activities.
- Proof of Principle. When a technology enters this stage, AAPS becomes more involved. Potential commercial partners are identified and consulted to assist in producing a prospective market analysis that identifies any sustainable differentiators and the value propositions. If these are compelling, AAPS will work with the principal proponents to prove the research can be productized. Opportunities to protect intellectual property are investigated and actions taken as required.

“EARTHLY” CT SCANS ATTRACTS FUNDING

01 April 2011

An ingenious idea that borrows techniques from medical imaging is looking for ore deposits deep in the earth. “Muon geotomography” is a technology initiated by Prof. Douglas Bryman, long-time TRIUMF scientist and the J.B. Warren Chair at the University of British Columbia. The technique uses an array of detectors deep underground to detect cosmic-ray muons. A grid of muon sensors work much like a CT scan and these sensors can map out in 3D regions of high density, where potentially valuable ore deposits could reside. This technique works as the underground muon flux picked up by the sensors is dependent on the density of the earth through which the muons pass.

Advanced Applied Physics Solutions Inc. (AAPS) completed a first round of proof-of-principle tests in collaboration with NVI-Breakwater, TRIUMF, the Geological Survey of Canada, and the BC Ministry of Energy and Mines. This project has enabled AAPS to attract $1.8 million in federal funding from the Western Economic Diversification office that will allow AAPS to develop and commercialize the technology.

- Development. A project moves into this phase when external partners are engaged with the goal to license technology or form a business venture. AAPS and the selected partner(s) work together to develop a profitable business plan. AAPS supplies, as required, the project and business-management expertise while the technology moves from prototype to pre-production versions.
- Commercialization. In this stage, AAPS continues to support the partner(s) while retaining either an equity or debt-instrument stake in the venture.

AAPS engages on a regular basis with its host, TRIUMF, to ensure that both parties are aware of major projects and initiatives, and that goals and operations are aligned. AAPS holds weekly project oversight meeting where all project managers attend and review project status including commercialization opportunities. Those TRIUMF group leaders that are involved in shared projects are invited to attend. These meetings ensure that adequate attention and resources are made available to keep projects on track and on budget.

A full discussion of AAPS, its corporate structure, and financial statement can be found in its annual reports. A strategic-planning session with the Board of Directors scheduled for September 2013 will generate a fresh roadmap for the organization and its support of TRIUMF's mission.

5.10.3 PARTNERSHIPS AND AGREEMENTS

TRIUMF's partnerships are shaped by formal agreements. These agreements not only facilitate TRIUMF's technical participation in certain private-sector consultations and development projects, but they also give TRIUMF expert informal advice on technologies, potential applications, and market forecasting. Formal agreements for collaboration with other academic-research organizations also add to TRIUMF's resources.

TRIUMF has arrangements with the following organizations for shared research and development activities. These agreements are reviewed on a regular basis and renewed, adjusted, or closed. Formal agreements allow TRIUMF to interact informally with key partners to seek advice on market trends, product-development trends, and overall commercial potential.

Canadian

- Advanced Cyclotron Systems, Inc.
- AECL, Inc.
- BC Cancer Agency
- BC Preclinical Research Consortium
- British Columbia Innovation Council
- Burnaby Board of Trade
- Canada Border Services Agency
- Canadian Association of Physicists
- Canadian Institute for Nuclear Physics
- Canadian Light Source, Inc.
- Canadian Mining Innovation Council
- Canadian Space Agency
- CANARIE
- Carleton University (CRIPT)
- Centre for Probe Development and Commercialization
- D-Pace, Inc.
- Defence R&D Canada (DRDC)
- General Electric
- Genome BC
- Geological Survey of Canada
- GPN Petroleum Technology, Ltd.
- IKOMED Technologies, Inc.
- Institute of Particle Physics
- International Safety Research, Inc.
- Jubilant-Draximage, Inc.
- Lawson Health Research Institute
- Nordion, Inc.
- NVI Mining Ltd.
- Pacific Parkinson's Research Centre
- PAVAC Industries, Inc.
- Perimeter Institute For Theoretical Physics
- Positron Emission Tomography Imaging at UBC
- Radiation Protection Bureau, Health Canada
- Science World British Columbia
- Selkirk College
- Shad Valley
- SNOLAB
- Teck Resources, Ltd.
- UBC Geophysical Inversion Facility
- University of Saskatchewan
- Vancouver Board of Trade

International

- Argonne National Laboratory, Argonne, USA
- Brookhaven National Laboratory, Upton, USA
- China Institute of Atomic Energy, China
- Chinese Tri-University Cluster, China
- Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany
- CERN, Geneva, Switzerland
- Fermi National Accelerator Laboratory, Batavia, USA
- GANIL, Caen, France
- GE Healthcare
- Gesellschaft für Schwerionenforschung mbH (GSI), Darmstadt, Germany
- High Energy Research Organization (KEK), Tsukuba, Japan
- Institut des Sciences Nucléaires (ISN), Grenoble, France
- Institute of Basic Science (IBS), Republic of Korea
- Institute for High-Energy Physics (IHEP), Beijing, China
- Institute for Nuclear Research (INR), Russia
- Inter-University Accelerator Centre (IUAC), Delhi, India
- International Atomic Energy Agency (IAEA), Vienna, Austria
- IsoTherapeutics Group, LLC, USA
- Istituto Nazionale di Fisica Nucleare (INFN), Italy
- Japan Atomic Energy Agency (JAEA), Tokai, Japan
- Japan Proton Accelerator Research Complex (J-PARC), Tokai, Japan
- Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
- Kavli Institute for the Physics and Mathematics of the Universe (IPMU), Kashiwa, Japan
- Korean Institute of Radiological and Medical Sciences, Korea
- Laboratori Nazionali di Frascati, Frascati, Italy
- Lantheus Medical Imaging, Inc.
- Lawrence Berkeley National Laboratory (LBL), Berkeley, USA
- Lawrence Livermore National Laboratory (LLNL), Livermore, USA
- Los Alamos National Laboratory (LANL), Los Alamos, USA
- Manhattan Isotope Technology, LLC, Lubbock, USA
- MEPhI (National Research Nuclear University), Moscow, Russia
- Ministry of Education, Science, and Technology (MEST), Seoul, Korea
- National Superconducting Cyclotron Laboratory (NSCL), East Lansing, USA
- Oak Ridge National Laboratory (ORNL), Oak Ridge, USA
- Osaka Graduate School of Science, Osaka, Japan
- Paul Scherrer Institut (PSI), Switzerland
- Rutherford Appleton Laboratory (RAL), UK
- RIKEN Nishina Centre for Accelerator-Based Science, Wako, Japan
- SLAC National Accelerator Laboratory, Menlo Park, USA
- SOREQ, Israel
- Thomas Jefferson National Accelerator Facility (JLab), Newport News, USA
- Toyota Central R&D Labs, Inc.
- University of Missouri Research Reactor (MURR), USA
- UT-Batelle, LLC, USA
- Variable Energy Cyclotron Centre, Kolkata, India

TRIUMF has amassed a good deal of technical expertise and experience that when leveraged with external partnerships offers an extraordinary set of innovation commercialization opportunities. Combined with the business and market expertise at AAPS, TRIUMF brings a lot to the table for Canada.

[1]For details, see http://www.ieeeghn.org/wiki/index.php/Milestones:First_500_MeV_Proton_Beam_from_the_TRIUMF_Cyclotron,_1974.

The Plan

Delivering on the Promise 2015–2020

6

COMPLETE TABLE OF CONTENTS

This chapter presents Five-Year Plan 2015–2020. The discussion starts with the foundation of Five-Year Plan 2010–2015 (see Section 6.1) and then outlines the proposed chief activities organized by the three themes with explicit objectives presented for each program area (see Section 6.2 and 6.3). A summary of the strategic outcomes and key performance indicators is then presented (see Section 6.4.1) followed by a discussion of the international context in which TRIUMF operates (see Section 6.4.2). A discussion of the implementation of Five-Year Plan 2015–2020 is divided into two sections; the first examines the roles of TRIUMF's multiple stakeholders (see Section 6.5), and the second outlines three different scenarios indexed by the level of the NRC Contribution Agreement (see Section 6.6). The chapter concludes with comments on how the strategic plan was developed.

6.1 BUILDING ON FIVE-YEAR PLAN 2010–2015

A common quest for the past decade, if not century, of humanity has been advancing isotopes for science and medicine, understanding the basic building blocks of matter and how they shape our universe, and harnessing particles and beams to drive discovery and innovation. How did our universe get started, and where is it going? Where did the elements that make up everything in our world come from? How can we master the elements inside our own bodies so we can diagnose and cure disease? Ultimately, how can we use our modern understanding and technology to harness the physics of the universe for our own intentions?

These questions are the successors of those that inspired the founders of Canadian science stretching back to Ernest Rutherford in the early years of the last century to the pioneers of TRIUMF in the 1960s. What is presented in this section is the next five-year step forward on this quest of curiosity, inspiration, and discovery.

In 2008, TRIUMF laid out a plan for accelerator-based basic science in Canada, and with the federal government's budget decisions in 2009 and 2010, TRIUMF's role in advancing progress in this endeavour was assured. Core operations for the laboratory were secured in the 2010 federal budget. The ARIEL project was launched in mid-2010, with support from the Government of British Columbia, the Canada Foundation for Innovation, and the five-year NRC Contribution Agreement.

Prepared with extensive input from its user community, Five-Year Plan 2010–2015 offered a new vision for Canadian subatomic physics. This vision built on the success of the ISAC rare isotope program over the previous 15 years and added an e-linac (electron linear accelerator) to complement the proton cyclotron as the driver for rare-isotope production. One of the crucial considerations was to expand the discovery potential of the facility and provide more beams to the array of world-class, unique detector facilities already available in the ISAC experimental halls.

That vision also proposed a second proton beam line and target station, supplementing the new e-linac driver, for even more rare-isotope production along with continued support for the larger Canadian subatomic physics community. In Federal Budget 2010, the funding awarded to TRIUMF supported the progress of this program but, in light of the global economic downturn, at slower rate than desired.

The vision also called for a strong engagement in specific international particle physics endeavours, such as ATLAS at the LHC and the T2K neutrino experiment in Japan. Furthermore, TRIUMF set out to grow its Nuclear Medicine program in the production and use of radioisotopes.

The results have been spectacular. TRIUMF has consolidated its position as a global leader in the pursuit of isotopes for science and for medicine. Prestigious scientific publications generated from ISAC are on a steep rise. One indication of the success of this program is that Carl Svensson, a TRIUMF user from the University of Guelph, was the winner of the 2008 E.W.R Steacie Memorial Fellowship and the 2008 Herzberg Medal. Another indication is that Jens Dilling, a TRIUMF staff scientist, won the 2013 CAP-TRIUMF Vogt Medal for Excellence in Subatomic Physics for his rare-isotope work at TRIUMF. The contribution of the Canadian part of the ATLAS experiment in the discovery of the Higgs boson was recognized by CBC Radio naming Pierre Savard, who holds a joint appointment between TRIUMF and the University of Toronto, as its "Scientist of the Year". University of Pennsylvania graduate student Anna Grasselino received the 2013 IEEE Nuclear and Plasma Sciences Society PAST Doctoral Student Award for her research at TRIUMF on the materials physics of superconducting cavities used for accelerators. TRIUMF's Dr. Tom Ruth has been appointed to serve as the Canadian representative of the United Nations International Atomic Energy Agency's (IAEA) Standing Advisory Group for Nuclear Applications (SAGNA).

The new paradigm of accelerator-produced isotopes for medicine has attracted more than $13 million of additional funding to the nuclear medicine program. Moreover, Canada's participation in the "science of the century" was showcased not only in the analysis of the spin of the Higgs boson (moving it from a "Higgs-like" boson to a "Higgs" boson in March 2013), but also in the selection of a Canadian physicist (TRIUMF's Michael Wilking) to make the global announcement of a major discovery from a Japan-based neutrino experiment at a prestigious conference in Stockholm in July 2013. Canada also has a leadership role (via TRIUMF) in understanding how to probe the new world of antimatter via antihydrogen, for which TRIUMF's Makoto Fujiwara was awarded the APS Dawson Prize.

TRIUMF has accomplished a lot during the last five years; however, it could not complete everything initially proposed in Five-Year Plan 2010-2015. In fact, with only the flat-flat budget through the NRC Contribution Agreement many of the above accomplishments would not have been possible. They were enabled by TRIUMF and its university partners successfully competing for additional funding, in particular from the Canada Foundation for Innovation for the ARIEL project, the operation of the ATLAS Tier-1 Data Centre, and the construction of the M20 muon beam line. Several of these accomplishments are also a result of the investments made in the previous Five-Year-Plan, such as the investments into the LHC and ATLAS. Sustained funding from NSERC for the various experimental programs is another contributor to the level of TRIUMF's accomplishments.

Nevertheless, TRIUMF undertook serious belt tightening with a ~7% reduction of its core workforce and some hard choices about what to pursue and what not to pursue. For the present five-year period (2010–2015), the laboratory and its community chose two priorities: the first phase of ARIEL construction and the production of science from the existing facility and offshore investments. TRIUMF's choice stands in stark contrast to that of other laboratories (e.g., GSI and GANIL) where the decision has been made to curtail the science program in order to make major upgrades. With a distinct stretch to TRIUMF's core staff and with strict management, TRIUMF has made enormous gains. However, the compromise of simultaneously building ARIEL and producing science meant the timeline for the full ARIEL project had to be extended with parts of the project moving to the 2015–2020 five-year period. It also meant that international, high profile projects like the ultra-cold neutron facility had to be delayed and some urgent major maintenance items had to be deferred, resulting in increased risk of equipment failure. As an example, preventive maintenance was deferred, leading to a failure of a vacuum seal on a beam line and a significant loss of scientific output from the μSR program.

Five-Year Plan 2015–2020 builds on the substantial infrastructure improvements over the last five years: the new isotope production facilities and the e-linac, which will be ready to produce beam by autumn 2014. The proton cyclotron is being upgraded as part of a multi-year refurbishing and development program, to ensure reliable operation at the increased beam intensity required for a new beam line. A reinvigorated TRIUMF Nuclear Medicine Program has made great strides, supported by additional funding from Natural Resources Canada, in developing the process for making crucial medical isotopes with conventional cyclotrons and target materials. The molecular and materials science program has two new beam lines (M20 and M9A).

This chapter presents the next stage of the vision laid out five years ago and picks up where the previous plan leaves off. The objectives are: to generate three independent beams of rare isotopes, to build and operate a world-class facility for ultra-cold neutrons (UCN), to expand the Nuclear Medicine Program, to develop a competitive molecular and materials science program, to develop a world-leading program in accelerator science research and education, to provide the infrastructure support for the larger Canadian subatomic physics program, and to dedicate attention to commercialization opportunities that benefit Canadians. TRIUMF and its partners will again compete for the necessary project funds to achieve these goals, in particular to complete the ARIEL project. However, TRIUMF has taken on more responsibilities in terms of operating ARIEL, the ATLAS Tier-1 Data Centre, M20, and UCN as well as other new experimental facilities. As a consequence, another flat-flat operating budget via the NRC Contribution Agreement would seriously compromise TRIUMF's ability to extract value from these facilities and deliver a science program based on global excellence.

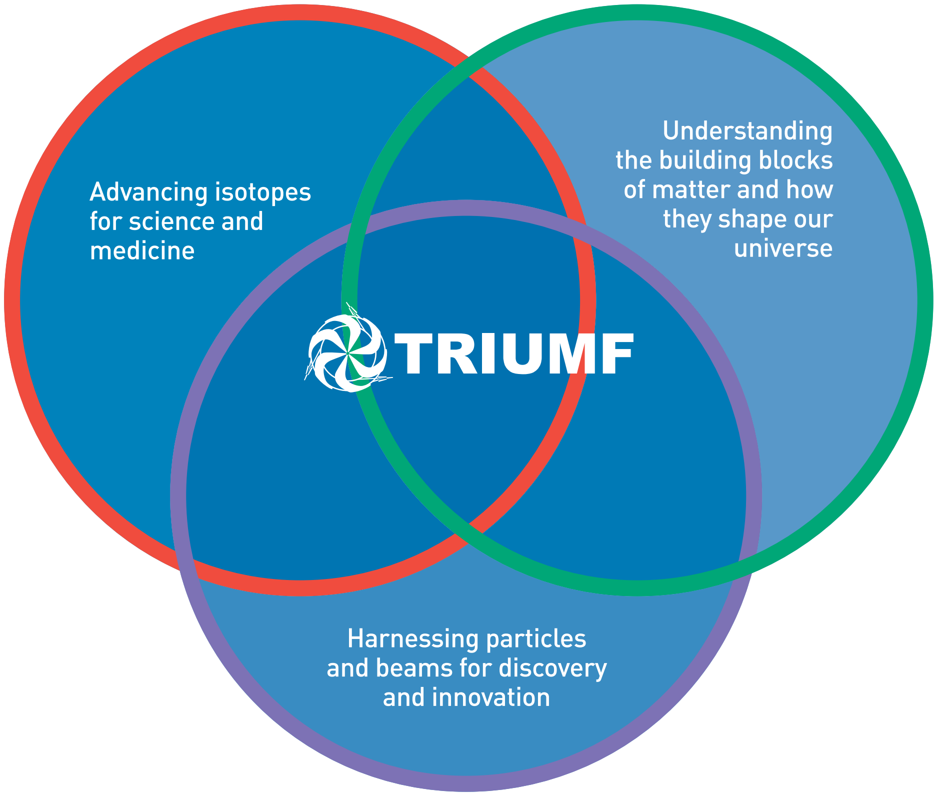
6.2 FIVE-YEAR PLAN 2015–2020: EXCELLENCE WITH IMPACT

TRIUMF has prepared a strategic plan for the 2015–2020 period that fulfills the decadal vision launched in 2010. The next phase of this plan is centred on three overlapping themes, which are portrayed in this section:

Theme 1	Advancing isotopes for science and medicine (see Section 6.2.1);
Theme 2	Understanding the building blocks of matter and how they shape our universe (see Section 6.2.2); and
Theme 3	Harnessing particles and beams to drive discovery and innovation (see Section 6.2.3)

During this period, TRIUMF will continue to excel in its leadership role for the Canadian nuclear and particle physics community, facilitate cutting-edge research programs in subatomic physics, and enable innovation in molecular and materials science, nuclear medicine, and accelerator science and technology. The priorities of each program will be guided by TRIUMF's mission and vision, while building on strengths and maximizing the return on investments.

Before elaborating on each theme in the subsequent sections, a summary of the proposed research program is provided in terms of the research fields of subatomic physics, molecular and materials science, nuclear medicine, and accelerator science.



Subatomic Physics (Themes 1, 2, 3)

TRIUMF's activities in nuclear and particle physics are guided by the Long-Range Plan of the Canadian Subatomic Physics (SAP) community, the most recent of which was completed in 2011. TRIUMF is an active and influential member of this community and has direct involvement in it (see Section 6.4.1.). While TRIUMF is ever mindful of this context, it sets the priorities for its own programs, building on its strengths and past investments and pursuing research directions that will give the lab its highest impact.

TRIUMF has clear priorities for its main on-site experimental efforts: the world-leading rare-isotope beam (RIB) program at ISAC, and in the near future ARIEL (Advanced Rare IsotopE Laboratory). The RIB program will continue to push the limits:

1. In the study of the structure and dynamics of very exotic short-lived nuclei;

2. In using exotic nuclei to search for new physics beyond the Standard Model (SM) of particle physics; and

3. In measuring the important nuclear properties and reaction rates for stellar burning and stellar explosions.

The experimental RIB program is complemented and supported by strong nuclear-physics expertise in the TRIUMF Theory Group. Experimental measurements at ISAC are guided by discussions with theory experts at TRIUMF who lead the field in terms of making progress on a systematic theory of nuclear structure and understanding the impact of sensitive measures of nuclear transitions and reactions in terms of astrophysics or fundamental symmetries.

The ARIEL facility will dramatically enhance the RIB program by providing beams of new isotopes not attainable at the current ISAC facility and by enabling multi-user operation that will allow for a much better utilization of the existing cutting-edge ISAC experimental facilities. The completion of ARIEL will be implemented in phases, and each phase will provide new and exciting physics opportunities to be exploited.

During the 2015–2020 five-year period, TRIUMF will bring online one of the highest density sources for ultra-cold neutrons (UCN) and enable one of the most sensitive experiments yet for the measurement of an electric dipole moment (EDM) of the neutron (nEDM). Together with efforts to measure the atomic electric dipole moment in radon isotopes and the electron electric dipole moment using francium isotopes, both abundantly produced at ISAC/ARIEL, TRIUMF is gearing up to become a world leader in EDM measurements. These measurements have the capability to constrain dramatically the parameter spaces of theories predicting new physics beyond the SM and are thus complementary to experiments at the energy frontier.

In addition to its on-site program TRIUMF is involved in selected high-profile international external projects. TRIUMF, an integral partner in the ATLAS Canada consortium, will continue to be a major player in the discovery efforts of the ATLAS experiment at the LHC (Large Hadron Collider) and its upgrade projects. The ATLAS Tier-1 Data Centre, located at TRIUMF, continues to play a crucial role in the distribution and analysis of ATLAS data, and will undergo a major expansion in the next Five-Year Plan to keep pace with the increasing data rates from ATLAS. The TRIUMF Theory Group, through its collaboration on beyond-SM theories with the Perimeter Institute for Theoretical Physics and Canadian universities, will continue to provide guidance for this experimental program.

TRIUMF and its Canadian partners continue to play a leading role in the long-baseline neutrino experiment, T2K in Japan, and its foreseen upgrades. T2K will continue to improve the accuracy of its measurements of neutrino mixing parameters. The T2K collaboration is also starting R&D efforts for the planned successor experiment Hyper-Kamiokande in Japan, which uses a megaton water Cherenkov detector.

TRIUMF will also continue to lead the Canadian ALPHA collaboration with the aim of performing the first laser and precise microwave spectroscopy on antihydrogen in the next five years and develop an antihydrogen gravity experiment.

In addition to these major initiatives TRIUMF, through its unique expertise and infrastructure for high-end instrumentation, will support the Canadian subatomic physics community at SNOLAB and in other offshore activities.

Molecular and Materials Science (Themes 1 & 3)

TRIUMF will continue to strengthen the Centre for Molecular and Materials Science (CMMS) user facility with its capabilities for muon spin rotation/relaxation/resonance (μSR) and beta-detected nuclear magnetic resonance (β-NMR) providing information about local magnetic fields on a molecular level inside materials and at interfaces, and enabling studies of chemical reactions.

The μSR facility at CMMS is used to study a wide range of science from superconductivity and magnetism to green chemistry and biological systems. μSR is important in studying frustrated magnetism and new superconducting materials as well as specific chemical reaction rates.

The β-NMR technique is conceptually similar to μSR except that it is sensitive to a different timescale and can provide depth-resolved information within several hundred nanometres of an interface. The multi-user capability of the ARIEL and ISAC facilities will ensure that the β-NMR program can, for the first time, be carried out with sufficient beam time to allow a vibrant user program to investigate the newest materials just when they emerge.

On the applied side μSR will continue to play an important role in the investigation of the behaviour of free radicals and their impact in the extreme environment of Generation IV nuclear reactors, while β-NMR is being used to study lithium ion diffusion in advanced battery materials.

In the period 2015–2020 TRIUMF will exploit the existing CMMS facilities, including two brand new muon channels with world-unique capabilities and will prepare for a major refurbishment of the aging main beam line (BL1A) currently preventing the operation of one of the three meson channels, M9.

Nuclear Medicine (Themes 1 & 3)

The NRU reactor in Chalk River, ON, will cease isotope production in October 2016. TRIUMF is at the helm of a multi-institutional effort to implement an alternative production process for Tc-99m using hospital-based medical cyclotrons.

In the face of increasing demand for accelerator-produced isotopes, TRIUMF proposes to combine its nuclear medicine capabilities in physics and chemistry with regional partner strengths in biology. This new centre of regional excellence would be dedicated to expanding the strong partnerships in place with the Pacific Parkinson's Research Centre (PPRC) and the British Columbia Cancer Agency (BCCA) while leveraging new opportunities for commercial involvement with the BC Preclinical Research Consortium. The proposed Institute for Accelerator-Based Medical Isotopes (IAMI) will focus on enhancing the research and development capacity in the region while allowing TRIUMF to continue working with the broader Canadian molecular imaging community as it moves to standardize radiopharmaceutical production in a manner required for the use in clinical applications.

TRIUMF will continue to drive innovation with a focus on enabling technologies for new and emerging radiometallic isotopes and novel molecular imaging probes. In an effort to explore relevant adjacencies, IAMI will begin work with the BCCA to initiate a program on radiotherapeutic isotopes. This program will leverage the new ARIEL laboratory at TRIUMF and will be substantially enhanced by implementing a new higher energy (24 MeV) medical cyclotron that will replace the current TR-13 and enable access to new radiotherapeutic isotopes.

Accelerator Science and Technology (Themes 1, 2, 3)

Accelerators play an increasing role in many areas of life, from medical isotope production, treatment of cancer, and modification and characterization of new materials to basic research. All of these areas are continuously developing to become more versatile and efficient and to push the limits of discovery science. TRIUMF, as Canada's steward for accelerator technology, plays an important role not only in the operation of a versatile set of accelerator facilities, but also as a driver in accelerator science to develop new and improved technologies for its own accelerator complex, for its contributions to large-scale international projects, like the LHC at CERN, and for industrial or medical applications. TRIUMF also has a history of successfully transferring the accelerator technologies it develops to Canadian industry.

In the 2015–2020 plan, TRIUMF will continue to leverage its unique expertise in accelerator science to the advantage of Canada's competitiveness by improving the performance of on-site accelerator facilities and by pursuing the design, construction, and operation of new, state-of-the-art facilities using leading edge technology at TRIUMF and around the world. In addition, research in novel beam generation and manipulation techniques and development of advanced technologies will lead to improved performance of future accelerators. Through these activities TRIUMF will continue to educate the next generation of accelerator scientists and engineers that are needed in the growing field of accelerator applications in research, health and industry.

6.2.1 ADVANCING ISOTOPES FOR SCIENCE AND MEDICINE

In Five-Year Plan 2015–2020, TRIUMF will continue to strengthen Canada's already formidable rare-isotope program, which revolves around five major research topics:

- Isotopes for developing a standard model for nuclear physics;
- Isotopes as laboratories search for new forces in nature;
- Isotopes to determine how and where the heavy elements were produced in the universe;
- Isotopes as probes of magnetism at interfaces and surfaces of new functional materials; and
- Isotopes for molecular imaging of diseases and treatment of cancer.

Discussion of harnessing isotopes for business opportunities is discussed in Section 6.2.3.

TRIUMF will exploit its unique capability to target the most important isotopes for each of these research areas, basically producing designer isotopes for their specific uses. In each of the above areas TRIUMF is already at the forefront of research, and the expanded capabilities that will be generated by the next Five-Year Plan, such as the completion of ARIEL and IAMI, will elevate the national and international standing of the program even further and generate scientific impact and socio-economic benefits.

6.2.1.1 RARE ISOTOPES TO DEVELOP A STANDARD MODEL OF NUCLEAR PHYSICS

A central goal of nuclear physics is to develop a theoretical framework that is able to make accurate predictions of the properties of all nuclei while being based on nuclear forces derived from the underlying properties of the fundamental strong force, governed by quantum chromo dynamics (QCD). This framework will be equivalent to establishing a standard model of all atomic nuclei complementing the well-established Standard Model of particle physics. Such a development will be a paradigm shift in the understanding of the evolution of nuclear structure and dynamics far from stability. Eventually it will be possible to describe the evolution of single-particle structure as well as the emergence of simple collective excitations in nuclei in a self-consistent framework that is rooted in the basic properties of QCD. The experimental and theoretical nuclear physics research at TRIUMF will produce transformational results in the next five years that will have a substantial impact in this endeavour of the international nuclear physics community.

Recent developments show great promise for the application of *ab initio*-based methods for medium-mass and heavy nuclei, for which currently only effective interactions in combination with various many-body approaches can be used. These new developments build on major advances in the development of realistic nuclear forces using effective field theory that employ one of the fundamental symmetries of QCD, chiral symmetry. These realistic forces are successfully used in *ab initio* models, such as no-core shell model, coupled cluster theory, or hyperspherical harmonics, to describe the properties of light nuclei from first principle. Major advances will, in particular, be made on the experimental and theoretical side at and beyond the drip line where few-body correlations and the interaction between bound states and continuum states are extremely important and lead to phenomena like halos. With its worldwide-highest intensities for ion beams of exotic light nuclei, such as the halo nuclei Li-11 and Be-11, TRIUMF continues to be at the forefront of experimental studies of these light exotic nuclei. At the same time the TRIUMF Theory Group is making major strides towards extending *ab initio* approaches from calculating nuclear structure properties of light nuclei to calculations of electro-weak excitations and nuclear reactions and as well as expanding the theoretical framework to heavier nuclei. In this field, experimental and theoretical advances feed of each other, and TRIUMF's experimental and theoretical researchers are advancing the field through joint projects.

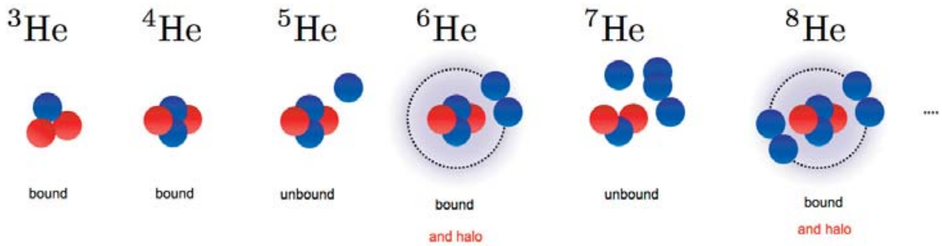


Figure 1: The isotopic chain for helium showing two protons and one neutron up through two protons and six neutrons.

Due to the vast range of energy scales (from the 1 GeV proton mass to the 40 keV energy of an excited rotational state in an uranium nucleus), approximations and constraints of the model space are unavoidable. Therefore the challenge in developing a standard model of nuclear physics is to preserve all relevant degrees of freedom in each step of approximation. Only comparison to experimental data can tell if this has been successfully achieved, and it is critical to go to extremes of isospin (neutron-to-proton ratio) to test the predictions of the new theories because the effect of specific components of the nuclear interaction, e.g., three-body forces, only becomes apparent through the investigation of long isotopic chains (see Figure 1). Recent results from ISAC have highlighted this (please see Section 4.2.2.2). In this context, the major themes for experimental investigations in the next five years will be the evolution of shell structure, the role of three-body interactions, the competition of single-particle degrees of freedom with collective excitations, and the search for new excitation modes near the drip line. Near stability, where high intensity RIB beams are available, it is possible to carry out precision studies that allow tests of long-standing paradigms of nuclear structure theory. At the same time it is essential to develop further and explore simple but characteristic experimental signatures for the main underlying mechanisms of structural evolution for nuclei far from stability where rare isotope beam (RIB) intensities are low, resulting in limited precision of the experiments.

With exciting theoretical developments on the horizon, and a farther reach to more neutron-rich nuclei from the e-linac of the ARIEL facility, TRIUMF will play a leading role on the international stage in the development of the standard model for nuclear physics. New experimental capabilities, such as the much higher sensitivity of the GRIFFIN gamma-ray decay-spectrometer as well as the new instruments for nuclear reaction studies, EMMA and IRIS, will play key roles in establishing this leadership. In combination with the TITAN Penning Trap facility (see Figure 2), the collinear laser spectroscopy beam line, and the TIGRESS gamma-ray spectrometer—with its various auxiliary detector systems—critical information will be extracted about the properties of ground states and excited states of exotic nuclei. The cleaner charge-bred ion beams from the new ARIEL electron-beam ion source (EBIS) charge state booster will be key to studying the structure and dynamics of very exotic isotopes. Through the CFI-funded CANREB project it will be possible to build this EBIS as well as a new high-resolution mass separator (HRS) and begin to exploit their unprecedented capabilities with beams from the current ISAC target station, well before RIBs from the actinide target station of the e-linac become available.

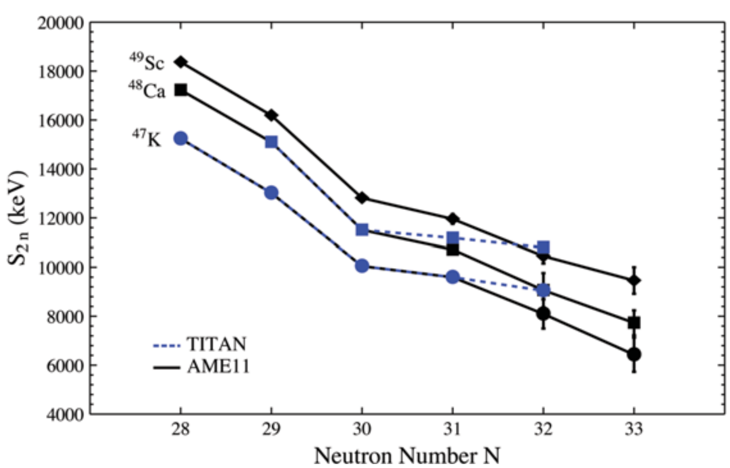


Figure 2: Evolution of two neutron separation energies for several isotopes comparing experimental and theoretical results. It is suspected that the leveling out of the measured energies is due to three-body nuclear interactions.

The various ISAC experiments (please see Sections 5.5.1 and 5.5.2) provide complementary information on the nucleus, including properties of its ground state and excited states as well as reaction and decay rates. No single experiment can by itself provide the full information necessary for the tests of modern theoretical predictions. Therefore, the available complement of world-class experimental stations for RIB beams at ISAC can only be exploited fully and effectively once TRIUMF operates three RIB production targets in parallel, one using photo-fission via the e-linac, one with the new proton beam line BL4N, as well as the current ISAC target station.

Once the construction for EMMA and GRIFFIN has been completed within the current Five-Year Plan, there is no need for major new experimental equipment at ISAC for nuclear structure studies. In some cases complementary detector systems will be brought to TRIUMF for experimental campaigns by outside collaborators. Examples are the 3Hen and VANDLE neutron detectors from the U.S. These complement the capabilities of DESCANT. The addition of anti-Compton shields to GRIFFIN, as originally foreseen, would further enhance its sensitivity, which is of particular importance for very exotic nuclei with low production yields. The other proposed initiative is the installation of a Penning trap for mass measurements behind the EMMA focal place which would provide access to some isotope species that cannot be extracted from the existing ISAC targets either due to their chemical properties or their short half-lives.

GOALS FOR 6.2.1.1 BY 2020

- Gain understanding of the role of three-body and tensor forces in unstable light and medium-mass nuclei as well as test emerging theoretical descriptions based on realistic forces.
- Develop a comprehensive *ab initio* nuclear reaction theory applicable to light nuclei based on a unified description of bound and unbound states.
- Carry out extensive studies of unstable light nuclei that test *ab initio* models in weakly-bound systems (e.g., halo-nuclei) and the role of correlations between bound and continuum states.
- Carry out extensive studies of the shell evolution in medium-mass and heavy unstable nuclei, delineating the evolution of single-particle and collective motion as a function of isospin.

6.2.1.2 RARE ISOTOPES AS LABORATORIES TO SEARCH FOR NEW PARTICLES AND FORCES

The beta decay of rare isotopes provides the opportunity to carry out precision measurements of weak interaction parameters at low energy. The weak interaction is qualitatively different from the other known forces since it is the only known source of parity (P), charge conjugation and parity (CP), and flavour violation. It also plays a key role in nuclear structure and astrophysics.

With the completion of ARIEL, TRIUMF will be in a unique situation for high-precision weak interaction studies with rare isotopes. Not only will it continue to be the highest power ISOL facility in the world with the RIB intensities needed for these kinds of experiment, it will also have the multi-user capability necessary to carry out several of these high-precision studies in conjunction with the other programs in nuclear physics, nuclear astrophysics, material science, and medical isotope production. Several ongoing or future experimental programs will be able to take full advantage of these capabilities.

The precise angular correlations between the electron, neutrino, and nuclear recoil relative to the aligned nuclear spin of a beta decaying isotope is sensitive to signs of new forces and the TRINAT atom trap (please see Section 5.5.1.2.) is already among the best experiments in this field. Major improvements of the trap and the associated detection systems were recently completed and first experiments were carried out on K-37. The ultimate goal is to reach a 0.1% uncertainty and to carry out studies for several different nuclei, such as Rb-80 and K-38m. To reach this unprecedented sensitivity it is essential to obtain sufficient statistics and carry out various studies of systematic effects. Such a program requires a substantial amount of beam time, which will only be fully possible with the advent of ARIEL.

Another sensitive test of weak interaction physics, and the possibility to discover new physics beyond the SM, is given through the study of parity non-conserving (PNC) atomic transitions, which enable the search for a nuclear anapole moment (a donut-shaped magnetic field) as well as new forces. With the recent installation and commissioning of the Francium Trapping Facility (please see Section 5.5.1.6), TRIUMF has initiated a world-leading program on PNC studies, taking advantage of the highest production rates of francium (Fr) isotopes at ISAC. These were enabled by the use of actinide targets at ISAC with beam intensities of currently up to 10 μAmp for the 500 MeV protons from TRIUMF's main cyclotron. The produced Fr isotopes are delivered into a laser trapping facility where they are captured and stored in a magneto-optical trap to study the rate of parity forbidden atomic transitions. The parity violation is induced by the weak neutral current and/or new physics. The simple electronic structure of Fr, with only one electron outside a noble gas configuration, makes it ideal for such studies. The most efficient way of producing the francium isotopes is done from spallation reactions in actinide targets, which are currently available with the highest power at ISAC and later at ARIEL. In particular, the availability of a series of odd- and even-mass number Fr isotopes is unique to ISAC. In combination, the results from odd- and even-mass number isotopes will make it possible to measure both the isoscalar and isovector components of the weak hadronic current in the same experiment. A distinct effort to measure the parity-violating interactions between the electron and the nucleons in optical atomic transitions is sensitive to corrections to the Standard Model weak neutral current from TeV-scale bosons and from ultraweakly-coupled lighter bosons.

Figure 3: Rn Nature Cover page volume 497 number 7448 pp 157-282

Isospin-breaking corrections in beta decays are at the centre of attention more than ever, first because of new developments in theory and experiments, and secondly because of renewed focus on the matrix-element V_{ud} in the Cabbibo-Maskawa-Kobayashi (CKM) quark mixing matrix. This focus stems from an improved measurement for V_{us}, which now requires V_{ud} to be determined with better precision than previously needed in order to test the unitarity of the CKM matrix. TRIUMF will continue to make major contributions to the study of superallowed Fermi emitters through a coordinated effort to determine decay Q-values (TITAN), half-lives and decay branching ratios (GRIFFIN, GPS) of superallowed Fermi emitters with highest precision. In addition, measurements of charge radii via laser spectroscopy, as well as investigations of the structure of mother and daughter nuclei, will provide critical information to reduce the uncertainties of the isospin-breaking corrections. For example, the much increased coincidence efficiency of the GRIFFIN spectrometer will enable first precise branching ratio measurements for the heavy superallowed emitters As-66 and Br-70 and to measure weak non-analog Fermi β-decay branches to excited 0^+ states in the daughter nuclei which directly constrain the isospin mixing component of the theoretical corrections to superallowed decays. Also, precision half-life and branching ratio measurements are planned for $N=Z-2$ superallowed emitters such as Ar-34.

It has recently been pointed out that V_{ud} can be obtained from the study of beta-decay transitions between isospin doublets in mirror nuclei, and will be pursued in the upcoming years. The experimental program with the 4π gas counter GPS and its upgraded tape transport system at ISAC will include precision half-life measurements for several of the isospin $T = ½$ mirror decays that currently provide the second most precise determination of V_{ud}, including O-15, Ne-19, Na-21, and Ar-35. Since these transitions are mixed Fermi and Gamow–Teller they are, like neutron decays, mediated by both vector and axial-vector interactions. The analysis is slightly more complicated than in the case of superallowed Fermi decays since the axial-vector current is not conserved in nuclear decays and one therefore needs to measure correlations that enable the separation of vector and axial vector components; correlations in K-37 with TRINAT are pursued locally. Overall, the accuracies that can be reached are at the same level as from the superallowed transitions and provide additional access to V_{ud}.

A non-zero electric dipole moment (EDM) of a fundamental particle would signify a violation of CP and time-reversal (T) symmetry providing insights into the nature of the observed matter-antimatter (baryon) asymmetry of the universe. The abundant production of radon isotopes at ISAC offers the possibility to embark on an experimental program to measure the atomic electric dipole moment in octupole-deformed isotopes of these elements. First activities for an experiment on radon isotopes have already started (please see Section 5.5.1.9) but before the main EDM experiment can move forward it is essential to identify the ideal candidate isotope. Octupole deformation is important because it enhances the effect of an EDM dramatically, and recent experiments at ISOLDE on Rn-220 indicate that a reasonable candidate exists in Rn-221. Further nuclear structure investigations of Rn-221,223 are planned for late 2013 at ISAC using the 8π spectrometer. Follow-up experiments will be carried out with GRIFFIN. These experiments have been made possible by the very recent development of the ion-guide laser ionization source (please see Section. 5.4.2) that enables suppression of surface ionized species like francium by up to six orders of magnitude while selectively ionizing the isotopes of interest without dramatic losses in beam intensity. Using this innovative cleaning technique, astatine (At) beams of sufficient purity can be produced to study the decay of At-221 into Rn-221 in order to deduce its level structure, which is a sensitive indicator of the octupole deformation via the splitting of parity doublet bands. Further development of the EDM apparatus, techniques for spin polarization, and magnetic shielding for the RnEDM experiment will be continued in the next years so that first measurements can be carried out in the second half of the 2015–2020 period. To achieve a world-leading limit of better than 10^{-27} e cm, the experiment needs more than 100 shifts of beam time with beam intensities of $2.5x10^{7}$ pps. This will only be feasible once the new proton beam line BL4N within the ARIEL project becomes operational, since today the available 200-250 shifts per year have to be shared among more than 10 different experiments. This limit would be more than a factor of 3 lower than the current world-leading limit from mercury, Hg-199.

Its simple electronic structure and its abundant production also make francium isotopes very attractive for an experiment to measure or set limits on the electric dipole moment of the electron. A proposal has been made for an EDM experiment using a Fr atomic fountain (please see Section 4.2.1.3). The goal is to improve the sensitivity to the electron EDM by up to a factor of 100. Discovering an electron EDM would demonstrate the existence of a new source of CP violation and point to undiscovered TeV scale particles. The underlying technology for this experiment has been developed for stable caesium (Cs) atoms but Fr offers the prospects for much higher precision due to its large atomic charge, which ultimately leads to a larger enhancement factor for Fr compared to Cs. Larger electric polarizability of certain Fr isotopes (209, 211,213) leads to an additional order of magnitude suppression of systematic effects with respect to Cs in this experimental method. Developments of the experimental apparatus are currently starting at Berkeley and will be carried out with a Cs fountain. Once the technique has been demonstrated it is planned to bring the experiment to TRIUMF for an extensive measuring campaign at ISAC, which would require beam times of several months to reduce the statistical and systematic limits of the experiment to make a world-leading measurement. This program will be facilitated by the new proton beam line BL4N and the multi-user capability that the full ARIEL implementation will bring for the ISAC science program.

Another way to probe fundamental symmetries using rare isotopes involves the precise measurement of the Mott scattering anisotropies of the electrons produced in the beta-decay of polarized Li-8. Using this technique, the MTV (Mott polarimetry for T-Violation) (please see Section 5.5.1.7) experiment searches for violation of time reversal symmetry, which is predicted by certain models of physics beyond the SM. To reach the required statistics for a leading measurement on the 0.1% level, sufficient statistics as well as careful evaluations of systematic effects, will be needed. The experiment can benefit from the abundant Li-8 production of the e-linac and ample beam time available during the first phase of the ARIEL completion project. Once the Li-8 measurements have been completed, the collaboration intends to switch to different isotopes to establish any effects depending on the final state interaction of the emitted electron.

GOALS FOR 6.2.1.2 BY 2020

- Set new limits on scalar contributions in the electro-weak sector from beta-neutrino correlations.
- Set limits on parity non-conservation in the francium system.
- Make first measurements with radon for an atomic EDM experiment.
- Advance electron EDM measurements toward a francium-fountain experiment; and
- Measure key super-allowed beta emitter V_{ud} parameters with unprecedented uncertainty and make complementary mirror nuclei measurements with similar precision.

6.2.1.3 ISOTOPES TO UNDERSTAND THE ORIGIN OF THE CHEMICAL ELEMENTS

The prospects for a full understanding of the origin of the elements within the foreseeable future have dramatically increased with recent advances in astrophysical modelling, in observations of elemental abundances back to the first stars, and in advances in experimental and theoretical nuclear physics.

Advances in high-power computing, and the associated computational techniques, are enabling realistic multi-dimensional modelling of stellar evolution and cataclysmic stellar events, such as novae, supernovae, or neutron star mergers. These advances have brought the prospect of fully modelling the nucleosynthetic output of such events within reach. The availability of rare-isotope beams of short-lived species allows for recreating the microscopic conditions inside stars and stellar explosions in the laboratory and to measure the relevant nuclear properties and reaction rates, with the aim to eliminate nuclear physics as a source of uncertainty in these astrophysical models. Consequently, the comparison with observed elemental abundances of the nucleosynthetic outputs of these realistic astrophysical models using accurate nuclear physics input can be used as a diagnostic tool to determine the astrophysical production sites for the various elements.

The Experimental Nuclear Astrophysics and Theory Groups at TRIUMF, in conjunction with numerous national and international collaborators, play an important role in these developments and will continue to make significant advances in this field through diverse experimental and theory programs pertaining to a variety of astrophysical scenarios. This will involve experimental and theoretical efforts over the full range of astrophysical scenarios, from the Big Bang to solar neutrino production and the origin of the heavy elements.

DRAGON GROUP REACHES MILESTONE IN UNDERSTANDING NOVAE EVENTS

11 July 2013

TRIUMF's DRAGON Group has made the first successful observation of the fusion of radioactive F-18 with hydrogen, producing 19Ne. In time, this will give astrophysicists another way to observe the inner workings of novae. During this stellar event, an accumulation of energy eventually causes a violent explosion that ejects matter into space. In the aftermath of these outbursts, 18F is produced and reacts with hydrogen to form Ne-19.

Astrophysicists are keen to better understand this fusion reaction as it gives insight into the early workings of our universe. However, until now, it was not possible to study this reaction as intense ion beams are required to separate out a tiny fraction of the desired 19Ne ions from the one thousand billion 18F ions produced in each reaction.

TRIUMF's DRAGON team, in collaboration with physicists in the UK, United States, and across Canada were able to resolve just two of the 19Ne ions amongst the 18F deluge, thereby giving scientists yet another tool to use in the investigation of our early universe.

Some of the important outstanding questions in nucleosynthesis and stellar energy release, involving rare-isotope beams on both sides of the valley of beta stability, are:

- What is the astrophysical environment in which the r-process elements are formed?
- Where are the so-called "p-process" nuclei formed?
- Does breakout of the hot-CNO cycles occur in novae?
- What are the contributions of active galactic nuclei, Type II supernoave, and general novae to galactic Al-26, which is observed by gamma-ray satellites?
- Can we use radioactivity and meteoric abundances, combined with neutrino observations, to refine solar and stellar models?

Experimental efforts will continue to utilize the cutting-edge radioactive beam technology at ISAC with the precise, high-sensitivity instruments, like DRAGON and TUDA, as well as other ISAC facilities (e.g., IRIS, TIGRESS, DSL) or under construction (e.g., EMMA, GRIFFIN), to answer these questions (please see facility descriptions in Sections 5.5.1 and 5.5.2).

While the solar neutrino problem can be considered solved now, the focus has shifted to determining neutrino-mixing parameters from the measurements of different solar neutrino observatories, for which a detailed understanding of the neutrino production in the sun is required. Most of the signal at these observatories results from high-energy neutrinos produced by the decay of B-8 that in turn is produced by the solar $^{7}Be(p,\gamma)^{8}B$ reaction.

The measurement of direct reaction rates and nuclear properties relevant for explosive hydrogen and helium burning in novae, X-ray bursters, or the proton-rich outflow in core-collapse supernovae, is another major focus of the TRIUMF program. Substantial progress in this area will depend on intensive beam development efforts, with the particular long-term goal of producing sufficient intensities of some of the most critical beams for this program, such as O-15, P-30, and Ti-44. Beam time for the necessary beam development will become available when ARIEL is fully operational, target turnaround has been substantially reduced, and multi-user operation of the facility allows us to set aside substantial time for development work.

Even though the so-called 'p-nuclei' represent only a minute contribution to the overall abundances, the origin of these nuclei is only partially understood. However, it is clear that several processes are responsible for their production. Recent developments of the DRAGON facility have opened up the possibility of carrying out measurements of capture reactions for heavy nuclei in the A=80 regime, which will allow us to address some of the reaction rates needed to understand the production of the lighter 'p-nuclei'. In the next five years, a program for such measurements is planned that will take advantage of the unique capabilities of DRAGON.

The elements from iron to uranium cannot be created by fusion processes in the interior of stars. For these elements neutron capture processes play an important role. About half of the abundance of these isotopes originates from the so-called "slow neutron capture process" in red giants and massive stars. Most of these isotopes are well investigated because they lie in the valley of stability. For the other half of the isotopes the progenitors are very neutron-rich isotopes far off stability, which are produced in the so-called "rapid neutron capture process" (r-process). Most of these isotopes are presently out of reach for experiments, but are a main motivation for all presently upgraded or newly built ISOL and in-flight RIB facilities, including the ARIEL e-linac. The astrophysical scenarios for the r-process are still being debated, but our understanding of nuclear physics tells us that one needs environments with extremely high temperatures and enormous neutron densities in which these heavy elements are produced within a few seconds.

For a long time the favoured astrophysical scenario for the r-process has been that of a core-collapse supernova at the end of the life of a massive star. However, while multidimensional simulations of core collapse supernovae (CCSN) using modern supercomputers are getting more realistic, the conditions for the r-process remain elusive in this scenario and it is time to question and potentially abandon this long-standing paradigm on the r-process site. Today, very sophisticated r-process model calculations are carried out with parameterized models that might not have any connection to the real r-process site. At the same time, simulations for realistic sites either fail to produce the observed r-process abundances (e.g., CCSN), or the events, such as neutron star mergers (see Figure 4), occur too rarely in the early universe to explain the observed amount of heavy elements in early stars. The present understanding is that the r-process abundances do not only originate from one scenario like a CCSN, but most likely from at least two scenarios operating at different times. More exotic scenarios, such as black hole accretion disks, jets in collapsars, and quark novae are being proposed but are currently lacking a clear path to validation. An important aspect in solving this mystery of the origin of the heavy elements is to establish accurate nuclear physics input for the ever more sophisticated and realistic astrophysical models that can validate these models via elemental observations with current and next-generation telescopes.

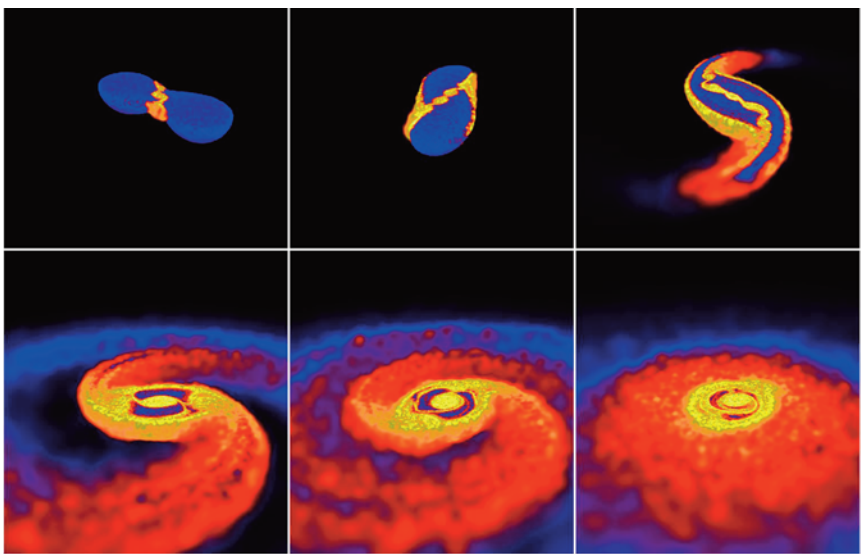


Figure 4: A computer simulation of neutron stars mergering. Courtesy of Daniel Price (u/Exeter) and Stephan Rosswog (Int. U/Bremen).

The recent addition of actinide targets at ISAC has been a major step towards directly investigating the relevant nuclear physics input needed for realistic modeling of possible r-process sites. This capability was the result of a step-by-step analysis driven by safety and process-control considerations over the course of a year. Analysis, documentation, and training were required to earn the necessary licence approvals from the federal regulator to implement these targets.

The e-linac, with its much higher production yields for the neutron-rich isotopes will be an “r-process machine”, enabling a world-leading experimental program to determine the critical nuclear properties like masses with TITAN, half-lives with GRIFFIN, neutron-capture rates—through (d,p) surrogate reactions—with TIGRESS and SHARC, and branching ratios for beta-delayed neutron emission using GRIFFIN, DESCANT, 3HEN, and VANDEL. Through this program TRIUMF will make a major contribution to solving this long-standing mystery.

In this context, Canada with TRIUMF is leading a 4-year Coordinated Research Project (CRP) of the International Atomic Energy Agency (IAEA) concerning “Beta-Delayed Neutron Emission Evaluation.” The CRP objective is to enhance IAEA member states’ knowledge and capabilities in the fields of nuclear energy, safeguards, used fuel and waste management by creating a Reference Database for Beta-Delayed Neutron Emission. This data is important for astrophysical modelling of the r-process. In addition to its leadership role, TRIUMF will also contribute to this project with measurements of important beta-delayed neutron emitters with various techniques.

GOALS FOR 6.2.1.3 BY 2020

- Measure directly all reactions critical for breakout from the hot-CNO cycle in nova reactions in the relevant energy range (Gamow-window).
- Measure directly the most critical reactions, identified by sensitivity studies, for explosive hydrogen and helium burning in novae, X-ray bursters, and core collapse supernova explosions.
- Make measurements of nuclear properties and reaction rates to constrain calculations of r-process nucleosynthesis.
- Substantially contribute to the understanding of the solar neutrino flux from Be-7.
- Constrain the capture (γ,n), (γ,p) , and (γ,α) reaction rates for key branching-point nuclides in the p-process.

6.2.1.4 ISOTOPES AS PROBES OF MAGNETISM AT INTERFACES AND SURFACES OF NEW FUNCTIONAL MATERIALS

As microelectronic devices shrink in size, the role of interfaces becomes increasingly important or even integral to their function. Giant magneto-resistance (Nobel Prize, 2007) in magnetic multi-layers is a prominent example, and one that was only discovered 15 years ago but is now in widespread use in read heads for hard disks. Interfaces are a new frontier in condensed matter physics since the behaviour of electrons at an interface is distinct from that in the bulk and have unpredictable but potentially useful properties. This has implications for understanding the origin of high-temperature superconductivity and the functionality of nano-devices, as well as for the development of quantum computers.

Depth-controlled β-NMR is one of the most promising methods for investigating local magnetic properties of surfaces and buried interfaces as a function of depth. TRIUMF is the only facility in the world where such measurements can be carried out with isotopes; approaches using slow muon beams in Japan and at PSI are complementary. β-NMR can also probe the depth dependence of dynamics in soft matter, which could have implications in lithography, and measure the hopping rate of lithium ions in rechargeable batteries (see Figure 5).

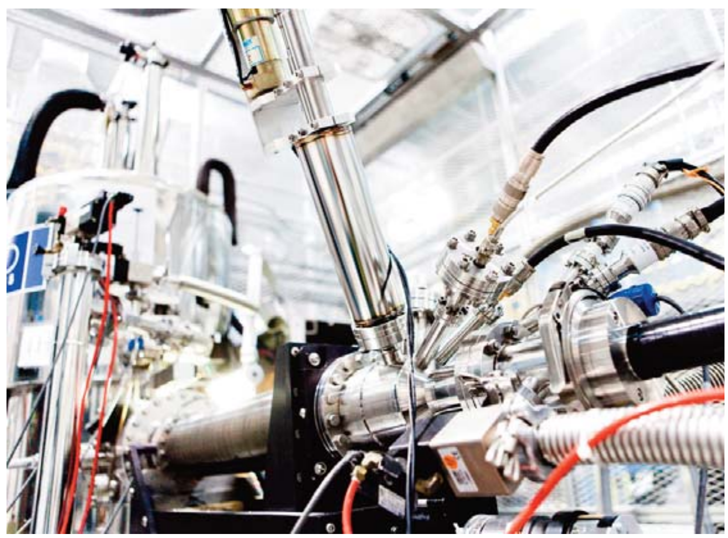


Figure 5: The β-NMR facility at TRIUMF. Courtesy of Laura Scotten.

Today the TRIUMF β-NMR program is carried out by a small group of local investigators, with limited access for non-expert users and thus is not really operated as a user facility. This is due to the fact that in typical years only five weeks of beam time can be made available for this program, which competes with the rest of the ISAC Rare Isotope Program. With the intense Li-8 beam becoming available from the e-linac and the availability of more than three months of beam time per year in the early stages of the ARIEL Science Program, this very promising technique will develop its full potential during the next reporting period. In order to allow for the resulting longer running periods and non-expert users it will be important to automate the spectrometers, data acquisition systems, and beam lines. Expanding the accessible temperature range will make it possible to investigate novel physical phenomena, such as superconductivity in oxide multilayer thin films and lithium ion diffusion in electrode materials. With the installation of an available He-3 cryostat and a furnace the range of controlled temperatures can be expanded from currently 5–300 K to 300 mK–600 K. Further considerations for expanding the facilities capabilities include the introduction of external stimuli such as electric fields or lasers. An *in-situ* sample preparation chamber with sputter cleaning, annealing and gold evaporation source for capping films and surface characterization techniques like XPS is also planned.

The use of different isotopes would enable us to broaden the spectrum of β-NMR applications. For example, the short-lived isotope Mg-31 would enable the study of chemical shifts that represent the screening effect of electrons surrounding the nucleus and is used widely as a diagnostic of the local chemical binding environment of an atom/ion. Because of its relevance in biochemical systems β-NMR with magnesium would open up the possibility of studying the role of magnesium in the catalytic activity of enzymes, in chlorophyll in photosynthesis, and membrane protein ion transport. Be-11 is another isotope of interest.

TRIUMF has pioneered studies of materials-surface science in niobium at the advent of the superconducting phase transition; graduate student Anna Grasselino won the IEEE Particle Accelerator Science and Technology doctoral dissertation award in 2013 for her groundbreaking research on this topic at TRIUMF. These studies will continue as TRIUMF establishes greater mastery of superconducting radio-frequency accelerating cavities and the fundamental physics that governs their performance.

GOALS FOR 6.2.1.4 BY 2020

Our goals centre on advancing understanding of magnetism and functional materials to address:

- Depth dependence of topologically protected surface states,
- Fluctuating order parameters in the superconducting proximity effect,
- Lithium ion conduction in battery materials,
- Spintronic materials and devices,
- Heterogeneous catalysis on metal surfaces, and
- Local environments in biological materials, such as magnesium-containing enzymes.

6.2.1.5 ISOTOPES FOR MOLECULAR IMAGING OF DISEASES AND TREATMENT OF CANCER

TRIUMF applies accelerator and isotope technologies specifically to address critical unmet needs to the economic and health benefit of all Canadians. TRIUMF's role in driving this field forward falls into these categories:

- Accelerator target design and innovation;
- Medical isotope production and isolation; and
- Radiopharmaceutical synthesis and applications.

Each of these is discussed in turn below. A proposal to combine TRIUMF's strengths in these areas with regional activities to create an efficient and effective centre of excellence for accelerator-based medical isotopes is discussed in Section 6.3.3.

Accelerator Target Design and Innovation

Research and development of production targets for medical cyclotrons continues as one of TRIUMF's basic strengths. In Five-Year Plan 2015–2020, TRIUMF will focus on developing technologies to produce more radiometals and to improve fundamental improvements in target design.

MIKE ADAM ELECTED TO BOARD OF SRS

19 March 2013

Dr. Michael J. Adam, TRIUMF's Deputy Division Head of Nuclear Medicine, as well as an Adjunct Professor at the University of British Columbia Chemistry department, was recently elected to become one of the 16 voting members for the Board of Directors of the Society of Radiopharmaceutical Sciences (SRS).

The SRS is a not-for-profit organization dedicated to the advancement of excellence in education and research in radiopharmaceutical science and in the study and use of radiopharmaceuticals. It is an organization that gathers professionals from multiple disciplines for the purpose of fostering the communication, discussion, and dissemination of information. Dr. Adam is one of the four exceptional scientists elected to the board this year. He will represent the North America/South America region.

As a Senior Research Scientist with TRIUMF, Dr. Adam is currently developing radiopharmaceuticals for the neurological program in the PET chemistry group at TRIUMF, developing new agents for oncology research, and new labeling strategies for the incorporation of a variety of radioisotopes into organic and inorganic compounds.

Various activities are planned to improve the yields and extraction efficiencies of the radioisotopes produced at the TR-13 cyclotron. This includes improvements to the target cooling, enabling higher target loading pressure, and to the materials used for the target cell lining providing better collection efficiency.

For the planning of new isotope production and the design of new solid targets, it is important to estimate the yield of the desired isotope and the yield of all contaminants. For this purpose we will use theoretical calculations and Monte Carlo simulations, using the FLUKA code to estimate the yields of several radio-metallic isotopes and to determine—in comparison with data from experimental irradiations—which method more accurately describes all processes involved in the production. This work will result in an important tool for future solid target designs.

Liquid targets have great potential for isotope production but are not very well understood. Some development has been done, but was often driven more by producing a higher yield than understanding the thermodynamic processes during irradiation. We propose to develop a time-dependent Monte Carlo simulation of an irradiated target, taking into account the heat transfer behaviour and the transport phenomena. Experimental data will form input parameters for the simulation. With this model, we hope to gain insight into the impact of target geometry and material on temperature and pressure build-up during irradiation, and ultimately develop a new liquid-target design with higher yields.

Medical cyclotrons have long been viewed as machines for producing non-metallic positron emitting isotopes (F-18, C-11, N-13, O-15) for use in PET imaging. All of these isotopes are produced from either gas or liquid target materials that are easy to manipulate via pneumatic transfer from the production space, to the chemistry space (hot cell) for radiopharmaceutical production. Positron emitting radiometals (Sc-44, Mn-52, Cu-64, Ga-68, Y-86, Zr-89, Tc-94m, etc.) have been steadily increasing in popularity due to their decay properties, facile chemistry, compatibility with aqueous media, and favourable reaction kinetics, all of which enable their rapid incorporation into a growing number potential radiotracers, which are used to target (and image) specific physiological structures or metabolic processes.

The widespread acceptance of new and promising radioisotopes is typically challenged by their availability and accessibility. Many radiometals have demonstrated promise in molecular imaging; however, many laboratories are required to purchase an isotope generator or invest substantially in unique solid-target infrastructure for the production and isolation of radiometallic isotopes from a cyclotron—a substantial technical and financial commitment, especially if preliminary biological studies are required to warrant their purchase. These obstacles likely inhibit the development of novel tracers that may possess a better match between the physical half-life of a promising new radioisotope and the pharmacokinetic profile of the vector to which it is attached.

Having recently demonstrated the concept of liquid target production of Tc-94m and Sc-44 by irradiating ammonium heptamolybdate and calcium nitrate respectively, TRIUMF is currently working on an innovative new target design for higher current (>20 mA) irradiation, higher yielding production of Zr-89, Ga-68, Cu-61,64,67, Mn-52, Co-55, and many others. The goal is to continue pushing the envelope on the utility of the modern hospital-based cyclotron for the production of a number of newer isotopes coming online. The design and testing of new target technology will also create a better fundamental understanding of the science behind medical isotope production.

Medical Isotope Production and Isolation

TRIUMF's ongoing essential contribution and commitment to the Pacific Parkinson's Research Centre (PPRC) has been through production of radioisotopes and radiotracers, while investigators from the PPRC led the neurology-related imaging research. This joint venture maintains one of the best PET brain imaging centres in the world and is one core of TRIUMF's Nuclear Medicine Program (see Figure 6). The main clinical research focus is to establish pathogenesis, progression and treatment-related complications in Parkinson's disease. Other areas of research include Alzheimer's disease and mood disorders as well as the development of novel imaging protocols. Evolving tracer development is enabling studies directed solely at the dopaminergic system to investigations of more current hypotheses that predict involvement of other systems in disease origin and treatment-related complications. This results in seven tracers being routinely provided for human and pre-clinical imaging studies on a routine basis.

Currently, two other factors contribute to an increased importance of brain imaging: the worldwide recognition of the heavy economic and social burden imposed by brain illness and the knowledge that imaging is one of the best tools for diagnosing (and eventually treating) such illnesses. There are current plans at UBC to expand the dementia program and apply imaging to brain trauma studies as well as addiction. The second factor is an increased recognition of genetic components that predispose to brain illness. UBC has a very strong genetics program which, combined with imaging provides a unique opportunity to image subjects at risk for disease due to genetic mutations before clinical symptoms become manifest. PPRC, for example, has studied the largest cohort of subjects with LRRK2 mutations (risk for Parkinson's disease) and has identified neurochemical changes that precede clinical symptoms. Significant expansion of such studies is planned.

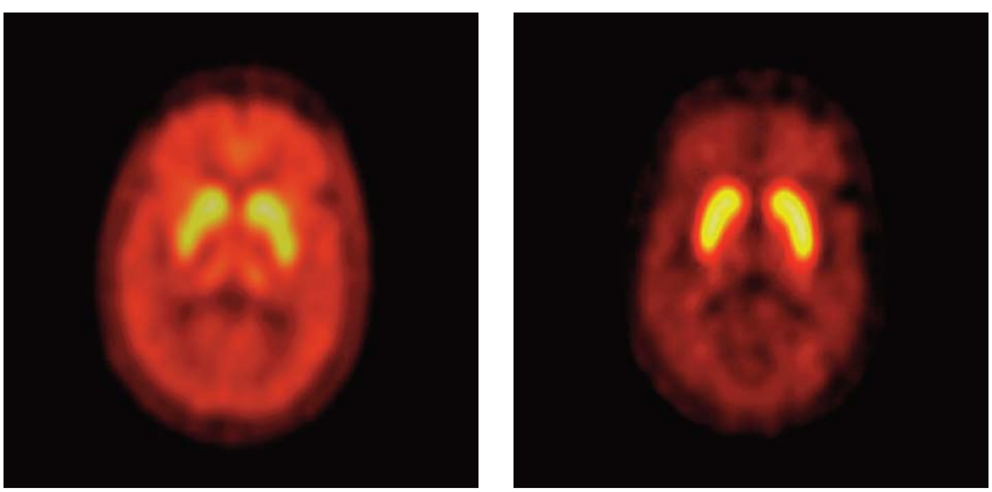


Figure 6: PET in Affected Members is Identical to Sporadic Parkinson's disease shown with (a) F-DOPA and (b) Raclopride.

This environment presents a unique opportunity for TRIUMF's Nuclear Medicine Program. As disease understanding progresses, there is an increasing need to develop new radiotracers that will target new sites that are hypothesized to be involved in pathogenesis. The radiochemistry program can thus expand its role from implementation of published tracers to actual novel brain-disease related tracer development and thus become a world-leader, substantially increasing TRIUMF's visibility in this field.

In order to foster both TRIUMF-based and collaborative research, it is important to focus heavily on safety as well as good manufacturing practices (GMP). The paradigm of radiopharmaceutical production is shifting. Regulatory requirements for the production of radiopharmaceuticals are increasing, requiring the Nuclear Medicine Division at TRIUMF to implement formal quality control and quality assurance programs. With the recently completed GMP laboratories (please see Section 5.6.2), which were implemented with support from Western Economic Diversification Canada, TRIUMF has the infrastructure and procedures in place to meet these requirements.

The BC Cancer Agency (BCCA) and TRIUMF continue to partner to implement the production and use of radiotracer [^{18}F]-EF5 (a nitroimidazole-containing compound) that is preferentially taken up by hypoxic tissues. Thus, EF5-PET allows clinicians to measure oxygenation, which can be compared to blood perfusion, using complementary CT scanning (i.e. PET/CT), providing a quantitative, non-invasive means to quantify tumour blood flow and oxygenation before, during, and after chemotherapy. Current studies underway include head and neck as well as a continuation of non-small cell lung cancer. Upcoming studies will extend this technique to ovarian cancer. It is believed that hypoxia may be an important prognostic and predictive factor in all three of these types of cancer and thus could lead to early detection and treatment. As well as early detection, the degree of oxygenation is an important factor that can determine more accurately what course of treatment is most likely to succeed.

TRIUMF and the BCCA will also continue to work together on the use of ^{18}F-FDOPA (currently the only Canadian centre making this radiopharmaceutical) for imaging both high-grade gliomas and neuroendocrine tumours. Recently, this collaboration, including expertise from BC Children's Hospital, has been able to positively diagnose neuroendocrine tumours in a 16-year-old child who was not clearly diagnosed by other imaging modalities. After surgery the child made a good recovery. In addition, a one-year-old baby from Seattle was diagnosed using FDOPA produced by our group (this child also recovered). The BCCA is currently carrying out a Phase II clinical study using ^{18}F-FDOPA and PET for the planning of neurosurgery and the assessment of resection for high-grade gliomas as well as surgical planning of neuroendocrine tumours.

Production of radiotherapeutic isotopes is typically done via neutron activation in a nuclear reactor or by using higher-energy cyclotrons. The time has come for the Nuclear Medicine Program to implement a radiotherapeutic isotope research and development program. This will be facilitated by the planned installation of a new higher current, higher energy TR-24 medical cyclotron (please see Section 6.3.3), the commissioning and ramping up of the ARIEL science program, as well as the long-standing 500 MeV irradiation capabilities on TRIUMF's main cyclotron.

The use of radioactivity bound to biological vectors that bind to specific sites for cancer treatment has been the Holy Grail for nuclear medicine for several decades. Of particular interest is the use of alpha-emitting radionuclides that have the appropriate alpha particle energy and half-life. One of the more promising candidates is astatine-211 (At-211) with a 7.2 hour half life. At-211 offers the possibility of selectively delivering a lethal dose of radiation to the tumour cells by means of targeted radionuclide therapy, such as labelled anti-bodies. A number of laboratories have concluded that At-211 needs to be made available in clinically relevant amounts since the chemistry of astatine has been shown to be amenable to bio-molecules. It brings significant advantage in cancer therapy compared to β-emitting isotopes and is actively sought after for use in cancer trials.

Consequently, targeted alpha-particle therapy is attractive for a number of applications. One of the most significant impediments to the clinical application of At-211 labelled radiotherapy agents is the limited supply of this radionuclide. This does not reflect complexities in production and purification technologies but the limited availability of accelerators with appropriate beam characteristics. At TRIUMF, research quantities of the At-211 precursor Rn-211 can be produced using proton-induced spallation on actinide targets like thorium. Within the ARIEL project the installation of an isotope collection station is planned behind the high-resolution mass separator (HRS). This is part of the funded CANREB CFI project. Using this facility, ample amounts of Rn-211 can be produced, collected, and extracted for shipment to the appropriate collaborators. The At-211 is generated in transit through the decay of Rn-211. TRIUMF will focus on demonstrating the production, packaging, and shipment of Rn-211 generators (from thorium). Radiopharmaceutical production of choice therapeutics will also be explored in a dedicated space.

TRIUMF will continue its collaboration with the UBC Department of Earth, Ocean, and Atmospheric Sciences on the investigation of the impact of metal concentrations and chemical speciation in global marine primary productivity including effects of trace metal limitation and toxicity. To better understand the role copper plays in phytoplankton subsistence and growth in low-iron waters, radioisotopes of Cu are used to track and identify trace metal acquisition, metabolism and nutrition of marine bacteria and phytoplankton. This research on the factors controlling oceanic phytoplankton productivity will proved insights into the regulation of the global carbon cycle.

Radiopharmaceutical Synthesis and Applications

TRIUMF has long focused on developing and maintaining world-class capabilities in the production of literature-based radiopharmaceuticals. However, new opportunities exist for the development of novel radiopharmaceuticals and their applications.

The new preclinical PET/SPECT/CT Imaging Program at the UBC Centre for Comparative Medicine (CCM) provides exciting new opportunities. It facilitates development and testing of new compounds that might use either positron or single gamma emitters as radiolabels, thus allowing a broader range of radiochemistry developments, and enriching TRIUMF radiochemistry-based research. At the same time it expands the pool of potential research collaborators, both in academia and, importantly, in industry. Furthermore the existence of both a pre-clinical and clinical imaging program in the same setting enables unique translational research. The synergy between the medical researchers, imaging expertise, and the TRIUMF Nuclear Medicine Program provides a unique research environment that has an enormous potential for growth.

Other new development efforts have started shifting focus onto novel biomolecular targets. Specifically, TRIUMF will pursue a deeper understanding of oxidative stress as associated with the initiation, development, and progression of disease. One target of interest includes the cystine transporter and its role in regulating the intra- and extracellular levels of the amino acids cystine and glutamate.

Amino acids play an important role in many biological processes, and these serve a key role in protein synthesis and as substrates for important intermediary metabolic processes and cell-signalling pathways. Documentation on the effects of intra- and extracellular concentration and availability of many amino acids are growing, proving that amino acids are critical nutrients that can regulate cellular physiology by modulating gene expression and signal transduction pathways. For this reason, radiolabelled amino acids have become increasingly attractive tools in the search for, and development of, novel molecular imaging probes.

Using radiolabelled amino acids, researchers and clinicians have been gaining significant insight into the functional status of tumours outside of the traditional ^{18}F-FDG-PET (enhanced glycolysis) envelope. ^{18}F-FDG remains as one of the most frequently used PET radiopharmaceuticals in use today, this despite clinicians having identified a number of limitations for it. High basal uptake of ^{18}F-FDG in tissues such as the brain, heart, and brown adipose tissue make early detection of tumour growth, atherosclerotic plaques, and other conditions difficult to achieve in those tissues. In addition, poor uptake in tumours exhibiting low or consistent glycolytic activity (prostate, breast, lung, melanoma, low-grade gliomas, and lymphomas) has led to low sensitivity and/or no clinical applicability for ^{18}F-FDG in those types of cancers. ^{18}F-FDG is known to accumulate into inflamed tissue as well, thus complicating the interpretation of post-surgery or post-therapeutic follow-up scans due to the increased background tissue uptake.

To date, most radiolabeled amino acid research has focused on important studies to understand alternative metabolic pathways during tumour formation and growth. By studying the cystine transporter, TRIUMF, along with its collaborators at General Electric and BCCA, seeks to examine non-metabolic tumour cell compensatory mechanisms related to oxidative stress. The goal of this work is to understand: (1) when aberrant oxidative burden on cells becomes detectable, (2) whether the cystine transporter expression levels and transport activity provides a measurable response to aberrant oxidative load within tumour cells, and (3) whether this marker can provide clinically useful information for detection of cancers that typically don't respond to ^{18}FDG, for earlier detection of those cancers that do, or on the effectiveness of tumour response to treatment.

Beyond small molecule radiopharmaceuticals, TRIUMF is developing isotope production and isolation methods for the design and synthesis of novel molecular imaging agents that include small molecule and large molecular weight radiotracers, such as peptides, proteins, oligonucleotides, and peptide nucleic acids with radiometals. A collaborative effort with UBC scientists has resulted in a new class of chelates that have been proven effective toward a number of different radiometals. This is a promising start. With a new set of molecular tools at our disposal, we will selectively bind, and functionalize to direct, main group ions such as those of Ga and In; many transition metal ions such as Cu^{2+}; and all the lanthanide and rare earth metal ions such as those of Sc, Y, Sm etc. Our new chelates are inherently versatile and can be chemically altered to select for certain isotopes. This is an unprecedented capability not offered by existing chelate systems and allows TRIUMF to pursue applications for a variety of medical isotopes across imaging and therapeutic applications.

GOALS FOR 6.2.1.5 BY 2020

- Lead the Canadian cyclotron community in defining the thermodynamics of target irradiation as a function of target gas density, target composition, and geometry.
- Enhance liquid-target processes and procedures for the purpose of improving F-18 and radiometallic isotope production yields.
- Deliver a superior C-11 gas target design.
- Expand the TRIUMF-PPRC PET research program to new tracers for non-dopaminergic applications and to non-Parkinson's applications of PET (i.e. mild-traumatic brain injury and Alzheimer's disease).
- Implement a full radiopharmaceutical production program that will keep pace with emerging Health Canada regulations.
- Implement a pre-clinical radiopharmaceutical pipeline for new radiopharmaceuticals, leveraging new infrastructure at the Centre for Comparative Medicine to enhance interactions with the private sector.
- Develop novel amino acid tracers for monitoring non-metabolic processes *in vivo*. Specifically, establish new radiopharmaceuticals toward using the cystine transporter as a non-metabolic marker for tumour detection and treatment monitoring.
- Establish clinical utility, with PPRC and BCCA, of novel tracers in neurodegeneration and oncology.
- Produce radiometallic isotopes (Zr-89, Ga-68, Cu-61,64,67, Mn-52, Co-55) for the BC research community as well as TRIUMF-internal research interests.
- Initiate a radiotherapeutic isotope program, starting with the production and isolation of Rn-211 as a feedstock for At-211 generators and commence radiotherapeutic pharmaceutical production in a dedicated 'α-emitter' laboratory space.

6.2.2 UNDERSTANDING THE BUILDING BLOCKS OF MATTER AND HOW THEY SHAPE OUR UNIVERSE

With major international laboratories such as TRIUMF, the Perimeter Institute for Theoretical Physics, and SNOLAB, as well as a strong university community, Canada is uniquely positioned to play a significant role in answering the major questions of the Universe that centre on the nature of dark matter, matter-antimatter asymmetry, and other fundamental particles and forces yet to be discovered.

6.2.2.1 PRECISION MEASUREMENTS OF STANDARD MODEL PROCESSES

The Standard Model (SM) of particle physics developed over 40 years ago has proved extraordinarily successful in describing all the observed interactions of elementary particles. With the recent observation at the LHC (Large Hadron Collider) of a Higgs boson consistent, within experimental uncertainties, with the single Higgs boson of the SM, it might be tempting to regard the quest as complete. But that is not the case. Finding a Higgs boson confirms the mechanism by which the electroweak symmetry is broken, but tells us nothing about what is actually responsible for its breaking. While the Higgs mechanism precisely determines the masses of the gauge bosons, it makes no prediction for the masses of fermions that extend 12 orders of magnitude from meV/c^2 scale for neutrinos to 172 GeV/c^2 for the top quark, which has the natural scale of electroweak symmetry breaking. The SM can accommodate CP violation, needed to explain a universe where matter predominates over antimatter, but not enough CP violation is observed in the quark sector to explain the observed ratio of baryons to photons. Neutrino experiments are only now reaching the sensitivity needed to explore the possibility of CP violation in the lepton sector. The SM does not predict the mass of the Higgs boson, and without fine-tuning or the addition of new particles, the Higgs boson mass would increase by many orders of magnitude. In order to look for the first cracks in the armour of the SM, or for smoking guns for a larger pattern, it is essential to make accurate measurements of all the quantities that it does predict, as well as the free parameters.

High-Energy Standard Model Tests and Search for New Forces

By studying weak processes at the TeV scale, the ATLAS experiment aims to understand the mechanism that has led to the electroweak symmetry breaking in the early universe. Extensive studies are being carried out to determine the properties of the observed Higgs boson and its couplings as well as of other electroweak SM processes never before tested at the LHC energy scale (see Figure 8). These studies of SM parameters will continue at higher energy as the LHC reaches its design operation parameters. Much effort is already directed toward measuring the Higgs boson properties: the relative cross-sections for its various production processes, the branching ratios of its different decays, its spin, and its parity. Careful

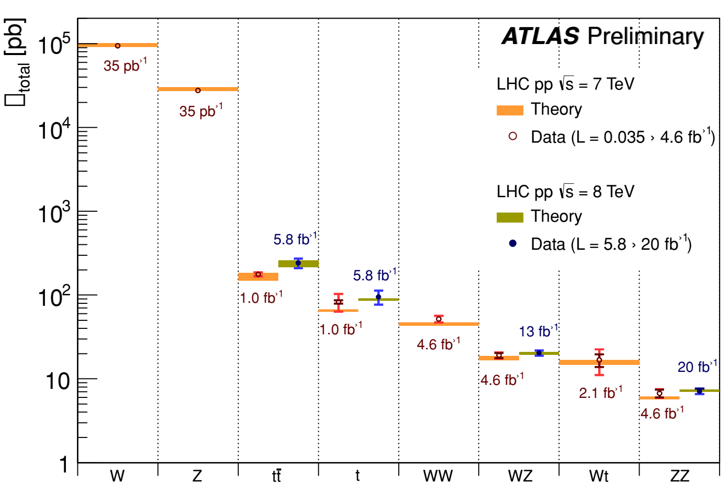


Figure 8: Summary of several Standard Model total production cross section measurements, corrected for leptonic branching fractions, compared to the corresponding theoretical expectations.
ATLAS Experiment © 2013 CERN

comparison of all of these measurements with the SM predictions constrains the numerous extensions to the SM (such as supersymmetry) which require extended Higgs sectors. At the same time physics beyond the SM appears to be necessary for a natural occurrence of the electroweak symmetry breaking.

The ATLAS experiment is intensely searching for supersymmetric particles, extra dimensions of space-time and new forces, evidence for which may be found in the high-energy proton-proton collisions at the LHC (please see Section 6.2.2.2). Since particles too massive to be directly produced at the LHC can nevertheless contribute to rare interactions, just as the W-boson mediates beta-decays, it is vital to make the most precise measurements possible at the energies available, in order to look for any deviations from the expected behaviour which might be due to additional higher-energy phenomena.

The TRIUMF ATLAS physics group is expected to continue to play leading roles in a number of searches for new particles, and in the characterization of the newly discovered Higgs boson.

As global discussions for a new major international accelerator project develop, TRIUMF will participate in analyzing the physics case, identifying opportunities for technical and industrial involvement, and facilitating Canadian community discussions about participation. At the moment, Japan's discussions about an International Linear Collider to create a "Higgs factory" look promising. This machine is a good match for Canadian industry, TRIUMF's technical prowess, and Canada's scientific goals.

Low-Energy Precision Experiments

Precision experiments of weak processes at low energy are complementary to high-energy measurements and provide vital information about the running of the SM couplings over the full range of accessible energies. By searching for subtle deviations from the SM predictions, these experiments also have the potential to discover indications of new particles and forces.

Building on the successful efforts and developments during the current Five-Year Plan, TRIUMF is continuing the precision experiments at ISAC that have not yet reached their maximum sensitivity while at the same time embarking on new initiatives that provide exciting opportunities for discoveries. These experiments use rare isotopes as laboratories to search for physics beyond the SM (please see Section 6.2.1.2). To recap, this includes (1) the search for scalar currents or R-parity conserving supersymmetric left-right sfermion mixing via a 0.1% beta correlation measurement, (2) the measurement of the parity-violating coupling between electrons and nucleons in atomic parity violation in francium isotopes (FrPNC, see Figure 9), as well as (3) the precise determination of the V_{ud} matrix element of the Cabbibo-Kobayashi-Maskawa (CKM) quark mixing matrix.

In addition to these rare-isotope experiments, the new source for ultra-cold neutrons in the Meson Hall will enable precision experiments of the beta decay of the neutron, experiments similarly sensitive to new physics.

Canadian researchers are also gearing up to get involved in the proposed MOLLER experiment at Jefferson Lab in the U.S., which will measure the weak charge of the electron to 2.3%, attempting a determination of $\sin^2 q_w$ with an uncertainty of ±0.00026(stat)

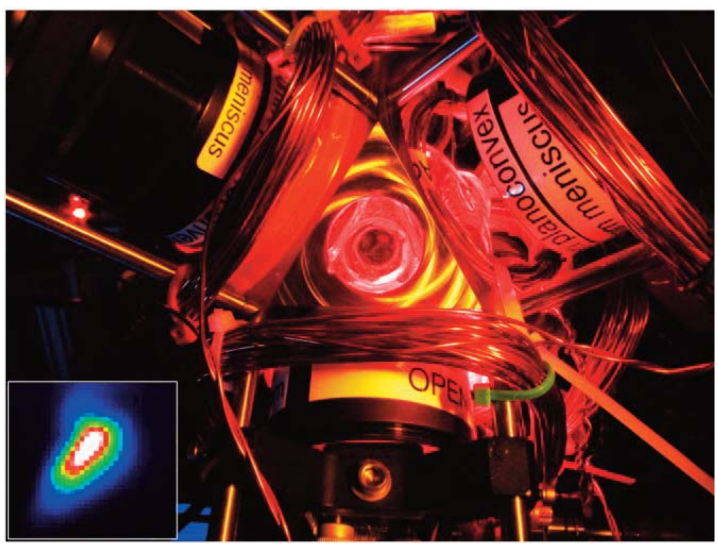


Figure 9: Magento-optical trap in the Francium Trapping Facility. The insert shows the fluorescence signal from trapped Fr atoms.

±0.00013(syst), at very low momentum transfer. Although not directly involved in this experiment, TRIUMF may help with the detector readout electronics, fulfilling its mission in supporting member universities in their research activities through TRIUMF's unique expertise and infrastructure. The atomic electron-nuclear parity-violating strength in FrPNC could achieve similar statistical uncertainties with the long beam times enabled by ARIEL, with systematic errors to be determined—this search would be sensitive to physics beyond the SM at even lower momentum transfer. When combined, these experiments would have complementary sensitivity to a much wider class of models.

Neutrino Mixing Parameters

Neutrinos pose another puzzle for the SM and weak interaction physics. Recent measurements have clearly established that neutrinos have very tiny but finite masses and that all three neutrino mixing angles are non-zero and large. In 2011, T2K presented the first indications of a non-zero value for the mixing angle θ_{13} through the observation of electron-neutrino appearance, which was followed by precise measurements from reactor-based neutrino disappearance experiments. In 2013, T2K reported the first definitive observation of electron neutrino appearance. Scientists at TRIUMF and in Canada played a central role in these results by pioneering methods to extrapolate the near detector measurements and introducing a new event reconstruction algorithm in the Super-Kamiokande detector, which led to significant reductions in systematic uncertainty and backgrounds. These accomplishments built on the major Canadian and TRIUMF contributions to the neutrino beamline and near detectors for the experiment.

In contrast to the CKM quark mixing matrix, the mixing in the neutrino sector is large. This may be an indication of a new physics scale, and various models aim to describe the mixing parameters and the fact that neutrino masses are orders of magnitude smaller than those of other fermions. The T2K experiment has only taken about 8% of its envisioned data and plans to operate at least until 2018. The collaboration is also continuously improving the precision on the measurement of the mixing angle θ_{23} and the mass difference $(\Delta m_{32})^2$ by measuring the disappearance of muon-neutrinos. The possibility that θ_{23} may be consistent with maximal mixing (45°) has led to speculation that this may be the manifestation of an underlying unknown symmetry. Thus, precision measurements of θ_{23} will be a critical test of these models. In 2013, T2K presented the most precise measurement of $\sin^2 2\theta_{23}$ to date, and is expected to provide the world's best measurements throughout the rest of the decade. TRIUMF and Canadian scientists have played a leading role in estimating critical uncertainties relating to the modelling of neutrino-nucleus interactions, which have become increasingly important as the statistical precision of the measurement continues to improve rapidly with beam exposure.

Unlike reactor neutrino experiments, which are sensitive only to θ_{13}, electron neutrino appearance at T2K also depends on the CP-violating phase δ_{CP} of the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix and on the sign of the neutrino mass hierarchy (see Figure 10). Further improvements in T2K's electron neutrino appearance measurement, in combination with other experiments, may provide the first hint for CP violation in the neutrino sector by the end of the decade if δ_{CP} is sufficiently large. In addition, T2K measurements will be an essential input to the resolution of the so-called "θ_{23} octant degeneracy," in which a non-maximal value of $\sin^2(2\theta_{23})$ could result from θ_{23} not being equal to 45°.

T2K's goals for the next several years are to improve the precision for all neutrino mixing parameters, especially θ_{13} and θ_{23}, measure several important neutrino interaction cross-sections, and to lay the groundwork for a next generation upgrade to definitively measure CP violation in the neutrino sector. This will involve the construction of a new megaton-scale water Cherenkov detector, called Hyper-Kamiokande (near the site of Super-Kamiokande), and possible upgrades to the near detector complex at J-PARC. Such upgrades will be proposed in the next few years and, if funded, will not only provide sensitivity to CP violation, but will also extend sensitivity to proton decay. Proton decay, if observed, would probably be the only way of probing the energy scale of the potential grand unification between the electroweak and strong interactions. TRIUMF is well positioned to make leading contributions to these upgrades and subsequent experiments.

Matter-Antimatter Asymmetry

The early universe in its radiation-dominated phase is assumed to have contained essentially equal numbers of matter and antimatter particles. After further expansion, cooling, and annihilation, only a small number of matter particles survive (see Figure 11). The question that remains is: Which physical processes generated this asymmetry? It is evident that a violation of the CP symmetry is a necessary ingredient. Presently, CP violation is only observed in the quark sector for neutral K, B, and D particles, and the observed effect is consistent with the CKM mass-mixing matrix in the SM. The size of this CP violation is not sufficient to account for the excess of matter over antimatter in the universe. Thus, it is important to search for other examples of CP violation. Investigations of baryon- and lepton-number violating processes, as well as the trapping and spectroscopy of antihydrogen, may shed light on this mystery.

Baryogenesis

Electroweak baryogenesis models assume that the matter-antimatter asymmetry was produced during the electroweak phase transition when the Higgs field spontaneously broke the electroweak symmetry. Such CP violation would induce permanent electric dipole moments (EDMs). A permanent EDM of any fundamental particle, or of an atom in an angular momentum eigenstate, can only occur if both parity (P) and time reversal (T) are violated. Because of CPT conservation in local quantum field theory (CPT theorem), an EDM violates CP. While SM predictions for particle EDMs are many orders of magnitude below current experimental sensitivity, virtually all extensions to the SM, e.g., multiple-Higgs theories, left-right symmetry, and supersymmetry, generically predict EDMs within, or tantalizingly close to, the reach of current experimental techniques.
Present limits on the EDMs of the neutron, electron, and Hg-199 atom, $< 2.9 \times 10^{-26}$ e cm, $< 1.0 \times 10^{-27}$ e cm and $< 3.1 \times 10^{-29}$ e cm respectively, have, in fact, already ruled out significant fractions of the parameter spaces of these models, and a substantial improvement on current limits would have profound implications for the spectrum of viable extensions to the SM.

It is TRIUMF's ambition to become a leader in setting limits on or even discovering permanent electric dipole moments and therefore we are embarking on projects that aim to constrain theoretical models that predict the EDM of the neutron (UCN, nEDM), electron (FrEDM), as well as the atomic EDM of radon (RnEDM).

The new source for ultra-cold neutrons (UCN), which will be operational by 2017, uses the production of neutrons via proton-induced spallation with a UCN converter based on superfluid helium. A first version of this concept has been demonstrated at RCNP Japan and the new source is currently being constructed in Japan

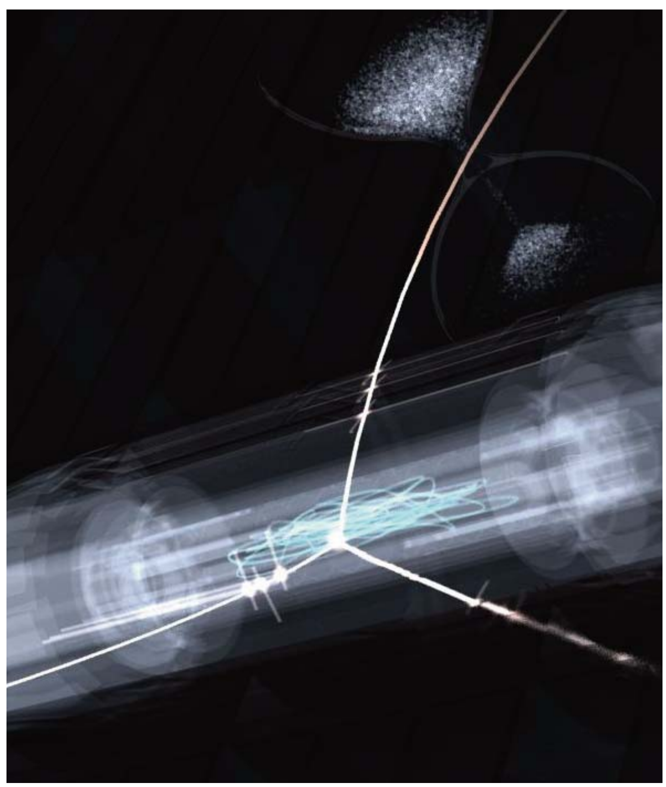


Figure 11: The ALPHA experiment at CERN studies antihydrogen. This images shows an annihilation event. Courtesy of Chukman So/ALPHA

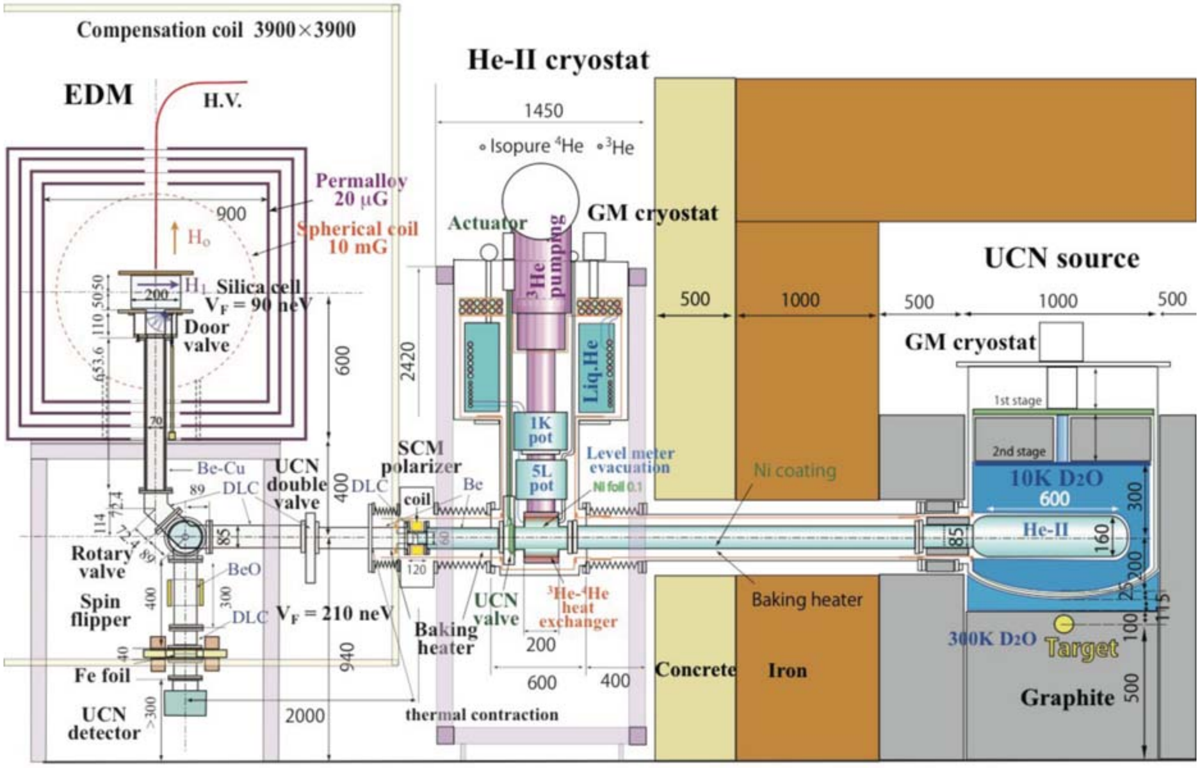


Figure 12: Schematic of the neutron EDM apparatus.

where it will be tested before being brought to TRIUMF for installation. The anticipated UCN densities are competitive on the world stage with anticipated trapped polarized UCN density of 1300 UCN/cm^3 delivered to the experiment (see Figure 12). Detailed plans for the CFI-funded UCN facility are described in Sections 5.5.3.2 and 6.3.2.3. The experiment has a target sensitivity of 10^{-28} e cm, which would be achievable in the next Five-Year Plan.

As described in Section 6.2.1.2, there is also substantial progress towards an experiment to search for an atomic EDM in odd-mass radon isotopes (RnEDM) and developments have started for a francium fountain experiment to search for an electron EDM. While the RnEDM experiment is aiming to improve the current best limit for an atomic EDM by at least a factor of 3, the electron EDM experiment has the potential to improve the current limit by a factor of 100.

Assuming that the CPT theorem (where C is charge conjugation) holds, T-violation is the equivalent of CP violation and thus also experiments looking explicitly for T-violation are carried out. The MTV (Mott polarimetry for T-Violation) experiment (see Sections 5.5.1.7 and 6.2.1.2.) at ISAC searches for violation of time reversal symmetry via a precise measurement of the Mott scattering anisotropies of the electrons produced in the beta-decay of polarized Li-8 and other nuclei. The measurements on Li-8 will dramatically benefit from the first science phase of the e-linac.

Leptogenesis

Alternatively, the matter-antimatter asymmetry may be the result of leptogenesis, where CP violation takes place at much higher energies through decays of heavy Majorana-neutrinos. It has been shown that neutrinos have non-zero masses, which implies that neutrinos have a right-handed component, making it possible for a neutrino to be its own anti-particle, or a Majorana particle. Mixing of a very heavy right-handed Majorana neutrino with left-handed light neutrinos would provide a natural explanation for the fact that the neutrino masses are many orders of magnitude lighter than the masses of charged leptons and quarks (the see-saw mechanism). It would also explain the large neutrino mixing angles. While it is not possible to search for such heavy Majorana neutrinos directly, a consequence of this process would be the occurrence of neutrinoless double beta-decay. If this process is discovered, it will also enable the determination of the electron neutrino mass. Since the properties of the light and heavy neutrinos are inextricably tied via the mixing, one would also expect to observe CP violation in the mixing of the light neutrinos. The projected mass of the heavy Majorana neutrinos coincides roughly with the expected scale of Grand Unification, which generically predicts a finite lifetime for the proton. These potential consequences of leptogenesis could be studied at Hyper-Kamiokande (see Section 6.2.3.3), which will provide a high sensitivity search for CP violation in the (light) neutrino oscillations and also expand the sensitivity to proton decay by an order of magnitude beyond the current bounds.

TRIUMF is actively involved in the SNO+ experiment (please see Section 5.5.5.5), which will begin operation in 2013 and search for neutrinoless double beta-decay in the decay of Te-134. TRIUMF has joined the EXO collaboration that is currently investigating the double-beta decay of Xe-136 using a liquid xenon TPC with a fiducial mass of 200 kg. EXO has recently measured the decay rate for two-neutrino double beta decay of Xe-136 for the first time directly and has set stringent limits on the rate for neutrinoless double-beta decay, effectively ruling out the claims by part of the Heidelberg-Moscow collaboration of an observation of a signal in the decay of Ge-76. This exclusion was just confirmed by the germanium based GERDA experiment. The EXO collaboration plans to scale the current technology up to the five-ton level with the nEXO experiment. The preferred location for this experiment would be the Cryopit in SNOLAB, and the relevant discussions have started.

With the five-ton detector of liquid xenon it would be possible to cover the whole range of decay rates for the inverted mass hierarchy of the neutrino masses, going well beyond the reach of SNO+. With the addition of tagging of the barium ions that are produced in the double beta decay further background reductions are possible allowing for covering of a substantial part of the parameter space for a normal mass hierarchy.

TRIUMF will develop the application of silicon photomultiplier (SiPM) light sensors to the double-beta decay experiment nEXO using expertise that arose from the T2K involvement. Also, TRIUMF has a leading role in the development of barium tagging techniques that may rely on ion-guide technologies such as radio frequency quadrupoles (RFQs), for which the relevant expertise is present in the TITAN group.

Antihydrogen

The CPT theorem demands that atomic spectra of hydrogen and antihydrogen be identical. The optical 1s-2s transition in atomic hydrogen has been measured to a precision of 4×10^{-15}, and the ground state hyperfine splitting to the 10^{-12} level. Following its enormous success in trapping antihydrogen for more than 1,000 seconds and carrying out the first microwave spectroscopy on antihydrogen atoms, the ALPHA experiment (please see Section 5.5.5.4) will carry out a program of laser and microwave spectroscopy to test the symmetries between matter and antimatter at the highest possible precision. In the period 2015–2020, the recently completed ALPHA-2 apparatus will be fully exploited for these spectroscopic tests. Laser and microwave spectroscopy are complementary in that they are sensitive to new physics at different energy scales.

Antihydrogen atoms also offer the possibility to test if gravity acts in the same way on matter and antimatter. While there are a number of indirect arguments against gravitational asymmetry between matter and antimatter (e.g., from the Eötvös-type experiments), no one ever has seen antimatter actually fall in the field of gravity. The ALPHA collaboration, under TRIUMF leadership, proposes to develop a new antihydrogen gravity (ALPHA-g) trap during the period 2015–20. Possible contributions by TRIUMF could involve the development of a new annihilation detector.

Flavour Physics

Precision experiments on flavour mixing play a complementary role to the TeV energy frontier physics explored at the LHC. The effects of new heavy particles can be observed through their appearance in quantum loop corrections via flavour-changing neutral currents.

Studies of flavour physics can contribute to answering a number of important questions, such as: Is there an additional CP-violating phase? Is there evidence for new right-handed currents?; Are there measurable effects from the Higgs field? Is charged lepton flavour violated? Is there any new flavour symmetry that explains the hierarchy of the matrix elements in the CKM matrix?

Several Canadian universities have recently joined the international collaboration for the Belle II experiment at the SuperKEKB electron-positron collider at KEK in Japan. The Canadian Belle II group is taking the lead on the upgrade of the Belle II forward endcap electromagnetic calorimeter (F-ECL) project with pure CsI crystals, which should be ready for installation in 2018 or 2019. The collaboration would seek access to TRIUMF's technical and engineering infrastructure for a number of aspects such as prototype construction, R&D on scintillator crystals, overall design of F-ECL and fabrication oversight, procurement, electronics development, assembly and testing, and computing support.

Another way to look for charged sector lepton flavour violation is to search for evidence of muon-electron conversion in nuclear fields, which will be pursued by the DeMee experiment at J-PARC, with a small TRIUMF involvement.

GOALS FOR 6.2.2.1 BY 2020

- Maintain leading involvement in the ATLAS experiment, including comprehensive measurements of the Higgs boson couplings and decay branching ratios, searches for supersymmetric and more exotic particles, as well as precision top quark measurements.
- Maintain pre-eminence in precision neutrino mixing measurements and studies of neutrino-nucleus scattering, with TRIUMF scientists playing a leading role via T2K.
- Perform first laser spectroscopy and improve microwave spectroscopy for antihydrogen, and develop an antihydrogen gravity experiment.
- Perform first measurements of the neutron electric dipole moment and the atomic electric dipole moment using radon isotopes.
- Demonstrate the concept for an electric dipole moment experiment on electrons using a francium fountain.
- Carry out theoretical studies combining data from high-energy direct searches and lower-energy precision experiments for the most stringent tests of the SM or the greatest possible sensitivity to new physics.

6.2.2.2 DIRECT SEARCHES FOR NEW PARTICLES

The SM has been extremely successful and has now been tested to very high precision. With the discovery at the LHC of a Higgs Boson it is likely that the last missing building block of the SM has been found after a 40-year hunt. However, the SM is at best a very successful low-energy effective theory, with seemingly ad hoc features, such as the fermion masses, which it does not attempt to explain. It does not tell us what is responsible for breaking electroweak symmetry; it provides no candidate for the dark matter observed by astronomers; nor does it give any reason for the asymmetry between matter and antimatter; nor does it attempt to relate gravity to the other known forces.

One of the most intriguing questions in this context regards the nature of the elusive dark matter particles that clearly show their gravitational effect in the structure formation of the early universe, rotational velocities of stars in galaxies, and gravitational lensing (see Figure 14, 17). Various well-motivated theories have been developed that predict a plethora of new particles beyond the SM: for example, in supersymmetric models, each known elementary particle has a supersymmetric partner, and the lightest supersymmetric particle makes an excellent dark matter candidate. In models where supersymmetry is invoked to explain dark matter or the scale of electroweak symmetry breaking, new physics is to be expected at the TeV energy scale. The observed scalar particle at 125 GeV/c^2 appears to be a Higgs boson, but it is not yet clear whether it is the unique Higgs boson of the SM, or one of a family of Higgs bosons (supersymmetry requires at least five) or if it may be a composite particle as suggested by composite Higgs models. The observed Higgs boson would be consistent with supersymmetric models where the top quark and Higgs boson both have relatively light supersymmetric partners, while the additional Higgs bosons could be rather heavy and difficult to find. TRIUMF analysis groups are focusing on searches for top quark and gauge boson partners.

Figure 14: Bullet Cluster. Courtesy of NASA CXC CfA M.Markevitch et al.

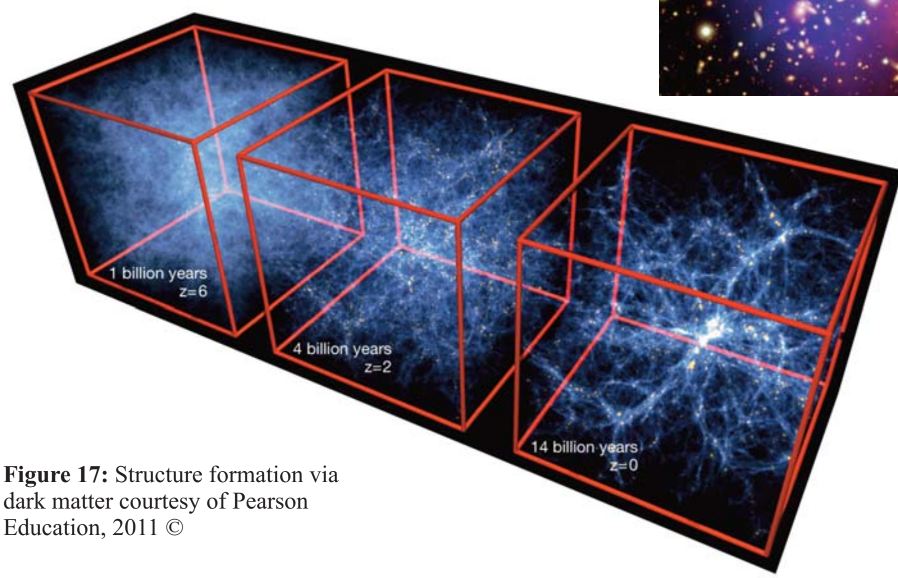


Figure 17: Structure formation via dark matter courtesy of Pearson Education, 2011 ©

Searches for Dark Matter

Dark matter particles are very special, since they are stable or extremely long-lived and have endured since the beginning of the universe. Therefore these primordial particles, which are often assumed to be weakly interacting massive particles (WIMPs), can be detected either via their annihilation signal in space or through their interaction in massive detectors deep underground where the background from cosmic rays is dramatically reduced. Dark matter is sought in any of four approaches: direct detection of particles in a quiet, underground chamber; signatures of the annihilation of dark matter particles in our solar system or galaxy; direct production at the LHC; or by gravitational affects on extra-galactic phenomena.

TRIUMF participates in the DEAP3600 dark matter experiment at SNOLAB, which will become operational in 2014 and will be one of the most sensitive WIMP detectors in the world (see Figure 15). Canadian groups have also joined the CDMS collaboration in order to build SuperCDMS and locate it at SNOLAB. TRIUMF will support the SuperCDMS activity of the university community predominantly with the electronics readout and data acquisition (DAQ) system. This will bring the well-established MIDAS DAQ system, extensively used at TRIUMF but also used for T2K and ALPHA (please see Section 5.8.2), to SNOLAB.

The other way to search directly for new particles, whether stable or promptly decaying, is to produce them directly in the collision of high-energy particles. This is the approach the ATLAS collaboration, in which Canada and TRIUMF play a significant role, is taking. After running since 2010 with centre of mass energies of up to 8 TeV and a peak luminosity of close to 8 x 10^{33} $cm^{-2}s^{-1}$, the LHC has entered its first long shutdown, which will last until 2015.

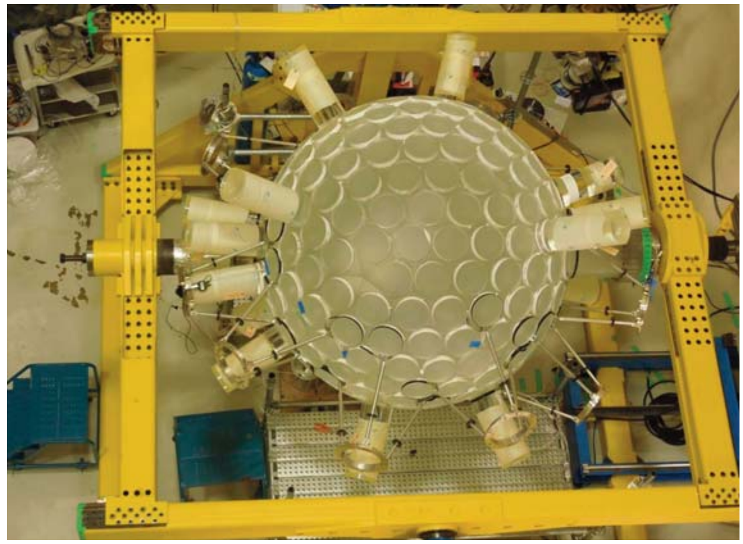


Figure 15: DEAP 3600.

Once the LHC turns back on, with up to 14 TeV centre of mass energy, ATLAS will focus its attention on the full characterization of the observed Higgs boson in order to determine, through precision measurements of its mass and its couplings to other bosons and fermions, if this is indeed the SM Higgs. ATLAS will also search for additional Higgs bosons as well as other new particles such as dark matter candidates like the neutralino, new force carries (e.g., Z'), and other exotic particles. The only other energy frontier machine that could begin construction before 2020 is the Linear Collider.

Supersymmetry

Low-energy supersymmetry is regarded as one of the most promising theories for physics beyond the SM. SUSY postulates the existence of a supersymmetry particle (or sparticle) for each SM one. The lightest SUSY particle, the LSP, is an excellent dark matter candidate and the supersymmetric partner for the top quark cancels the quadratic divergences that plague the SM Higgs boson mass (in the absence of extraordinary fine tuning, the self-coupling corrections to the mass of a SM Higgs boson tend to increase its mass by orders of magnitude; this is referred to as the "Higgs mass instability"). Discovering (or disproving) SUSY is therefore one of the highest priorities for the LHC experiments.

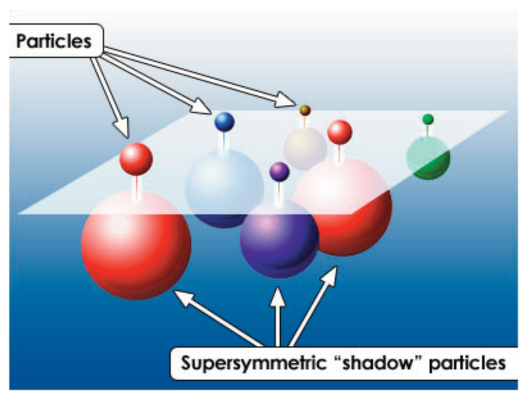


Figure 18: Schematics of doubling particles, © 2012 by the Particle Data Group.

The TRIUMF ATLAS group has led flagship analyses in the context of the 8 TeV search program and the study of sensitivity at 14 TeV (as mentioned in Section 6.2.2.1). Results from the current searches exclude the existence of first and second generation squarks and gluinos (an "s" at the beginning indicates the supersymmetric scalar partner of a SM fermion, while "ino" at the end indicates the supersymmetric fermion corresponding to a SM boson, see Figure 18) with masses below about 1.4 TeV and 1.0 TeV respectively under the assumption of a massless LSP and short decays. Due to smaller expected cross-sections, the current sensitivity to stops, sbottoms, sleptons, and the partners of the gauge and Higgs bosons (called "charginos" and "neutralinos" since the Higgs and gauge partners can mix) is in the few hundred GeV range.

If SUSY is to provide a solution to the Higgs mass instability, the sparticles participating in the Higgs mass corrections must be relatively light. These include the stop, charginos and neutralinos, and the gluino. The increase of the LHC centre-of-mass energy from 8 to 14 TeV will lead to a significant increase in production cross-section of the strongly produced sparticles, and the expected increase in collected data will allow rare processes such as the electroweak production of SUSY to be probed.

With 300/fb of integrated luminosity at 14 TeV, the LHC is expected to discover gluinos and stops with masses up to 2 TeV and 800 GeV, respectively (see Figure 16). An increase of data size to 3000/fb will allow the discovery of charginos and neutralinos if their mass is below about 1 TeV. These results indicate that the LHC has the potential to discover SUSY if SUSY provides a natural solution to the Higgs boson mass instability.

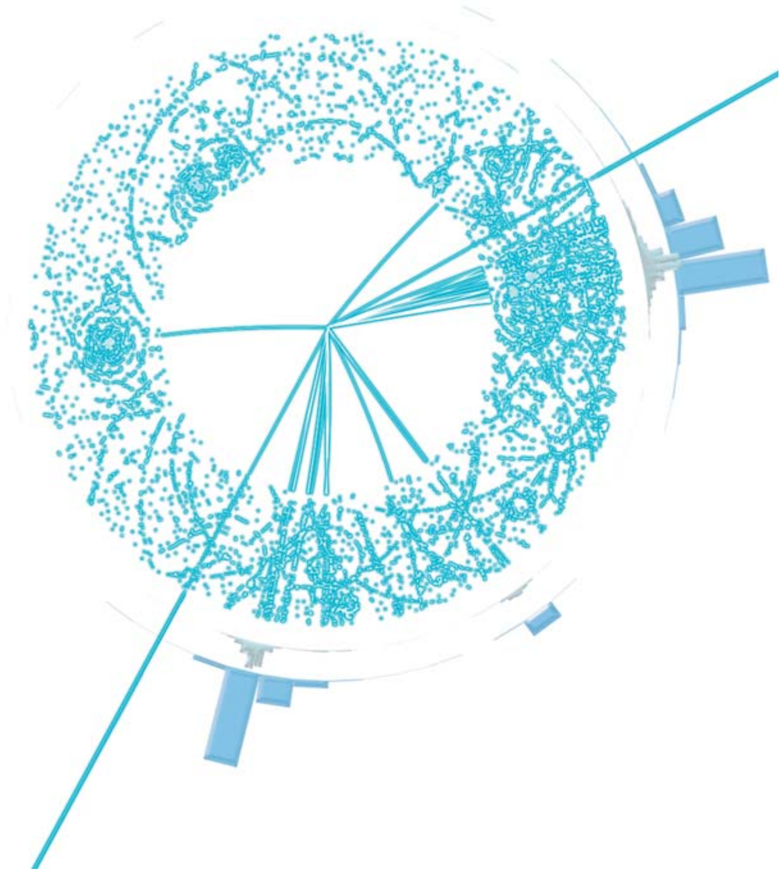


Figure 16: ATLAS simulated supersymmetry event, ATLAS Experiment © 2013 CERN

Exotica

"Exotic physics" is a catch-all phrase describing a wide range of alternative models that extend the SM and solve some of its outstanding mysteries, much as SUSY does. These models typically predict the existence of extra dimensions of space-time, vector-like quarks, new forces, etc. These new particles are expected to be heavy and therefore to decay into leptons, photons and jets with high transverse momentum, and substantial missing transverse momentum. The TRIUMF ATLAS group has led a number of promising searches for exotic particles, including a search for heavy resonances decaying into either two leptons or two top quarks. These benchmark models, namely Kaluza-Klein gluons in the Randall-Sundrum model, and Z' bosons, are also used to assess the discovery potential of the upgraded LHC, and TRIUMF scientists are heavily involved in these activities.

GOALS FOR 6.2.2.2 BY 2020

- Search for and either discover or significantly constrain the parameter space for new physics at the electroweak symmetry-breaking scale with TRIUMF scientists playing leading roles in these key searches with ATLAS.
- Reach leading sensitivity for the detection of weakly interacting particles with DEAP 3600.
- Investigate the implications of LHC data and searches for dark matter on theories of new physics beyond the Standard Model.

6.2.3 HARNESSING PARTICLES AND BEAMS TO DRIVE DISCOVERY AND INNOVATION

The third theme connecting TRIUMF's program of work concerns the use of particles and beams to probe materials, provide services to industry, and develop new businesses. This third theme emphasizes primarily the applied and technological aspects of the program but obviously has substantial overlap with the first two themes, in particular regarding the use of isotopes for nuclear medicine and material science. However, while parts of these programs have already been mentioned in the discussion of the first two themes, this section provides an overview of additional or complementary aspects.

As Canada's centre for accelerator-based science TRIUMF leverages its accelerator infrastructure and its expertise in accelerator science and technology in numerous ways. TRIUMF develops next generation accelerator technology and employs its particle beams for applications in molecular and material science and for the accelerator based production of medical isotopes. TRIUMF also carries out irradiations to cure tumours and to investigate the effects of radiation on electronics components used in modern applications, from cell phones to airplanes and satellites.

6.2.3.1 DEVELOPING NEXT-GENERATION ACCELERATOR SCIENCE AND TECHNOLOGY

Accelerator science encompasses a wide range of disciplines, from fundamental studies of particle beam behaviour under internal and external environmental parameters to practical efforts pushing the envelope of particle beam performance on multiple fronts through technological innovation. Researchers in the field command a vast and diversified knowledge base with rigor and sophistication, and enjoy active cross-fertilization between theory, simulation and experiment. As a result, a specialized advanced degree program is needed to produce the next-generation researchers in the field. As particle accelerators become the essential tool for a large and fast growing family of scientific disciplines: high energy physics, nuclear physics, material science, energy science, biology, medicine, chemistry, to name a few, accelerator science is destined to play a major role in advancing the whole scientific enterprise as well as benefiting society.

Accelerator science is critical to the success of TRIUMF's scientific program and to the fulfillment of the vision of the laboratory. TRIUMF accelerators and associated technologies enable world-leading research in nuclear physics, and TRIUMF's expertise supports Canada's participation in large-scale international projects, such as T2K and LHC. In addition, the TRIUMF accelerator complex is the basis for high-impact Canadian research in materials science and the growing nuclear medicine programs, and has a history of successfully transferring accelerator technologies to Canadian industry.

> Particle accelerator systems have been key drivers for a broad array of fundamental discoveries and transformational scientific advances since the early 20th century. Since their inception, they have also been core components of U.S. technological innovation and economic competitiveness.
>
> U.S. National Science Foundation, Division of Physics, Accelerator Science Program Solicitation PD 13-7423

The main objectives of accelerator science research at TRIUMF are the following:

- Improvement of performance of on-site accelerator facilities;
- Design, construction and operation of new, state-of-the-art facilities using leading-edge technology at TRIUMF and around the world (see Figure 19);
- Research in novel beam generation and manipulation techniques and development of advanced technologies leading to improved performance in future accelerators; and
- Education of next generation accelerator scientists and engineers.

The past five years saw significant progress in establishing a robust program of accelerator science research and education at TRIUMF. Accelerator staff mentor graduate students towards advanced degrees, and teach many newly conceived and developed graduate courses at BC universities. Under a new initiative for TRIUMF and Canada, NSERC now supports accelerator science research and graduate student training, with TRIUMF accelerator scientists supervising and mentoring the students for their thesis projects.

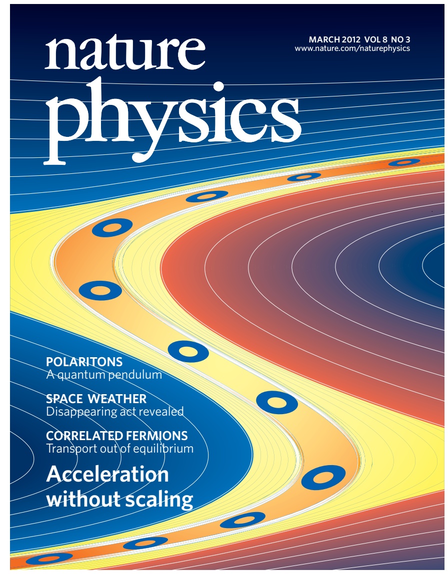


Figure 19: TRIUMF contributed to a Nature Physics Cover story on novel FFAG accelerators. Reprinted by permission from Macmillan Publishers Ltd: Nature Physics, copyright 2012.

Enhanced Operational Reliability and Performance

TRIUMF's goal is to evolve accelerator operations to the highest standards across all TRIUMF accelerators, by ensuring beam delivery on time with highest reliability and efficiency, and meeting user specifications for cutting-edge experiments. To this end, TRIUMF has made a commitment to implement model-based accelerator control across all systems, starting with those under the EPICS environment. This requires development of the following ingredients: proven machine and beam models based on hardware/alignment data and empirical beam-based measurements, a BPM-based beam monitoring system allowing fast and high-statistics data acquisition, and provision in database/ hardware control to facilitate conversion between engineering and physics parameters. This work will involve collaboration between the Beam Physics group and experts in Controls, Diagnostics, Magnets and other groups. Outside collaboration with control and high-level application experts is also expected to benefit this undertaking.

A new capability expected to be realized early in the 2015–2020 plan is the rotating proton beam on the ISAC targets. Because of the relatively poor thermal conductivities of oxides, proton beam intensities on such targets are limited to ~20 mA with the existing passive radiatively cooled target containers. To reach higher irradiation intensities, development of actively cooled targets will be required. An alternative option would be to change the proton beam profile on target. Rather than a relatively broad static proton beam, a narrow rotating beam on annular target foils could be used. Beam power deposited close to the target container surface would be more efficiently dissipated and a higher beam power density may also enhance product release through increased Radiation Enhanced Diffusion effects.

Another new capability is a two-step neutron converter for the production of neutron rich isotopes. In this option, the proton beam impinges onto a converter material, for example, W, Nb, Mo, or Ta. The U target is made as an annulus into which the proton beam goes without interacting with the U target. This target is placed in the backward position in such a way that only low energy neutrons can reach the U target. In this case the power deposited in the U target is small since it arises mainly from the fission products stopping in the target material. Other advantages of this development include the production of cleaner beams (no spallation and fragmentation products), and development of new target materials.

Superconducting Radio-frequency Technology

Building on a strong and successful R&D program on superconducting radio-frequency (SRF) resonators and niobium materials science, TRIUMF will create a centre for SRF research to study fundamental properties of niobium and other superconducting materials, motivated by improving performance of superconducting RF cavities. This will leverage current investment into TRIUMF SRF infrastructure, unique in Canada, existing experimental facilities at TRIUMF, and resources offered by local universities—UBC, University of Victoria, and SFU—and our commercial partner PAVAC. In particular this program will utilize two world-class installations at TRIUMF, the μSR and β-NMR facilities, as unique diagnostic probes of the superconducting state. R&D tasks more applied in nature include cavity development for the ANURIB project in India, accelerator driven systems (ADS) in China, and the RIB facility RISP in Korea, and the International Linear Collider (ILC).

Rare-isotope Beam Target Materials and Technologies

Production of RIBs from ISOL targets by irradiation with a 500 MeV proton beam has been successfully employed at TRIUMF for many years. The nuclear reactions induced by the proton driver beam lead to the formation of a multitude of isotopes of elements across the periodic table. One of the accelerator science R&D thrusts is the investigation of thermodynamic and chemical processes in ISOL targets to understand the optimal condition for effusion unique to each element. Research in this area will significantly expand the reach of TRIUMF's RIB program with new species, improved production yields, cleaner beams with less isobaric interference, and unprecedented measurements.

Plasma Wakefield Accelerators

Prototypes of this concept, both laser and beam-driven, have achieved thousand-fold gains in gradient on conventional accelerators. A demonstration project AWAKE, first of its kind in the world, was recently approved at CERN to accelerate electrons with a plasma wake field generated by high-energy protons. Successful demonstration of this concept can pave the way for significantly compactified TeV-scale e^+e^- colliders with drastically reduced number of driver stages. TRIUMF accelerator scientists will participate in AWAKE and contribute beam-dynamics calculation and simulation, development of novel diagnostics designs, and possibly the electron bunch injection system and diagnostic equipment.

ARIEL E-linac Upgrade Possibilities

The ARIEL electron linac is compatible with the addition of a recirculation arc, which can either be used for energy doubling or for energy recovery. In the energy-doubling mode, the 45 MeV beam recirculates and goes through the main linac for a second pass, with a final beam energy of 75 MeV. This increased energy reach offers opportunities for additional kinds of photo-fission experiments. If the energy doubling mode is implemented at Phase 1 of ARIEL Completion, when the single-pass e-linac energy is 30 MeV, it will boost the electron beam energy to 50 MeV, and lead to increase in Li-8 production rates by a factor of up to 50, thus dramatically increasing the productivity of β-NMR experiments.

In the energy recovery linac (ERL) mode, a high-brightness electron beam can be interleaved with a single-pass RIB beam and accelerated in the same linac. This beam could be used to drive a powerful IR or THz free electron laser (FEL) or a compact monochromatic X-ray and gamma-ray source based on Thomson scattering of laser light off the high-quality electron beam for high-resolution imaging. Such a facility could be the first linac-based light source in Canada, and could serve as a technology demonstration device for ERLs, FELs, and compact light sources, as well as a user facility for high average power, coherent IR and THz radiation.

Both beam recirculation and ERL/FEL systems require advanced accelerator science and technology expertise, which are new frontiers for TRIUMF and Canada. Optics design will focus on the merger and separator systems with adequate acceptance for beams of diverse phase space characteristics while preserving beam quality, the 180 arc transport and chicane design to optimize beam condition going into the FEL for lasing while facilitating longitudinal transport gymnastics for bunching and energy recovery, and integration of undulator and laser systems following finalization of laser parameters.

Progress Toward and Participation in an International Linear Collider

Another exciting prospect opening up in the next few years is the imminent realization of the Linear Collider (LC) Project. Japan has expressed a serious interest in hosting the LC, which recently published a Technical Design Report. Confirming a site for the LC would start a major transformation of the high-energy precision measurement landscape. TRIUMF's expertise in SRF cavities makes this an obvious opportunity for the lab to play a significant role. Another possible topic is rotating target R&D for a positron source. In particular, TRIUMF's significant expertise in high power target systems, and strong interest in the development of a high power converter for the 500 kW e-linac beam, might present another opportunity for the lab to contribute towards the Linear Collider R&D.

The Linear Collider is designed to carry out precision measurements of the Higgs boson and will have the capability to discover particles that might go undetected at the LHC, such as a low mass supersymmetric partner of the Higgs. Once the project is approved, it is expected that participation by the particle physics community in Canada will grow significantly, but given the timescale for construction, physics results on new particle searches will not be forthcoming in the 2015–2020 time period.

GOALS FOR 6.2.3.1 BY 2020

- Continuously improve the performance of on-site accelerator facilities. Ensure beam delivery on time with reliability and efficiency, meeting user specifications for experiments.
- Design, construct, and operate new, state-of-the-art facilities at TRIUMF and around the world using next-generation technologies and developing partnerships with industry.
- Expand the TRIUMF-based R&D program in accelerator science and technology.
- Create a prestigious, in-demand program for accelerator science education.

6.2.3.2 MOLECULAR AND MATERIALS SCIENCE USING μSR AND β−NMR

μSR is a very successful probe of magnetic materials, particularly low dimensional and geometrically frustrated materials, where the magnetism has a substantial disordered character to it, even at very low temperatures. The technique plays an important role in the areas of correlated electron physics, quantum magnetism, and superconductivity, which are at the forefront of condensed matter physics research.

A great strength of contemporary condensed matter physics lies in the diversity and complementarity of the experimental probes, which are at the disposal of cutting-edge research teams. μSR, β−NMR, sophisticated neutron and X-ray scattering techniques all play important roles in successfully advancing the most challenging problems in condensed-matter and materials physics.

An aspect of spatial inhomogeneity that is common to all materials is that which arises as at a surface (on one side there is a material, and on the other, something different!). How the physical properties of a material at its surface evolve as one moves into the bulk defines a class of questions that emerging as a new research frontier: so-called "interface physics." As technology is irrevocably marching towards the nano-scale, where the relative contribution of a system's properties coming from the "interface" compared to the "bulk" becomes more important, new experimental methods to study such "buried physics" are much needed. From that perspective, β-NMR and slow-muon μSR, which are complementary because they are sensitive to different timescales, could play a dramatically important role in unravelling novel and exciting physics associated with surface, near-surface, and interfacial materials science. One can anticipate important discoveries to be made in this area, and β-NMR and/or slow-muon μSR may well be key players in facilitating such discoveries.

β-NMR is a unique technique for characterizing thin films and interfaces. At present, two experimental stations at ISAC have been optimized by CMMS for these experiments. The related research activities have been constrained by the availability of beam time. This has made it difficult to develop the use of isotopes other than Li-8, e.g., spin-½ isotopes to be used as purely magnetic probes. In its present stage of development and exploitation, the full potential of the β-NMR technique remains untapped. Increasing the beam time available through the new ARIEL facility will allow this unique technique to exploit its potential in the study of a large variety of heterostructures, thin films, and surfaces, where novel phenomena have recently attracted significant interest (please see Section 6.2.1.5).

The present upgrade program for the μSR beam lines will provide the facility with state-of-the-art infrastructure and increase their scientific output. The new M20 beamline is equipped with the capability to deliver one muon at a time (muon on request) to one experiment while providing a continuous beam of muons to another experiment. The muons-on-request technique allows for low background measurements of long time correlations.

The CMMS facility is also working to improve the remote control of all instruments and to develop user-friendly run control routines on all of the instruments and cryostats. This will improve the efficiency of the experiments and make it easier for casual users to run and reduce the number of people required on-site during the experiment, which will significantly reduce costs for users.

GOALS FOR 6.2.3.2 BY 2020

- Make low-background μSR measurements in high transverse fields using muons-on-request.
- Investigate quantum phase transitions and critical points in magnetic and superconducting materials in high transverse fields and high pressure environments.
- Progress using β-NMR (see Section 6.2.1.4).

6.2.3.3 ADVANCING ISOTOPE-PRODUCTION TECHNOLOGIES WITH ACCELERATORS

In Five-Year Plan 2015–2020, TRIUMF seeks to develop and commercialize several new technologies related to the production of medical isotopes. Beyond the research program outlined in Section 6.2.1.5, the Nuclear Medicine and Accelerator Divisions will combine forces to: (a) develop advanced technology for high-current and high-performance external ion sources for medical cyclotrons in collaboration with major manufacturers, and (b) demonstrate and deploy a commercial solution for cyclotron-based production of Tc-99m.

Modern medical cyclotrons compete in several areas of performance: reliability, beam current (intensity), and ease-of-use. Generally speaking, the energy of the machine dictates what isotopes can be produced, but as TRIUMF has revealed for Tc-99m, there are “sweet spots” for the production of certain isotopes. ACSI in Richmond, BC, manufactures commercial medical cyclotrons based on a TRIUMF design and these are the highest-current devices in the world. This feature helps drive their expanding market share. TRIUMF is in discussions with several partners about the potential for advancing the beam-current capabilities of certain machines using either modifications to existing machine or a new design for the ion source itself.

With the decision of the Canadian government to discontinue the reactor-based isotope production, which relies on the use of enriched uranium, the need for alternative production methods has clearly come into focus. TRIUMF is well along the way to use its long-standing expertise in the accelerator-based production of isotopes to develop a viable alternative for the production of the most popular imaging isotope Tc-99m (see Figure 21).

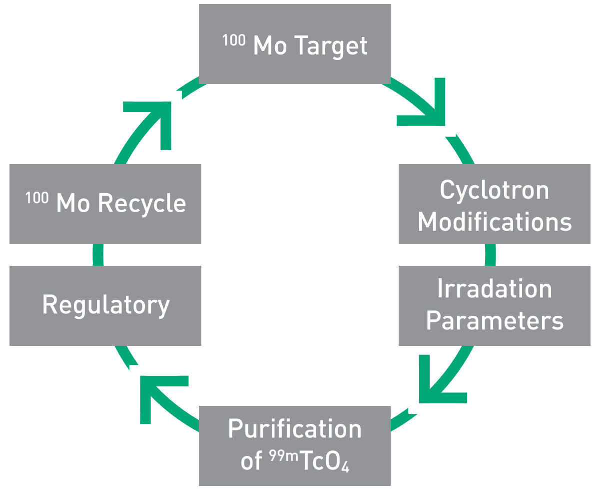


Figure 21: $^{100}Mo(p,2n)^{99}mTc$ at the commercial scale.

Since 2010, TRIUMF has led a multi-institutional, multidisciplinary team of physicists, engineers, chemists, and physicians from TRIUMF, the BCCA, Lawson Health Research Institute, and the Centre for Probe Development and Commercialization (CPDC) to demonstrate the feasibility of producing Tc-99m using Canada's existing medical cyclotron infrastructure. Having established the parameters for optimal irradiation of Mo-100 targets, the team is ready for clinical translation. By 2015, the consortium led by TRIUMF will have developed a mastery of the control parameters that influence reproducibility and predictability of Tc-99m yields and radionuclidic purity and therefore can be used as a baseline to implement a decentralized production paradigm. After 2015, the consortium will work to push the technology to new sites across Canada. This effort will take place in two phases. The first phase will involve an assessment of production needs at each site, followed by the installation of appropriate upgrade hardware (see Figure 22). The second phase will see commercial implementation, with regulatory assistance, thus leveraging those lessons learned during the recent Natural Resources Canada-funded initiatives. Discussions have already been started with key stakeholders in Saskatoon, Toronto, and Halifax.

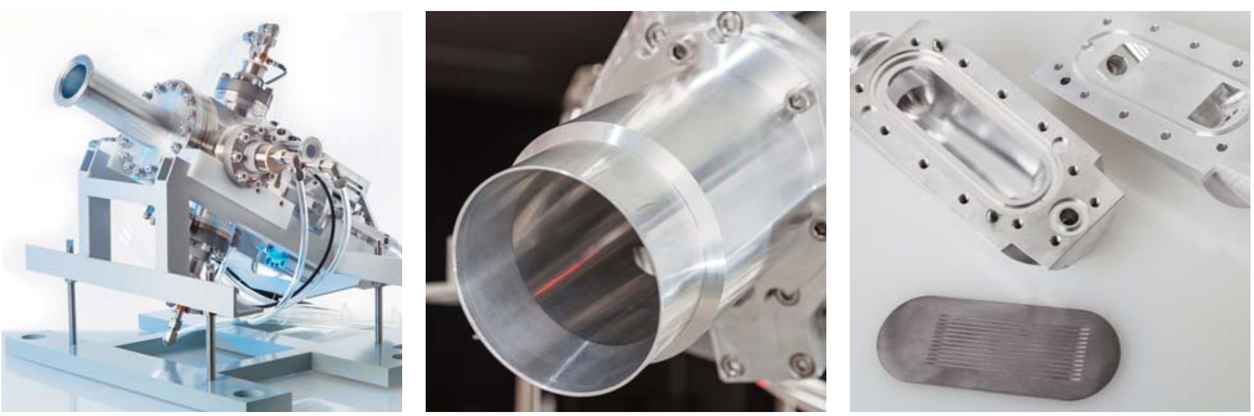


Figure 22: Target technology developed at TRIUMF for the production of Tc-99m with medical cyclotrons.

These are only some of possible new applications of accelerators in isotope production, and TRIUMF is using its unique set of competencies to develop new production technologies and make improvements to existing production techniques. TRIUMF maintains a complement of highly skilled individuals with world-leading expertise in many aspects of accelerator operations and targetry. With an ability to train highly qualified personnel in the cyclotron and isotope production sciences, TRIUMF simultaneously differentiates itself from other nuclear medicine centres, while having the ability to feed much-needed talent into the field. The focus remains on advancing the field of accelerator target design for the purpose of improving medical isotope production, as described in more detail hereafter.

GOALS FOR 6.2.3.3 BY 2020

- Explore the development of enhanced beam-current technologies with commercial partners via AAPS, Inc.
- Commercialize the cyclotron-based production of Tc-99m and develop production capacity in BC and Ontario with progress in other provinces.
- Install and commission a new medical cyclotron at TRIUMF (see Figure 23) that will develop new isotopes for research, provide commercial quantities of Tc-99m for BC, and drive other business opportunities.

Figure 23: A photograph of a modern TR cyclotron, courtesy of ACSI Inc.

6.2.3.4 PROTON AND NEUTRON IRRADIATION FACILITIES (PIF & NIF)

Today, TRIUMF is recognized as a premier test site for space-radiation effects on electronic equipment using protons and neutrons. The available neutron spectrum is well matched to the atmospheric neutron spectrum and thus also ideal for testing avionics and ground-based electronic systems, such as network and power-distribution servers, or even the latest cell-phone chips. In addition, irradiations of electronics can be performed with electrons from M11 and, more recently, muons from M20.

In addition to commercial electronics testing and qualification, the PIF & NIF infrastructure enables applied research by users from several different institutes, laboratories, and universities, often supported by industrial contracts. Many of the studies are performed by graduate students working on their theses or by young engineers beginning their careers in the testing community. Undergraduate students from physics and engineering have also benefited from PIF & NIF through work-term exposure to the facilities and testing programs.

Over the years, TRIUMF has made modest investments in updating and improving the PIF & NIF facilities. Recently, in reaction to user demand, TRIUMF decided to enhance the capabilities of the BL1B testing facility. The proposed BL1B upgrade would include a remotely movable lead or tungsten converter, an ion chamber to measure the incoming beam intensity, removable collimation, a higher intensity, and all of the associated controls and readouts to allow accelerated testing with either a focused beam or large-area beam of neutrons. This upgrade is well underway and will maintain TRIUMF's position as the only laboratory where research and testing with 500 MeV protons is possible.

Another area of concern for the radiation-effects community is whether or not cosmic-ray generated muons can cause problems with new technology. Recent data from testing at TRIUMF using M20 have demonstrated that low-energy muons can cause direct ionization in specific types of electronic microcircuits. Once again, TRIUMF is in a unique position to offer a testing facility for muons and plans are underway to create a compact set-up that can be used at M20 to allow for the accelerated testing of electronics. Once the muons-on-request system at M20 is commissioned, testing of electronics can be performed concurrently with science experiments, making use of the unused muons to irradiate electronic components, providing another service to both industry users and applied researchers.

GOALS FOR 6.2.3.4 BY 2020
• Increase the number of users by 30%.
• Demonstrate heavy-ion capability for use in commercial irradiations.
• Provide muon-irradiation services in line with industry demands.

6.2.3.5 TUMOUR THERAPY OF OCULAR MELANOMA

Proton beams are an effective way to treat cancer patients because of their selective dose delivery into the defined target volume while at the same time sparing the surrounding healthy tissue from radiation damage. TRIUMF operates Canada's only proton therapy facility. We have successfully treated ocular melanomas with proton therapy since 1995, the accepted best treatment choice for large ocular melanomas or melanomas close to the optic nerve (please see Section 5.6.3).

Despite the high success rate of the treatment, further improvements include better verification of the applied dose, further optimization of spatial control of the irradiation, minimization of dose from secondary particles, and optimization of the treatment plan.

In order to better understand the existing facility and its capabilities and to further improve it, the computer program FLUKA, a particle physics Monte Carlo–simulation package has been employed to model the proton therapy beam line. The simulation is currently being verified against several sets of experiments (please see Section 4.2.3.6). We envision using this computer model for several different projects, four of which are detailed below.

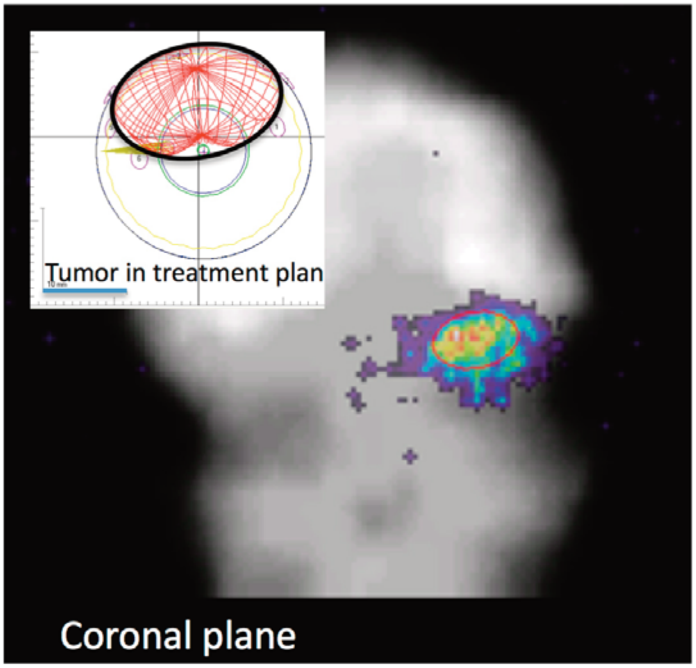


Figure 24: PET overlay of treatment plan.

Dose Verification with PET Imaging

The treatment plan for an ocular melanoma consists of four fractions administered on subsequent days. The dose planning involves measurement and marking of the tumour with tantalum clips and a sophisticated planning software to optimize the gazing angle, incoming beam energy and spread, and the final patient collimator. Before each fraction, the proton beam is carefully aligned for treatment. This is very important: proton therapy is a very precise form of radiotherapy with steep dose gradients at the target boundaries. At present, there is no way to measure if the proton dose has been deposited exactly as planned. Currently, we are investigating the usefulness of positron emission tomography (PET) after proton treatment (PT) as a way to visualize the proton dose deposited, as during PT the PET isotopes O-15, N-13 and C-11 are produced via nuclear reactions in small numbers within the patient (see Figure 24). The production cross-section of the PET isotopes, produced during proton irradiation, will be included in the FLUKA simulation in the near future. The measured activation profile will then be compared to the simulation. If the resolution is sufficient, a conclusion about the success of the patient alignment can be drawn. In the future, any misalignment could be compensated for in a subsequent fraction, avoiding missed dose to the tumour, and thereby reduced probability of local tumour control and excess dose to an adjacent structure with unnecessary damage to healthy tissue. This will ultimately lead to better patient care.

Dose Verification with Prompt Gamma-ray Emission

When the proton beam interacts with tissue, prompt gamma-ray radiation occurs due to nuclear reactions, which can be measured in real time and compared to a simulation. This radiation can therefore be used to monitor the depth of the dose deposition. In addition, the use of surrogate clips can be utilized to measure the proton dose depth. Currently, several tantalum (Ta) clips are surgically inserted around the tumour as markers. Substituting one of these clips with, for example a gold clip, will result in a different characteristic gamma-ray spectrum when the gold clip is reached by the proton beam.

Secondary Dose Reduction

The simulation will be used to quickly and economically study changes to the beam line while avoiding significant disruptions in beam line operations. Modifications intended to improve beam characteristics can then be tested experimentally with the goal of reducing patient dose from secondary particle emissions and, as a direct consequence, the occurrence of secondary cancer to the treated patient.

Treatment Plan Stability

The treatment plan (TP) currently used for clinical treatment can be simulated with FLUKA and be assessed for stability, meaning how robust the TP will be to slight patient misalignments and movement during treatment that are unavoidable in clinical operation. As there are often several choices of a TP, the most stable plan can be selected for treatment, or more than one TP can be realized to reduce further the dose to healthy tissue and reduce the occurrence of side effects.

GOAL FOR 6.2.3.5 BY 2020

- Realize improved patient care through control of the applied dose, dose verification, reduction of dose through secondary particles, and more stable treatment plans.

TRIUMF SELECTED AS CENTRE OF EXCELLENCE FOR COMMERCIALIZATION AND RESEARCH

14 February 2008

The Government of Canada announced $163 million to establish 11 new Centres of Excellence for Commercialization and Research (CECRs), including TRIUMF-incorporated Advanced Applied Physics Solutions (AAPS). AAPS focuses on commercializing TRIUMF-developed technologies with several partners including D-Pace, THALES Corp., University of British Columbia, Canadian Mining Industry Research Organization, and the China Institute of Atomic Energy. AAPS will initially focus on technologies for laser production of diamond-like foils, superconducting mini-cyclotrons, and a novel liquid xenon-based PET imaging scanner.

"Today's announcement marks a milestone in Canadian research history," said Industry Minister Jim Prentice. "The technologies, therapies, services and products generated by these new centres will help improve the well-being of all Canadians while positioning Canada at the forefront of priority research areas."

6.2.3.6 COMMERCIALIZATION AND MARKETING TECHNOLOGY VIA AAPS, INC.

TRIUMF's commercialization arm AAPS, Inc., (please see Section 5.10) plays a critical role in many of the proposals discussed in this section. Ultimately, AAPS seeks to market and commercialize Canadian-derived technologies using particle and beams from accelerators, radiation detection and control, or nuclear medicine— areas where TRIUMF has profound knowledge, skills, and abilities.

AAPS is presently pursuing a half-dozen different technology development and commercialization projects. Most of these efforts will complete within the next three to five years either as successful, stand-alone ventures or as technologies shelved for a future opportunity. What is missing, however, is the ten-year outlook that will answer the following questions: What are the new opportunities and from where will they come? What platform technologies will emerge that TRIUMF can influence, select, and develop through interactions with the market and industrial partners?

To develop a persistent institutional capacity in this regard, Five-Year Plan 2015–2020 proposes to create a Manager of Product Development staff position at TRIUMF. This role would be accountable for the 5-10 year business-development plan of TRIUMF and would support the Head of the Business and Administration Division in guiding opportunities to AAPS or other vehicles as they become ripe.
The technologies that AAPS will commercialize in 2020 and beyond are just now emerging at TRIUMF; this role (and up to two supporting positions) would forecast and manage that process to strengthen the technology-development bridge between TRIUMF, its partners, and AAPS.

GOALS FOR 6.2.3.6 BY 2020

- Achieve self-sufficiency for AAPS, Inc., develop a working capital fund, and return certain proceeds to TRIUMF's programs.
- Complete the domestic and international commercialization of cyclotron-produced Tc-99m with an appropriate set of industrial partners.
- Expand isotope-production capacity at TRIUMF through strategic recruitment of customers as upstream investors (e.g., Sr-82).
- Fully develop and launch two new accelerator-based technologies from TRIUMF (e.g., high-resolution mass separators with ACSI, Inc. and superconducting cryomodules with PAVAC Industries, Inc.).
- Move early ventures into profitable, high-performing businesses (e.g., MicroMatter via new product using the chemical-vapour deposition facility and neutron well-logging joint venture with GPN Petroleum Technology, Ltd.).

6.3 MAJOR INITIATIVES

In order to achieve the ambitious scientific goals defined in the previous section for Five-Year Plan 2015–2020, TRIUMF will pursue several major initiatives that will be supported through the NRC Contribution Agreement as well as external funding. The highest priority for the laboratory is the completion and scientific exploitation of the new ARIEL facility, TRIUMF's flagship project; however, several other initiatives and upgrades are also important to preserve or extend TRIUMF's leadership position.

6.3.1 ARIEL: COMPLETION TO SCIENCE

The completion of the ARIEL project will elevate TRIUMF's rare isotope program even higher on the international stage and clearly establish TRIUMF as the premier North American ISOL facility and a world leader in rare isotope science. ARIEL complements the main cyclotron and the ISAC targets at TRIUMF (see Figure 1).

At its heart the completed ARIEL facility will comprise a 500 kW, 50 MeV electron accelerator (e-linac) for isotope production via photo-production and photo-fission, as well as a second proton beam line (BL4N) from TRIUMF's main cyclotron for isotope production via proton-induced spallation and fission. In addition to the associated production targets and related infrastructure, this also includes the beam delivery infrastructure: mass separators, radio frequency (RFQ) coolers, and an electron-beam ion source (EBIS) for charge breeding. The current CFI project for the first phase of ARIEL, which will be completed in 2014, includes the new ARIEL building and beam line tunnel from the Electron Hall to the Target Hall in the lowest level of the ARIEL complex as well as a 100 kW, 30 MeV stage of the e-linac. The path towards the full completion of the ARIEL project will proceed in several phases, each of which

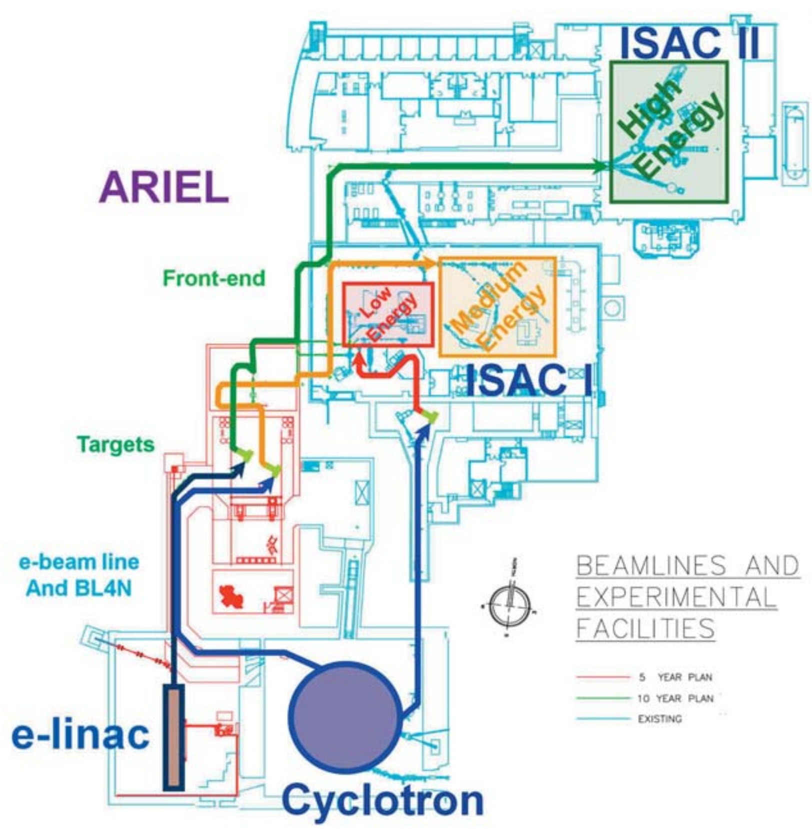


Figure 1: An overview of TRIUMF's accelerator complex for producing beams of rare isotopes. Shown is the existing main cyclotron and the ISAC production targets. To the west is the emerging ARIEL facility that includes the e-linac (electron linear accelerator), a new proton beamline from the cyclotron called BL4N, an underground tunnel, two production targets, and a front end and mass-separator facility to deliver new isotopes to the detectors in ISAC-I and ISAC-II. Funding for the ARIEL building, e-linac, and underground tunnel has already been secured.

will add important capabilities to enable exciting opportunities for scientific exploitation as well as developments towards the final target stations that can accept the full 500 kW ultimate beam power.

Hereafter a brief description is provided of the main components included in each phase as well as selected examples of the science that is enabled by each phase.

Phase 1: Li-8 for β-NMR and tests of time reversal symmetry

The first scientific program to be implemented will take advantage of the direct photo-production of Li-8 in a Be-9 target using bremsstrahlung photons produced by stopping the 100 kW e-linac beam in a solid tantalum converter.

This phase of the project will be carried out according to the framework of the next addendum of the Memorandum of Understanding between VECC Kolkata and TRIUMF with a completion of construction in 2016 and science exploitation beginning in 2017. The first step is the construction of the west target station, followed by an electrostatic pre-separator and the low-energy beam transport (LEBT) line that connects the e-linac target station to the ISAC-I experimental hall (see Figure 2).

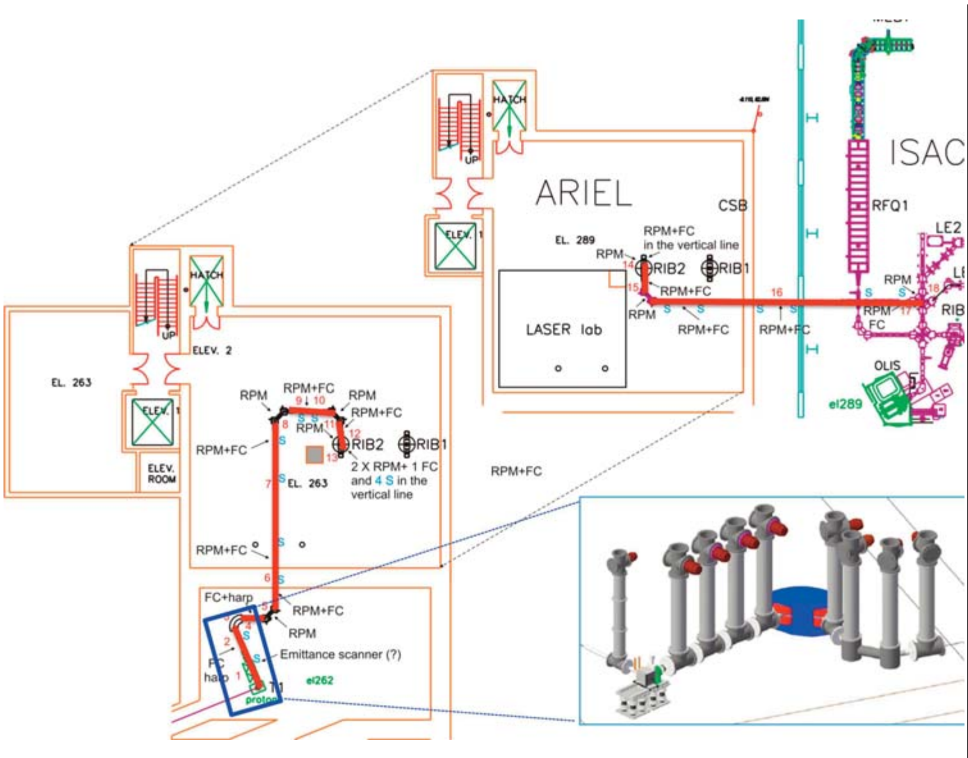


Figure 2: Plan view of the isotope-production area for ARIEL. The west target station is shown in place (lower left) and would be used to produce Li-8 beams transported upstairs and over to ISAC (see upper right). The inset on the lower right of the diagram shows a model of the target station.

These Li-8 beams will be polarized in the ISAC-I polarizer beam line and made available for β-NMR experiments studying the magnetic functionality of new materials, particularly at surfaces, interfaces, and in nano-structures, which are gaining in importance as devices shrink and become key ingredients in their functionality. β-NMR is one of the most informative ways to study local magnetic properties of surfaces and interfaces as a function of depth. Depth-controlled β-NMR, to the level of a few nanometers, is only possible at the β-NMR facility at TRIUMF.

The Li-8 beams produced with the e-linac will allow the β-NMR facility (please see Section 5.5.1.8) to reach its full potential as a user facility by dramatically expanding the amount of beam time for the CMMS program. This expansion is critical for a viable experimental user program in a fast-moving field that requires the capability to quickly carry out characterizations of new materials. It is expected that expanded use of the β-NMR facility would be handled through a proposed joint experiment-evaluation committee with Japanese facilities to ensure timely access to the best characterization techniques for materials developed in North America and Asia.

The polarized Li-8 beam will also enable dedicated beam time for the MTV (Mott polarimetry for T-Violation) (please see Section 5.5.1.7) experiment that searches in the nuclear beta-decay of polarized Li-8 for effects of the violation of time reversal symmetry, which are predicted by models of physics beyond the SM. The e-linac will allow for sufficient amounts of beam time to reach a statistical precision of 0.1% and to study all relevant systematic effects.

Phase 1 also includes the preparation of a new accelerator operations control centre in a new building, which will consolidate the currently separate control rooms for the 500 MeV cyclotron and ISAC as well as the controls for the e-linac.

In summary, Phase 1 of ARIEL completion will be important to achieve the goals for section *6.2.1.4 Isotopes as Probes of Magnetism at Interfaces and Surfaces of New Functional Materials*, by enabling the full β-NMR user program.

Phase 2: Purified accelerated high-mass rare-isotope beams for ISAC-II

In the framework of the CFI-funded CANREB project, essential components of the ARIEL front end will be constructed and made available for use with beams from the current ISAC targets. This approach for ARIEL was the result of an international review committee convened to examine options for TRIUMF to improve its capability for isolating and accelerating so-called "high-mass" isotopes in the ISAC-II complex.

In this scheme (see Figure 3), beams from the ISAC target will be guided into the ARIEL mass-separator room where they will be purified using the combination of an RFQ-cooler and a high-resolution magnetic mass separator (HRS). The mass-selected beams will be collected in an RFQ cooler and buncher from which they are injected into an electron beam ion source (EBIS) for charge breeding to charge states that

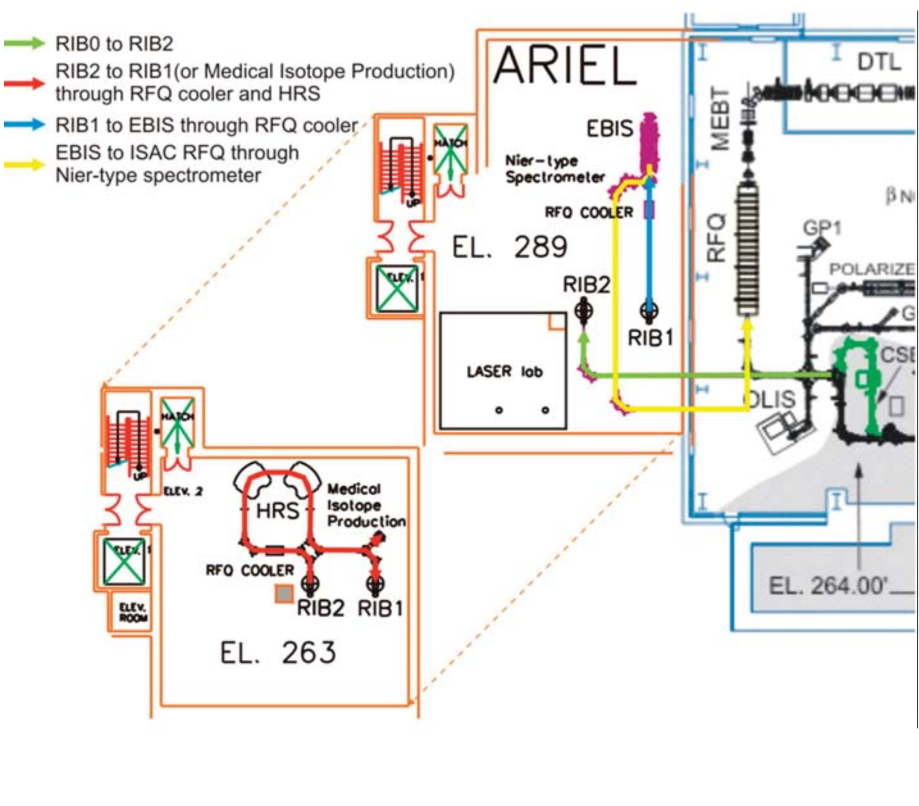


Figure 3: Plan view on several elevations for Phase 2 of completing ARIEL showing implementation of the CANREB mass separator and electron beam ion source (EBIS) in ARIEL with coupling to the ISAC production target. The lower left shows the 263' elevation level and the placement of the high-resolution separator magnet. The upper right of the diagram shows upstairs at the 289' elevation. As shown via the coloured line segments, Phase 2 involves making isotopes using the main cyclotron and the ISAC production target, transporting them to ARIEL at the 289' level, sending them downstairs for mass separation and/or medical-isotope collection, and then back upstairs for conditioning through the RFQ cooler and EBIS. The clean beams are then transported back to the RFQ in the ISAC-I hall.

can be accelerated by the ISAC-II accelerator chain to experimental facilities like TIGRESS, EMMA, and IRIS. The EBIS has a much higher charge breeding efficiency and purity than the current ISAC ECR based charge breeder, and overcomes the current severe limitations in the use of high-mass (A>29) beams in ISAC-II.

The CANREB project is thus a key enabler of the full physics program in nuclear structure and reactions and nuclear astrophysics using RIBs from the current ISAC proton target station using ARIEL beam delivery infrastructure.

With CANREB, TRIUMF will be able to take full advantage of its high-power production targets, enabling reaction studies of nuclei along N=Z and the proton drip line. For example, CANREB will provide clean beams of the N=Z nucleus Rb-74 and enable the extraction of the electromagnetic matrix elements via Coulomb excitation. This will provide important structure information on the superallowed Fermi-emitter Rb-74 constraining calculations of isospin-breaking corrections for the extraction of the V_{ud} quark mixing matrix element.

The CANREB infrastructure also includes a collection station for medical isotopes that are produced in the proton induced spallation in actinide targets using a 10 µA, 500 MeV proton beam. Rn-211, will be produced, captured, and purified for shipment of At-211 generators to collaborators around Canada to foster research in the area of alpha particle therapy.

In summary, Phase 2 will advance progress on the goals for sections *6.2.1.1 Rare Isotopes to Develop a Standard Model of Nuclear Physics*, in particular by enabling studies of shell evolution; *6.2.1.3 Isotopes to Understand the Origin of the Chemical Elements*, in particular enabling studies of (d,p) reactions; and *6.2.1.5 Isotopes for Molecular Imaging of Diseases and Treatment of Cancer*, by providing research quantities of At-211.

Phase 3: Photo-fission for r-process studies

Phase 3 will see the production and delivery of neutron-rich fission fragments by implementing actinide targets (uranium or thorium) in conjunction with the solid photo-converter. The initial 100 kW beam of the e-linac will enable production of approximately $2x10^{12}$ fissions per second in the target, which is substantially larger than the current fission fragment production rate with the 10 µA,500 MeV proton beam. Using the already developed beam delivery infrastructure, purified beams of very neutron-rich nuclei will be delivered to any of the experiments in ISAC-I (please see Section 5.5.1) or ISAC-II (please see Section 5.5.2).

The e-linac will not only produce unprecedented intensities of neutron-rich isotopes through photo-fission but at the same time avoid the production of high-intensity contaminants that are produced in the current ISAC target via proton induced spallation. These intense contaminants would limit access to the most neutron-rich nuclei produced.

In nature these very neutron-rich nuclei are only created for fractions of a second in violent star explosions (supernovae) or mergers of neutron stars during the so-called astrophysical r-process. However, they hold the key to our understanding of where in the universe the chemical elements heavier than iron were produced. With the production of even more neutron-rich nuclei the e-linac will bring the nuclear physics of supernova explosions to the laboratory and enable the identification and study of the nuclei involved in the r-process. In conjunction with precision astronomy and sophisticated astrophysical modelling using large scale computing facilities, these studies will allow us to identify the astrophysical site of the r-process.

Measuring the properties of these nuclei is also critical for the quest to make major advances towards developing the long-sought standard model for all nuclei that will provide accurate predictions for all nuclei based on the underlying fundamental theory at work inside protons and neutrons, quantum chromo-dynamics (QCD). In particular, experimental investigations of the evolution of shell structure and collective behaviour in very neutron-rich nuclei will be essential to test the accuracy of modern theoretical approaches which predict substantial deviations from the well-known nuclear structure near stability. For example, we will be able to perform studies of (d,p) neutron transfer reactions with TIGRESS and IRIS to obtain information on neutron-capture rates beyond Sn-132. Recent sensitivity studies of r-process models show that constraining neutron-capture rates in certain nuclei in this region can constrain uncertainties in the abundance predictions of neutrino-driven wind scenarios for the astrophysical r-process. Fission fragment rates from ARIEL will enable studies of surrogate (d,p) reactions to obtain information on (n,γ) rates. Also studies of neutron separation energies with TITAN, charge radii and ground state spins and moments via laser spectroscopy, or decay half-life and beta-delayed neutron emission with GRIFFIN will be of great importance.

The beams provided by ARIEL, in combination with the available state-of-the-art experimental facilities at ISAC, will enable the characterization of the important properties of these very neutron-rich nuclei and thus facilitate the development of this unified theoretical framework for nuclear physics.

During this stage of the project, a second target station (the east target station) will be built (see Figure 4). The electron beam from the e-linac can be deflected towards the east or west target stations at arbitrary patterns, so that it can be shared between the two target stations. The east target station will be outfitted with its own pre-separator and low-energy beam transport lines so that delivery from both ARIEL target stations to the ISAC experimental hall will be possible.

The delivery of three independent RIB beams to the ISAC experimental facilities marks another important milestone for ARIEL.

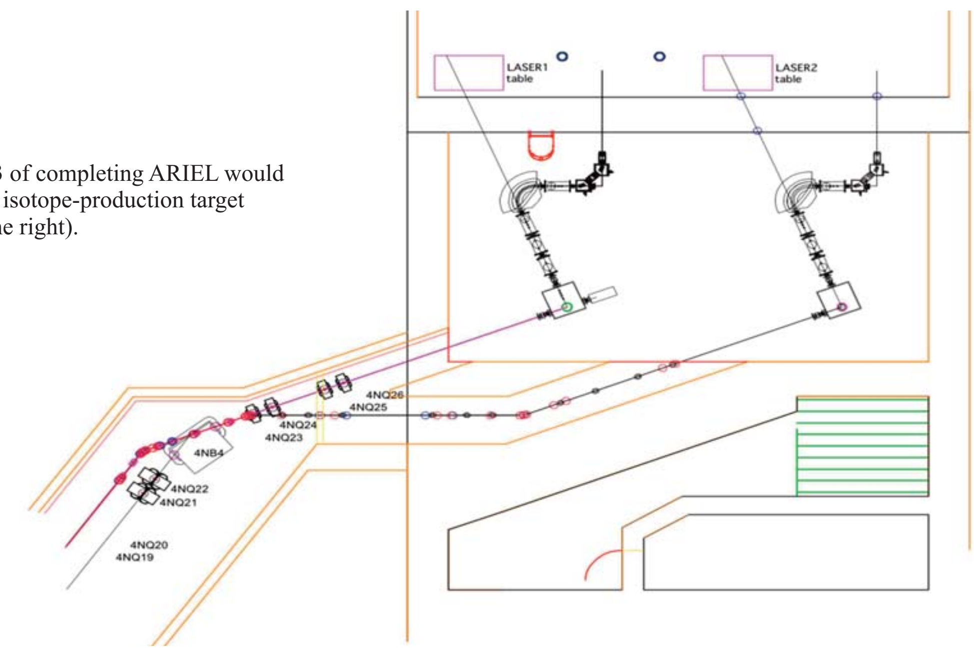


Figure 4: Phase 3 of completing ARIEL would construct the east isotope-production target (shown here on the right).

Aside from isotope production for science the electron beam will be used at this target station for the development of the challenging technology of the liquid lead converter that is needed for the exploitation of the full power of 500 kW of the final e-linac. The liquid metal technology is needed because cooling of a solid converter is not sustainable above approximately 100 kW.

In summary, Phase 3 will make progress on the goals in Sections *6.2.1.1 Rare Isotopes to Develop a Standard Model of Nuclear Physics*, in particular by extending studies of shell evolution, and *6.2.1.3 Isotopes to Understand the Origin of the Chemical Elements*, in particular to study r-process nuclei.

Phase 4: Actinide production for fundamental symmetry tests

Phase 4 will see the implementation of the new proton beam line (BL4N) from TRIUMF's main cyclotron, delivering up to 100 µA of proton beam to the west target station (see Figure 5). At this time, isotope production from the e-linac will shift to the east target station, and RIB production will be carried out in parallel on three target stations.

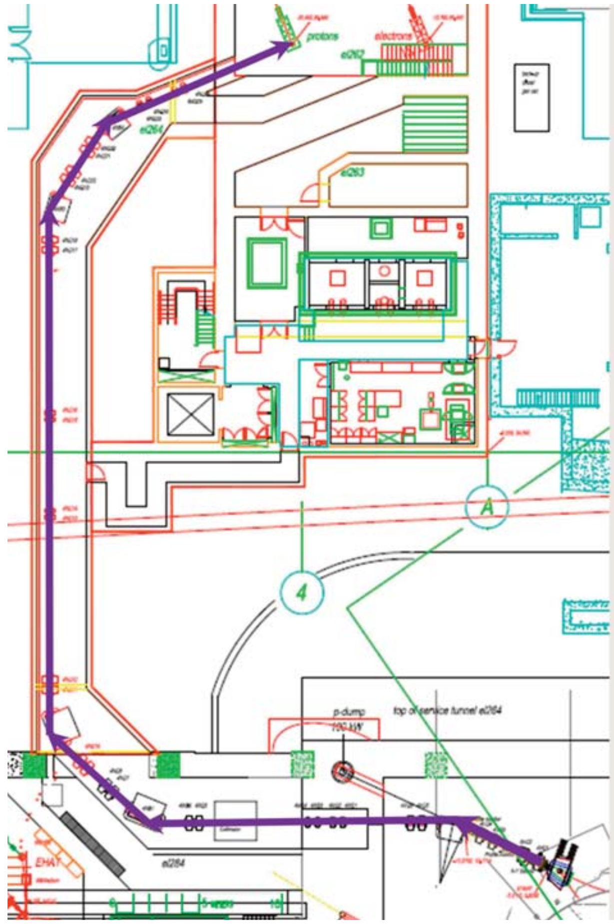


Figure 5: Phase 4 of completing ARIEL completes BL4N from the main cyclotron and carries protons to the west ARIEL isotope-production target.

With the new proton target station, it will be possible to provide intense, clean beams of heavy elements, purified using the ARIEL high-resolution mass separator, for extended beam times of precision experiments that use rare isotopes of elements such as francium and radon as laboratories to search for physics beyond the SM. Important examples in this context are the recently initiated francium parity non-conservation program and the search for non-vanishing EDMs using radon and francium isotopes. These experiments need to run for hundreds of shifts per year to achieve sensitivities to the tiny effects they seek to measure. Only the multi-user capability facilitated by ARIEL will unlock the full discovery potential of those experiments.

In summary, Phase 4 will be of particular importance to achieve goals for section *6.2.1.2 Rare Isotopes as Laboratories to Search for New Particles and Forces*, by enabling studies of atomic and electron EDM as well as other precision experiments.

Phase 5: Full power e-linac to reach the most exotic neutron-rich nuclei

The final phase towards completion of the ARIEL project will be the implementation of a second accelerator cryomodule (ACM) (see Figure 6) to boost the energy from 30 MeV to 50 MeV to reach the full beam power of 500 kW, producing up to 10^{14} fissions per second, and pushing the limits of experiments to even more neutron-rich nuclei.

With a production gain of close to a factor of hundred, this will enable precise measurements of beta-decay Q-values (TITAN) and beta-decay half-lives (GRIFFIN) of the most exotic neutron-rich nuclei, for example around Sn-140 and the mass-160 rare earth r-process abundance peak. The higher production yields will also enable in-beam studies like Coulomb excitation and transfer reactions for those nuclei for which only ground state properties could be accessed in the earlier phases of ARIEL. These studies will provide essential information about the evolution of single-particle structure at the extremes of isospin, where theory predicts dramatic changes to shell structure, which in turn have substantial impact on the location of the r-process path on the nuclear chart.

In summary, Phase 5 will be important to enable goals for sections *6.2.1.1 Rare Isotopes to Develop a Standard Model of Nuclear Physics*, by extending the reach to larger isospin, and *6.2.1.3 Isotopes to Understand the Origin of the Chemical Elements,* by enabling access to more r-process nuclei.

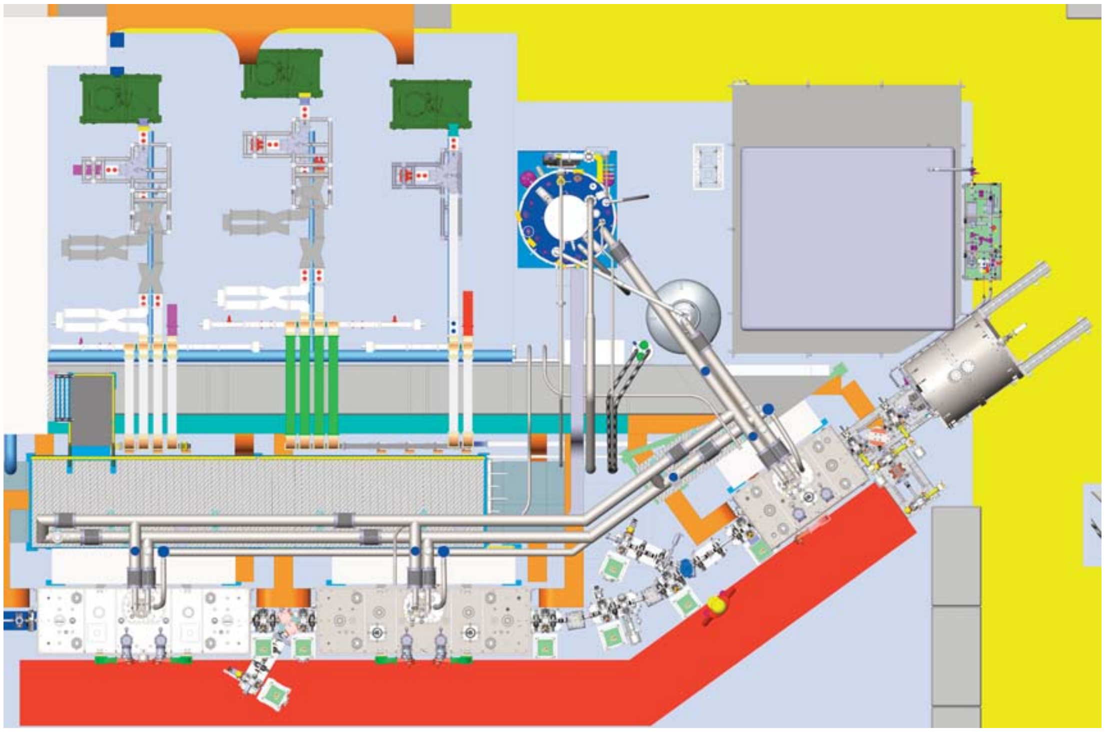


Figure 6: Sketch of the high power e-linac.

ARIEL Completion and Five-Year Plan 2015-2020

Full implementation and exploitation of ARIEL will extend beyond 2020. TRIUMF, in close consultation with the University of Victoria and the Board of Management, has assembled a working group (including a full-time project engineer) to map out the most effective strategy. The preceding discussion is one of the early outputs from this process. It is expected that most of the capital support for completing ARIEL will come from a successful proposal to the Canada Foundation for Innovation to be submitted in spring 2014. This report contains preliminary information on the project plan that is gaining form and substance each day. The working group has developed a three-level work breakdown structure for the project and is consulting subject-matter experts to develop a well-understood bottoms-up, resource-loaded schedule. Early outputs from this process are presented here.

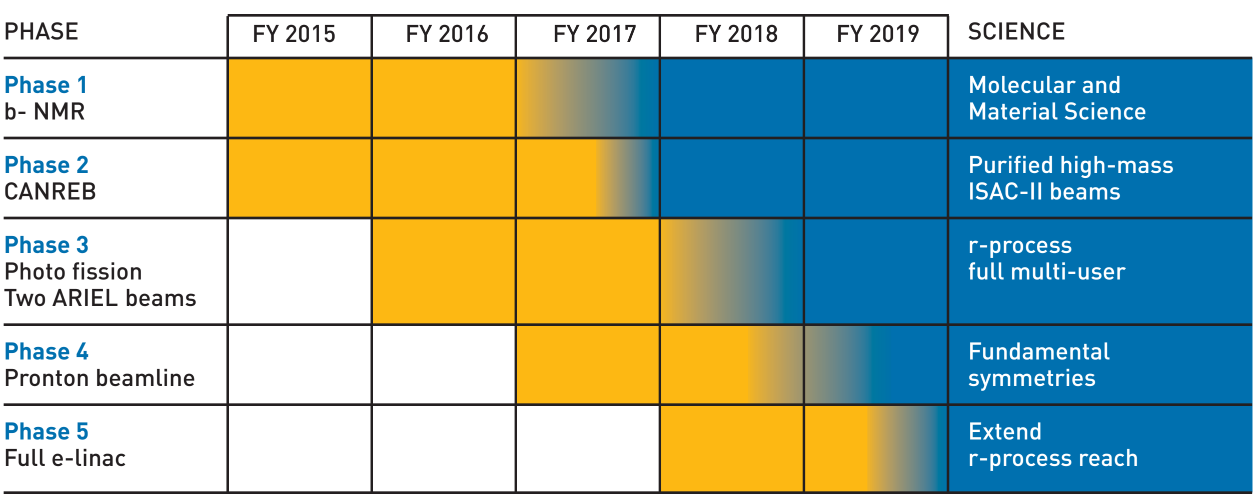


Figure 7: Preliminary timeline for ARIEL completion indicating key science outcomes.

ARIEL CONSTRUCTION REACHES MILESTONE

23 May 2013

The construction of TRIUMF's coveted facility, the Advanced Rare IsotopE Laboratory (ARIEL) has reached an important milestone towards its completion, marked by the dismantling of the tower crane suspended over the site. The ARIEL facility is a major addition to the TRIUMF complex that will greatly expand the scientific potential of the TRIUMF radioactive ion beam facility.

Over the course of a day, staff and crew admired the careful disassembly of the tower crane. The removal represented the completion of a year's worth of work – from the site excavation to the establishment of ARIEL's structure, which required about 600 truckloads of concrete.

Serving as a milestone toward completion, the crane disassembly also marks the beginning of the next stage. The roof can now be completed and the interior work of preparing the building for the e-linac can begin. Constructions crews are working fervently to finish all of the electrical work that is required to install and maintain ARIEL experiments.

Figure 7 provides an overview of the timelines for construction and science exploitation of the five phases of the ARIEL Completion project and indicates the science enabled by each phase. Experience with the current phase of the ARIEL project indicates that one should expect a 12-15 month ramp-up phase for conceptual design studies and design decisions for the two initial phases. The in-progress, bottoms-up analysis of the five phases indicates that the total manpower needs are consistent with a levelized load of 50-55 FTEs during the main part of the project were each phase transitions from design to manufacturing to installation and commissioning. This level of effort is equivalent to what TRIUMF is presently directing to the ARIEL project.

Preliminary timelines show that Phases 1-3 would be operational with installation and commissioning of Phase 4 in progress by the end of Five-Year Plan 2015–2020. This schedule fulfills ARIEL's promise to deliver new capacity to TRIUMF (a new electron-driven isotope production target and a new proton-driven isotope production target) as well as new capability (isotope production via photo-fission on actinide targets using electrons). Additional planning may indicate that an accelerated schedule is feasible.

Figure 8 presents the high-level work breakdown structure and preliminary capital costs for each major work package.

Meanwhile, progress on ARIEL completion has already begun.

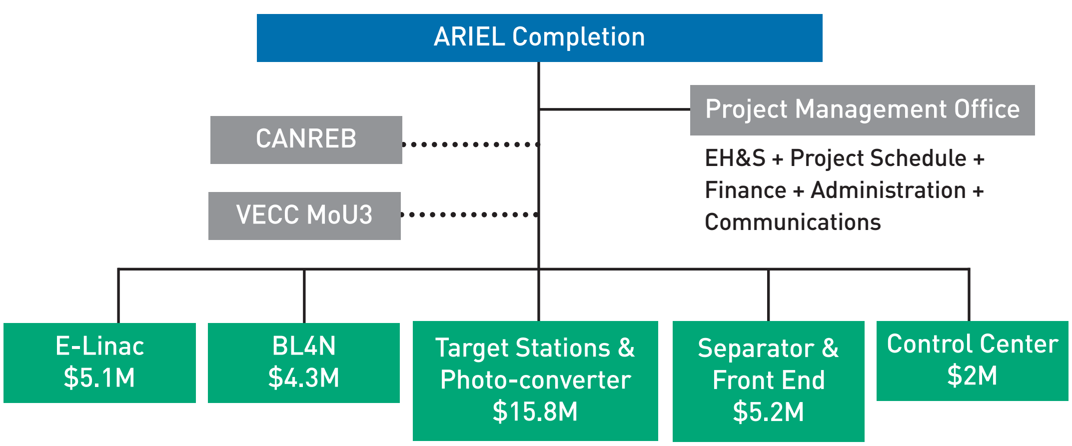
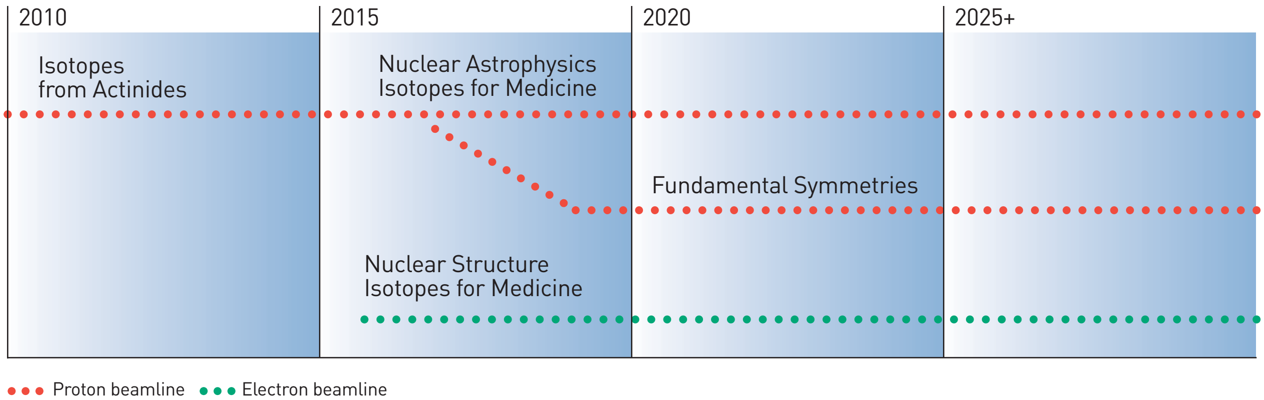


Figure 8: Top-level work breakdown structure of the ARIEL Completion project.

ARIEL 10 YEAR PLAN



In August 2013, TRIUMF signed a new addendum to its Memorandum of Understanding with the Variable Energy Cyclotron Centre (VECC) in Kolkata, India. The full scope of work is valued at \$10.4M and includes components to expedite key parts of Phase 1. That is, by pooling resources between TRIUMF and India, work on ARIEL and India's ANURIB project will move forward more quickly.

In January 2013, CFI announced approval for its \$1.6 million contribution to the \$4.5M CANREB project related to Phase 2. Matching funds have been approved by AAPS, Inc., (\$1.1M for the technology transfer of the HRS to ACSI), Nova Scotia (\$0.4M), and Manitoba (\$0.2M) while the approval process for the provincial matching funds has not yet been completed in British Columbia.

In November 2012, the TRIUMF Board of Management formed a task force that is jointly coordinating development of the \$32.4M CFI proposal that would support the capital for the ARIEL Completion project. This coordinated initiative by the TRIUMF consortium, each setting CFI envelope-quota aside for this flagship project and making commitments to pursue provincial-government matching contributions, is unprecedented and demonstrates the level of commitment of the 18 universities to TRIUMF and the ARIEL research program.

6.3.2 OTHER INITIATIVES AND UPGRADES

In addition to the ARIEL project there are several other key initiatives that TRIUMF will pursue in order to capitalize on previous investments in the local facility as well as international endeavours. International initiatives include upgrades to the ATLAS detector at CERN and the T2K experiment in Japan, while initiatives at TRIUMF include an expansion of the ATLAS Tier-1 Data Centre, the complete implementation of the UCN facility, and work towards a full use of the new μSR beam lines M9A and M20. TRIUMF also plans to capitalize fully on its unique expertise for accelerator-based medical isotope production by founding the Institute for Accelerator-Based Medical Isotopes (IAMI). These initiatives are described in more detail in the following sections.

6.3.2.1 ATLAS

ATLAS Tier-1 Data Centre

The ATLAS Tier-1 Data Centre at TRIUMF, one of 10 such centres worldwide, played a key role in the analysis leading to the discovery of the Higgs boson, in particular, through the timely deployment in 2012 of additional computing resources, which were part of an earlier expansion. Looking towards the future, it is important to leverage Canada's significant investments in this world-class facility with an exceptional track record in reliability and performance. This record is due to a small but very effective team of highly qualified personnel, high quality hardware, and an ideal location at the TRIUMF national laboratory for 24 x 7 efficient operations.

Tier-1 computing-resource planning is tightly coupled to ATLAS operations and to the Large Hadron Collider (LHC) schedule and running efficiency. The LHC is in a long shutdown (LS1) in 2013 and 2014; upgrades are necessary to operate at the design energy and luminosity. Full LHC operations are expected to resume in 2015. During LS1, several developments are foreseen for ATLAS distributed computing operations. For instance, a new distributed data management system will be deployed with an improved grid production system and more dynamic features. The new systems will be deployed in various stages and in parallel to the current production system to avoid any impact on ongoing data processing, simulation, and analysis activities.

During LS1, the major expected activities are full reprocessing of all of the 2011 and 2012 data, extensive physics analysis activities, and large-scale simulations at 2015 beam energies. The TRIUMF ATLAS Tier-1 Data Centre will continue to play an essential role in all of these activities. The scientific output of the ATLAS experiment heavily depends on successful and efficient distributed computing operations worldwide.

From 2010–2013, more than 7.5 billion proton-proton collision events were recorded, and successfully distributed and processed on the Worldwide LHC Computing Grid (WLCG) infrastructure. In 2012, the average high-level trigger rate of ATLAS was 400 Hz.

From 2015 on, significantly higher data rates are foreseen. In order to maximize the physics reach of ATLAS, the objective is to increase the trigger rate to 1 kHz, entailing a significant increase in the required computing resources. Table 1 below shows the cumulative resources to be provided by the Tier-1 centres worldwide from 2013–2017 as currently projected. In 2018, there will be another LHC shutdown (LS2) to increase the luminosity further and to perform ATLAS detector upgrades. It will be crucial for the TRIUMF ATLAS Tier-1 Data Centre to continue to meet ATLAS requirements and to fully comply with our international commitments and the MOU with CERN.

Through a recently approved CFI proposal it will be possible to replace some of the older computing resources dating back to 2007. In order to maintain the current 10% contribution to the total Tier-1 level computing resources for ATLAS, a substantial expansion of the Tier-1 is envisioned.

A full hardware refresh of the Tier-1 Data Centre will be needed over the course of the 2015–2020 timeframe, including significant infrastructure upgrades. The available floor space in the current Tier-1 Data Centre is fully occupied, and the tape library cannot be expanded any further. Therefore, a high priority will be to reconfigure an existing storage building, including the connection of adequate power and cooling services, as early as possible in 2015 and to deploy new tape library infrastructure with the required storage capacity. The renovation costs are estimated to be close to \$0.5M and will be carried by TRIUMF through the NRC Contribution Agreement.

Major hardware acquisition will be needed in 2016 to refresh all computing equipment purchased in early 2012 and for further expansion. The estimated capital cost for the computing equipment—with a five-year warranty—is \$4.6M, excluding taxes. The ATLAS Canada collaboration will apply for CFI investment funds for the computing hardware for this major expansion. The overall estimated operating cost is \$1.5M, excluding salaries. Another computing hardware expansion and refreshing of equipment purchased in 2013 and 2014 will be necessary by 2019.

	2013	2014	2015	2016	2017
CPU (kHS06)	319	373	502	676	909
DISK (PB)	35	36	51	72	102
TAPE (PB)	43	53	78	115	169

Table 1: Projected cumulative computing resources to be provided by the Tier-1 data centres worldwide for ATLAS. Disk and Tape capacities are in Petabytes (PB). The CPU capacity is expressed in HEP-Spec 2006 (HS06) units, a common benchmarking unit that is suitable for high-energy physics applications. A modern CPU is equivalent to 14 HS06. TRIUMF's current share in ATLAS Tier-1 computing is 10%.

TRIUMF will transition the 9.5 FTE Tier-1 personnel, currently supported through CFI IOF funds, into its core salary budget, and operational funds, predominantly electrical power and networking cost, are budgeted in the NRC Contribution Agreement to continue this high profile and highly successful operation.

ATLAS Detector Upgrades

As part of the Phase-I upgrades for installation in ATLAS during LS2, in 2018, ATLAS-Canada plans to be involved in two major projects: the production of thin gap chambers (sTGC) for the new small wheels (NSW) of the muon spectrometer and an upgrade to the level-1 trigger electronics for the electromagnetic calorimeter. NSERC RTI funds have been obtained for R&D efforts and to set up the tooling required for these efforts, and a CFI proposal will be submitted for the full-scale chamber production.

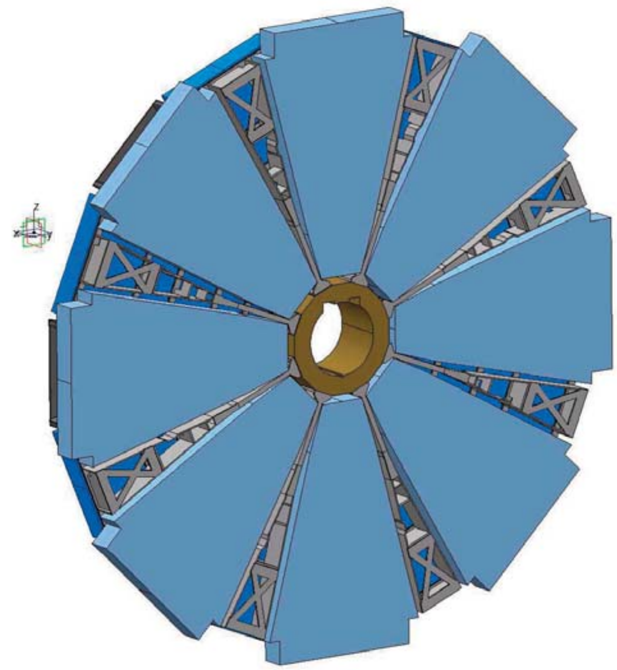


Figure 1: Preliminary design for ATLAS New Small Wheel showing the mechanical supports and envelopes of the wedges of detector elements. Courtesy of ATLAS Muon Collaboration.

The NSWs (see Figure 1) are needed to add improved trigger and tracking capability in the forward direction where otherwise the rate of misidentified (fake) muons, due to activation of the forward toroid magnet coils, will become too high once the instantaneous luminosity increases. The technology of choice for these chambers combines sTGCs (for fast triggering) with Micromegas (for precision tracking) with the individual thin gap chambers being quadruplets of individual gas gaps with copper pads on one side for fast trigger readout, copper strips on the other side for precision readout, and anode wires in the gap with readout for the second coordinate. One-third of the NSW sTGCs will be built in Canada: 256 gas gaps plus spares built over 18 months (one per working day). The final product will be assembled at Carleton as 64 quadruplet (4-gap) chambers and tested for efficiency in a cosmic ray testing facility at McGill prior to shipping to CERN. Assembly into azimuthal sectors would be done at CERN after re-testing.

Work at TRIUMF would primarily consist of the carbon coating of the cathode planes, as well as some cathode plane assembly, for which a suitably ventilated room for carbon spraying and temperature/humidity-controlled drying is required as well as a semi-clean area with suitably equipped granite tables for the other cathode plane work. In the next few years, discussions will take place regarding the need for and a possible involvement in building replacements for the trigger chambers of the “Big” wheels (those nearest to the beam pipe) with higher-resolution sTGC. This would happen in the Phase-2 LHC shutdown (LS3) of 2022–23. Producing these additional chambers would require only minor modifications to the set-up for NSW cathode planes.

The ATLAS endcaps and forward calorimeters use liquid argon as the active detector element. The Canadian-built hadronic endcaps (HEC), including the HEC front-end electronics, and forward calorimeters (FCals) are inside common cryostats and a common liquid argon volume with the electromagnetic endcaps (EMECs) and share electronics crates. With increasing luminosity the electron triggers also suffer from a higher rate of “fake” electrons and will consequently require an upgrade to the crate base-plane of the EMEC to mitigate this problem.

ATLAS-Canada plans an upgrade of the HEC/FCal motherboard for the LAr Trigger Digitizer and Driver Board (LTDDB) to be installed during the LS2 2018 Phase-1 shutdown of the LHC, and an upgrade of the FCals themselves, scheduled for the LS3 2022–23 Phase-2 shutdown.

These activities are expected to be supported by a number of Canadian funding agencies. TRIUMF will be engaged by providing intellectual and technical expertise, personnel, and laboratory space.

TRIUMF research scientists and joint faculty members benefit from the flexibility that comes with reduced teaching responsibilities and are well positioned to continue to be leaders, both in coordinating analyses, detector construction projects, and in taking on management responsibilities within the ATLAS collaboration and its sub-detector groups.

NSERC has funded an RTI ($0.41M) for ATLAS-Canada to cover infrastructure set-up for the sTGC and LAr calorimetry in 2013–14 at the various institutes involved. A second RTI is being requested to cover the remainder of the set-up and prototyping work in 2014–2015. CFI will be asked to fund the LAr electronics and sTGC chamber production activities in 2015–2016.

The upgrades to the ATLAS detector and the ATLAS Tier-1 Data Centre are critical to achieve goals of sections *6.2.2.1 Precision Measurements of Standard Model Processes*, and *6.2.2.2 Direct Searches for New Particles.*

6.3.2.2 UNDERGROUND DETECTOR FOR LONG BASELINE NEUTRINO OSCILLATIONS AND PROTON DECAY

Hyper-Kamiokande (HK) is a proposed upgrade to the Super-Kamiokande (SK) water Cherenkov detector. HK would consist of two water volumes with nearly one megaton total mass (20 times SK) instrumented with 99,000 photosensors to detect Cherenkov radiation emitted from charged particles traversing the water (see Figure 2). While HK has a very broad scientific program, its primary goals are to search for CP violation in neutrino oscillations using a muon neutrino beam from Tokai (an extension of the current T2K experiment) and to search for proton decay. A funding decision on HK in Japan is expected within the next three years.

Through its leading role in T2K and other neutrino experiments, the Canadian T2K collaboration and TRIUMF are in a strong position to make highly visible contributions to the experiment. R&D effort has started in the following areas:

1. **Photosensors:** The required number of photosensors is determined mainly by the effective surface photocathode coverage, which determines performance of the detector in terms of energy thresholds and resolution. The 99,000, 20” photosensors lining the volume are also one of the major cost drivers for HK. There is an ongoing effort at TRIUMF to investigate passive optical techniques that collect Cherenkov photons over a large area and guide them towards the photosensor, providing a cost-effective means of effectively increasing the photosensor coverage. A photosensor testing facility at TRIUMF has been built to characterize the performance of new photosensor technologies, including light-collection schemes. Canadian groups are also discussing developing front-end electronics for digitizing the photosensor output.
2. **Calibration:** The Canadian group is leading the design of the calibration source deployment system for HK. The development will leverage the experience of building the universal interface for source insertion, designed and built by TRIUMF for SNO+, as well as the cable-based source manipulation system used in SNO. These will allow automation of the source insertion, deployment, and manipulation procedures that are currently performed manually at SK. While SK consists of one inner water volume, the baseline HK design calls for ten optically isolated volumes each of which must be individually calibrated, necessitating the automation of the calibration procedure.

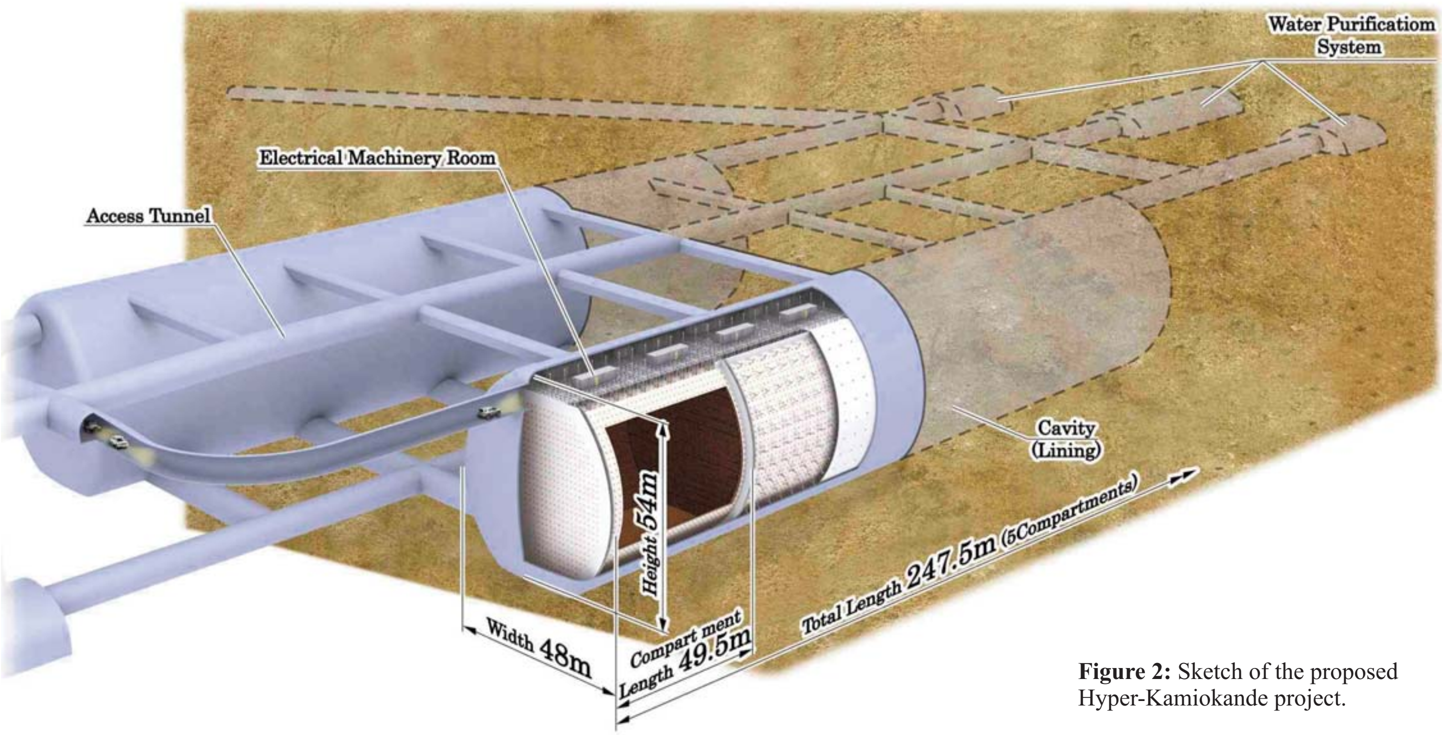


Figure 2: Sketch of the proposed Hyper-Kamiokande project.

3. **Near Detector:** The Canadian T2K group and TRIUMF played a central role in the design and construction of the T2K near detectors, and are now leading investigations into possible upgrades or new detector concepts to achieve the targeted systematic uncertainties on neutrino flux and cross-sections.
4. **Software and Reconstruction:** TRIUMF Geant4 experts recently completed a full geometry description of the HK detector to allow a detailed Geant4 Monte Carlo simulation. The reconstruction algorithm developed by the Canadian group for T2K and SK has been adapted to the HK simulation. These tools are the basis for detector performance and optimization studies necessary for producing a full technical design.

While the nature and scope of a potential Canadian contribution to HK are still under discussion, along with partnerships and collaboration with HK groups in other countries, the magnitude of the contribution is anticipated to be approximately $5 million with 20 FTE-years of TRIUMF personnel support from TRIUMF. TRIUMF scientists will be involved in these activities and the project will use laboratory space and test beams at TRIUMF. Operating funds of approximately $2 million/year, the current level of support for Canadian activities on T2K, will be requested from NSERC.

The upgrades to T2K and the R&D on Hyper-Kamiokande are critical to achieve goals of section *6.2.2.1 Precision Measurements of Standard Model Processes,* in particular relating to neutrino mixing parameters.

6.3.2.3 ULTRA-COLD NEUTRON FACILITY

Ultra-cold neutrons (UCN) with their remarkably low energies (< 300 neV) are totally reflected from the surfaces of a variety of materials and can therefore be stored in bottles for long periods of time. The challenge in producing UCNs is in the efficient cooling of the neutrons without suffering large losses. Superthermal sources for UCNs, like the one being developed for TRIUMF, take advantage of cooling via phonon excitation and is based on an innovative technology using a superfluid helium (He-II)-based, spallation, UCN source that is currently undergoing development at RCNP in Osaka, Japan. At TRIUMF, UCN densities of 1,300 UCN/cm^3 will be achieved, and these are comparable to the goals of other international facilities.

In the period 2015–2020, the CFI funded TRIUMF UCN facility will be completed including an expansion of the new helium liquefier facility for full power operation of the UCN target (see Figure 3). The UCN facility will begin operation in 2016 at a beam current of 1 µA, which will be stepped up to the design current of 40 µA over several years.

The top priority for the UCN facility will be a measurement of the neutron electric dipole moment (nEDM) with a target sensitivity of 10^{-28} e cm. The nEDM experiment will build on the current developments at RCNP and is complemented by an intensive R&D effort of the growing Canadian nEDM collaboration. This includes work on the UCN storage cell, the co-magnetometer, as well as a major upgrade to the magnetic shielding. In addition possible upgrades to the UCN source are under consideration, including the use of a liquid D_2 moderator.

It is also planned to add a second extraction port to the UCN source, which would provide the exciting possibility to expand the scientific reach of the TRIUMF UCN facility. Other high profile experiments that can be carried out at the second port are measurements of the neutron lifetime, of the gravitational law at very short distances, and decay correlation experiments searching for indication of new particles or forces.

The Canadian collaboration is increasing in size with six new faculty members at TRIUMF, Manitoba, UBC, and SFU joining over the past few years. In particular, a newly hired TRIUMF research scientist (Ruediger Picker) with extensive experience in experiments using UCN (neutron EDM, neutron lifetime, and neutron beta decay asymmetry experiments) joined the TRIUMF UCN team in 2013.

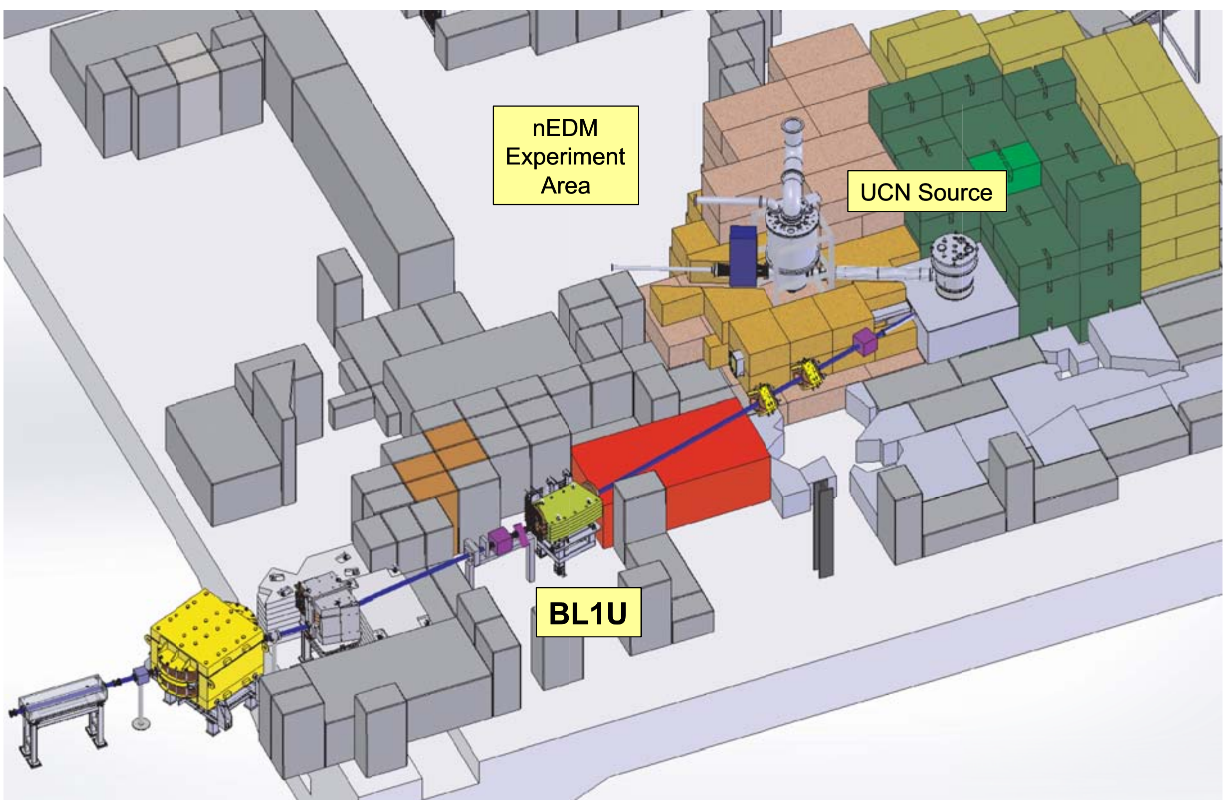


Figure 3: Layout of UCN facility.

In Japan, an international review held in December 2012 chose the UCN/neutron EDM project at TRIUMF as the main neutron EDM project for the KEK Institute of Particle and Nuclear Studies (KEK-IPNS), leading to additional support for the project from KEK-IPNS, including a new assistant professor position for UCN. In spring 2013, the Research Center for Nuclear Physics (RCNP) in Osaka, where the initial test of the UCN apparatus is taking place, also approved additional funding for the neutron EDM experiment as an RCNP project. In the beginning of July, a milestone was reached with the cooling the new UCN source to below 0.8 K, paving the way for a UCN production test to start in the fall of 2013.

To support this effort, approximately $2 million is needed through the NRC Contribution Agreement to upgrade the LHe liquefier and beam line magnet power supplies, acquire He-3, create an additional UCN port, and install shielding for higher intensity operation. A total of 21 FTE-years of TRIUMF engineering, design and technical support for the completion and upgrade of the UCN facility, as well as data acquisition and beam line operations support, is also needed. A $3.5 million request to CFI or NSERC for magnetic shielding and a LD_2 moderator upgrade is expected, along with a $500,000/year operating grant application to NSERC.

Enabling the full capacity of the UCN facility is critical to achieve the goals in section *6.2.2.1 Precision Measurements of Standard Model Processes*, in particular the measurement of the neutron EDM.

6.3.2.4 BEAM LINE 1A AND MESON CHANNELS

Beam line 1A (BL1A) delivers protons at 480 to 500 MeV with currents of 100-140 μA into the Meson Hall and serves a multitude of scientific programs:

- 4.2 MeV surface muons mostly for the μSR program at M15 (from target T1) and the newly installed muon channels M9A, M20 (from T2) with their worldwide unique muons on demand capability.
- Energetic μ^+ and μ^- for μSR and other muon experiments at M9B (from T2). M9B is a worldwide unique channel that enables μSR experiments in extreme environments, such as high-pressure, which has substantial scientific potential for chemistry studies related to Generation IV reactors, battery materials, etc.
- Beams of electron, pions, and muons for detector testing and development at M11 (from T1), which is important for projects like the ATLAS detector upgrades, T2K/HyperK as well as Belle II.
- Neutrons for irradiation studies of electronic devices at TNF.
- Neutron production at UCN via the new beam line branch BL1U (replacing M13).

Simultaneous operation of all of these from one proton beam makes BL1A highly productive; however BL1A is now 40 years old, and as a result of intensive operations and deferred maintenance over the past 10 years various problems are arising, both directly at the beam line, such as vacuum leaks of the beam line, leaks in the target and magnet water cooling systems, magnet coils shorting (ground faults), and cooling problems, as well as in the supporting systems, such as DC power supplies, vacuum pumps, controls, and diagnostics. It is therefore essential to develop and start a maintenance program for this aging infrastructure.

M9 is currently disconnected from T2 due to the inability to make a reliable vacuum seal. The quadrupole doublet M9:Q1-Q2 has been removed. The root cause is movement driven by an expanding concrete block pushing M9 to the west.

While removal and replacement of the T2 target monument and the M9 and M20 front ends are likely too costly, TRIUMF is evaluating alternative options that can be implemented step by step, thus allowing for more or less continuous science exploitation. One such option may consist of rebuilding the M9 front end with non-active quadrupoles, mounted on new poured-in-place concrete. In this scenario, the cause of the M9 shift would not be removed, and the current indium sealing technology would be used. A new radiation resistant Q1 could be shorter to make more space available at the T2-M9 seal to ease remote handling and to build in some flexibility to follow any further movement of the M9 front end. This fix will be applied as soon as reasonably feasible, to allow the use of the M9A and M9B meson channels for the CMMS science program. This would provide sufficient time to carry out, in the first years of Five-Year Plan 2015–2020, a detailed engineering study and prototype any more involved future refurbishment activities, including, for example, changes to remote handling concepts and new vacuum seal technology. About $2 million has been allocated in the proposed budget for this engineering study.

On the experiment side, there are plans to equip the M9A beam line with a dedicated μSR spectrometer that will allow for high-throughput characterization of magnetic and superconducting samples. Also, a new high-field μSR spectrometer is being developed with improved magnetic field homogeneity and solid-state detectors, which have improved performance and lower cost. This will be invaluable for characterizing the mixed state of Type-II superconductors.

The engineering study on BL1A and the activities to improve the capability of the μSR spectrometers are important to achieve the goals of Section 6.2.3.2 *Molecular and Materials Science Using μSR and β−NMR.*

6.3.3 INSTITUTE FOR ACCELERATOR-BASED MEDICAL ISOTOPES (IAMI)

TRIUMF's historical basis in Vancouver, BC, has generated the ingredients for a regional centre of excellence that would catapult Vancouver from the significant but presently separated capabilities to "Isotope Valley," a local network of accelerator-based science, technology, innovation, and commercialization. A regional centre is motivated not only by the synergies that arise by housing the multiple disciplines and sectors of nuclear medicine under one roof, but also by the advantages of sharing resources and centralizing managing the reliable production of isotopes and radiotracers for clinical research and commercial transactions.

Nordion, Inc. based a major element of its isotope manufacturing and distribution plant at TRIUMF 35 years ago because of the laboratory's technical and operating expertise. Ebco Industries, Inc. in Richmond, BC, helped build TRIUMF's main cyclotron in the 1970s and then commercialized a TRIUMF-inspired design for compact (TR-series) medical cyclotrons via Advanced Cyclotron Systems, Inc., in the 1980s. The UBC PET program and the Pacific Parkinson's Research Centre leveraged TRIUMF expertise in isotope production and PET/CT imaging technologies to establish world-leading research programs over the past 20 years. Over the past 15 years, the BC Cancer Agency built on TRIUMF's accelerator and isotope expertise to establish its own Centre for Functional Cancer Imaging and now owns and operates its own cyclotron in central Vancouver to serve the cancer patients of BC.

More recently, the BC Preclinical Research Consortium (BC PRC), the Centre for Drug Research and Development, and the Centre for Comparative Medicine have been established in the Vancouver region. With different specific intentions, these "end-user" biology-and-health organizations are focused on promoting and developing a network of skills, resources, and capabilities than can provide easy access, central planning, and efficient user experiences for everything from drug discovery and development to studying the structure and evolution of disease.
The tools of medical isotopes, via molecular imaging, could make an enormous difference for this growing cluster. Five-Year Plan 2015–2020 proposes to capitalize on this opportunity with the creation of a regional centre of excellence called the Institute for Accelerator-Based Medical Isotopes (IAMI).

Isotopes from accelerators are a growing part of society and have become a mainstay in many different fields of research. With isotopes, molecular imaging is inherently interdisciplinary and transdisciplinary. It requires intensive collaboration from teams of researchers in the areas of molecular biology,

SNMMI RECOGNIZES TOP TALENT AT TRIUMF

07 May 2013

Two young TRIUMF professionals, Eric Price and Hua Yang, have been recognized by the Society of Nuclear Medicine and Molecular Imaging (SNMMI). They represent the extraordinary success and talent behind TRIUMF's Nuclear Medicine Program.

Eric Price, UBC Chemistry and TRIUMF graduate student, won the prestigious SNMMI Berson-Yalow Award 2013 for his abstract which describes a new way to incorporate radiometals into antibodies and other biological agents. It will be published in the Abstract Book Supplement to the Journal of Nuclear Medicine, June issue.

Hua Yang, an R&D support chemist at TRIUMF is the recipient of the 2nd place "Best Science" award from the SNMMI Young Professionals Committee. Yang's area of research is in radiotracers with a focus on oxidative stress imaging. She was recognized for her abstract titled "Development of F-18 labelled aminosuberic acid derivatives for in vivo analysis of cystine transporter expression and oxidative stress".

The SNMMI YPC award is a young professional award that recognizes the best research-based presentation on basic science or clinical topics.

radiochemistry, cyclotron target design, medical imaging, preclinical testing, pharmacokinetics, radiation dosimetry, and pilot clinical trials. As this cannot be competitively achieved at any one facility in Canada, a regional network is the only way to accomplish the goal of benefiting Canada's healthcare system.

One specific opportunity is related to the relocation of the UBC Centre for Comparative Medicine across the street from TRIUMF. An imaging centre is being constructed there and will be coupled to the TRIUMF isotope production facilities by a short delivery pipeline enabling unique pre-clinical research using short-lived radiotracers. This imaging facility will enable the preclinical assessment of newly developed tracers, providing critical early information on their potential to be developed further for clinical use. This facility is anticipated to be fully operational during the 2015-2020 period and support personnel will need to be hired in time for start-up. Working through the BC PRC, two different drug-development companies have approached TRIUMF in the last month requesting C-11-based radiotracers to assist their benchmarking studies of pharmokinetics and drug action. The physics of creating the isotopes and the chemistry of synthesizing the tracer would happen at TRIUMF and the biological analysis would take place at the CCM using an imaging suite led by an investigator in the UBC Department of Physics and Astronomy.

The Nuclear Medicine Program and the associated infrastructures at TRIUMF are currently undergoing a substantial upgrade, a portion of which includes a newly refurbished laboratory, partly financed by Nordion, Inc. Nordion's support is a testament to the value this long-standing private-sector partner sees in TRIUMF. It is important to note that the research carried out by the Nuclear Medicine Division will continue to be accomplished using peer-reviewed funding from various agencies. These efforts will be supported through funding provided by agencies such as the Canadian Institute for Health Research (CIHR), the Natural Sciences and Engineering Research Council (NSERC), Genome BC, Western Economic Diversification of Canada (WD), and others.

IAMI will allow TRIUMF to continue redefining state-of-the-art cyclotron technology, isotope production, the extraction and manipulation of radioisotopes, GMP-compliant radiopharmaceutical production, and other applications. To do so, the program will require sufficient resources to support a core complement of operational staff for operations (TR-13, GMP-lab/clean room) and safety (Quality Assurance, Quality Control of radiopharmaceuticals), while having the capacity to support the research efforts of our partners in state-of-the-art isotope research facilities. This includes space for researchers, engineers, and other skilled individuals to work together to achieve the scientific goals established through the program and associated peer-reviewed funding. By bringing multiple disciplines together, the institute will foster scientific excellence by enhancing BC (and Canada) as a world-leading location for isotope-based research.

Formalizing the TRIUMF isotope production and radiopharmaceutical effort into an institute will serve to unify TRIUMF and its partners in the PPRC and BCCA and elevate all programs to the national and international stage.

At the heart of the new institute will be a new 24 MeV TR-24 cyclotron (see Figure 1), funded through additional external agencies, to replace TRIUMF's TR-13 as the workhorse cyclotron for the division. For more than 20 years, the TR-13 cyclotron has been the heart of the TRIUMF Nuclear Medicine Program. This machine is aging and, given the growing demands for isotope production, a replacement cyclotron will be required in the near future. In addition, the maximum allowed energy (13 MeV) and beam current of the proton beam have long been dictated by the location of the cyclotron being in an open area of TRIUMF's Meson Hall, setting limits to the amounts of isotopes that can be produced with it. In order to continue delivering on our existing commitments, and at the same time grow the program, a replacement cyclotron with higher energy and beam current, has to be placed inside an appropriate shielded environment. This machine will need to be housed in a vault with close proximity to the radiochemistry facilities.

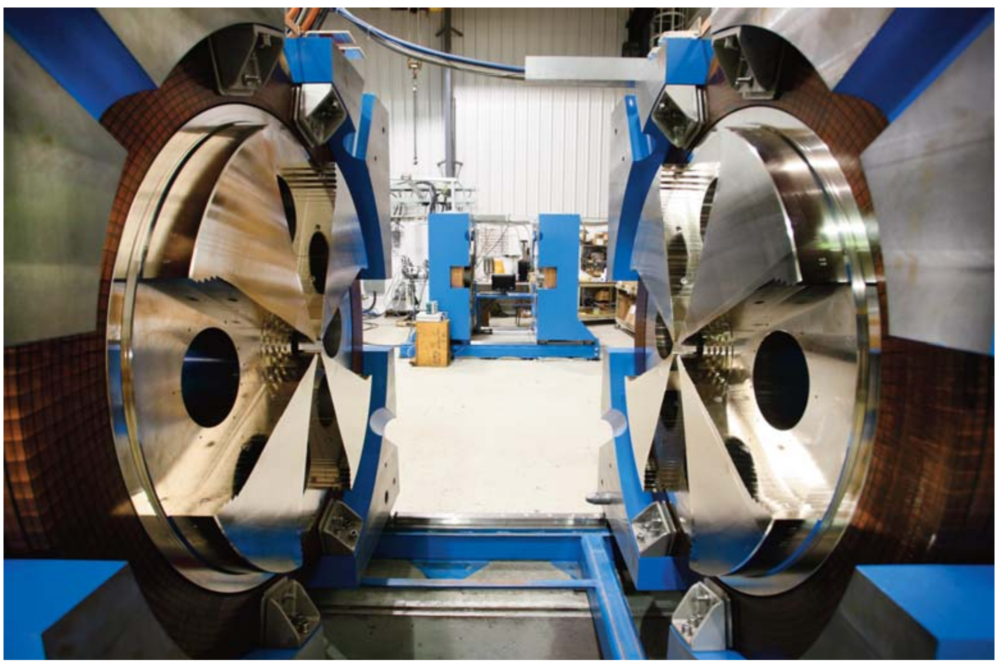


Figure 1: Modern TR24 cyclotron manufactured by ACSI, Inc.

With a modern cyclotron and operational support IAMI will:

1. Enable the reliable commercial-scale production of Tc-99m for all of BC and serve to stabilize the supply for all medical isotopes used in the province;
2. Support part-time commercial operation to produce other related medical isotopes;
3. Support an expanded radioisotope and radiopharmaceutical research program in line with the program goals discussed above; and
4. Facilitate interactions with the remaining molecular imaging programs in Canada, allowing for participation in efforts such as the CIHR-funded MITNEC (Medical Imaging Trial Network of Canada) and the MINet (Medical Imaging Network) proposal in the framework of the Networks of Centres of Excellence of Canada program.

The IAMI program would encompass:

- Accelerator Research: cyclotrons, e-linac, target science;
- Isotope Research: nuclear chemistry, hot atom chemistry, radiochemistry, radiopharmaceutical chemistry;
- Applications: Researcher-based investigations into novel imaging and systems;
- Research Translation: Opportunistic, facilitate private sector, academic interaction;
- Knowledge Transfer: Facilitate research dissemination, technology accessibility; and
- Training: Provide the Canadian and international community with world-class highly qualified personnel in the cyclotron and isotope sciences.

At the core of the IAMI is a new TR-24 medical cyclotron, for which TRIUMF and its partners are currently seeking funding outside the NRC contribution agreement ($3-5 million based on a cost-sharing model among multiple partners that would repurpose significant existing infrastructure at the TRIUMF/Nordion interface). The proposed budget includes funds for an additional 2 FTE for cyclotron operation, radiochemistry, and quality assurance. To summarize, the TR-24 and funding for the IAMI are will enhance the capacity, capabilities, and compliance of the TRIUMF Nuclear Medicine effort. A higher current, variable energy machine when coupled to the requested operational support will give TRIUMF and its partners access to a larger repertoire of isotopes, enabling a broader effort and larger impact. The Institute will provide essential staffing and expertise to promptly follow fast changing regulatory demands by Health Canada for radiopharmaceutical production, which is in particular important in view of the larger set of radiotracers being produced.

In summary, the Institute for Accelerator-Based Medical-Isotopes is critical to achieve the goals of sections *6.2.1.5 Isotopes for Molecular Imaging of Diseases and Treatment of Cancer* and *6.2.3.3 Advancing Isotope-Production Technologies with Accelerators.*

6.3.4 PERSONNEL AND STAFFING

As a resource for Canadian science and innovation, TRIUMF provides highly trained and specialized talent and advanced technical and engineering equipment and facilities. It is no surprise, then, that much of the support for TRIUMF is directed toward salaries and wages for permanent, temporary, and contract staff. (Please see Section 5.2 for a characterization of the skills mix of TRIUMF's core and continuing staff.)

By the completion of Five-Year Plan 2010–2015, about 70% of the funding provided through the NRC Contribution Agreement will have been applied to TRIUMF's (fully loaded) salary budget, funding around 305 people in 2015. Current estimates show that an additional $3.4M/year from other sources will have been used by TRIUMF to cover additional personnel needed for carrying out its cutting-edge research program. (Staff associated with salary-recovered activities such as Nordion operations, AAPS technical consulting, TRIUMF House staff, and so on are not included.)

TRIUMF tracks staff effort through monthly timesheets that are electronically managed. Individuals report their time against the list of commitments. (Please see Section 5.9.4 for a discussion of TRIUMF's project management system and the commitment list.) This data provides powerful insights into how TRIUMF operates. On the highest level a distinction is being made between operational and project commitments.

Table 1 shows the long-term operational commitments of TRIUMF staff over the past three years. It should be noted that as a consequence of the limited funds available through the 2010-2015 NRC Contribution Agreement TRIUMF went through significant belt-tightening and efficiency gains with approximately 7% overall staff reduction (note that the 2012 operational manpower would be at 221.4 FTE without moving the 10 FTE janitorial staff to the salary budget with additional reductions for project commitments). Further staff reductions were made but in order to maintain critical core competencies several strategic hires were needed.

FTEs	Category	2010	2011	2012
Basic Services	Administration	44.4	41.7	39.0
	Infrastructure	38.6	37.9	49.5*
	Cost Centres	5.6	7.3	5.1
Accelerator Ops	Accelerator Operations	87.8	87.1	87.4
Research	Teaching and related	3.3	2.1	1.5
	Accelerator Research	0.0	1.6	3.7
	CMMS	1.3	1.7	2.2
	Particle Physics	11.6	11.4	10.1
	Nuclear Medicine	2.1	2.9	2.8
	Nuclear Physics	11.0	11.2	9.7
	Theory	8.8	10.0	10.7
Applied	AAPS	2.6	2.3	1.5
	Tech Transfer, Commercial	5.7	5.7	4.4
Other	Detector Development	2.4	2.4	2.6
	Electronics & Controls	4.1	1.0	1.2
Total FTEs		229.3	226.3	231.4

Table 1: History of TRIUMF operations staff in FTE. *Note that between FY2011 and FY2012, 10 FTE janitors were added to the salary budget; this service had been provided as a contract under materials and supplies in an earlier budget.

This section discusses several observations about TRIUMF's deployment of human resources and its impact in the proposed Five-Year Plan 2015–2020:

- To accomplish its full program of work, TRIUMF relies on multiple funding sources to support the required staff.
- TRIUMF staff are highly matrixed.
- Five-year salary support through the NRC Contribution Agreement is efficient and effective.
- Five-Year Plan 2015–2020 seeks to (a) keep TRIUMF's personnel compensation sufficiently competitive to attract and retain the needed mix of talent, and (b) transition a number of temporary staff positions to long-term core and continuing positions to fully exploit new capabilities coming online at the lab.

Multiple Sources of Salary Support

Individuals working at TRIUMF are supported through funds contributed by NRC (via the Contribution Agreement), NSERC grants and awards, Canada Foundation for Innovation awards (both infrastructure development awards and infrastructure operating funds awards), Natural Resources Canada (via contribution agreements from the NISP and ITAP programs), funding mechanisms with external institutions, and earned commercial revenues. (See Section 6.4.1 for additional details.) Figure 1 shows the relative proportions.

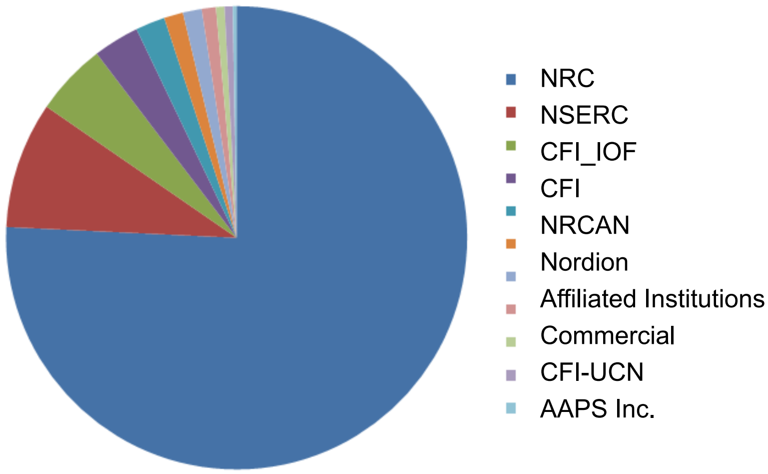


Figure 1: The proportion of TRIUMF staff supported by each funding source; this chart includes 403 FTEs. The data is for the first quarter of FY2013 and includes all staff paid though the TRIUMF payroll including post-doctoral researchers but excluding students and casual labour.

The partnership between agencies and patrons of TRIUMF is seamless. In the area of nuclear-medicine research, for instance, 3 FTE are supported through NRC-contributed funds and 4 FTEs are supported by Natural Resources Canada until March 2015 for work on the ITAP cyclotron-production of Tc-99m project. Elsewhere, NRC supports the salaries of 10 FTEs for the operations of nuclear-physics research facilities and NSERC supports the salaries of nearly 14 FTEs working in the same vein.

For 2013, the group of activities whose salaries were mostly supported by non-NRC-contributed activities were particle physics, nuclear physics, nuclear medicine, and materials science research.

Matrixing of Staff

Many individuals at TRIUMF split their time between working on core operations and contributing to new projects. Moreover, skills sets are sufficiently rare and sparsely distributed. In recent years, roughly 190 people spent 90% or more of their time purely on operations, including the commercial group that operates Nordion, Inc.'s cyclotrons. Only 36 people spent more than 90% of their time on projects. More than a hundred people split their time between 30% and 70% on operations and projects. Figure 2 shows a histogram of the number of commitments per person that TRIUMF staff contribute to over the course of FY2012.

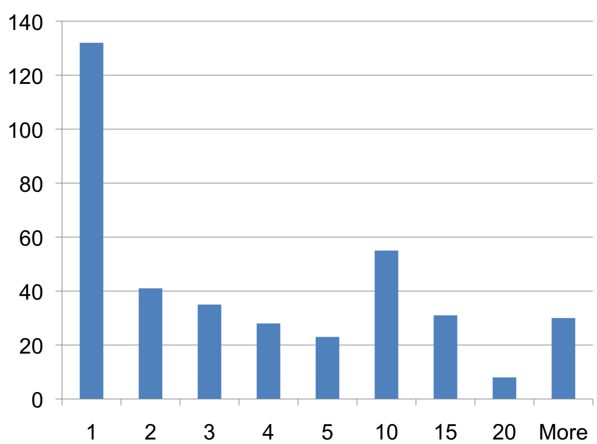


Figure 2: Histogram of number of staff working on different commitments accumulated over FY2012; the data includes commitments supported by NRC, CFI, and cost-recovery activities. The chart indicates that a majority of staff members are involved in multiple, distinct commitments every year.

Type of Salary Support

In the world of research and innovation, salary support is typically divided into "hard" and "soft" money. This distinction points to a somewhat arbitrary degree of permanency in a hired position. A salaried position supported by hard money means that the funds to support the fixed (and loaded) salary costs of that position are available for a substantial number of years in the future and are certain (to the degree that anything in the future is certain).

As indicated above, the TRIUMF program of work is actually delivered by a complement of staff supported by NRC "hard" monies (for up to five years at a time) and a network of short-term, focused "soft" monies. TRIUMF continues to experience some challenges in recruitment on both fronts; certain agencies are unwilling to invest in TRIUMF knowing that "in five years, the laboratory could be closed" and many talented individuals are uninterested in a five-year "grant-tenure" type position that has no long-term commitment with more security. In spite of this, TRIUMF has operated for 40+ years and continues to be effective in attracting some of the most talented individuals around the world (cf. Head of the Accelerator Division, recruited from a U.S. lab; Head of the Science Division, recruited from the most senior, most secure academic rank in Germany).

NRC-supported positions are the most secure that can be offered by TRIUMF, and as a result are a critical element in attracting and retaining the best people. As TRIUMF's service to Canada grows with the addition of ARIEL and new nuclear-medicine capabilities, the lab seeks to deploy more NRC-based funds to guarantee salary support for a minimum of up to five years at a time for the best people.

The NRC funding also provides the stability needed to develop and maintain the specialized expertise required for cutting edge scientific experiments. This expertise is frequently not available on the open market but must be developed and maintained in house. The core NRC funding can support this expertise on an ongoing basis and make it available to different projects as it is needed. Cost of resources utilized outside of its NRC funded purpose will be recovered.

Five-Year Plan 2015–2020

Five-Year Plan 2010–2015 has a tight profile for adjustments to salaries for TRIUMF personnel. On the NRC-contributed budget, salary adjustments have been 0%, 1%, 1%, 1.5%, and 1.5% for each of the sequential years in the five-year period. The highly constraint budget only allowed for limited amounts of additional merit bonus payments and few selected merit based salary increases and promotions. During the first few years of Five-Year Plan 2010-2015 in which the salary increases were very restricted, TRIUMF allocated funds to address a small number of internal salary inequities and pay anomalies, as well as to make strategic pay adjustments for emerging leaders within the lab.

The annual salary budget increases have been very constrained during the current five-year plan, ranging from 0 to 1.5%; employees changing jobs or companies expect raises of 2 to 4 percent, and thus the starting salaries of new hires can exceed that of current incumbents. TRIUMF needs to address salary compression and retention. Salary compression beyond our current five-year plan is not sustainable if we are to retain talent. The observation that university salaries exceed TRIUMF compensation has been recognized by TRIUMF's Board of Management as an issue to be resolved.

To attract and retain the highly competent staff needed for its program, TRIUMF seeks a salary profile for 2015–2020 that accommodates merit-based increases, promotions, and modest economic adjustments totalling 2% per year, starting from the current salary base. TRIUMF's program is attracting some of the top talent in the world, however, it must also pay competitively to be successful in hiring and retaining that talent.

As additional facilities at TRIUMF come online in the 2015–2020 era (e.g., ARIEL e-linac for isotope production and accelerator physics), and the operational responsibility moves from CFI to TRIUMF for other new facilities (e.g., M20 for materials science, ATLAS Tier-1 Data Centre for particle physics), the laboratory seeks a shift from "design & construct" funding to "commission & operate" funding to extract the promised science for Canada. Because different agencies support staff at TRIUMF for different purposes, this evolution suggests an overall constant operating envelope with a shift to increased NRC-contributed salaries.

Specifically, Five-Year Plan 2015–2020 proposes the following:

- NRC-supported staff engaged in operating present TRIUMF facilities (cyclotron, ISAC, Meson Hall science, detector-development facilities, machine shop and design office capabilities) will continue to support the Canadian research community in domestic and international projects at the same level;
- The scientists, engineers, and technicians presently engaged in designing and building ARIEL Phase I will continue to be available to design and build ARIEL completion (target stations, beam-delivery infrastructure, proton beam line, and high-power e-linac); that is, TRIUMF staff supported by NRC-contributed funds would provide the bulk of labour required for the ARIEL completion CFI proposal;
- Project staff presently completing the design and building of detector facilities in ISAC and M9 and M20 in the Meson Hall as well as SNO+ and DEAP at SNOLAB will transition to supporting ARIEL operations and exploiting science; others will pick up the task of designing, assembling, and commissioning the Ultra-Cold Neutron facility;
- A handful of strategic hires will secure the nuclear-medicine program's research and innovation capabilities within IAMI, add capacity to TRIUMF's ability to partner with AAPS, Inc. and other Canadian businesses, and enhance Canadian university involvement in TRIUMF through joint faculty appointments of fixed term; and
- CFI-supported staff operating the ATLAS Tier-1 Data Centre will move to NRC-contributed salary support.

The bottom line is that TRIUMF would shift the number of core and continuing staff supported by the NRC-contribution salary budget from 305 to 340. Note that this is not a growth in the program but a shift in the basis for its support. Table 1 below indicates the manpower needed to fulfill TRIUMF's vision described above and support all the ambitions of the Canadian university community through TRIUMF's unique infrastructure and skilled personnel.

The request for the NRC contribution agreement includes funding for staff at the 340 FTE level. It is expected that demands beyond this level will be supported through project funds, e.g., through CFI projects, or resources will have to be used selectively for the highest priority demands.

FTEs	FY2015	FY2016	FY2017	FY2018	FY2019
Current operations	230	230	230	230	230
ARIEL operations	30	35	45	50	50
ATLAS Tier-1	9	9	9	9	9
IAMI	6	6	6	6	6
ARIEL Completion	50	55	50	45	45
Science Projects	35	25	25	25	25
Total FTEs	360	360	365	365	365

Table 1:. Workforce in FTEs needed for different aspects of the TRIUMF program.

In addition to this core staff, TRIUMF intends to make a handful of strategic hires in the context of the planned program enhancements. As already mentioned above, 2 FTE will be needed for cyclotron operation, radiochemistry, and quality assurance in support of the Institute for Accelerator-Based Medical-Isotopes. We also intend to add 2-3 staff to expand TRIUMF's activities in developing new industrial partnerships and exploiting new opportunities for technology transfer to Canadian companies. Finally 2-3 half-time positions would be used to strengthen the Canadian scientific community through several strategically placed joint faculty positions.

6.3.5 DEFERRED MAINTENANCE STRATEGY

The TRIUMF site contains hundreds of thousands of square feet of laboratory and technical space including eight different particle accelerators and dozens of scientific experiments and detectors along with significant supporting infrastructure for electrical power, cooling, specialty gases, vacuum, computers and networking, and so on. Some of these foundational elements have been operating for decades and have aged significantly.

In constrained funding environments, TRIUMF has historically deferred large-value maintenance activities or regular replacement strategies in favour of maintaining operations and extracting high-quality science. The lab is now approaching 45 years old (the main cyclotron will have been running for 40 years in 2014) and key elements need urgent attention. Canada's continued leadership in subatomic physics is in jeopardy as the risk of failure of core components at TRIUMF escalates.

This section discusses the inventory of deferred maintenance issues and outlines relative priorities for addressing them as part of Five-Year Plan 2015–2020.

Reviewing TRIUMF's highest operational risks, the following areas are those that can be dramatically and reasonably mitigated by structured spending of capital and maintenance budgets over the next five years.

Maintaining cyclotron performance and reliability

A majority of TRIUMF's research relies on the smooth and steady performance of the main cyclotron. Several systems associated with the cyclotron are past due for repairs or replacement.

Main magnet power supply (valued at $1 million): The power supply for the main magnet of the cyclotron is nearly four decades old and is at risk of system failure. Replacement parts are no longer available and a full replacement system would take 6-9 months for procurement and installation. Modern power-supply systems would offer several enhanced features including greater energy efficiencies. To reduce the risk of unacceptable downtime, TRIUMF would purchase a power-supply system for $1 million and install the new system during a shutdown period.

Refurbishment of cyclotron controls and systems (valued at $2 million): As part of a decade-long refurbishment program for the cyclotron, TRIUMF uses its annual shutdown to replace and update a portion of the main cyclotron and replace ageing and obsolete equipment. The replacement and upgrade of these systems also enhances the performance of the cyclotron by increasing stability at high-intensities (required for running ISAC and BL4N within ARIEL). These systems include:

- Complete vault re-cabling program (including BL1A tunnel)
- New 4-unit solid state power amplifiers (IPA)
- Switchable 3 power amplifiers for RF operation
- Transfer-line matching section upgrade
- 1.5 MW dummy load
- RF booster solid state driver

- TRIMAC controllers replacement with programmable logic circuits
- Cyclotron tank vacuum control system upgrade
- New cyclotron cryopumps
- BL1 Beam Profile Monitors implementation
- Centre region diagnostics upgrade
- Diagnostics electronics upgrade
- New operating ion source in I2 (I1 will be hot spare)
- ISIS vertical injection beamline buncher
- ISIS horizontal section upgrade
- Filament-less H- ion source development
- Tank thermocouples refurbishing
- RF system high power upgrade
- Nitrogen cryogenic refrigerator

The upgrade of the major systems of the main cyclotron will involve partnership with universities, industries and other labs. This will foster knowledge base development and technology transfer to other institutions and industries.

Site-wide services and utilities

TRIUMF's research program relies on a network of common utilities including power and water that are distributed across the site from a central distribution centre that connects with the UBC "municipal" grid. The site-wide high-voltage transformer needs upgrading as does the network of site-wide mechanical (HVAC, water) systems.

Site-wide electrical transformer: The present TRIUMF electrical grid is about 42 years old. It has two main nodes, T-1 and T-2 each fed by a 12 MVA, 60 kV-12.47 kV transformer, that operate at different voltages. The T-1 node operating at 11.6 kV (node 1) supplies the Cyclotron Main Magnet and the RF system; the T-2 node at 12.47 kV (node 2) supplies the rest of the site and a number of UBC South Campus activities.

Node T-1 is loaded about 30% (4 MVA) while node T-2 is loaded approximately 67% (8 MVA). The future demand of the e-linac and ARIEL alone on node T-2 is estimated to add a peak of 5 MVA at regime around 2018, which will exceed its capacity. The present substation transformers have been in operation for more than 40 years at relatively small loading. Loading to capacity one of the two units is not advisable given the age of the equipment.

The proposed scope of work would include:

1. Engineering consultants services
2. Replacement of both T-MM and T-RF transformers with ones that allow compatible operation with the node T-1 transformer at 12.47 kV
3. Upgrade of the 12.47 kV switchgear and re-distribution of loads among T-1 and T-2; and
4. Upgrade of the TRIUMF load-monitoring and fault-protection systems.

This need stems from the requirement to free up capacity from the T-1 node to use for ARIEL and other future loads as well as easing the loading of ageing transformers by re-allocating some of the T-2 loads to T-1. The project will also address a lack of redundancy concern: if either T-1 or T-2 fails there is no redundancy in the present system. Under the proposed upgrade it will be possible to operate either the e-linac or the cyclotron and associated experimental programs with one substation transformer and possibly both if the peak operating demand will be within the capacity of either T-1 or T-2 until the failed one is repaired or replaced. Preliminary estimates from the local utilities suggest $1M of capital would be required for the chief elements of this work package.

Mechanical systems upgrade (valued at $0.5 million): HVAC systems in several of the TRIUMF buildings are failing and relatively low efficiency systems are getting worse. Similarly, cooling-water systems including pumps, piping, and interconnects (e.g., purification, heat exchangers) have been running without interruption for decades. Key elements of these non-glamorous mechanical systems need replacement in order to maintain high performance of TRIUMF's research infrastructure.

Upkeep and refurbishment of specific infrastructure: In addition to operating risks associated with the cyclotron and site-wide mechanical systems, leaks in the roof of the Accelerator Building present a hazard and a risk. TRIUMF's Machine Shop also requires regular equipment upgrade and/or replacement to stay relevant and effective.

Accelerator Building roof: The Accelerator Building at TRIUMF not only houses the main cyclotron and the e-linac, it is the oldest experimental area on the site, dating back to the early 1970s. Research activities in this building now include treatment of ocular melanoma, production of medical isotopes, study of advanced materials with muon beams, irradiation of aerospace and computing systems for industry, and provision of probe beams for detector development and certification. The roof on this facility needs replacement; it routinely leaks water and debris onto the experimental areas and serves as a steady nuisance for scientists and students working in the lab space. The area to be re-roofed is approximately 45,000 sq ft. The scope of work was quoted at $800k in 2008 and would cost about $1M in today's pricing.

Machine Shop and Design Office Upkeep: TRIUMF's Machine Shop and Design Office are in high demand by the Canadian research community; both facilities experience backlogs of work that can range up to a year or more. (Please see section 5.9.4 on project management to learn more about priorities and work-queue management.) In order to maintain relevance and high productivity, roughly one machine tool at the Shop should be replaced each year (about $100k). Likewise, design and engineering software in the Design Office undergoes a major upgrade and licensing-fee renewal at least once every five years. Keeping these two activities at high functioning level is a priority and would require about $500k.

Beam Line 1A: This beam from the main cyclotron is the oldest at TRIUMF and drives beams for proton therapy, PIF & NIF irradiation testing, medical-isotope production, and the muon program for materials science. It is starting to fail due to long-term use and suspected movement of the concrete pad on which one of the production targets is mounted. During 2015–2020, TRIUMF will undertake a detailed engineering study to assess the systemic weaknesses and develop a mitigation and repair plan, including reliable cost estimates, that modernizes the infrastructure. This activity would cost $2 million.

This set of large-ticket maintenance items is consistent with the program of maintaining and operating the overall TRIUMF laboratory and are therefore considered priority items for the NRC-contributed operating funds. In the event of insufficient resources for Five-Year Plan 2015-2020, the items would be handled in priority order: the cyclotron and site-wide transformer are the most critical and most important and would be addressed at some level in all scenarios. Mechanical-system upgrades and Meson Hall roofing would be deferred to a subsequent Five-Year Plan, as would maintenance and upkeep of the Machine Shop and Design Office equipment.

Expanded technical and administrative space

The TRIUMF site is densely packed with buildings, underground infrastructure, and support facilities. The on-site accelerators are sophisticated and often require elaborate systems to support them on a crowded piece of real estate. For instance, the ARIEL project includes not only the main isotope-production building but also a helium-compressor building and the underground Electron Hall to house the e-linac and an underground tunnel to connect the accelerators to the target areas. In fact, the main ARIEL building was sited on top of an existing facility at TRIUMF that handled shipping, receiving, and small-supplies stores. The facility was demolished and rebuilt at the edge of the TRIUMF site in order to make room for ARIEL.

The laboratory has a need for new technical space and administrative offices. A network of ageing trailers house technicians and engineers, scientific visitors, and students outside of a limited number of offices in the Main Office Building and ISAC complexes. UBC's occupational health inspections have indicated that many of the trailers are unhealthy work environments.

The Institute for Accelerator-based Medical Isotopes (please see Section 6.3.3) will include a modern medical cyclotron at TRIUMF. This device will require a shielded vault and supporting technical space to house control systems and power supplies. There is one favoured location at TRIUMF that already includes some of these services, but it would require decommissioning and refurbishment along with access agreements. As the ATLAS Tier-1 Data Centre expands its disk and tape storage capacity for the new volumes of data, it too will require additional floor space. Other projects are also placing increasing demands on the limited amount of technical, serviced laboratory space at TRIUMF.

Maintaining reliable ISAC performance and enhancing reliable operations: The ISAC facility was built nearly 14 years ago and the beam delivery systems exposed to the highest levels of radiation are showing signs of ageing. During the period 2010-2015 two target modules (TM1, TM3were refurbished as part of an upgrade and refurbishment program that has improved beam delivery reliability. Since ISAC will still carry most of TRIUMF's rare isotope program during the period 2015-2020, it is important to establish a continuous refurbishment program for target modules. As an example, further refurbishments of target modules are essential to continue reliable beam delivery, such as a complete reconstruction of the service cap, service tray, source tray and the containment box for TM2. Adding remote quick connection/disconnection mechanism for the target and ion source services will substantially reduce the turn-around time for target changes on the current ISAC facility, by eliminating the long cool-down periods currently required for a technician to make the connections by hand. A second hot cell (the North Hot Cell) will reduce dependence on a single hot cell for both routine target exchanges and radioactive repair or refurbishment jobs. The combination of these systems, together with the newly installed and operating conditioning station, will allow us to reduce the target exchange cycle from weeks to days, and further increase the reliability of the RIB production. The ISAC refurbishment program will cost $2.5M.

TRIUMF seeks to address these issues in Five-Year Plan 2015-2020. These types of unglamourous but crucial refurbishments and upgrades would be candidates for use of commercial revenue funds if available.

6.4 VALUE FOR CANADA

Support for science is driven by three considerations: advancing knowledge, creating future leaders, and generating societal and economic benefit. In Five-Year Plan 2015–2010, TRIUMF proposes to advance all three. Naturally, the impact will be determined, in part, by funding decisions. This section outlines the results that would be realized under a constrained but balanced scenario.

6.4.1 KEY OUTPUTS AND OUTCOMES

TRIUMF's program for 2015–2020 is driven primarily by the ARIEL project and its transition to full operation, full exploitation of cyclotron-based research for subatomic physics and materials science, and creating a platform for nuclear medicine excellence. The outcomes of these efforts are detailed here.

Advancing Knowledge

The simplest measures of knowledge advancement are scientific publications and international prizes or recognition. Invited presentations at prestigious conferences also denote a measure of accomplishment but are harder to measure and project.

TRIUMF's research program supported more than 900 peer-reviewed scientific publications in 2003–2007, and nearly 1,300 from 2008–2012 inclusive. With the high productivity of the various particle-physics experiments as well as increasing publication numbers from the RIB, CMMS, and Nuclear Medicine programs TRIUMF's publication will grow to more than 1,500 papers for the next five years (2013–2018). With the advent of ARIEL's capabilities to supply additional isotopes simultaneously with the existing proton-based ISAC targets, it is projected that TRIUMF's publication impact will expand even further. However these new capabilities will only come online in 2017 and will show most of their impact in the subsequent five-year period.

As measured by the Science Metrix advanced bibliometric study, TRIUMF is directly involved as a contributing author in about 15% of Canada's subatomic physics publications (more than 16,000 papers during 1996–2010, including conference papers). During 2015–2020, this situation will improve slightly such that TRIUMF is involved as a contributing author in 20% of Canada's subatomic physics publications.

One of the key research thrusts enabled by TRIUMF is in the area of fundamental symmetries and physics beyond the SM. With a set of investigations into electric dipole moments of the neutron, atom and electron, TRIUMF is ideally positioned to play a seminal role in this discovery science.

Creating Future Leaders

In terms of attracting, retaining, and circulating talent, TRIUMF measures the number of students to which it provides direct research experiences and the overall participation in its informal science education activities.

In the 2015–2020 plan, TRIUMF will continue to expand its engagement with young people as well as the science-interested public. During the 2008–2012 cycle, TRIUMF offered direct research experiences to more than 575 high school, undergraduate, and graduate students. For the next five-year cycle, TRIUMF projects that additional graduate students from overseas will come to Canada to participate in world-leading explorations with ISAC and ARIEL. The total number of research experiences offered to students will therefore increase to more than 675 for the 2015–2020 period. In addition, TRIUMF hosted the

2013 inaugural of the Tri-Institute School on Elementary Particles (TRISEP) for graduate students initiated jointly with SNOLAB and the Perimeter Institute; in 2014 TRIUMF will host the International Accelerator School for Linear Colliders for the first time in Canada for graduate students from around the world.

In the 2015–2020 plan, TRIUMF will seek continued expansion of the reach of its informal science education activities. The lab will reach more than 35,000 people through direct tours of the laboratory, community events, and public science lectures such as the *Unveiling the Universe* series with the Telus World of Science..

Generating Societal & Economic Benefits

As discussed in Section 4.4, powerful models of "mechanism" for the economic impact of scientific research are still in the development stage. As measured by "Return on Investment in Large Scale Research Infrastructure," by Hickling Arthurs Low (HAL), TRIUMF has unambiguously contributed $941 million to the GDP of Canada for a public investment of $552 million.

A five-year economic impact analysis is short compared to the inherently long timescale for direct economic payoffs from basic science research. Nevertheless, TRIUMF projects that its decadal economic impact from 2010-2020, computed according to the rules of the HAL study, will increase. With the advent of ARIEL, the development of self-sustaining technology development capabilities at AAPS, and the success of current industrial partnerships based on isotopes and accelerators, TRIUMF projects that its economic impact 2013–2022 will increase by $50 million per year, adding a $500 million impact for the coming decade.

TRIUMF will continue to enhance the health and vitality of Canadians through the provision of proton therapy for ocular melanoma and the production and distribution of medical isotopes for BC Cancer Agency and the brain-research programs at UBC. Deployment of cyclotron-based production of Tc-99m will also improve the security of this vital ingredient in modern medical imaging for Canadian patients.

UBC and TRIUMF are exploring pathways for recovering the redirected heat energy from TRIUMF's accelerator complex (generated by cooling the magnets and power supplies) to a neighbourhood district energy system for the nearby on-campus residents and local businesses. Figure 1 illustrates the approach. UBC is presently in a Request for Information phase with several potential vendors. When successful, this system will be the first in North America to repurpose heat energy from a research complex using accelerators, and would save 13,000 tonnes of greenhouse gases each year.

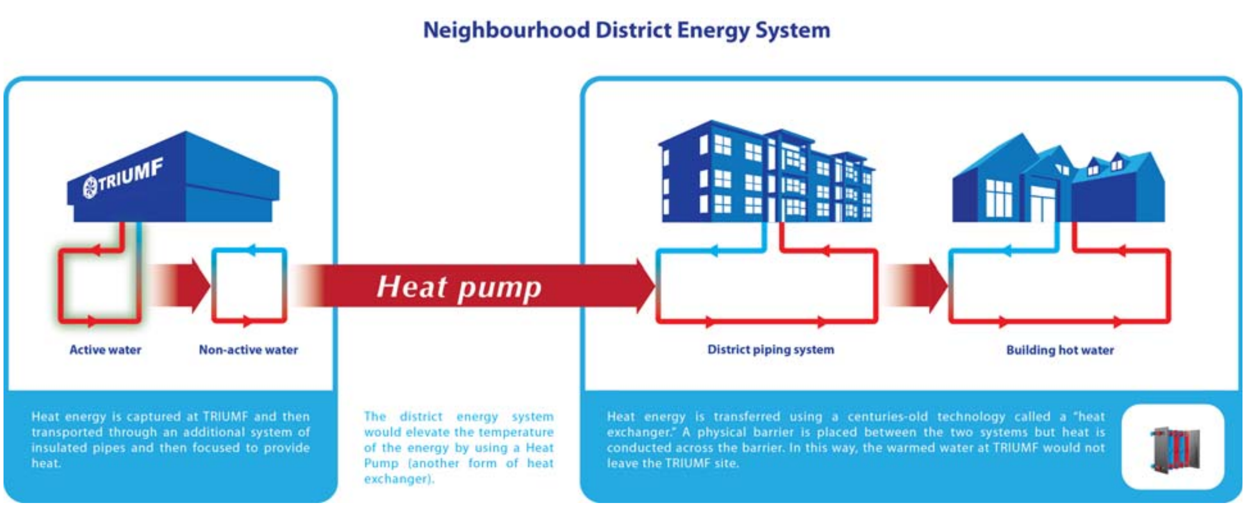


Figure 1: Schematic of Neighbourhood District Energy System involving TRIUMF and UBC.

6.4.2 INTERNATIONAL CONTEXT

The 2015–2020 plan for TRIUMF will ensure international competitiveness for Canadian science, keeping Canada at the forefront of innovation and research. In this section, projections about the international competitiveness of Canadian capabilities based on TRIUMF's proposed plan are discussed.

Particle Physics

Particle physics is the study of the most fundamental building blocks of nature and their interactions. Our current understanding could only be obtained with the results from experiments conducted at the highest energies, the most intense beams, and detectors placed in the deepest mines. Experimental collaborations are usually large and often international in scale, and a healthy national particle physics program balances local, regional and global efforts.

TRIUMF is not only fully engaged in major data-analysis efforts, it also plays a central role in Canada's particle-physics infrastructure and is the go-to partner for Canadian involvement in international physics projects. The detector development and electronics expertise, as well as clean rooms and large construction space available at TRIUMF, have been essential for offshore experiments such as ATLAS, T2K, and Qweak. The accelerators provide beams for testing detectors for these international projects. Accelerator physicists at TRIUMF have designed and built beam line infrastructure for the LHC, J-PARC, and other accelerator facilities around the world. The technology of the ARIEL e-linac is closely related to the needs of the Linear Collider, and both TRIUMF accelerator physicists and local industry are poised to play leading roles in future accelerator projects.

The Ultra-Cold Neutron facility will deliver a trapped polarized UCN density of 1300 UCN/cm^3 the experiment, which is comparable or higher than most other facilities in the world. Table 1 shows a comparison of the projected capabilities of UCN facilities world-wide. The approach at TRIUMF is unique in UCN production and co-magnetometry for the nEDM experiment. A superthermal UCN source of He-II is employed, which is installed in the vicinity of a spallation neutron target together with an arrangement of neutron moderating and cooling materials that maximizes the cold neutron flux in the source, thereby optimizing the resulting UCN density. The uniqueness of the EDM measurement is in using a smaller cell made possible by the high UCN density, and a Xe-129 comagnetometer. A recent review by international experts of the TRIUMF/RCNP/KEK plans for the UCN/nEDM project gave the project high marks for its international competitiveness.

	Source type	Maximum UCN energy Ec (neV)	Storage lifetime (s)	UCN production volume	UCN density (UCN/ccm) at exp. (Ec)
TRIUMF	Spallation He-II	210	150	11	1300 polarized (90)
ILL	Beam He-II	250	150	11	1000 (250)
SNS	Beam He-II	134	500	7	150 (134)
LANL	Spallation SD_2	335	1.6	0.24	30 (180)
PSI	Spallation SD_2	335	6	27	1000 (250)
Munich	Reactor SD_2	250			1000 polarized (250)
PNPI	Reactor He-II	250	23	36	12000 (250)

Table 1: Comparison of the UCN projects worldwide.

TRIUMF also has the expertise, the infrastructure, and the continuous support of specialized staff in its Science and Engineering Divisions to build complex detectors for experiments in Canada (for example at SNOLAB: DEAP, SNO+, HALO) and provides unique beams and equipment to in-house experiments that bring the world to Vancouver. TRIUMF's specialized expertise is not widely available elsewhere and, in some cases, is unique in the world.

To be an effective contributor and participant in the global science of particle physics, Canada needs a laboratory that combines a thriving, innovative, and relevant local accelerator program with a broad range of detector-building skills and facilities.

Nuclear Physics

Five-Year Plan 2015–2020 foresees substantial advancement of the nuclear physics related capabilities needed to maintain a leading position in the domain of rare-isotope beam physics. Rare-isotope beam physics is a rapidly growing field worldwide with major production facilities using the so-called in-flight approach and the ISOL (isotope separation on-line) method, which is the technique applied at TRIUMF, both for ISAC with protons and the e-linac system at ARIEL.

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 (for example using resonant laser ionization). The ions are then electrostatically accelerated to several tens of 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 emerge at energy similar 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 by the chemical selection (refractory elements don't diffuse out of the target matrix) and the half-life of the isotope (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.

JAPAN AND CANADA TO COMPETE FOR TOP AMERICAN RESEARCHER

11 July 2013

In an unusual alliance between TRIUMF and the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) in Japan, a long-term joint research position has been created in order to recruit, develop, and support a world-leading scientist in two countries. The catch? After working for the first four years with 75% of his time in Japan and 25% in Canada, American physicist Dr. Mark Hartz will choose which laboratory's long-term job offer to accept.

From either side of the Pacific Ocean, there will be a great demand for Hartz. He has been appointed as assistant professor and is expected to carry out the full range of duties of a grant tenure track research scientist at both institutes. Additionally, he will serve on internal committees and represent both institutes at the national and international level.

Dr. Nigel S. Lockyer, director of TRIUMF said, "We need more competitive, cross-border positions like this to enrich and strengthen top talent. I'm delighted that Japan agrees that Hartz is worth fighting for, and yet I'm confident that in the long term Canada is the right place for him and his world-class research ambitions."

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 often less mass resolved (different charge states are simultaneously produced, limiting unambiguous identification) and can have poorer beam quality (higher longitudinal and transversal energy spread). It has discovery potential for new isotopes but will not provide for most of the science sought by 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 at several in-flight facilities (RIKEN, MSU, GSI) to establish low-energy programs by stopping high-energy rare-isotope beam in a gas-stopper cell from which it can be extracted to form a low-energy beam for use with stopped or post-accelerated beams. 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. The ISOL technique is the only method that can provide very high beam intensities of specific rare isotopes for experiments in nuclear astrophysics or for the high-precision experiments aiming to discover physics beyond the SM.

Worldwide overview: The high demand of the world wide rare beam community has resulted in a number of new facilities, including two currently under construction. Additional facilities are planned.

Existing and operational major in-flight facilities (E > 50 MeV/u) are:
- GSI Darmstadt, Germany
- HIRFL-CSR, Institute of Modern Physics Lanzhou, China
- NSCL, Michigan State University, U.S.A.
- RIBF, RIKEN, Japan
- SPIRAL, GANIL, France

New in-flight facilities under construction are:
- FAIR Darmstadt, Germany
- FRIB Michigan, U.S.A.

Major planned in-flight facilities are
- RISP, Institute for Basic Science, Daejeon, Rep. of Korea

Existing major ISOL facilities are:
- ALTO, Orsay, France
- CARIBU, ATLAS, ANL, U.S.A. (based on a Cf-252 radioactive source)
- HRIBF, ORNL, U.S.A. (currently not operational)
- IGISOL, Jyvaskyla, Finland
- ISAC, TRIUMF, Canada
- ISOLDE, CERN, Switzerland

New or major upgrades for ISOL facilities are:
- ANURIB, VECC, India
- ARIEL, TRIUMF, Canada
- BRIF, Bejiing, China
- HIE-ISOLDE, CERN, Switzerland
- RISP, Institute for Basic Science, Daejeon, Rep. of Korea
- SPES, INF Legnaro, Italy
- SPIRAL2, GANIL, France

The planning of these international efforts is governed by regional plans, such as the European Nuclear Physics long range plan (NUPECC roadmap 2010), and more globally through the Working Group 9 (WG) of the International Union of Pure and Applied Physics. This ensures regional and global efforts optimization and expertise distribution, as well as competitiveness.

In the report by the Working Group of Nuclear Physics of the Organisation for Economic Cooperation 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]

Five-Year Plan 2015–2020 will solidify Canada's leadership position in rare isotope physics by firmly establishing the ISAC/ARIEL accelerator complex as the regional ISOL facility for the Americas with significant discovery potential.

As described earlier, Five-Year Plan 2015–2020 provides expanded capabilities in stages, especially the ARIEL program.

The science capabilities enabled by the ARIEL science phases, are aligned with the goals for the research at TRIUMF in nuclear physics and material science:

- **Phase 1:** Electrons from the e-linac strike Be targets for production of polarized Li-8 beam for β-NMR and tests of fundamental symmetries. TRIUMF will be the first facility in the world with independent, multiple-RIB beam capabilities.
- **Phase 2:** The CANREB system coupled to the ISAC RIB production facility. High resolving power of the HRS provides quasi-contamination free RIB, and the efficient EBIS charge breeding allows for high-intensity post-accelerated beams. This allows new nuclear structure and nuclear astrophysics studies.
- **Phase 3:** First electron-based fission fragments RIBs are produced using photo-fission in actinide targets and provide access to new neutron rich isotopes. At this point triple RIB capabilities are established at TRIUMF for independent science programs with two electron-produced beams from the e-linac and the current ISAC production target using protons from the main cyclotron.
- **Phase 4:** With the implementation of the new proton beam line TRIUMF is able to provide maximal flexibility for RIB sciences; material science, nuclear structure, both neutron and proton rich isotopes, nuclear astrophysics, and tests of fundamental symmetries from electron and proton produced RIBS.
- **Phase 5:** Maximal power (0.5 MW) is available from the e-linac for production of the most neutron-rich isotopes, increasing production yields by close to factor of 100 compared to the initial e-linac implementation.

These phases allow maximal harvesting of the science and provide international competitiveness and leadership. The competitiveness lies in the reach and focus of the research program, which aims to answer questions in the core themes of Five-Year Plan 2015–2020. Key to the success is that at TRIUMF experimental facilities with track records of outstanding performance already exist, and the five phases provide new and enhanced production capabilities, both in reach and available beam time.

To provide evidence for the competitive reach for isotope production, we have calculated the yield (number of extracted isotopes per second) for a set of standard isotopes, rubidium and krypton, where both experimental and predicted numbers exist from various facilities. The computed values for the e-linac production are based on FLUKA, using the converter-target geometry described in TRIUMF design notes (TRI-DN-11-19, TRI-DN-11-20), the expected energy and intensity of the electron beams given, and experimental diffusion times, and extraction and ionization efficiencies from ISOLDE, overlaid with the isotope specific half-live. The experimental values are taken from the ISAC yield table (https://www.triumf.info/public/research_fac/yield.php), the ISOLDE values are taken from the ISOLDE yield table (https://oraweb.cern.ch/pls/isolde/query_tgt), and the calculated SPIRAL data are based on the given energies and intensities of the driver beams, and are taken from (http://pro.ganil-spiral2.eu/spiral2/spiral2-beams/).

The comparisons (see Figure 1) shows that the measured yields for ISAC and ISOLDE are comparable for Rb, which is a result of higher beam power densities at lower average power for ISOLDE due to the pulsed beam (note that the ISOLDE Rb yields were measured for the 600 MeV SC proton beam while the ISOLDE Kr yields were measured for the 1.4 GeV PSB proton beam). Clearly the projected e-linac yields at 100 kW (4mA, 25 MeV) are already going much beyond what ISOLDE can produce today and with the 500 kW e-linac operation (10mA, 50 MeV) expected yields will be comparable or higher than the projected SPIRAL2 yields at GANIL. In particular for the very neutron-rich short-lived isotopes the smaller targets used for ARIEL will be an advantage in terms of extraction times over the large SPIRAL2 targets, leading to higher yields.

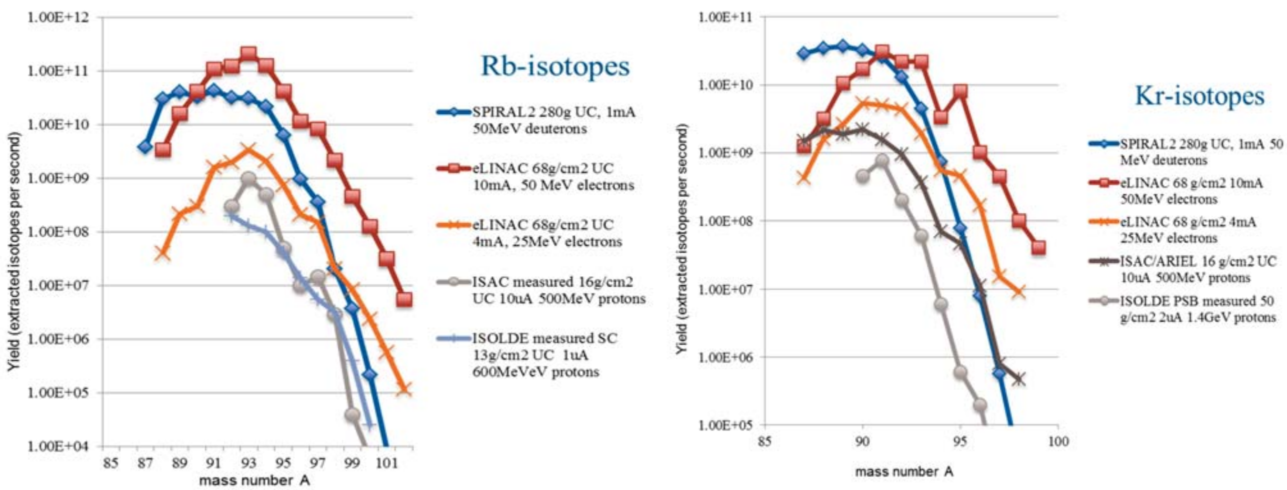


Figure 1: Measured and calculated yields of Rb (left) and Kr (right) isotopes for ISOLDE, GANIL, ISAC, and e-linac-based ARIEL yields.

As indicated earlier, the largest range of isotopes can be produced at in-flight facilities. The existence proof of an isotope can be carried out with production intensities as low as 10^{-6} ions/s. Some experiments, such as decay studies, have been carried out with production rates as low as one per hour (10^{-4}/s). In comparison ISAC experiments have been performed at intensities as low as 1 ion/s.

The physics scope probed at these facilities is mostly complementary to what is aimed for at ISAC; that is, no in-flight facility has physics programs that include all of the four research components of nuclear astrophysics (in particular, those using post-accelerated beams), nuclear structure, test of fundamental symmetries (such as searches for permanent EDM or parity non-conservation, PNC) 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. With the addition of the CANREB system, which will complete the accelerator chain, and the existing expertise, a truly unique system is available. However, it is noteworthy that some of the future facilities also incorporate the multiple beam option as a critical component, a component that will be key to TRIUMF's future.

Table 1 shows a comparison of key science programs addressed at present and future rare-isotope facilities. The table displays the projected/proposed participation in physics fields for the next decade.
Listed are the important parameters that ensure successful execution of the envisaged programs in Nuclear Structure, Nuclear Astrophysics, and Fundamental symmetries, which require long (uninterrupted)

Facility	Type	Max beam time	Multi-beam ops	Experiments at rest	Experiments at high energy (> 50 MeV/u)	Post-accelerator (MeV/u)	Nuclear Astrophys. in inverse kinematics	Nuclear Structure	Fundamental Symm.	Nuclear Medicine	Material Science
ISAC I & II	ISOL Proton (50 kW)	Up to 6 weeks	N	Y	N	Y (12)	Y	Y	N	N	Y
ARIEL	ISOL Proton (50 kW) photo-fission (500 kW)	Up to 6 weeks	Y(3)	Y	N	Y (12)	Y	Y	Y	Y	Y
ISOLDE	ISOL proton (2kW)	Up to 6 days	N	Y	N	Y (3)	N	Y	N	Y	Y
HIE-ISOLDE	ISOL Proton (9 kW)	Up to 10 days	N	Y	N	Y (5/ 10)	Y	Y	N	Y	Y
SPIRAL	ISOL ions (6 kW)	Up to 3 weeks	N	Y	N	Y (20)	N	Y	N	Y	Y
SPIRAL	In-flight		Y(3)	Y	Y	N	N	Y	N	Y	N
SPIRAL II	ISOL (ions & deuteron (200kW)	Up to 12 weeks	Y(3)	Y	N	Y (20)	Y	Y	Y	Y	Y
GSI	In-flight		Y(2)	Y	Y	N	N	Y	N	Y	N
FAIR	In-flight		Y(5)	Y	Y	N	N	Y	N	Y	N
NSCL	In-flight (gas-stopper)		N	Y	Y	Y (3)	Y	Y	N	N	N
FRIB	In-flight		N	Y	Y	Y (12)	Y	Y	Y	Y	Y
ATLAS	In-flight		N	Y	N	N	Y	Y	N	N	N
CARIBOU	Cf- source (1 Ci)		N	Y	Y	Y (15)	Y	Y	N	N	N
RIBF	In-flight (1 kW)		N	Y	Y	N	N	Y	N	Y	Y

Table 1: Comparison of the capabilities of major RIB facilities worldwide.

experimental beam times, corresponding to extended target life times, precision measurements of ground state properties, corresponding to experiments at rest, acceleration capabilities to energies relevant for nuclear astrophysics scenarios and nuclear structure, but also complementary competitive science programs in nuclear medicine and material science.

Overall TRIUMF's rare isotope program is unique in the world in its scientific breadth and with the combination of available beams and experimental facilities. However, TRIUMF is in direct competition with the capabilities that are being developed at other world-leading facilities. RIBF at RIKEN is already producing neutron-rich nuclei through in-flight fission of uranium beams. Asides from decay spectroscopy experiments the investigations at RIBF are mostly complementary to experiments at ISAC.

HIE-ISOLDE, which will bring its 5 MeV/u accelerator online in 2014 and will have a 10 MeV/u capability in 2016 has comparable beam-intensities to ISAC for medium-mass neutron-rich nuclei and will compete directly with the ongoing program from the actinide target, including the post-accelerated beams where ISAC-II is currently unique in the world. The CANREB EBIS as well as facilities like EMMA and IRIS will give the ISAC-II accelerated beam program another edge in this competition. ISAC will continue to have a clear advantage on the proton-rich side with its up to 50 kW proton beams and with the development of full-multi-user capability.

SPIRAL2, ramping up RIB production in 2018, and FRIB, scheduled for completion in 2022, will produce r-process nuclei with comparable intensities to ARIEL and have comparable experimental capabilities. While the delineation of the nuclear physics properties along the r-process is a long-term effort, it is critical to have an edge on high-profile experimental programs such as mass measurements, transfer-reaction studies, and beta-delayed neutron emission. FRIB is also developing a separator for low-energy nuclear astrophysics experiments in inverse kinematics using gas-stopping and reacceleration of in-flight beams. FRIB is also pursuing the development of an atomic EDM experiment using radium isotopes.

The examples in this discussion highlights that there is a particular window of opportunity for the TRIUMF ISAC/ARIEL program in the next period 2015–2020 and that therefore a timely completion of the full ARIEL project is important to establish and maintain leadership in a very competitive field.

Materials Science

The Centre for Molecular and Materials Science at TRIUMF provides researchers with intense beams of muons and radioactive nuclei, state-of-the-art spectrometers, equipment and support personnel that enable visiting researchers to apply the μSR or β-NMR spectroscopic techniques to their scientific problems and probe the properties of materials at the microscopic level. A proper understanding of a material requires that it be characterized with a range of techniques and μSR and β-NMR are essential as they frequently provide unique information and are complementary to other techniques such as neutron scattering or synchrotron radiation.

The μSR and β-NMR facilities provided by TRIUMF make CMMS unique in Canada. Indeed, there is no other high intensity muon source in the Americas, nor are there equivalent facilities anywhere in the world for β-NMR. There are only two sources of high intensity continuous muon beams in the world: TRIUMF and the Paul Scherrer Institute (PSI) in Switzerland. Two other sites provide intense pulsed muon beams suitable for muon spin spectroscopy: ISIS-RAL in the U.K. and J-PARC in Japan. The continuous beams available at TRIUMF make it possible to perform experiments in high transverse magnetic fields and to study systems with large internal fields and fast fluctuations. The inclusion of the Muons-On-Request (MORE) system in the new M20 and M9A beam lines means that experimenters will have all the advantages of the continuous beam along with the ultra-low backgrounds previously only available at the pulsed sources. While a few other laboratories are capable of β-NMR (notably ISOLDE at CERN), none have a dedicated facility to study materials science with depth-resolved capabilities, nor with the beam intensities and versatile spectrometers of CMMS.

Nuclear Medicine

Canada's position in nuclear medicine vis-a-vis TRIUMF is more subtle. TRIUMF has leading expertise and capabilities in the physics and chemistry of nuclear medicine (i.e. isotope production with accelerators and the subsequent separation, purification, and synthesis chemistries), and partners with other organizations for the biology. There are a dozen high-quality nuclear medicine research institutes in Canada.

TRIUMF is planning for success with its cyclotron-based production of technetium-99m, and this accomplishment would be unique in the world and would dramatically distinguish the laboratory. This effort is the product of four different teams working together.

Perhaps more important is what Five-Year Plan 2015–2020 proposes for regional excellence. The plan proposes to crystallize "Isotope Valley" in the lower mainland of British Columbia by using enhanced capabilities and capacities at TRIUMF (new cyclotron, more wet and hot lab space, more permanent technical staff) to leverage efforts at the BC Cancer Agency, St Paul's Hospital, Vancouver Health Research Institute, Advanced Cyclotron Systems, Inc., AAPS, Inc., and the UBC and SFU universities. This combination of talent and resources will place the region among the world leaders for molecular imaging research and technology for oncology and neurology.

Accelerator Physics

The e-linac at the heart of ARIEL will be unmatched elsewhere around the world and it will become a platform for new research and development at TRIUMF. The laboratory is already exploring joint research activities with advanced-accelerator efforts in the U.S., Europe, and Japan (especially in plasma-wakefield, laser-driven, free electron laser, and energy-recovery techniques). Together with PAVAC, TRIUMF has global attention in its use of superconducting radio-frequency. It is projected that by the end of Five-Year Plan 2015–2020, TRIUMF will count among the top five accelerator science and technology centres in North America and one of the top five in the world for dealing with high-intensity beams on target.

6.5 IMPLEMENTATION: WORKING WITH MULTIPLE STAKEHOLDERS

As a legal entity, TRIUMF is a joint venture of Canadian universities (please see Section 3.2). In practice, it is also a partnership among multiple public stakeholders who bring different resources to the table: its overall steward NRC; federal agencies, such as Canada Foundation for Innovation, Natural Sciences and Engineering Research Council of Canada, Natural Resources Canada, Western Economic Diversification Canada; and provincial governments across Canada—most notably the Government of British Columbia via the BC Knowledge Development Fund but also Manitoba, Ontario, and Nova Scotia. Other investors in TRIUMF's program come from the international sphere and the private sector.

Figure 1 illustrates the combination of investments that support TRIUMF's overall program. This section discusses the different roles these stakeholders play in driving TRIUMF's success and then discusses how these roles may evolve in Five-Year Plan 2015–2020.

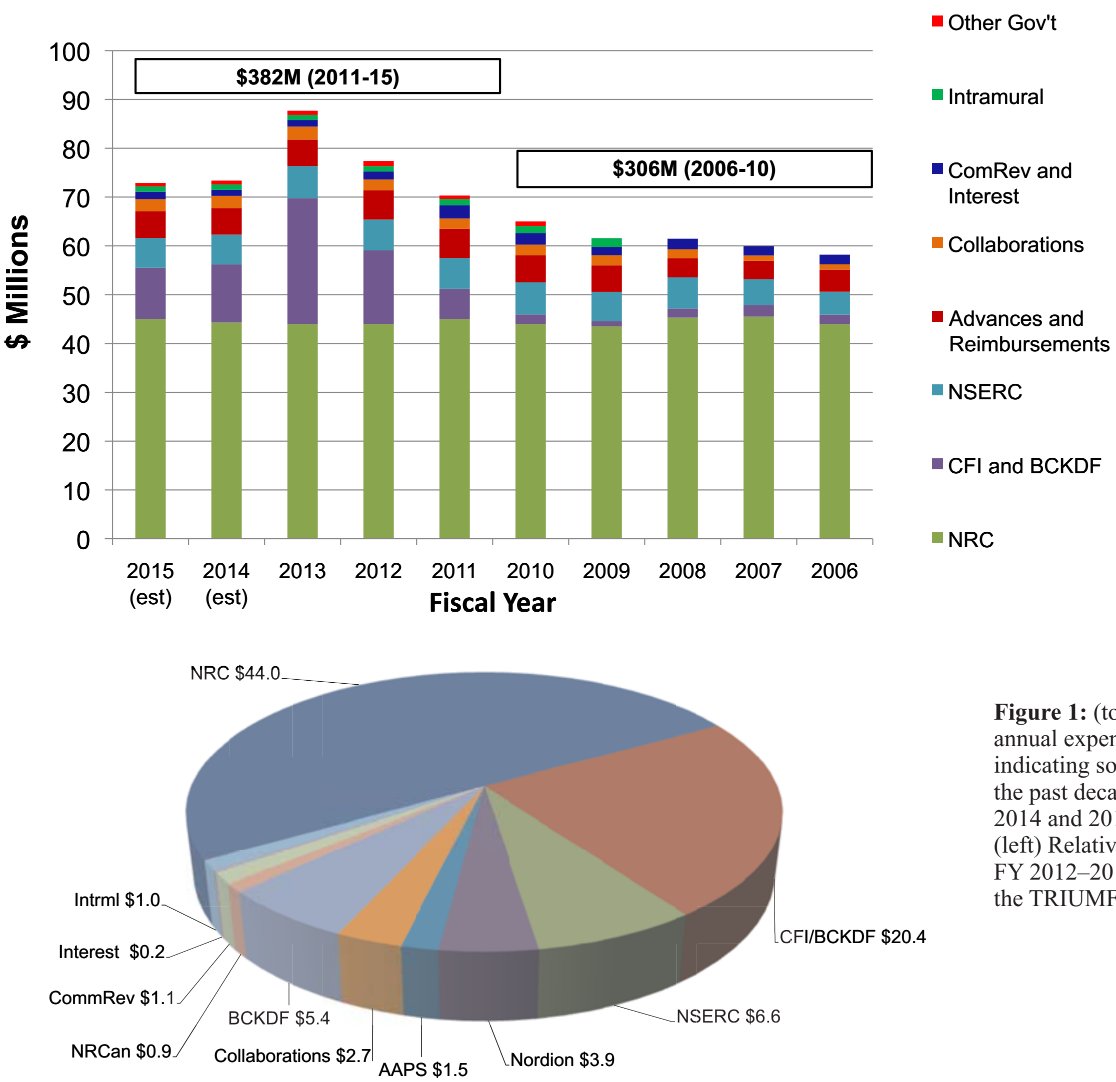


Figure 1: (top) History of annual expenditures at TRIUMF, indicating sources of funds over the past decade. Estimates for 2014 and 2015 are included. (left) Relative sources of FY 2012–2013 funding for the TRIUMF program.

6.5.1 GENERALIZED ROLES

Each patron of TRIUMF shares a common belief in, and commitment to, excellence in basic research and the value it provides to Canada. These patrons support activities at TRIUMF, through their programs with specific objectives reflecting the patrons' mission, resulting in differentiated and unique contributions from each stakeholder.

The general characteristics of those roles are described here. The federal Agency Committee on TRIUMF (ACT) is one forum for many of these groups to interact and coordinate their involvement in and guidance of TRIUMF. For completeness, a short discussion of international investments is also included.

NRC

National Research Council Canada (NRC) has been the federal steward of TRIUMF for decades. Not only does it oversee the TRIUMF Five-Year Contribution Agreement that funds core operations, but it also convenes advisory and review committees and provides regular oversight of the laboratory's activities. A senior representative of NRC attends Board of Management meetings as well as the meeting of the Board's Audit Committee and is fully briefed on the broad program of work at TRIUMF. NRC also serves as the formal voice for TRIUMF in the Government of Canada and spearheads the preparations every five years for the federal Cabinet to renew its support for TRIUMF's core operations. The five-year Contribution Agreement funds have become a smaller fraction of TRIUMF's overall support, but they constitute the majority of funds. Generally speaking, the Contribution Agreement supports core and continuing operations including salaries, utilities, and generalized maintenance / repair / operations costs. Some support for students is included and some specific capital support for upgrades or infrastructure upgrades is often provided.

It is said that "NRC funds up to the end of the beam line," meaning that nearly all activities required to run the accelerators and produce isotopes and direct them to a scientific end station are eligible for reimbursement under the Contribution Agreement.

NSERC

The Natural Sciences and Engineering Research Council of Canada (NSERC) supports university students and post-doctoral fellows in their advanced studies, promotes and supports discovery research, and fosters innovation by encouraging Canadian companies to participate and invest in postsecondary research projects. NSERC interacts with the TRIUMF program in several ways. University-based researchers and eligible TRIUMF researchers apply to NSERC for funding to support their research; the funds are awarded on a peer-reviewed, competitive basis. Because of TRIUMF's research focus, the laboratory has most of its involvement with NSERC through the Subatomic Physics suite of programs. Although the majority of the Canadian subatomic physics community is based at the universities, much of the research relies on or builds upon TRIUMF capabilities.

The TRIUMF involvement with a grant may be through a TRIUMF funded researcher as a co-applicant, the research being done in whole or in part at TRIUMF, or the research using TRIUMF infrastructure. Over the past five years (FY2007–2008 to FY2011–2012), TRIUMF was involved in more than 70% of the research support awarded by NSERC's Subatomic Physics Evaluation Section (SAPES) (see Table 1). The large percentage is not surprising since TRIUMF is involved in all the large subatomic physics programs in Canada: ATLAS, T2K, SNOLAB, and ISAC.

NSERC SAPES Awards	Involves TRIUMF		NSERC SAPES Totals	
Fiscal Year	No	Yes		
	$	$	$	Number of Awards
2007–2008	$9,772,197	$14,779,902	$24,552,099	151
2008–2009	$6,368,985	$16,298,151	$22,667,136	158
2009–2010	$6,138,271	$17,099,895	$23,238,166	148
2010–2011	$5,611,879	$16,409,174	$22,021,053	143
2011–2012	$5,478,500	$17,198,695	$22,677,195	141
Grand Total	$33,369,832	$81,785,817	$115,155,649	

Table 1: NSERC SAPES Awards from 2007 to 2012.

The Centre for Molecular and Materials Science (CMMS) at TRIUMF is supported by NSERC funding, most recently through a Major Resources Support grant. TRIUMF researchers also participate in NSERC-sponsored research in other programs including Cooperative Research and Development grants with industrial partners (e.g., Nordion, Inc). Finally, TRIUMF researchers serve as collaborators and co-applicants on NSERC grants based at other institutions. For instance, some of the nuclear-medicine research program has been supported through NSERC and CIHR grants based at UBC and the BC Cancer Agency (notably, the early work on cyclotron-production of Tc-99m).

Generally speaking, NSERC supports "doing the science at TRIUMF" including students and post-doctoral fellows, as well as costs to build and maintain the scientific experiments themselves. Over the past five years, an average of 7 FTEs per year and 27 post-doctoral fellows per year were supported at TRIUMF by NSERC. By tracking students who were paid through accounts at TRIUMF, NSERC supported 118 graduate students and 35 undergraduates in the FY2008–2009 to FY2012–2013 period. These numbers do not include students whose financial arrangements did not include TRIUMF's business office; estimates are that this category would include another 50-75 graduate students who conducted their thesis research at the laboratory.

CFI

Created by the Government of Canada in 1997, the Canada Foundation for Innovation (CFI) strives to build the nation's capacity to undertake world-class research and technology development to benefit Canadians. CFI invests in state-of-the-art facilities and equipment at universities, colleges, research hospitals, and non-profit research institutions through a peer-reviewed competitive process. CFI awards typically provide 40% of the total project budget and proponents must secure the remaining 60% through other sources (provincial governments are often asked to provide 40%, and the remaining 20% may come from international or industrial sources). Additionally, CFI will provide up to 30% of its investment (typically 12% of the overall project budget) as a five-year "Infrastructure Operating Fund" contribution that gets the equipment or facility up and running.

TRIUMF is not institutionally eligible for CFI funds. However, universities across Canada are eligible and on key occasions select to site the infrastructure at TRIUMF to best exploit adjacent capabilities. In other cases, TRIUMF may be called on to contribute expert talent or capabilities to build infrastructure elsewhere as part of a CFI project, sometimes on a cost-recovery basis. TRIUMF views these arrangements as advantageous and effective; infrastructure built at TRIUMF must generate sufficient interest in the university-based community to be fully utilized, and the university-lead requirement is an efficient mechanism to ensure this aspect.

In general, CFI is emerging as the dominant source of capital funds for "significant" Canadian research infrastructure.

Depending on the scale of a project sited at TRIUMF, the laboratory may be engaged as simply a service provider or a full managing partner. For example, the ARIEL project was supported through a $18M award from CFI in 2010 as part of a $63M package. Led by the University of Victoria, the project encompasses design and construction of a superconducting electron linear accelerator (e-linac) at TRIUMF for the production of isotopes. TRIUMF and the University of Victoria entered into a letter of agreement where TRIUMF staff provide the project management and day-to-day leadership of the project. For this project, TRIUMF is also providing about $13M of in-kind support through skilled labour contributions.

As shown in Table 2, TRIUMF is involved in a small but important number of CFI projects. The table identifies the successful CFI proposals that directly involve new infrastructure at TRIUMF but does not include minor awards at TRIUMF member universities that may modestly impact the prototyping or research capabilities of teams that often come to TRIUMF for research. TRIUMF is directly involved in 11 awards out of 2,698 made between 2008 and 2013, representing $29.9M out of $1.1 B awarded, or about 2.6%. Over this period, 11/13 TRIUMF-related CFI proposals were successful. Note that these dollar amounts represent only the CFI award contribution and do not reflect matching funds or the Infrastructure Operating Funds.

Year	PI	Lead University	Title	CFI Award
2008	Andreiou	Simon Fraser University	The Simon Fraser University Clover-Type Germanium Detector for Use at the Focal Plane of EMMA at TRIUMF-ISAC II	$125,000
2009	Karlen	University of Victoria	Superconducting Electron Accelerator at TRIUMF	$17,797,256
2009	Kanungo	St. Mary's University	ISAC Charged Particle Spectroscopy Station (IRIS)	$535,598
2009	Svensson	University of Guelph	Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN)	$3,837,763
2009	Martin	University of Winnipeg	Canadian Spallation Ultra-cold Neutron Source	$4,225,000
2009	Svensson	University of Guelph	The Guelph Spectrometer for Internal Conversion Electrons (SPICE)	$124,832
2009	Oser	University of British Columbia	A Data Centre for the Canadian T2K Analysis Effort	$39,105
2009	Tanaka	University of British Columbia	Laboratory for Photosensor Development and Applications for Particle Physics	$126,574
2010	Martin	University of Winnipeg	Polarized Xenon Laboratory for Fundamental Physics	$155,852
2011	Sossi	University of British Columbia	Hybrid microPET/SPECT and CT preclinical imaging	$398,600
2012	Vetterli	Simon Fraser University	Upgrade to the ATLAS Tier-1 Data Analysis Centre	$1,000,000
2012	Kanungo	St. Mary's University	Canadian Rare Isotope Facility with Electron Beam Ion Source	$1,599,333

Table 2: CFI awards since 2008 involving TRIUMF.

NRCan

Natural Resources Canada (NRCan) is the federal agency with primary responsibility for the country's natural resources but also supports innovative science at a small network of laboratories and is engaged in active technology development and translation with industrial partners. NRCan also has oversight and responsibility for the National Research Universal (NRU) nuclear reactor in Chalk River, Ontario. Through this portfolio, NRCan is involved in the production of medical isotopes at the NRU through the irradiation of highly enriched, weapons-grade uranium imported from the U.S. Over the past five years, the Government of Canada has developed a set of policy initiatives designed to stop the isotope-production mission at the NRU in 2016 and develop a comprehensive, commercial alternative that is "fully captured" within the private sector (i.e. is free of taxpayer subsidies for operations).

As a result, NRCan convened an Expert Panel and developed a framework for two rounds of competitively awarded federal funds to develop and deploy alternative isotope-production methods. As outlined in Section 4.2.3.2, TRIUMF has led a multi-institution consortium to develop cyclotron-production capabilities for the key medical isotope, technetium-99m (Tc-99m). TRIUMF has been the lead institution on three Contribution Agreements with NRCan on this topic:

- 2008–2009: $60k to support TRIUMF's Task Force on Alternatives for Medical-Isotope Production;
- 2010–2012: $6M as part of the Non-reactor Isotope Supply Contribution Program (NISP); and
- 2013–2016: $7M as part of the Isotope Technology Acceleration Program (ITAP).

Generally speaking, NRCan has supported technology-development work at TRIUMF associated with medical isotopes, including salaries, operating costs, specific capital items, and so on.

Western Economic Diversification Canada (WD)

As an agency of the federal government, Western Economic Diversification Canada's (WD) mandate is to promote the development and diversification of the economy of Western Canada and advance the interests of the West in national economic policy. TRIUMF has enjoyed support from WD on several occasions to enhance its research infrastructure. In 2010, WD provided about $900k to assist TRIUMF in modernizing a set of radiochemistry laboratories to bring them closer into alignment with good manufacturing practice. The project was a success, and the minister visited TRIUMF the following August to see the final facilities. TRIUMF's commercialization partner AAPS, Inc. was the beneficiary of a $1.8M award for the development of cosmic-ray muon geotomography for mining exploration applications.

TRIUMF has also benefited from WD participation in supporting elements of the Centre for Comparative Medicine and the BC Preclinical Research Consortium. Finally, TRIUMF is presently engaged in discussions with WD about involvement in the Centre for Excellence for Accelerator-Based Medical Isotopes (please see Section 6.2.4.3).

Provincial Governments

In Canada, provincial governments also take ownership of science and technology investment. TRIUMF interacts with provincial governments in several ways.

Because the laboratory is situated on university land, new buildings are seen as the responsibility of the provincial government, which is accountable for post-secondary education. TRIUMF therefore works with the Government of British Columbia to secure capital funds for new buildings. For instance, the Government of British Columbia contributed $30.7M through its BC Knowledge Development Fund or the ARIEL building and supporting infrastructure in 2010. TRIUMF also works with provincial governments through the CFI framework; matching funds from multiple provinces may come together to support a CFI project based at TRIUMF. The recently approved CANREB proposal was led by Saint Mary's University in Nova Scotia and has secured funding from the Government of Nova Scotia and the Government of Manitoba for the project, which will be sited within ARIEL. The Government of British Columbia is currently evaluating its level of support for the project.

Being located in British Columbia, TRIUMF has a special relationship with the provincial government in Victoria. The laboratory is involved in discussions with elements of the provincial government about advanced health care technology and policy, innovation strategies, and public policy for science.

International Contributions

As science is a global enterprise, and talented individuals are inherently mobile, TRIUMF's programs are international on many different levels. TRIUMF benefits from these interactions, and, during the past five years, has secured key contributions from partners in other countries to enhance on-site infrastructure and support some operating costs. Typically, the investments come as part of a structured Memorandum of Understanding that provides a framework for personnel and knowledge exchange as well (please see Section 3.2.2). In some cases, for example UCN and PIENU, the international contributions were absolutely critical.

Support via the NRC Contribution Agreement provides resources to produce and deliver isotopes to the ISAC-I and ISAC-II experimental facilities. Using these isotopes for scientific research requires external funding, often through international collaborations, to design and build specialized detectors that then run dozens and dozens of experiments over their lifespan for multiple groups of national and international researchers.

Some of the key international investments, in Canadian Dollars, are listed here.

- Before FY2008, U.S. Brookhaven National Laboratory contributed in-kind equipment to the PIENU experiment at TRIUMF valued at $1M. In the 1990s, Japan's KEK laboratory helped build the M9B beam line for materials science research.

- In FY2006–2007, Germany's Max Planck Society contributed $100k to the TITAN Electron Beam Ion Trap at TRIUMF.

- In FY2007–2008, the UK's Science, Technology, and Facilities Council contributed $300 k to the SHARC experiment at TRIUMF. An additional $500k was added in the subsequent year with a final $470k in FY2009–2010.

- From FY2008–2012, the materials science program has benefited from $500k through a joint Japan/U.S. project called Super-PIRE/REIMEI that coordinates capabilities and research at TRIUMF with a network of a dozen other facilities and techniques for probing materials.

- In FY2009–2010, the U.S. Department of Energy provided $200k of support for the BAMBINO project.

- In FY2010–2011, the Japan Society for the Promotion of Science provided $600 k for the MTV experiment in ISAC-I and $103k for the IRIS project lead by Saint Mary's University, now based in ISAC-II. Finally, the State of Texas provided $33k to the TRINAT experiment at TRIUMF.

- From FY2011–2016, Japan's KEK laboratory will contribute $4.3 M to the UItra-Cold Neutrons Project (led by University of Winnipeg and being constructed/stationed at TRIUMF).

- In FY2011–2012, Germany's DFG agency proved $550k for the TITAN electron-cooler project at ISAC-I. The U.S. Department of Energy (DOE) provided $700k of support for the Francium Trap Facility in ISAC-I.

- In FY2012–2013, Cisco Systems in the U.S. contributed $150k to upgrade capabilities of the PIF & NIF irradiation facilities at TRIUMF. Germany's BMBF agency provided $120k for the TITAN Multi-TOF project at TRIUMF, and the Japan Society for the Promotion of Science provided an additional $103k for the IRIS experiment at TRIUMF.

Since the beginning of the ARIEL project, India's Department of Atomic Energy via the VECC laboratory has provided more than $2.5M as part of the partnership agreement. A new phase of work valued at $10M has been approved and was signed in early August 2013.

Other Support

Some of TRIUMF's activities are supported through cost-reimbursement for expense and services rendered, commercial royalty agreements, and partnered research agreements. Some of these activities have important direct economic impact: cost recoveries and royalties associated with TRIUMF's partnership with Nordion for medical isotope production and TRIUMF's PIF & NIF irradiation services that provide intense beams of protons or neutrons for industrial use (please see Section 4.4 and Section 5.10 for details).

6.5.2 COORDINATED SUPPORT IN FIVE-YEAR PLAN 2010–2015

Five-Year Plan 2010–2015 proposed a vision for Canadian excellence and called upon a network of public stakeholders to join forces to make it happen. The strategic plan outlined four budget scenarios indexed by different levels of the NRC Contribution Agreement. From the middle of the 2010–2015 lustrum, it is clear that TRIUMF's accomplishments have only been possible through coordination among the key Canadian stakeholders. Although the NRC Contribution Agreement provided flat-flat funding for the laboratory's core operations, other agencies got involved. With CFI support for not only the ARIEL project but also for the ATLAS Tier-1 Data Centre alongside the Government of British Columbia's game-changing investment in ARIEL, TRIUMF's Five-Year Plan 2010–2015 jumped from a flat-flat budget scenario to one pursuing global excellence with full support for its two highest-priority programs. By redirecting and realigning effort, TRIUMF was successful in partnering with WD and NRCan in strengthening the nuclear-medicine program.

6.5.3 EVOLVING ROLES IN FIVE-YEAR PLAN 2015–2020

Participation in TRIUMF's program of work is dictated by a combination of alignment with strategic priorities and availability of resources. For instance, as cyclotron production of the Tc-99m medical isotope becomes fully commercialized in Five-Year Plan 2015–2020, NRCan's involvement in the nuclear-medicine program at TRIUMF is likely to wane. However, as that program takes on more direct relevance to human health through clinical or preclinical collaborations, one could expect that the Canadian Institutes of Health Research (CIHR) would play a greater role.

Five-Year Plan 2015–2020 calls for an evolution of the roles of several key public stakeholders. This section highlights those changes.

FIVE-YEAR PLAN 2015–2020 WITH NRC STEWARDSHIP AS COMPETITIVE ADVANTAGE

Despite being one of the world's smallest national subatomic physics laboratories, TRIUMF has earned an excellent international reputation. One of the powerful competitive advantages that TRIUMF enjoys is the five-year structure of its budget cycle. Although the five-year Contribution Agreement is by no means a guarantee of future funding, it provides a level of planning that, for example, far exceeds anything found in the U.S. TRIUMF is able, with some degree of confidence and acceptance of risks, to develop strategic initiatives within a framework of up to five years into the future.

The utility of this commitment from the federal government was powerfully illustrated in 2010 when, amidst the global economic downturn, TRIUMF negotiated a five-year program of work and a contribution agreement via NRC. Despite the fact that the resources made available placed tight constraints on TRIUMF's ambitions and operating capabilities, the level of certainty provided by a five-year future allowed the laboratory to make decisions and move forward in key areas while competitors around the world fumbled and waited month-to-month on promises of renewed spending authority. For instance, the ability to launch the ARIEL project (at a pace slower than initially planned, but to get started all the same) has positioned Canada to challenge the leadership of CERN's ISOLDE, and the ambitions of France's SPIRAL2, and the U.S. FRIB laboratories in rare-isotope physics. Likewise, the coordination of NRC and CFI investment to secure operations of the ATLAS Tier-1 Data Centre from 2010 until 2015 turned out to be crucial to the discovery of the Higgs boson in July 2012. The international ATLAS collaboration relied heavily on extra computing cycles offered by the Canadian centre in the final months of the analysis.

Canada's continued success at the international level in subatomic physics is buttressed by its ability to make five-year commitments to the core operations of the TRIUMF laboratory. Over the past decade, the fraction of NRC's contribution to TRIUMF's overall program has become smaller. This feature is driven in part by flat funding via the Contribution Agreement and in part by TRIUMF's success at securing alternative resources.

From a public policy perspective, however, this trend is a positive signal: TRIUMF's research program and output is competitive and increasingly relevant on the national and international stage and therefore is attracting additional stakeholders. The new reality for TRIUMF is that the NRC contribution funds the core operations of the laboratory while major new initiatives are only carried out if additional funding can be secured. This model works well since teams of Canadian researchers from TRIUMF and its member universities are highly successful in securing competitive funding from NSERC, CFI, and other agencies. NSERC funding supports the experiments at the end of the TRIUMF beam lines as well as the exploitation of the offshore experiments. Funding for large infrastructure projects has been secured through CFI competitions and matching provincial support. Other government agencies contribute to projects that are especially relevant to their portfolios: the province of British Columbia invests into the building infrastructure, Natural Resources Canada is funding the initiatives addressing the isotope crisis. In addition foreign agencies fund experimental infrastructure that is necessary for their nationals to carry out their research program.

NRC deserves the credit for successful stewardship of an organization that is energized and engaged; the Contribution Agreement is the vital seed corn and operational base that is achieving greater leverage than ever before. The agency is historically familiar with large-scale research and development efforts and understands how to structure reviews, annual reporting, and performance monitoring to ensure that TRIUMF is on task, on schedule, and on budget. However, as a consequence of this overall funding concept the long-term operation (beyond e.g., CFI IOF funding) of major new infrastructures, such as the ATLAS Tier-1 Data Centre and e-linac operation will fall under NRC's stewardship of TRIUMF.

From this perspective, looking forward to 2015–2020 the following observations are evident:

- The NRC Contribution Agreement will continue to be a crucial, deciding factor in TRIUMF's success and the laboratory's ability to deliver value for Canada;
- As the "new construction" phase at TRIUMF ebbs, and new facilities and equipment move from design and construction to commissioning and operation, the core and continuing program at TRIUMF will expand. It is expected that TRIUMF will seek to maintain its overall portfolio and envelope while shifting expenses from one-time budgets like CFI and WD to long-term operating budgets such as the NRC Contribution Agreement;
- With a consortium of Western Canadian partners, TRIUMF will seek support for the Centre of Excellence for Accelerator-based Medical Isotopes from WD, the Government of British Columbia, and other industrial sources; and
- Led by the University of Victoria and a consortium of universities, TRIUMF will seek capital support for the ARIEL completion project from CFI with matching funds to be sought from a network of provincial and international sources.

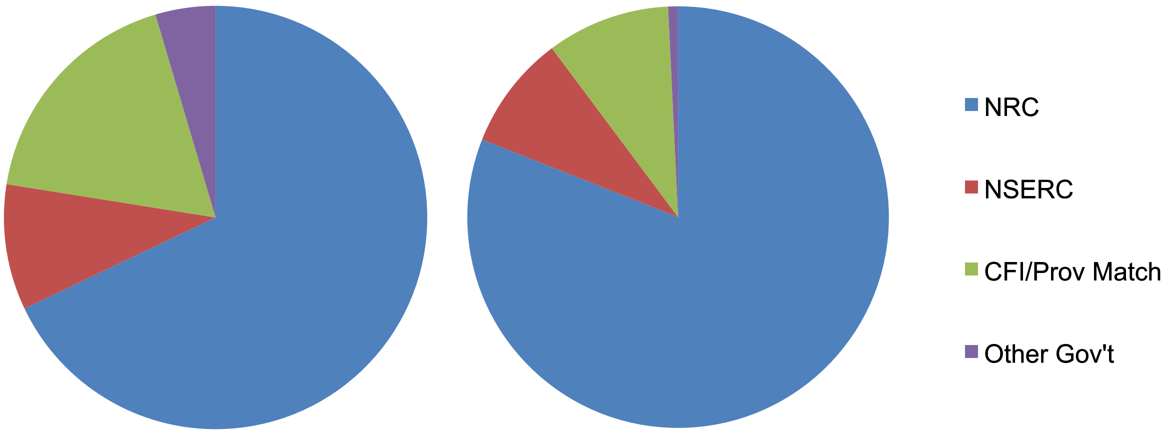


Figure 1: Distribution of TRIUMF funding from various sources for Five-Year Plan 2010–2015 (left) and projected forFive-Year Plan 2015–2020 (right).

International Contributions

It is expected that over the course of Five-Year Plan 2015–2020, international engagement and contributions will become increasingly important. Attracting investment from abroad provides validation of TRIUMF's program but must always be for the mutual benefit of both parties. Several such examples are predicted.

TRIUMF's August 8, 2013, Memorandum of Understanding with India's VECC laboratory covers a \$10.4M scope of work related to ARIEL and India's ANURIB projects. The initiative has some overlap with ARIEL completion but most importantly launches an early start on the long-lead-time conceptual and technical design studies. The engineering phase of completing the ARIEL target stations may also attract international partners either at CERN or in the U.S. ISAC and ARIEL place TRIUIMF clearly among the very top of RIB facilities worldwide as discussed in Section 6.4.2. TRIUMF will be the only ISOL RIB facility in North America and together with the FRIB in-flight facility in the U.S. will be the regional if not world leaders in RIB science. This leading position, the increased capabilities, and the substantially increased number of RIB hours, becoming available through the completion of ARIEL, will draw even more users from the U.S. and other parts of the world and make the facility very attractive for placing unique experimental equipment here. The investment into the Francium Trapping Facility by the U.S. DOE is a recent example.

As the ultra-cold neutron (UCN) facility becomes operational, Japanese scientists are likely to become more involved and will use support from their domestic agencies to collaborate with Canadians. Furthermore, TRIUMF is exploring an opportunity for Japan's KEK and/or RCNP laboratories to open a "field office" at TRIUMF that would facilitate such transactions. The UCN facility and the full implementation of the β-NMR facility will also attract more users including likely investments into facility and experimental infrastructure.

Engagement with NSERC in Subatomic Physics

Research happens at TRIUMF because of NSERC. Without the funding support for scientists and students, whether they are TRIUMF staff or not, the laboratory would produce only a fraction of its scientific output. Historically, NSERC's subatomic physics suite of programs provides $5M–$7M of annual support for scientists and students directly based at the laboratory (i.e. counting only NSERC funds disbursed through TRIUMF's business office).

NSERC's support for subatomic physics is managed through the Subatomic Physics Evaluation Section (SAPES), and a distinguishing feature of this process is that the Evaluation Section of peer reviewers makes recommendations regarding discovery grants, research tools and instruments grants, project operating grants, and major resource support grants from within a common "envelope" of about $20 M per year.

As observed in the recent community-based Long-Range Plan for Subatomic Physics, the SAPES envelope is under increasing pressure, due to the increasing operational demands of existing flagship programs as well as various new initiatives. As Canada's national laboratory engaged in subatomic physics research, TRIUMF is coupled to the NSERC SAPES. Therefore, expansions of TRIUMF's research program can have a direct impact on the pressure on the SAPES envelope.

In particular, when ARIEL becomes fully operational, the new e-linac and the new proton beam line will allow TRIUMF to deliver isotopes to up to three experiments simultaneously. The e-linac will have a different operating schedule than the main cyclotron, allowing almost year-round delivery of isotopes to certain experiments. TRIUMF predicts that its scientific output will ultimately double with the completion of ARIEL (taking into account the non-isotope-science programs).

In general terms, the SAPES envelope is pressured by three factors. Each is discussed here in turn with comments relevant to the TRIUMF program as presented.

New science. With new discoveries, the focus of cutting-edge research will naturally shift, and the Evaluation Section will need to weigh new frontiers against traditional programs. Dark matter and particle astrophysics are two examples of new frontiers in subatomic physics that attracted new researchers with new requests for equipment and students. Another example is accelerator-physics research; recent SAPES competitions have positively rewarded several proposals from TRIUMF dealing with the intellectual frontier of accelerator physics. While accelerator physics research will have broader impact beyond subatomic physics, the activities at TRIUMF are predominantly related to the subatomic physics program, leading to its inclusion in SAPES. Another example of "new science" creating proposal pressure is the migration of atomic and molecular and optics (AMO) physicists from traditional areas into antihydrogen (e.g., ALPHA) and ultra-cold neutron research that is squarely within the SAPES purview but heavily rely on AMO methods. In the next Five-Year Plan, TRIUMF anticipates a modest increase in "new science" proposals in the area of accelerator physics and UCN science to the SAPES.

New people. Another mechanism that increases proposal pressure is new researchers and students applying for Canadian funding. Canadian graduate students and post-docs are the primary beneficiaries of NSERC support at TRIUMF for subatomic physics. NSERC funds also cover selected operating costs and consumables for the experiments. Most of the available space in the ISAC-I and ISAC-II halls is occupied, so there will be relatively few large, capital-intensive, subatomic-physics construction projects driven by the new isotopes. Any new Canadian-led efforts will compete for CFI funding for their capital and other projects will be led and funded by international partners. At present, a significant fraction of the scientists and students using ISAC-I and ISAC-II to conduct their research come from outside Canada and bring their own research support. The present rare-isotope beam user community at TRIUMF is roughly 30%–40% domestic users, and the balance is made up of foreign visitors. With ARIEL's ability to run multiple experiments simultaneously, Canada will attract a much higher percentage of the international user community, thus elevating the experience of Canadian scientists and students working at TRIUMF. The brain circulation model of talent mobility (please see Section 4.3) implies that hosting a global beacon for excellence on Canadian soil has profound and positive impacts. In summary, Five-Year Plan 2015-2020 does not propose to substantially expand the number of principal investigators applying to the SAPES. The exceptions could be several new joint faculty positions proposed in the optimal scenario and any significant faculty-hiring decisions by university departments. For instance, recent new hires at TRIUMF and the University of Manitoba related to the UCN program will seek research support from SAPES.

New equipment and/or operations. In recent history, the greatest pressure on the SAPES envelope has been the operation of new equipment and facilities. The ATLAS detector at CERN is perhaps the largest example (ISAC-related detectors are only a few million dollars per year over the past decade, as per the Long-Range Plan). The advent of ALPHA as a subatomic physics experiment is an example in recent history along with the CFI-launched IRIS project and the TITAN-EC and Francium detector science experiments.

Looking forward to Five-Year Plan 2015–2020, it is projected that the EMMA detector facility will continue to seek SAPES support for operations and students; as the ultra-cold neutron facility comes online, it will seek SAPES support for scientific experiments examining the electric dipole moment of the neutron. The key changes at TRIUMF due to the ramping up of ARIEL operations will be handled entirely through the NRC Contribution Agreement. While funds will be sought from CFI for the main equipment for upgrades of ATLAS, T2K and other experiments, the R&D phase of these upgrade projects is already generating new proposals to SAPES in the RTI categories. As pointed out in the SAP LRP this is challenging for the SAPES envelope due to the continuously decreasing fraction of the envelope available for equipment.

One of the primary areas of scientific growth at TRIUMF will be in β-NMR, driven by photo-production of isotopes like Li-8 from the e-linac. This science program is about materials science, and physical chemistry, which is not under the purview of the SAPES envelope. While tools of subatomic physics are being “harnessed to drive discovery and innovation,” this growth in science will not increase the demands on the SAPES program. To a lesser degree than above, a higher throughput in the β-NMR facility, which is unique in the world, will also attract a much larger international community of users who will bring their own sources of research support with them.

In summary, TRIUMF’s Five-Year Plan 2015–2020 will advance Canadian scientific prowess in subatomic physics and is likely to increase proposal pressure on the SAPES envelope at about the 10% level based on projections about a handful of facilities becoming operational and several new faculty positions. As usual, TRIUMF will carefully screen its NSERC proposals to ensure that they pursue research opportunities distinct from those technology development and operations activities projected to be supported via the NRC Contribution Agreement. However, one has to recognize, that to fully realize the scientific discovery potential of the Plan, a commensurate adjustment in the NSERC SAPES envelope would be required.

Outlook

Canada’s science, technology, and innovation ecosystem is a network that connects government, universities, and industry. As a national laboratory, TRIUMF reflects this multi-sector approach, drawing on the strengths of multiple stakeholders to deliver a powerful program for Canada with clarity and confidence.

6.6 IMPLEMENTATION: TRADE-OFFS IN RISK, OPPORTUNITY, AND IMPACT

This section summarizes the fiscal support needed through NRC's Contribution Agreement to carry out TRIUMF's activities planned for this Five-Year Plan. Five-Year Plan 2015–2020 identifies the funding level that TRIUMF needs to provide optimal return on the investments made by the Government of Canada and its various institutions as well as Canada's international partners in science. Two alternative funding scenarios for the NRC Contribution Agreement are also presented and include discussion of the trade-offs in the program, the risks that would be incurred, as well as opportunities that would be lost with the funding level of these scenarios.

It is assumed in this that TRIUMF and its member universities will be able to secure competitive funding from CFI, NSERC, and other funding agencies for completion of ARIEL, the expansion of the computing power of the ATLAS Tier-1 Data Centre, and the upgrade of various experimental efforts such as ATLAS, T2K, nEDM, and ALPHA. Based on the previous successes in such competitions and the compelling scientific cases for these endeavours, there is confidence that a substantial portion of this additional funding will be secured.

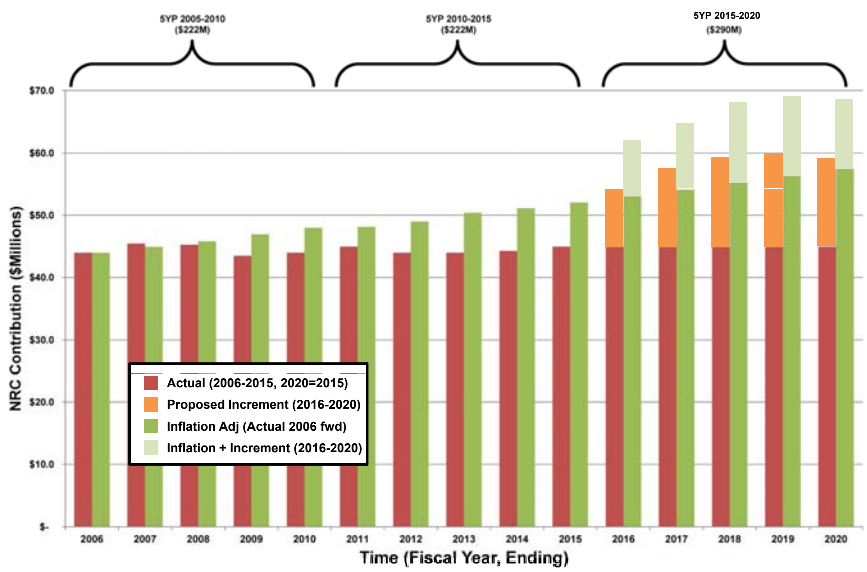


Figure 1: Annual NRC Contributions to TRIUMF in the context of inflation. The red bars show the as-spent annual NRC Contributions for 2006-2015; the 2015 value is shown flat for 2016–2020. The orange bars show the requested increment to handle TRIUMF's expanded operating program for 2016-2020. The green bars show the 2006 contribution with CPI-adjustments for inflation, as reported for 2006 2020 by Royal Bank of Canada. The light-green bars show the inflation-adjusted contribution combined with the program-scope increment.

6.6.1 OVERVIEW OF SCENARIOS

The main aspects of TRIUMF's programme and how they are affected in the three budget scenarios are summarized below.

A. OPTIMAL RETURN-ON-INVESTMENT SCENARIO

This budget will provide the fiscal and human resources that will allow TRIUMF to exploit fully the capabilities of the laboratory as developed since 2010 and make targeted, strategic enhancements to the program to strengthen particular areas of national priority, like the isotope program, partnerships with international organizations (CERN, KEK), and Canadian companies. Approximately 35 FTEs that are presently supported through temporary funds (from CFI transitional operating funds for ARIEL and the ATLAS Tier-1 Data Centre, NRCan, and so on) will be moved onto the stable platform of the salary budget via the Contribution Agreement.

This scenario will also enable some urgently needed upgrades of the aging infrastructure of the laboratory. These upgrades have been deferred over 10 years of flat-flat funding, and the upgrades will go far to mitigate the growing risk of failure of the laboratory's valuable physical assets.

All of these activities, under Scenario A, will guarantee Canada's continued position as an international leader in particle physics and rare isotope science and realize a strategic growth of the nuclear medicine program and its contribution to the development of medical isotopes for Canada.

This scenario would enhance TRIUMF's partnership with AAPS, Inc. to increase overall technology transfer and commercialization activities and to bring even more high-technology developments to the market.

B. INCREASED-RISK SCENARIO

In this scenario it would not be possible to capitalize on all of the opportunities laid out in the optimal scenario and stricter priorities would have to be set to retain a measure of scientific leadership in the short and long term. Moreover, TRIUMF and its stakeholders would have to accept a higher level of risk that the laboratory would not meet its goals.

This scenario has three high-level priorities: the completion of the flagship Advanced Rare IsotopE Laboratory (ARIEL) and with it the scientific exploitation of TRIUMF's existing accelerator infrastructure; the new program with ultra-cold neutrons (UCN); and the expansion and full exploitation of the Canadian ATLAS Tier-1 Data Centre.

Of course, this could only be done at the expense of some of the needed infrastructure upgrades and maintenance, which risks operational reliability, loss of scientific productivity, and reduced international credibility and reputation.

Several opportunities for program enhancements would also have to be scaled back to concentrate on the core mission of the laboratory in basic science, leading to a reduced societal and economic impact.

To put this scenario in context, if TRIUMF's core operating annual budget (as provided by the NRC Contribution Agreement) had been adjusted for inflation from 2005 to 2015 (2% per annum as per Bank of Canada guidelines), the 2015 level would be $52.6M. Thus, a five-year Contribution Agreement for 2015-2020 at this level without any future corrections for inflation (so-called flat-flat) would total $263M. The level of investment proposed in Scenario B, then, simply restores TRIUMF to the buying-power position it had in FY2005 but with operations of added infrastructures like ARIEL, ATLAS Tier-1 Data Centre, and M20.

C. RESTRICTED SCENARIO

Within a flat-flat budget scenario TRIUMF would not be able to deliver on the goals laid out in this plan.

This scenario would not capitalize on the investments already made by Canada and international partners over the past decade. TRIUMF's and Canada's reputations as reliable international partners would be tarnished. Student numbers would drop because TRIUMF's program would not be as competitive and attractive. In addition, societal and economic benefits driven by TRIUMF would drop. All of these effects would have long-lasting negative impacts not easily reversed.

Priorities	Scenarios for NRC Contribution Agreement Optimal $290.0M	Increased Risk $265.7M	Restricted $222.3M
ARIEL completion			
Skilled Personnel			
Operational M&S			
Program growth			
Infrastructure			
Confidence in maintaining Canadian leadership	**Impact** - High discovery potential - High impact in international endeavours - World leading facilities - increase in student numbers and high-impact publications	**Impact** - reduced operational reliability - lost opportunities for enhancements - reduced societal and economic benefits	**Impact** - risk of major failures - lost opportunity for discovery science - risk to lose key staff - loss of standing as international partner - diminished scientific impact - reduced student numbers due to non-competitive projects - minimal societal and economic benefits

Table 1: Summary of three budget scenarios indexed by NRC Contribution Agreement for Five-Year Plan 2015-2010.

6.6.2 SCENARIO A: OPTIMAL ($290.0M VIA NRC)

TRIUMF will provide maximal return on investment and maintain national and international scientific leadership with its high-performing infrastructure while completing the ARIEL project and gradually phasing in its scientific exploitation.

Operation at Full Capacity

- TRIUMF will operate its accelerator facility with the main cyclotron and the ISAC complex to deliver beams with maximum efficiency and to exploit the investments made by NRC, CFI, NSERC and international partners for a high-impact science program.

Completion and Exploitation of ARIEL

- TRIUMF will complete the ARIEL project with targets and infrastructure for remote handling and beam delivery, fully delivering on the vision laid out in Five-Year Plan 2010–2015.
- TRIUMF will ramp up the operation of the ARIEL accelerator infrastructure in a phased approach to deliver science as each of the planned phases comes on line.

Acting on Opportunities

- TRIUMF will expand its core support for the nuclear-medicine program, capitalizing on the strengthened competencies and new partnerships resulting from the Tc-99m development. Efforts will lead to new innovations for the benefit of every Canadian's health and economic potential for Canadian industry.

- The UCN facility at TRIUMF will be brought to full power, producing the highest density of ultra-cold neutrons of any facility to establish the most sensitive limit on or discover the neutron electric-dipole moment.
- The ATLAS Tier-1 Data Centre will be expanded to keep up with the increased data rates from the LHC. Reliable operation will be ensured through TRIUMF investments in staff, infrastructure, and operations.
- TRIUMF will make significant contributions to high-profile, offshore experiments such as ATLAS and ALPHA at CERN and the T2K experiment at J-PARC. These efforts will capitalize on previous investments and increase the stature gained by Canadian researchers in these international collaborations. The Canadian subatomic physics community will be supported in other international efforts through the TRIUMF detector facility.
- TRIUMF will grow its economic impact by adding up to three critical staff members for expanding partnership with AAPS, Inc., developing new industrial partnerships, and exploiting new opportunities for technology transfer to Canadian companies.

Investment in People and Infrastructure

- TRIUMF will invest in crucial infrastructure upgrades such as the replacement of the cyclotron main magnet power supply, refurbishment of the cyclotron needed for the new proton beam line, refurbishment of ISAC targets and beam delivery systems, as well as the site electrical transformer, the leaking Meson Hall roof, machine shop infrastructure, water and air systems, and modern communications systems.
- In cooperation with its partner universities TRIUMF will strengthen its scientific community in Canada through several strategically placed joint faculty positions.
- A substantial increase of Canadian and international HQP can be expected due to the increased operating hours and stronger involvement in international projects.
- TRIUMF will have constant buying power for utilities and other basic operating expenses while providing economic adjustments of salaries in line with inflation allowing TRIUMF to remain competitive in the market for top-notch researchers, and highly specialized engineers, and technical personnel.

Overall, this optimal scenario enables TRIUMF to exploit the existing in-house facilities for subatomic physics (ISAC), molecular and materials science (β-NMR, μSR), and nuclear medicine. A timely completion of ARIEL is particularly important since there are competing efforts under way in Europe, the US, and Asia. ARIEL's proposed timeline will give TRIUMF's rare isotope program the edge: we will be the first to reach important r-process nuclei and to carry out high-profile discovery experiments on physics beyond the Standard Model.

Science exploitation of ARIEL will start with β-NMR, dramatically expanding the impact of this world-unique facility for the characterization of material interfaces, nanostructures and biomolecules with impact on microelectronics, nanoscience, quantum computing, and energy storage.

The next major step will be the implementation of photo-fission, finally providing access to some of the short-lived isotopes involved in the production of the heavy elements in the r-process, opening the final chapter of the quest to understand the origin of the chemical elements.

The addition of a new proton beam line and target will allow for the implementation of a full multi-user capability with three independent rare isotope beams (RIBs) delivered to experiments, and, in particular, enabling the precision experiments on rare isotopes that aim to discover hints of new forces and particles beyond the SM. The final phase will see the ramp-up of the e-linac to full power of 500 kW, providing access to substantially more r-process isotopes. With three operating RIB production targets operational by 2020, the productivity of the ISAC experimental facility will more than double. TRIUMF will provide the expert staff for these projects through the NRC Contribution Agreement, while new capital will be provided in part through CFI funding via TRIUMF's member universities.

TRIUMF, together with the Canadian subatomic physics community, will maintain strong engagement in its high-profile, offshore activities with ATLAS at the LHC at CERN, the T2K long baseline neutrino experiment in Japan, and the antihydrogen experiment ALPHA at CERN.

TRIUMF will also be able to complete the high-power phase of the facility for ultra-cold neutrons, allowing for the chance to discover a neutron EDM and to support the Canadian subatomic physics community in developing new detector systems for experiments at SNOLAB and abroad, further enhancing Canada's position as a leading nation in nuclear and particle physics.

In this scenario, TRIUMF would prioritize any commercial revenues toward the refurbishment, acquisition, or construction of new technical and administrative space at the laboratory (please see Section 6.3.4). For instance, the IAMI initiative will need some new conventional facilities and services and a TRIUMF investment from commercial revenues might attract other partners. Some of the ageing trailers at TRIUMF would be replaced and modest upgrades of the detector development laboratories would be considered.

6.6.3 SCENARIO B: INCREASED RISK ($265.7M VIA NRC)

This scenario would have substantial negative impact on several aspects of the program.

Lost Opportunities

- TRUMF would have to scale back its plans to grow the nuclear medicine program. If no additional external funds could be secured, the opportunity to make innovations for the benefit of Canadian's health will be substantially reduced.
- With less investment into strengthening its industrial partnerships, TRIUMF would only be able to pursue a limited fraction of technology transfer opportunities.
- TRIUMF's experimental support facilities and beam lines would remain at 2010 levels and no upgrade would be implemented, reducing the opportunity to exploit the expanding secondary beam capabilities.

Increased Risks

- TRIUMF would be able to make only minimal investments in the most critical infrastructure upgrades thereby risking devastating consequences (e.g., failure of the site's power transformer or the 500 MeV cyclotron main magnet power supply). Other investments into needed infrastructure would have to be deferred, including the Meson Hall roof, mechanical services, machine shop, and communication systems.
- Due to curtailed material and supplies budgets, the operation of the accelerator facility would become less reliable because some maintenance activities, upgrades, and refurbishments directed at more reliable operation would not be carried out.

In this scenario, TRIUMF would prioritize commercial revenues toward refurbishment of technical space and administrative offices, especially IAMI and the ageing trailers.

6.6.4 SCENARIO C: RESTRICTED ($222.3M VIA NRC)

In this scenario TRIUMF would be forced to substantially cut back on its highest-priority programs, losing discovery opportunities and international standing, and would be forced to defer maintenance as well as infrastructure programs, dramatically increasing the risk of major failures. As a consequence, Canada would lose its international leadership position in nuclear and particle physics and its reputation as a reliable and strong partner for partners, such as Japan and CERN, and consequently jeopardize the investment Canada made in 2010–2015.

Damage to Discovery Science and International Reputation

- TRIUMF would have to stretch the construction schedule for ARIEL well into Five-Year Plan 2020–2025, effectively losing the opportunity to make a substantial scientific impact with full photo-fission and multi-user operation at a time when other new RIB facilities in the U.S., France, and Germany are still under construction. In particular, TRIUMF would lose the ability to carry out high-profile discovery science experiments like those searching for physics beyond the Standard Model (e.g., the RnEDM and FrEDM experiments that rely on the multi-user operation with the new proton beam line BL4N). Delay of the full power e-linac would allow other international facilities (e.g., SPIRAL2, FRIB), to be first in carrying out crucial experiments on neutron-rich nuclei on the r-process path, reducing Canadian capacity from one of discovery to one simply confirming others' work. TRIUMF's ability to deliver the Canadian side of the $10M memorandum of understanding with India's VECC laboratory would be compromised.
- The staff reductions would force TRIUMF to redirect staff to focus on the ARIEL completion project reducing the availability of expert engineering, design, and technical personnel for other projects. As a consequence TRIUMF would be reducing its capacity to be engaged in other priority projects of the Canadian community with negative impacts even on the highest-profile international efforts of ATLAS, T2K, and ALPHA (together involving more than half of the subatomic physics community). Support for other projects of the Canadian university community would be impacted more severely.
- TRIUMF would lose the capability to provide expanded space for the ATLAS Tier-1 Data Centre. The expansion would have to be limited to the bare minimum. A reduction in staff for this Tier-1 Centre with the smallest staff level worldwide would result in less reliable performance, and would negatively impact the excellent reputation of this facility. It would disrupt the ATLAS physics activities in Canada as well as around the world, causing serious delays in scientific output.
- TRIUMF would not have the funds to make the necessary investments into the beam line infrastructure and additional helium liquefaction system to bring the UCN facility from 1 to 40 μA, effectively delaying the phase when the neutron EDM experiment would become competitive until well into Five-Year Plan 2020–2025. TRIUMF would lose ground against the competition and potentially risk the possibility for a prize-worthy discovery. TRIUMF would not be able to fulfill its promises to the Japanese partners who are heavily investing in TRIUMF under the prospect of such discoveries.
- TRIUMF would have to defer the planned engineering study for the refurbishment of beam line BL1A in the Meson Hall until 2020–2025, risking failure and compromising the exploitation of new facilities (μSR and UCN) as well as commercial activities (irradiation, isotopes production).

Reduced Societal and Economic Benefits

- The budget would not allow investing into staff that is dedicated to foster industrial partnerships, resulting in a loss of technology transfer opportunities.
- The emergent Nuclear Medicine Program would stagnate and lose capability to attract external and industrial partners.
- The budget would make TRIUMF's science program less attractive and competitive on the international level, making it harder for TRIUMF researchers as well as the users from Canadian and international universities to attract top-level graduate students; the undergraduate co-op student program would be eliminated, thereby reducing the number of students and eventually impacting the level of highly qualified personnel.

Risks to Operations, Infrastructure, and Skilled Workforce

- TRIUMF would be forced to curtail maintenance and development activities for its in-house science program, which would lead to a dramatic increase in the risk of component failure or the loss of new components.
- TRIUMF would be forced to cut its staff complement by 36, severely reducing the capability to carry out maintenance, facility operation, and project development.
- Since only modest cost-of living adjustments could be made, staff salaries would become even less competitive, dramatically increasing the risk of losing key personnel and limiting TRIUMF's ability to attract the skilled staff it needs.

In this scenario, TRIUMF would direct any accumulated commercial revenues toward mitigating the largest impacts. For instance, resources if available would be prioritized to support limited undergraduate student participation in TRIUMF, to deal with the potential failure of a critical and major piece of equipment associated with the main cyclotron (main magnet power supply or site-wide transformer), or to keep ARIEL completion moving forward.

PRIORITIES	SCENARIOS FOR NRC CONTRIBUTION AGREEMENT		
	Optimal **$290.0 M**	**Increased Risk** **$265.7 M**	**Restricted** **$222.3 M**
ARIEL completion	Full completion = top international RIB facility	Full completion = top international RIB facility	Stretch project = loss of leadership in RIB science
Skilled Personnel	**$182,000,000**	**$182,000,000**	**$161,200,000**
Operational M&S	**$84,200,000**	**$73,100,000**	**$61,100,000**
Salaries, M&S adjustments	Fund required highly skilled staff, capable to follow utility prices = World-class excellence in science; increase HQP; deliver on all promises	Fund required highly skilled staff, capable to follow utility prices = World-class excellence in science; increase HQP; deliver on all promises	36 FTE reduction, min. economic adjustments, cut student program = Loss of key staff; fail on objectives for operations, projects, HQP
Cyclotron & ISAC	Optimal = World-class excellence in science	Sub-optimal = High impact science, risk of lower quantity	Reduced = Limited quantity and impact of science output
ARIEL operations	Timely exploitation = High-impact science, prize worthy discovery potential	Timely exploitation = High-impact science, prize worthy discovery potential	Limited exploitation = Some high-impact science, loss of discovery potential
Strategic Initiatives	**$9,100,000**	**$3,600,000**	**$0**
ATLAS Tier-1	Expansion and fully reliable operation = High-impact science, maximize international relevance	Expansion and fully reliable operation = High-impact science, maximize international relevance	Reduced reliability, limited expansion = Science output severely impacted, loss of international relevance
Ultra-Cold Neutrons	Implement full capabilities = Prize-worthy discovery potential, capitalize on international investments	Implement full capabilities = Prize-worthy discovery potential, capitalize on international investments	Reduced to minimum capabilities = Discovery potential lost, failure to deliver on international agreements
International endeavours (ATLAS/LHC, T2K, ALPHA, LC, etc.)	Support intl. experiments and new accelerator projects = Canadian leadership, maximum economic impact	Support intl. experiments and new accelerator projects = Canadian leadership, maximum economic impact	Limited support = Loss of Canadian leadership, loss of economic opportunities
Institute for Accelerator-based Medical Isotopes	Optimal staff = Maintain natl. leadership, address national priorities	Seek external staff funding = Maintain natl. leadership, address national priorities	No leverage for external funding = Loss of national leadership in isotope production
Industrial Partnerships	Invest into long-term tech transfer capability = Increased economic benefit	Maintain limited tech transfer capability = Limited economic benefits	Loss of tech transfer capability = Minimal economic benefits
Infrastructure	**$14,700,000**	**$7,000,000**	**$0**
Infrastructure renewal	Address deferred maintenance = Reliable infrastructure for scientific excellence	Minimal = Increased risk of equipment failure, lost time	Defer = Risk of unmitigated catastrophic equipment failure

Table 1: Summary of the impacts in three budget scenarios.

	Optimal	Increased Risk	Restricted
Total Salaries & Benefits	171,500	171,500	156,500
Inflation Adjustment	10,500	10,500	4,700
Operational Costs			
Net Power Costs	22,850	22,850	20,350
Administrative Support	3,650	3,150	2,950
ISAC Beam Development	3,000	1,500	1,000
Site Infrastructure	12,650	12,050	11,000
Safety, Security and Quality Assurance	2,930	2,730	2,730
Accelerator Division	11,600	11,100	8,150
Engineering Division	8,150	6,750	4,850
Science Division	9,000	6,000	4,500
Insurance, Office Services, ERP	2,970	2,870	2,770
Nuclear Medicine Division	2,500	1,800	1,500
Total Operational Costs	79,300	70,800	59,800
Inflation Adjustment	4,900	2,300	1,300
Strategic Initiatives			
IAMI Support	1,500	500	0
Commercialization Support	1,500	1,000	0
Ultra-Cold Neutron Facility (MOU)	1,600	1,600	0
Atlas Tier-1 Physical Expansion	500	500	0
University Engagement	1,500	0	0
Participation in International Endeavours	2,500	0	0
Total Strategic Initiatives	9,100	3,600	0
Infrastructure			
Site Power, Equipment, and Mechanicals	2,100	1,000	0
Cyclotron Refurbishing & Power Supply	3,000	2,000	0
Meson Hall Roof and Facilities	2,000	0	0
Beam Line 1A Engineering Study	2,000	2,000	0
Space Expansion (equip and operating)	3,100	400	0
ISAC Refurbishment	2,500	1,600	0
Total Infrastructure	14,700	7,000	0
Total NRC Contribution	290,000	265,700	222,300

Table 2: Summary of budget allocations in three scenarios.
Proposed operating budgets include funds for operating ARIEL, the ATLAS Tier-1 Data Centre, and so on.

6.6.5 CONCLUSION

In consultations with its various stakeholders, TRIUMF has developed a strategic plan that lays out how Canada can capitalize on its past investments in an optimal way and strengthen Canada's leadership position in particle and nuclear physics through strategic program enhancements and infrastructure upgrades.

To aid decision makers, several implementation strategies have been laid out, including a summary of
the trade-offs, lost opportunities, and risks that arise from reduced funding of TRIUMF's operation through the NRC Contribution Agreement. To achieve an optimal return on investment, $290 million is required over the period 2015 to 2020. TRIUMF will seek additional funding from CFI, WD, and provincial governments to support the ambitions for ARIEL completion, the Institute for Accelerator-based Medical Isotopes, and so on.

The priorities, trade-offs and impact of the three scenarios are summarized in Table 6.4.2.2. ARIEL completion and maintaining the highly specialized and skilled workforce to build ARIEL and operate the facility remain the highest priorities. The optimal scenario results in high impact in advancing knowledge, being an international leader, educating future leaders, and generating both societal and economic benefits.

In the increased-risk scenario, compromises will be made regarding materials and supplies for maintenance (Operational M&S) and program growth and investments to upgrade aging infrastructure needed to enable completion and operation of the flagship programs and to generate science output. These compromises will incur risk and result in lost opportunities.

The restricted flat-flat scenario will have a grave impact on all aspects of the program, including loss of international leadership in new flagship programs as well as existing ones and reduced output in science, highly qualified personnel, and societal and economic benefit.

6.7 DEVELOPMENT OF FIVE-YEAR PLAN 2015–2020

To develop its Five-Year Plan 2015–2020 TRIUMF engaged its user community through a process of consultation and feedback, which began in 2011, with the publication of the Long Range Plan of the Canadian Subatomic Physics Community. The formal five-year plan consultation process was started in the summer of 2012 at the joint meeting of the Institute for Particle Physics (IPP) and the Canadian Institute for Nuclear Physics (CINP) during the Annual Congress of the Canadian Association of Physicists (CAP) as well as at the Annual General Meeting of the TRIUMF Users Group (TUG-AGM). At these meetings, TRIUMF announced the planning process and requested input into the plan. In addition electronic messages with the same information were distributed to the whole TRIUMF user community.

The community submitted short project requests that included project cost estimates, resource requirements, and funding strategies, to the Policy and Priorities Advisory Committee (PPAC) by September 2012.

PPAC, which comprises representatives of the scientific community from its member universities, reviewed over 80 submissions and identified the highest priority projects, using the following criteria:

1. Potential for scientific impact considering the required TRIUMF resources;

2. Benefit to the Canadian university research community;

3. Benefit to broader Canadian society and industry; and

4. Technical feasibility, readiness, and the likelihood of success.

The PPAC chair reported the results of the Committee's evaluation at the November 2012 Advisory Committee on TRIUMF (ACOT) meeting.

The Five-Year Plan Steering Committee, which comprises community representatives and TRIUMF staff members across all scientific fields, developed the outline and strategy for Five-Year Plan 2015–2020 and in early 2013 engaged more than 80 authors to provide contributions and help with editing the document.

The overall plan was presented again, at the joint IPP/CINP meeting at the May 2013 CAP Congress and at the July 2013 TUG-AGM meeting. The TRIUMF Board of Management, ACOT, and the Evaluation Committees for Life Science (LSPEC), Subatomic Physics (SAP-EEC), and Molecular and Materials Science (MMS-EEC) have been providing feedback throughout the process, and ACOT and the Board of Management have endorsed the strategy and priorities of the plan.

6.8 OUTLOOK

Five-Year Plan 2015–2020 is bold; it is founded on the premise that Canadian leadership in key areas of research is worth capitalizing on and that this basic research excellence can be translated into societal and economic benefits for all of Canada.

But the real engine behind Canadian science and innovation, the real inspiration that fuels TRIUMF and its community, day after day, is the excitement and the wonder that comes from working with colleagues to pursue the answers to basic questions about not just the world around us but also the universe. It is a drive defines us as human beings. This plan fulfills on that fundamental drive and promises to deliver the broader benefits that make science a publicly shared enterprise.

[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.

Appendices

A

APPENDICES

COMPLETE TABLE OF CONTENTS

A.1 EXPERIMENTAL FACILITIES GLOSSARY

8π
A "super-microscope" used to examine the behaviour and structure of atomic nuclei, which are collected at the centre of 8π where they undergo radioactive decay, located in ISAC-I.
Contact: Adam Garnsworthy

ARIEL
(Advanced Rare IsotopE Laboratory)
A project to broaden TRIUMF's capabilities to produce rare isotope beams and to showcase new Canadian accelerator technology using electron beams.
Contact: Lia Merminga and Remy Dawson

β-NMR
An exotic form of nuclear magnetic resonance (NMR) in which the nuclear spin-precession signal is detected through the beta decay of a radioactive nucleus, located in ISAC-I.
Contact: Gerald Morris

CFBLS
(Collinear Fast-Beam Laser Spectroscopy)
An experiment designed to exploit the high beam intensity and radioisotope-production capability of the ISAC-I facility in order to measure the hyperfine energy levels and isotope shifts of short-lived isotopes.
Contact: Matthew Pearson

CsI Array
A detector used together with TIGRESS for detecting charged particles from reactions.
Contact: Kris Starosta

DESCANT
(DEuterated SCintillator Array for Neutron Tagging)
A neutron detector array to be used at ISAC.
Contact: Paul Garrett

DRAGON
(Detector of Recoils and Gammas of Nuclear Reactions)
A detector designed to measure the rates of nuclear reactions important in astrophysics, located in ISAC-I.
Contact: Chris Ruiz

DSL
(Doppler Shift Lifetimes facility)
An experimental setup for the measurement of the lifetimes of excited states of nuclei.
Contact: Barry Davids

EDM
The Radon EDM experiment uses contemporary spectroscopy techniques to measure the influence of a parity-violating external field on the angular distribution of gamma rays from polarized odd-spin Rn atoms.
Contact: Matthew Pearson

EMMA
(ElectroMagnetic Mass Analyzer)
A device being constructed to study the products of nuclear reactions involving rare isotopes located in ISAC-II.
Contact: Barry Davids

FTF
(Francium Trapping Facility)
A facility used to measure the anapole moment of francium in a chain of isotopes by observing its parity violating character, induced by the weak interaction.
Contact: Matthew Pearson

GPS 4π Gas counter
A high-efficiency detector for making very precise measurements of beta-decay half-lives.
Contact: Adam Garnsworthy

GRIFFIN
(Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei)
A detector at ISAC for studying nuclear decays at high resolution.
Contact: Adam Garnsworthy

HERACLES
(HEavy-ion Reaction Array for the characterization of Light Excited Systems)
A device used for multi-fragmentation studies at intermediate energies, located in ISAC-II.
Contact: Gordon Ball

IRIS
(ISAC chaRged partIcles spectroscopy Station)
A detector designed to use nuclear reactions as a microscope to look into the core of nuclear isotopes with large neutron to proton ratios, located in ISAC-II.
Contact: Ritu Kanungo

ISAC
(TRIUMF Isotope Separator and Accelerator)
A 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.

μSR
(Muon Spin relaxation and Resonance) Spectroscopy
An intense beam of polarized Muons are utilized to probe the properties of different materials at the microscopic level.
Contact: Syd Kreitzman

SHARC
(Silicon Highly-segmented Array for Reactions and Coulex)
Designed for stand-alone use or integration with TIGRESS, SHARC is a device suited for particle detection from reactions, located in ISAC-II.
Contact: Greg Hackman

SPICE
(The SPectrometer for Internal Conversion Electrons)
An in-beam electron spectrometer that operates in conjunction with TIGRESS, located in ISAC-II.
Contact: Adam Garnsworthy

TACTIC
(TRIUMF Annular Chamber for Tracking and Identification of Charged particles)
A device used in conjunction with TUDA.
Contact: Chris Ruiz

TIGRESS
(TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer)
A detector in ISAC-II for studying nuclear decays with high resolution.
Contact: Greg Hackman

TIP
(TIGRESS Integrated Plunger)
A device that uses accelerated radioactive or stable beams from ISAC-II and a variety of reaction mechanisms for electromagnetic transition studies of nuclei far from stability.
Contact: Greg Hackman

TITAN
(TRIUMF's Ion Trap for Atomic and Nuclear science)
An ion trap facility at ISAC-I for high precision mass measurements of rare isotopes.
Contact: Jens Dilling

TRINAT
(TRIUMF Neutral Atom Trap)
A device to trap and study the radioactive decays of neutral atoms, located in ISAC-I.
Contact: John Behr

TUDA
(TRIUMF U.K. Detector Array)
A detector designed to measure the rates of nuclear reactions important in astrophysics, located in ISAC-I
Contact: Chris Ruiz

UCN
(Ultra-Cold Neutrons)
The UCN source allows experimenters to precisely measure neutron beta decay and quantum levels of neutrons in Earth's gravitational field. It also facilitates the search for the non-zero neutron electric dipole moment (nEDM).
Contact: Akira Konaka

A.2 LOGIC MODEL

Inputs

NRC operating funds

Land and buildings (leasing agreements)

Equipment and facilities

In-house and external researchers and staff

Funds and equipment from private-sector partners (partners collaborate with and invest in TRIUMF activities)

Organizational and governance structure

Government direction and consent

Activities

Knowledge creation

Conducting research at a global scale on: particle & nuclear physics, nuclear medicine, accelerator physics, and molecular & materials science

Producing particles, beams, and isotopes for research uses

Technology services

Producing isotopes for clinical and industrial users

Providing particle beams for irradiation services

Designing and constructing accelerators and detectors

Developing business opportunities for physics-based technologies

Societal contributions

Providing radiation therapy services for specialized eye cancers

Producing isotopes for clinical use and commercial sale

Providing technical consulting services to Canadian universities, industry, and others

Providing training for post-secondary students & post-docs in advanced research environment

Conducting outreach & science promotion activities

Identifying & creating opportunities for international partnerships in science & business

Direct Outputs

Particle beams • Isotopes • Detectors, accelerators, and associated components (including related computing infrastructure) • Papers and publications • Highly qualified personnel (trained students and trained professionals) • Outreach events • MOUs and agreements for research collaborations • Technical consulting contracts and deliverables • Patents and licences

Beneficiaries

Canadian and international researchers, scientists, and university students and post-doctoral fellows

Canadian medical research organizations

Canadian firms involved in nuclear medicine and other isotope-science applications

Canadian high-technology SMEs

Canadian public, high school students and teachers

Immediate Outcomes

International recognition and participation

Canadian university researchers use TRIUMF as a hub for international science

Global scientists and students have access and use TRIUMF facilities and vice versa

Canadian scientists and engineers are highly valued in the areas of subatomic and accelerator physics

Canadian companies working with TRIUMF generate economic output and expand exports

Attraction and retention of global talent in areas of TRIUMF expertise

Societal enhancement

Canadian firms supply equipment and apparatus required by TRIUMF and international projects

Canadian firms develop and commercialize new products

Canadian universities are more competitive in terms of attraction and recruitment

HQP

Canadian high-school students, teachers, and public understand the role of subatomic physics R&D and accelerators

Intermediate Outcomes

Scientific advancement

Canadian scientists and researchers participate in and contribute to the worldwide network of subatomic physics & accelerator facilities located in the major countries of the industrialized world

Continued Canadian worldwide excellence in physics & astronomy

New knowledge and discoveries stemming from international research collaborations and partnerships

Breakthroughs in diagnosing and treating Parkinsons' diseases, other degenerative brain diseases, and cancer

Mobilization and circulation of Canadian talent

Economic impacts

Enhanced global competitiveness resulting in direct and substantial benefits accruing to Canadian companies and the economy

Enhanced quality of life for employees/workers in Canadian firms

Continued growth of an advanced technology cluster in BC, focusing on particle accelerators and their application to molecular imaging

Final Outcomes

Improved quality of life and economic growth in Canada through knowledge creation as well as the development and commercialization of new technologies in the physical and life sciences with potential applications in healthcare, environmental sciences, natural resources and engineering

A.3 SUMMARY STATISTICS

A.3.1 TRIUMF Involvement in NSERC 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 research community.

Figure 1 identifies the annual dollar value of the NSERC subatomic physics grant envelope 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. The envelope funds both theoretical and experimental subatomic physics.

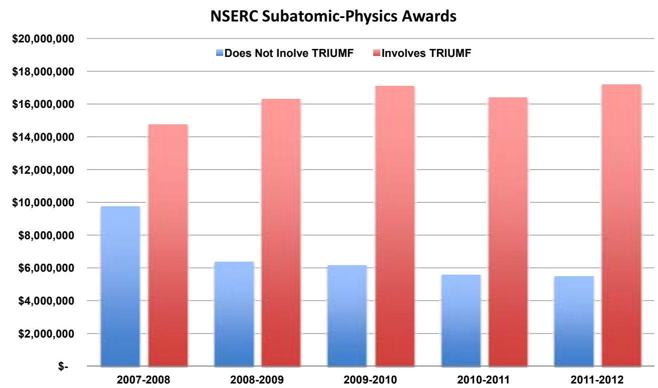


Figure 1: Value of NSERC-funded subatomic physics grants for each of the five past fiscal years separated into awards that involve TRIUMF in some fashion and those that do not.

A.3.2 Scientific Users

Many scientists and students from around the world visit TRIUMF each year to conduct research, participate in meetings, and receive training and support. TRIUMF tracks these visitors in a number of ways. Figure 2 shows trends in the origins of scientific visitors to TRIUMF over the past five years; these data are from the visitor's logbook at the front reception desk.

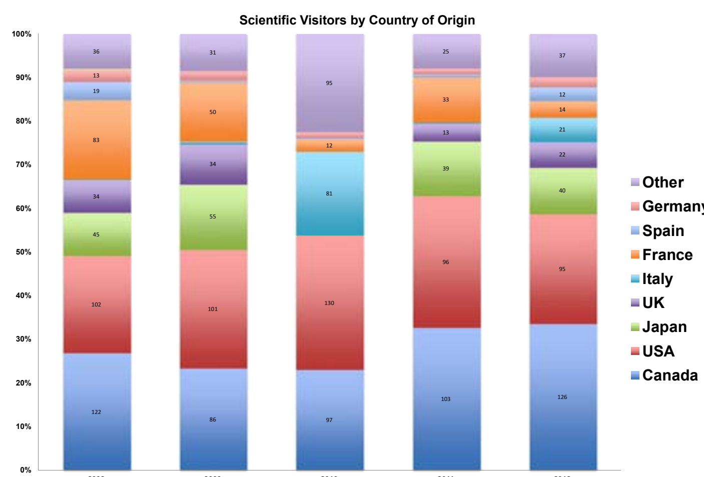


Figure 2: National origins of scientific visitors to TRIUMF over the past five years.

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. In 2013 there were 317 people in the TRIUMF users group. This group is diverse bringing in expertise from across Canada and the world to TRIUMF. The chart below shows the breakdown of the place of origin for this group.

Country	Number of TUG members
Canada	201
USA	61
United Kingdom	14

Country	Number of TUG members
Japan	13
Germany	9
Switzerland	5
Other	12

A.3.3 Awards

While TRIUMF does not track the awards or recognition given to the broad community of TRIUMF users we do have an informal tracking system for awards given to TRIUMF staff and several principal users of TRIUMF. TRIUMF's unique set of facilities and expertise make it a center of innovation in Canada and on the international scale. It is worth noting that in the present FY2013-2014, TRIUMF staff have already been awarded the most prestigious Canadian subatomic physics prize as well as collecting three prizes in nuclear medicine from the U.S.-based Society for Nuclear Medicine and Molecular Imaging.

Fiscal Year	# Awards
FY2008-2009	10
FY2009-2010	14
FY2010-2011	6
FY2011-2012	11
FY2012-2013	7

A.3.4 Student Training at TRIUMF

All research activities in which TRIUMF engages or supports involve students and post-doctoral fellows. This principle is fundamental to TRIUMF's mission as a laboratory for basic research that supports Canadian excellence in science and innovation. Apart from supporting its scientific endeavours, TRIUMF acts as a training ground and an inspiration for new scientists to gain the expertise that will then be applicable later on in life in a variety of industries in Canada. Creating and inspiring the next generation of innovators is one of TRIUMF's key goals. The table below lists the number of graduate students at TRIUMF each fiscal year as tracked by TRIUMF's financial systems (for stipends). Additional graduate students work at TRIUMF that are not paid through TRIUMF's financial office and are therefore not tracked.

Graduate Students

Funding Source	NRC		NSERC		CIHR		Other		TOTAL
Foreign Status	CAN	FOR	CAN	FOR	CAN	FOR	CAN	FOR	
FY2008-2009	3	6	12	14	0	6	0	0	41
FY2009-2010	7	5	13	9	0	5	0	0	39
FY2010-2011	3	6	17	10	1	6	0	0	43
FY2011-2012	5	5	8	13	1	5	0	0	37
FY2012-2013	4	4	8	14	1	4	0	0	35
Subtotals	22	26	58	60	3	26	0	0	195
Totals		48		118		29		0	195

Apart from graduate students TRIUMF also hires undergraduate co-op students. The students were hired to fill four-month work terms, carrying out tasks as assigned by their TRIUMF supervisors. In addition, TRIUMF awards scholarships to exceptional undergraduate students, one from each of the five geographic areas of Canada. As part of their work term students attend lectures regarding everything from particle physics to presentations skills, as well as participating in research, giving them a wide breadth of knowledge which will help them excel in their field of study. Again, additional undergraduate students work at TRIUMF but are not paid through TRIUMF's financial office.

Undergraduate Students

Funding Source	NRC		NSERC		CIHR		Other		TOTAL
Foreign Status	CAN	FOR	CAN	FOR	CAN	FOR	CAN	FOR	
FY2008-2009	56	3	5	1	0	3	4	0	72
FY2009-2010	53	5	2	1	0	5	2	0	68
FY2010-2011	60	6	3	1	0	6	0	0	76
FY2011-2012	58	4	9	2	0	4	1	0	78
FY2012-2013	58	3	10	1	0	3	1	0	76
Subtotals	285	21	29	6	0	21	8	0	370
Totals		306		35		21		8	370

A.3.5 Seminars

TRIUMF provides regular seminars to educate and update its 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. The table below 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 targeted at the general public, has proved to be extremely popular, and attendance is often "standing room only."

	2008 –2009	2009 –2010	2010 –2011	2011 –2012	2012 –2013	5 years Total
Accelerator Seminars	4	3	22	27	17	77
Journal Club	0	10	7	0	0	17
Saturday Lectures	12	10	14	18	20	78
ISAC Seminars	2	0	1	0	0	3
Technical Seminars	2	27	30	34	26	125
Theory	4	3	22	27	17	77
UBC Physics	0	0	0	1	2	3
Student	12	12	14	16	58	112
Science Seminars	63	48	46	57	67	306
Total Number of Seminars	99	113	156	180	207	798

A.3.6 Conferences

TRIUMF helps organize workshops and conferences, which are important in the scientific community to disseminate information and establish contacts among scientists. Below is a list of conferences, workshops, and institutes that TRIUMF has either organized or co-organized.

Staff reductions in TRIUMF's conference-services office have had an impact on the lab's overall engagement in organizing conferences, but the laboratory continues to bring a half-dozen mid-to-large-scale, international conferences to Canada each year.

Year	2007/2008	2008/2009	2010/2011	2011/2012	2012/2013
Number of conferences	7	8	11	9	5
Economic Impact	$1,615,000	$2,318,375	$2,651,575	$952,850	–

A.3.7 Public 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.

The table below 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 fiscal years 2008–2013. Tour groups of more than 15 people require multiple tour guides.

Category	2008-09	2009-10	2010-11	2011-12	2012-13
General Public					
# of people	475	1845	616	820	891
# of tours	143	150	179	208	214
# of guides	146	161	181	214	237
Science					
# of people	666	1004	1581	1184	1089
# of tours	45	55	83	91	78
# of guides	76	105	177	136	124
Students					
# of people	491	574	952	844	751
# of tours	23	26	37	47	35
# of guides	50	53	90	83	70
VIP					
# of people	356	198	190	97	99
# of tours	72	54	38	28	41
# of guides	92	63	52	28	42
Total					
# of people	1988	3621	3339	2945	2830
# of tours	283	284	337	374	368
# of guides	358	382	500	461	473

A.3.8 Media Coverage

TRIUMF subscribes to an online media monitoring service which aggregates articles related to TRIUMF and its work. In the past 5 years, over 950 articles about TRIUMF were printed in publications in Canada, the U.S., and on the World Wide Web (see Figure 3). These articles range from a discussion of TRIUMF's support of high school science fairs to the discovery of the Higgs boson. Features covered TRIUMF's activity in the field of nuclear medicine, its participation in the international community, and its effect on the local community.

Below are selected examples of the breadth and depth of TRIUMFs media coverage using 2012 as a sample year.

- **Aljazeera – Jul 20 2012**, "Scientists begin to safely produce isotopes" Daniel Lak, Researchers at TRIUMF develop a safe way to produce radioactive isotopes that treat cancer without the need for a nuclear reactor and the associated hazards.
- **BC Business** – **Mar 2012**, "Rise of the Cyclotron" Roberta Staley, A factory in Richmond which with TRIUMF's technological assistance has become the global go-to place for isotope-producing cyclotrons
- **CBC** (1 of 3 TRIUMF related articles in 2012) – **Mar 7 2012**, "Antimatter atom 'measured' for first time" Emily Chung, TRIUMF led team of scientists trap antihydrogen and perform measurements that have never before been possible.
- **CBC** (1 of 3 TRIUMF related articles in 2012) – **2012**, "Canadian experts eagerly await 'God particle' announcement" More than 100 Canadian researchers who have been working on gathering evidence for the Higgs boson await the announcement of it discovery.
- **The Globe and Mail** (1 of 2 TRIUMF related articles in 2012) – **Feb 19 2012**, "Canadians sparkle in galaxy of science stars" Mark Hume, TRIUMF's Lia Merminga discusses Canadian advances in accelerator physics at the American Association for the Advancement of Science conference held in Vancouver.
- **National Post** (1 of 3 TRIUMF related articles in 2012) – **Mar 29 2012**, "PET imaging has revolutionized cancer care" Susan Martinuk, A report on Canada's utilization of PET imaging for early cancer detection.
- **PHYS.org** (1 of 3 TRIUMF related articles in 2012) – **Oct 29 2012**, "Using the world's rarest element to study the world's rarest force" TRIUMF Scientists are studying the rare element Francium to delve into understanding the elusive strong force.
- **Montreal Gazette** – **Mar 6 2012**, "Student Project Draws attention" Marisa Babic, TRIUMF scientists invite Canada Wide Science Fair medalist to science symposium and for a private tour of the facility.
- **Vancouver Sun** (1 of 15 TRIUMF related articles in 2012) – **Oct 1 2012**, "Vancouver could become the Silicon Valley of medical isotopes" Nigel S. Lockyer and Richard Eppich, TRIUMF and the associated BC industries could soon turn Vancouver into a global hub of medical isotopes and nuclear medicine.

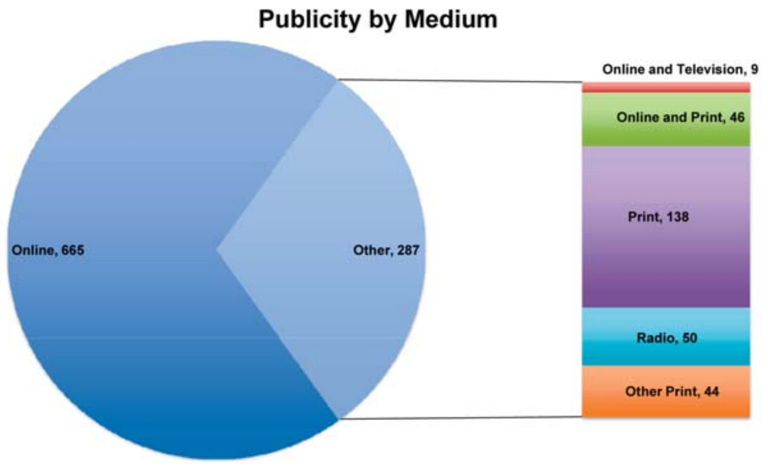


Figure 3: Media coverage featuring TRIUMF, sorted by type of medium. These data are collected through manual review of returns from Google News and Meltwater News clipping services.

A.3.9 Accelerator Availability

The cyclotron is the starting point of most of the science that comes out of TRIUMF, as such making sure that it is functioning is of prime importance. We pride ourselves on maintaining our cyclotron in such a way that experiments can go as planned, and we achieve this with a 90% success rate. This number remains consistent with cyclotron availability being just around 90% for the past 20 years (see Figure 4).

The TR13 cyclotron is a small medical cyclotron used to generate longer-lived PET isotopes primarily for brain research at UBC, cancer research at BC Cancer Agency, and smaller projects. Figure 5 chart provides a historical view of the number of “runs” per year for the TR13. The numbers tell the same story of TRIUMF’s commitment to efficiency as with the main 520 MeV cyclotron. The availability in 2010 was 98%.

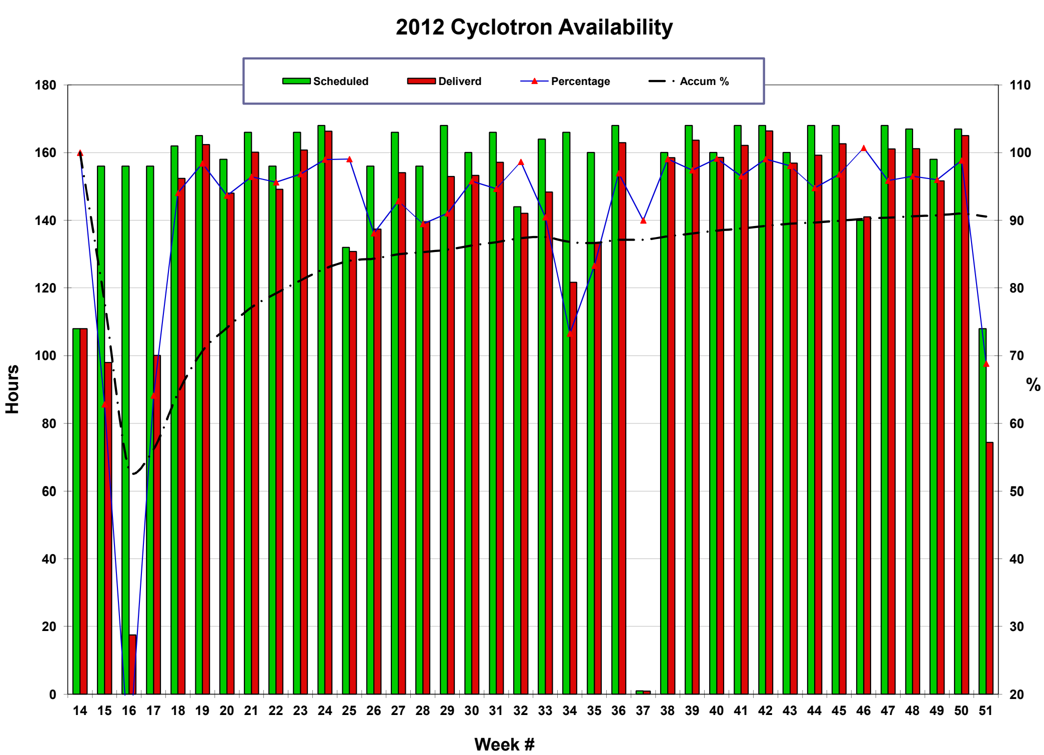


Figure 4: Historical uptime and availability of TRIUMF’s main cyclotron.

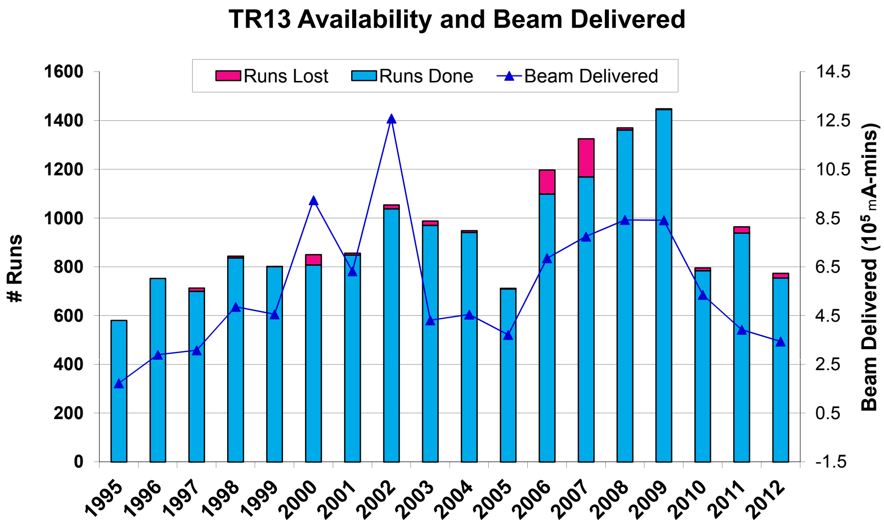


Figure 5: History of medical isotope production runs for the TR-13 cyclotron at TRIUMF.

A.3.10 Machine Shop & Design Office

The machine shop is a key part of TRIUMF used to create experiments efficiently and economically. For the Machine Shop (MS) and Design Office (DO), we report several measures. Hours-worked data collected by monthly timesheets confirm that these units have been fully occupied completing jobs for TRIUMF and its community.

The number of completed work packages ("jobs") is shown in the table as well. We now track Engineering Change Orders on an annual basis in the Design Office; in FY2012 this numbered 196 jobs in addition to the 80 listed below. Please note that jobs vary in complexity, duration, and level of effort.

Fiscal Year	MS FTEs	MS Jobs	DO FTEs	DO Jobs
FY2008-2009	17	570	12	72
FY2009-2010	18	590	11	67
FY2010-2011	17	475	11	48
FY2011-2012	16	529	10.5	38
FY2012-2013	17	592	9	80

The Machine Shop maintains a regular work queue that has a steady wait time of 8-16 weeks for a submitted job to make it to the floor. Detailed scheduling taking into account priorities and availabilities (of people and machines) determines what jobs get done first. At times, fabrication & assembly jobs will be sent to an outside vendor in order to meet schedule requirements when high-priority jobs are in competition. We report the total dollar value of externally contracted MS work here, year by year; these figures give a sense of the "oversubscription" of the Machine Shop.

Fiscal Year	Value $	Purchase Orders	Jobs
FY2008-2009	$296k	54	201
FY2009-2010	$5k	5	7
FY2010-2011	$226k	13	20
FY2011-2012	$229k	15	22
FY2012-2013	$37k	4	14

Some of the reduction in externally contracted work in FY2012-2013 was because of a new acquisition of hardware within the Machine Shop – a fully modern "water-jet cutter".

A.3.11 Patents

The table below lists the TRIUMF and AAPS, Inc. patent portfolio for the five-year period 2008–2012. Note the many instances of multiple foreign filings, which are normally executed after the Patent Cooperation Treaty (PCT) filing is granted. One new patent filing regarding cyclotron production of Tc-99m is not included.

Opportunity Title	Patent Title	Country	Filing Date	Granted Date
A Method and Apparatus for Vetoing Random Coincidences in Positron Emission Tomography	Method and Apparatus for Vetoing Random Coincidences in Positron Emission Tomographs	Japan	2006-09-19	2011-03-04
Unidimensional Array 3-D Position Sensitive Ionization Detector	Unidimensional Array 3-D Position Sensitive Ionization Detector	Japan United States	2006-09-19 2005-03-18	2011-02-10 2009-04-14
Method of Forming Composite Ceramic Targets	Method of Forming Composite Ceramic Targets	United States	2005-06-08	2010-03-23
Forced Convection Target Assembly	Forced Convection Target Assembly	European Union Canada Japan United States	2006-12-01 2006-12-22 2006-12-25 2005-06-29	2012-08-08 2012-04-09 2012-04-24 2012-08-21
Geological Tomography Using Cosmic Rays	Geological Tomography Using Cosmic Rays	United States United States	2007-11-19 2006-02-17	2009-05-12 2009-02-10
Self-Supporting Multilayer Films Having a Diamond Like Carbon Layer	Self-Supporting Multilayer Films Having a Diamond Like Carbon Layer	United States	2009-07-21	Abandoned
Higher Pressure, Modular Target System for Radioisotope Production	Higher Pressure, Modular Target System for Radioisotope Production	World / WIPO Australia	2008-06-23 2009-12-17	National Phase Lapsed
	High Pressure, Modular Target System for Radioisotope Production	Japan	2009-12-21	Lapsed
	Higher Pressure, Modular Target System for Radioisotope Production	Canada European Union United States	2009-12-21 2010-01-21 2008-06-23	Lapsed Lapsed Abandoned
Method and Apparatus for Isolating 186-Re	Method and Apparatus for Isolating a Radioisotope	United States	2010-02-26	2012-03-07
	Method and Apparatus for Isolating 186-Re	Australia United States	2009-09-29 2008-03-31	2013-03-28 2010-05-04
Improved Methods For Penning Trap Mass Spectroscopy	Methods For Penning Trap Mass Spectroscopy	World / WIPO	2008-05-05	Lapsed
	Improved Methods for Penning Trap Mass Spectroscopy	United States	2008-05-05	Lapsed

Opportunity Title	Patent Title	Country	Filing Date	Granted Date
Sugar-Ferrocenyl-Chloroquine Derivatives as a New Class of Antimalarial Agents	Carbohydrate-Metallocene-Antimalarial Conjugates	World / WIPO	2010-02-22	Lapsed
	Sugar-Ferrocenyl-Chloroquine Derivatives as a New Class of Antimalarial Agents	United States	2009-02-20	Converted
	Ferrocenyl Carbohydrate Chloroquine Conjugates as Potential Antimalarials	United States	2010-02-15	Converted
	Carbohydrate-Metallocene-Antimalarial-Conjugates	United States	2010-02-22	Lapsed
Detector for Gamma Rays	Detector for Gamma Rays	Japan	1999-09-02	2008-11-28
System and Method for the Production of 18F-Fluoride	System and Method for the Production of 18F-Fluoride	European Union Belgium Canada France Germany Italy Netherlands United Kingdom	2002-08-22 2001-02-23 2001-02-23 2001-02-23 2001-02-23 2001-02-23 2001-02-23 2001-02-23	2009-04-29 2009-04-29 2010-08-10 2009-04-29 2009-04-29 2009-04-29 2009-04-29 2009-04-29
High Resolution 3 D Position Sensitive Detector for Gamma Rays	High Resolution 3-D Position Sensitive Detector for Gamma Rays	Canada Japan Australia	2005-01-05 2005-01-07 2005-01-10	2011-09-13 2011-02-04 2009-01-22
Apparatus and Method for Generating 18 F-Fluoride by Ion Beams	Apparatus and Method for Generating 18 F - Fluoride by Ion Beams	Korea	2003-12-04	2008-08-22
	Apparatus and Method for Generating 18 F - Fluoride by Ion Beams	Canada	2003-12-11	2008-11-04
Radioactive Ion	Radioactive Ion	European Union	2004-07-09	2008-07-31
Method and Apparatus for Isolating the Radioisotope Molybdenum-99	Method and Apparatus for Isolating the Radioisotope Molybdenum-99	World / WIPO Canada United States	2009-10-01 2012-03-29 2009-10-01	Pending Pending Pending

A.4 COMMITTEES PROVIDING ADVICE AND REVIEW OF THE FIVE-YEAR PLAN

TRIUMF has a number of planning, advisory, and oversight committees. In preparing the Five-Year Plan report, TRIUMF has had extensive formal consultations with the Canadian and international community through these committees.

The groups 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, the Experiments Evaluation Committees (EEC), the TRIUMF Users Executive Committee (TUEC), and the Accelerator Advisory Committee (AAC).

The memberships of these committees are listed below noting the frequency of meetings. In addition to these standing committees, TRIUMF instituted a Five-Year Planning Steering Committee to oversee the preparation of the Five Year Plan report. Its membership is also provided.

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. The committee meets twice a year. The Committee provides scientific program advice to the Director of TRIUMF. The Committee reports to the National Research Council each year on its findings and recommendations, with particular reference to the arrangement entered into by the National Research Council and TRIUMF under which contribution payments are made, thereby ensuring that TRIUMF utilizes its program in support of its defined role as a national facility and works with all constituencies of the Canadian subatomic physics community to sustain a national program in the field of research, within the context of the funds available.

Members:

Chair: David B. MacFarlane, SLAC
Secretary: Deva Delanoë,
NRC Planning and Policy Analyst
Kerstin Borras, DESY
Cliff Burgess, McMaster U.
Jacques Lettry, CERN
Paul Mantica, NSCL
Bradley Sherrill, NSCL
Michel Têtu, Laval University (retired)
David Weitz, Harvard U.
D. Scott Wilbur, U. of Washington

Ex-Officio Members:

Samir Boughaba, representing NSERC
Bonnie Fleming, representing NSERC Subatomic Physics Evaluation Section
Gerald Gwinner, representing NSERC Subatomic Physics Evaluation Section
Kumar Sharma, representing Canadian Institute of Nuclear Physics
William Trischuk, representing the Institute of Particle Physics
R. Paul Young, representing the TRIUMF Board of Management

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 TRIUMF Board of Management meets twice a year and the executive committee of the BOM meets on an “as needed” basis.

Voting Members:

Chair: R. Paul Young, U. of Toronto
Richard Fedorak, U. of Alberta
John Hepburn, U. of British Columbia
Kim Matheson, Carleton U.
Kevin Hall, U. of Guelph
Digvir Jayas, U. of Manitoba
Laurent Lewis, U. de Montréal
Steven Liss, Queen’s U.
Norbert Haunerland, Simon Fraser U.
Howard Brunt, U. of Victoria
Robert Haché, York U.

Non-voting Members:

Robert Thompson, U. of Calgary
Fiona McNeill, McMaster U.
Ranjana Bird, U. of Northern British Columbia
David Malloy, U. of Regina
Adam Sarty, Saint Mary’s U.
Jino Distasio, U. of Winnipeg

Ex-Officio Members:

Danial Wayner, National Research Council Canada
James D. Hanlon, Secretary
David B. MacFarlane, Chair, ACOT
Nigel S. Lockyer, Director, TRIUMF

POLICY AND PLANNING ADVISORY COMMITTEE (PPAC)

The Policy and Planning Advisory Committee (PPAC) advises the Director on scientific policy, and facilitates two-way communications with the research communities at the member universities.

The Policy and Planning Advisory Committee includes one member from each of the full member universities. The members are selected by the Director from a list provided by the relevant research community in each member university.

To ensure representation from all areas of scientific interest to the laboratory, the Director, in consultation with the Chair, may appoint a limited number of members from the larger TRIUMF community, including the possibility of an additional person from a member university.

Each member of the Committee will be appointed for a two-year term. The term expiry dates will be staggered to ensure the Committee has continuity on important issues. Reappointment should only occur in exceptional circumstances and may be for one year. PPAC meets twice a year.

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.
Mike Wieser, U. of Calgary
Viktor Zacek, U. de Montréal

KITCHEN CABINET ADVISORY COMMITTEE

The TRIUMF director maintains an on-site advisory committee for guidance on implementing policies and plans. The Kitchen Cabinet Advisory Committee serves a number of functions including: providing advice from TRIUMF staff to the Director, facilitating communication between senior management and the TRIUMF community, and providing input on scientific priorities and comments on the next Five Year Plan (5YP). The committee meets every quarter.

Members:

Chair: Nigel S. Lockyer
Pierre Amaudruz
Friedhelm Ames
Sonia Bacca
Curtis Ballard
John Behr
Razvan Creanga
Barry Davids
Denice Dietrich
Tim Emmens
Mel Good
Peter Gumplinger
Conny Hoehr
Yetvart Hosepyan
Robert Laplante
Iain McKenzie
Marco Marchetto
Colin Morton
Bevan Moss
Petr Navratil
Matt Pearson
Doug Preddy
Roxana Ralea
Kel Raywood
Ted Schenkeveld
Oliver Stelzer-Chilton
Jana Thomson
Violeta Toma
Rob Welbourn

EXPERIMENTS EVALUATION COMMITTEES (EEC)

The Experiments Evaluation Committees provide 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. There are three committees: the Subatomic Physics Experiments Evaluation Committee (SAP-EEC), the Molecular & Materials Science Experiments Evaluation Committee (MMS-EEC), and the Life Sciences Projects Evaluation Committee (LSPEC). The Evaluation Committees each meet at least once a year.

Subatomic Physics Experiments Evaluation Committee (SAP-EEC)

Members:

Chair:
Alfredo Galindo-Uribarri
Ex-Officio:
Reiner Kruecken
Secretary:
Petr Navratil

Rod Clark
Alejandro Garcia
Adam Garnsworthy
Takashi Nakatsukasa
Kartsen Riisager
Guy Savard
Hendrik Schatz

Molecular & Materials Science Experiments Evaluation Committee (MMS-EEC)

Members:

Chair:
Stephen Nagler
Ex-Officio:
Dr. R. Kruecken (Reiner)
Secretary:
Iain McKenzie

Adrian Hillier
Yong Baek Kim
Douglas MacLaughlin
Alexander Moewes
John Preston
Emil Roduner
Oleg. Tchernyshyov

Life Sciences Projects Evaluation Committee (LSPEC)

Members:

Chair:
Joel Karp
Ex Officio:
Paul Schaffer
Secretary:
Michael Trinczek

Nicholaas Bohnen
Jason Lewis
Jon McConathy

TRIUMF USER 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. The committee meets every year with its users and holds special meetings as needed.

Members:

Chair: Adam Garnsworthy (TRIUMF)
Chair Elect: Khashayar Ghandi (Mt. Allison University)
Past Chair: Andrew MacFarlane (UBC)
Liaison Officer: Reiner Kruecken (TRIUMF)

Members-at-Large:

Ulrike Hager (Colorado School of Mines)
Kris Starosta (SFU)
Anadi Canepa (TRIUMF)
Catherine Deibel (LSU)

TRIUMF ACCELERATOR ADVISORY COMMITTEE

The Accelerator Advisory Committee (AAC) provides advice to the TRIUMF Director and the Head of the Accelerator Division before every 5-year plan and major project about recent activities and proposed future initiatives.

Members:

Chair: Mark de Jong, Canadian Light Source
Marco Schippers, Paul Scherrer Institute
Mats Lindroos, CERN
Sergei Nagaitsev, Fermi National Accelerator Laboratory
Hasan Padamsee, Cornell University
Charles Sinclair, Thomas Jefferson National Accelerator Facility (retired)
Geoff Kraff, Thomas Jeffferson National Accelerator Facility
Jacques Lettry, CERN
Richard Stanek, Fermilab

FIVE-YEAR PLAN STEERING COMMITTEE

The Five-Year Plan Steering Committee (5YPSC) is accountable for the formulation and preparation of the Five-Year Plan 2015-2020. More specifically, the 5YPSC was formed by the TRIUMF director to:

- Oversee preparation of the Five-Year Plan 2015-2020;
- Engage and consult the broader community; and
- Structure and edit the components of the 5YP.

Ultimately, the responsibility for the 5YP rests with the TRIUMF director and the content of the 5YP is subject to approval by the TRIUMF Board of Management. As such, the 5YPSC includes participants from the TRIUMF staff, the Canadian community, and several nominees from community-based advisory organizations.

Members:

Chair: Tim Meyer, TRIUMF
Ken Ragan, McGill
Colin Gay, UBC (PPAC chair)
Hiro Tanaka, UBC
Sampa Bhadra, York (Board member)
Paul Garrett, Guelph
Paul Schaffer, TRIUMF
Khashayar Ghandi, Mount Allison (TUEC Chair)
Jens Dilling, TRIUMF
Byron Jennings, TRIUMF
Lia Merminga, TRIUMF
Iain McKenzie, TRIUMF/CMMS
Reiner Kruecken, TRIUMF
Carsten B. Krauss, Alberta
Isabel Trigger, TRIUMF

A.5 FINANCIALS

This chart shows a history of TRIUMF's financial operations.

TRIUMF FINANCIAL INFORMATION
FISCAL YEARS 2002/03 - 2012/13

	TOTAL	2012-13 *	2011-12	2010-11	2009-10	2008-09	2007-08	2006-07	2005-06	2004-05	2003-04	2002-03
Public Funding												
NRC	482,500,000	44,000,000	44,000,000	45,000,000	44,000,000	43,500,000	51,500,000	45,500,000	44,000,000	40,000,000	40,000,000	41,000,000
NSERC	65,176,284	6,578,602	6,316,503	6,309,557	6,587,586	5,970,896	6,374,929	5,266,630	4,688,242	5,300,363	5,704,966	6,078,010
BCKDF	18,878,220	5,419,328	4,877,723	632,024	-	-	-	-	-	-	-	7,949,145
CFI	48,095,475	20,361,685	10,196,335	5,580,147	1,946,096	1,114,884	1,867,939	2,406,137	1,923,525	1,203,511	1,495,216	-
NRCan	2,598,053	853,827	1,043,988	700,238	-	-	-	-	-	-	-	-
WED	918,964	-	-	-	918,964	-	-	-	-	-	-	-
Total Public Funding	618,166,996	77,213,442	66,434,549	58,221,966	53,452,646	50,585,780	59,742,868	53,172,767	50,611,767	46,503,874	47,200,182	55,027,155
Other Revenue												
Nordion	45,703,901	3,892,558	4,190,636	4,219,420	4,350,138	4,370,636	3,938,506	3,771,760	4,523,406	4,299,391	3,727,465	4,419,985
AAPS	7,274,026	1,512,691	1,806,141	1,754,608	1,166,618	1,033,968	-	-	-	-	-	-
Affiliated Institutions	20,038,431	2,664,758	2,207,629	2,110,304	2,191,470	2,092,220	1,815,124	1,084,050	1,083,601	1,249,940	1,391,060	2,148,275
Commecial Revenues	17,279,669	1,127,465	1,441,927	2,628,668	2,338,207	1,529,721	1,711,706	1,486,266	1,728,178	1,433,679	1,048,967	804,885
General Fund	2,287,321	233,737	200,258	98,063	60,947	175,071	461,169	417,161	250,428	140,701	120,281	129,505
Intramural Accounts	6,674,995	1,039,663	1,116,365	1,275,087	1,442,797	1,801,083	-	-	-	-		
Total Other Revenue	99,258,343	10,470,872	10,962,956	12,086,150	11,550,177	11,002,699	7,926,505	6,759,237	7,585,613	7,123,711	6,287,773	7,502,650
Total Public Funding and Other Revenue	**717,425,339**	**87,684,314**	**77,397,505**	**70,308,116**	**65,002,823**	**61,588,479**	**67,669,373**	**59,932,004**	**58,197,380**	**53,627,585**	**53,487,955**	**62,529,805**
Expenditures												
Building and Improvements	40,609,927	16,750,364	6,387,794	847,283	334,315	1,176,123	505,470	586,523	379,467	3,088,368	1,642,048	8,912,172
Telecommunications	1,902,975	142,329	216,387	190,173	245,542	158,169	144,872	157,995	204,282	122,442	157,365	163,419
Computer	14,034,219	1,277,465	1,241,276	2,049,025	1,203,207	903,876	1,022,417	1,435,878	1,248,930	1,168,475	1,063,457	1,420,213
Consulting	10,220,799	1,759,592	3,374,520	2,390,710	1,347,242	1,348,735	-	-	-	-	-	-
Equipment	76,776,437	10,097,681	6,662,677	5,251,722	4,342,100	4,116,790	6,834,656	6,428,809	8,213,429	6,563,773	8,478,874	9,785,926
Power	24,984,489	3,092,094	2,724,992	2,608,866	2,551,233	2,343,671	1,905,098	2,192,484	1,889,040	1,890,107	1,843,775	1,943,129
Salaries and Benefits	397,488,105	40,434,297	40,588,275	40,281,034	40,102,553	36,638,698	35,794,712	34,138,291	34,355,746	33,014,827	31,760,528	30,379,144
Supplies and Other Expenses	125,625,990	12,817,742	13,355,698	10,720,245	11,527,208	13,763,186	12,953,653	13,052,245	12,065,206	8,997,681	7,867,075	8,506,051
Travel	9,328,640	1,778,402	1,949,168	1,847,246	1,833,428	1,920,396	-	-	-	-	-	-
Facility Conformity Costs	9,600,000	-	-	-	1,000,000	1,000,000	7,200,000	400,000	-	-	-	-
Total Expenditures	**710,571,581**	**88,149,966**	**76,500,787**	**66,186,304**	**64,486,828**	**63,369,644**	**66,360,878**	**58,392,225**	**58,356,100**	**54,845,673**	**52,813,122**	**61,110,054**
Increase/(Decrease) to Fund Balances	**6,853,758**	**(465,652)**	**896,718**	**4,121,812**	**515,995**	**(1,781,165)**	**1,308,495**	**1,539,779**	**(158,720)**	**(1,218,088)**	**674,833**	**1,419,751**

* Fiscal year 2012-13 figures are subject to completion of financial audit.

A.6 COMMENTARY ON TRIUMF SCIENTIFIC PUBLICATION PATTERNS

One of the most countable, attributable outputs of scientific research is a scientific article, often called a journal article or a scientific paper or publication. By strict tradition, scientific publications are signed and the authors indicate their institutional affiliations as part of the address field. Scientific journals are published collections of science papers that regularly deliver breaking science news to other scientists or interested observers. When papers are "peer-reviewed," this indicates that the paper was judged by a set of other scientists to be both sufficiently interesting and sufficiently accurate (in terms of results as well as presentation) in order to be published. Finally, there is a strict tradition in scientific research that a new paper must carefully reference (or "cite") other previous papers that contributed to the present work. In this way, papers that are more cited than other papers are judged to have influenced a larger volume of subsequent research. In this framework, individual scientists or groups of scientists create a "published body of work" that has a certain size (number of papers) and a certain level of influence (number of citations of their papers). One can then start to create methodologies that ascertain relative performance and publication patterns and practices among different scientists or groups of scientists.

Over the past few decades, a number of commercial publishers and database companies have amassed significant fee-for-access indices of "all" scientific publications. These indices are often stored as a database with direct online access to the publications themselves. Two of the global leaders in this technology are Scopus and Thomson-Reuters Web of Knowledge.

As part of the performance benchmarking exercise for preparing Five-Year Plan 2015-2020, TRIUMF contract Science Metrix in Montreal, Quebec, to conduct a comprehensive, independent study of TRIUMF's publication patterns over the past 15 years using advanced bibliometric techniques.

This appendix comments on the results of that analysis. The full report will be available on the TRIUMF website when it is delivered and will be shared with all of TRIUMF's stakeholders.

A.6.1 Limitations

The most common challenges in performing studies of publication patterns are (a) clearly establishing attribution, (c) identifying papers in a common area of research, and (c) creating relevant comparisons.

Although all scientific papers have an author list with identified institutions for each, the commercial databases don't necessarily store or obtain this information in a standard format. Moreover, some scientific papers may be based on data or equipment from another group (that might be formally stated in the acknowledgments section of the paper) but not include any authors from that group.

Another challenge is determining which papers are scientifically related by content. The research focus areas of certain journals, keywords tagged to articles, and titles of articles all help identify the "field of research" discussed in a scientific paper. This selection process is not 100% effective. For instance, in the Science Metrix analysis, some papers are counted as both particle and nuclear physics papers although a glance at the abstract would clearly place it one category or the other. Likewise, some nuclear medicine papers show up as accelerator physics papers. These effects are small in general, though.

A crucial challenge is making useful comparisons. Science Metrix, through careful research and development as well as following of current trends in social science research on these topics, has developed a number of indicators that help compare different organizations' scientific publication patterns. In this study, a hand-picked set of comparison institutions were used to allow TRIUMF publication patterns to be put into context of other similar organizations.

A.6.2 Results

This discussion is grouped into two subsections: the performance of Canada and the performance of TRIUMF compare to a reference set of 9 other international research organizations whose activities overlap TRIUMF's to varying degrees. Science Metrix worked with the Scopus database and has developed an extensive process of proprietary techniques to select papers, "clean" their bibliographic information to ensure that authors and institutions and citations are clear, and then measure and display results. The study covered the 1996–2010 period. The study looked at performance in five research fields (which have some degree of overlap) as well as the aggregate of all five.

- Particle physics
- Nuclear physics
- Accelerator physics
- Nuclear medicine
- Materials Science
- Aggregate: "Subatomic sciences"

Canadian Performance

From 1996–2010, Canada published 16,752 identifiable scientific papers across all five fields of research. The top published was the U.S. with more than 137,000 such papers. In terms of Average of Relative Citations (ARC) score, Canada was second in the world (behind the Netherlands). In terms of Average of Relative Impact Factors (ARIF) score, Canada ranked third (behind Israel and the Netherlands). The countries that outperformed Canada all have more "specialization" than Canada, meaning that a greater fraction of their publications are in this area than for Canada.

Science Metrix provides a powerful summary graphic of the relative positional analysis, shown in Figure 1. Over half of these Canadian publications were in the field of particle physics. The smallest field was accelerator physics. Table 1 below summarizes the rankings compared to the highest performing

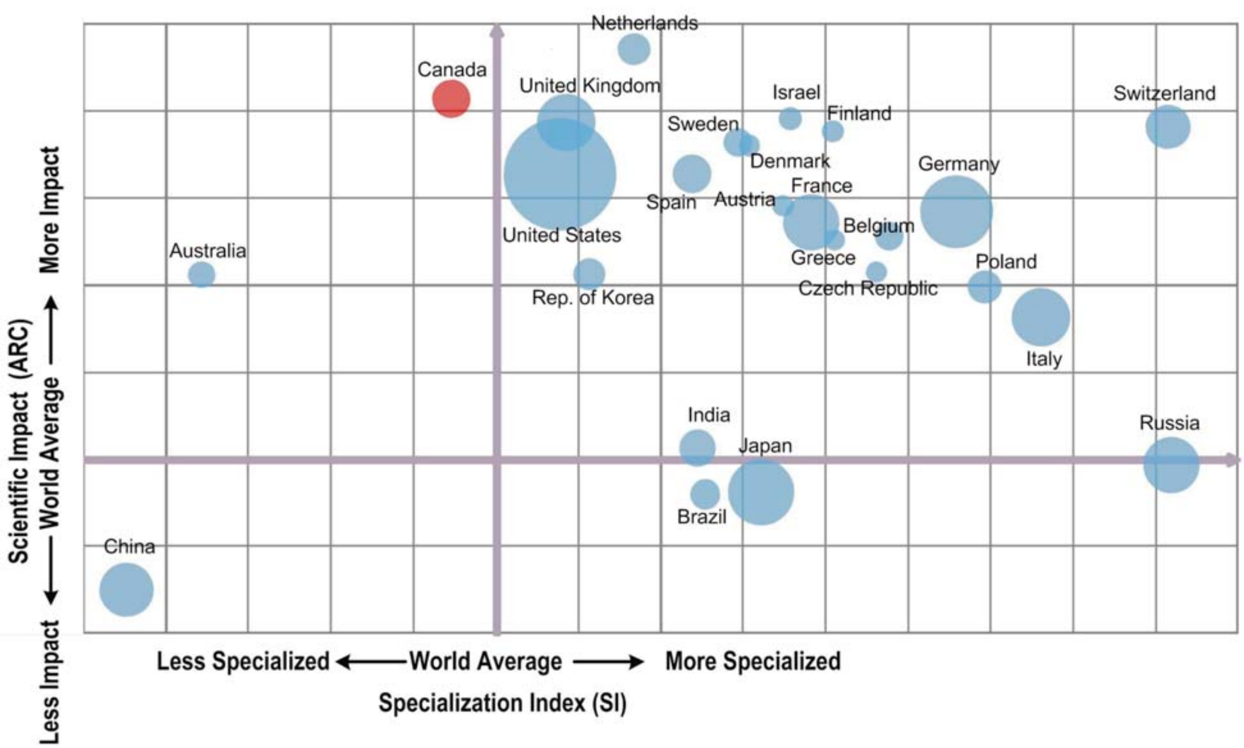


Figure 1: Positional analysis of Canada's scientific-publication performance (1996-2010) compared to other countries in terms of normalized specialization and citation indices in the aggregate of TRIUMF's five research areas. Courtesy of Science Metrix.

countries in the world. Generally speaking, all countries out-performing Canada in terms of ARC and ARIF score rankings were more specialized in that field than Canada, implying that there is a greater fraction of national effort on those fields than in Canada. In almost every single indicator, Canada outperformed the U.S.

Canadian Output	Particle Physics	Nuclear Physics	Accelerator Physics	Nuclear Medicine	Materials Science
Volume	9,771	4,620	2,126	4,355	1,867
ARC rank	3	8	5	3	4
ARIF rank	6	4	5	2	5

Table 1. Summary of scientific papers from Canada 1996-2010 as measured by Science Metrix using the Scopus database.

TRIUMF's Role

The Science Metrix analysis examined the role of TRIUMF in driving these Canadian results. This part of the analysis (and subsequent steps) required the ability to distinguish scientific papers to which TRIUMF contributed or participated. The typical approach is to look for authors in the Canadian papers who list TRIUMF as their institutional affiliation. In materials science, this technique is not as effective since many materials-science papers use TRIUMF characterization and analysis techniques for their results but a TRIUMF scientist is not a signing author of the paper.

Using the Scopus database, Science Metrix identified the top 40 organizations around the world publishing papers in the "subatomic sciences" aggregate. Not surprisingly, the U.S. Department of Energy (DOE) laboratory system ranked the highest in terms of volume with more than 34,600 papers from 1996-2010. Princeton University ranked 40th in terms of volume at 3,430 papers. By comparison, TRIUMF published about 2,300 papers. No Canadian institutions made the top 40. Of the top 40, the University of Tokyo was the highest ranking university at 11th position. The U.S. showed up 13 times in the list, Japan ranked second with five occurrences, followed by Russia, the UK, Italy, and France with four institutions each (see Figure 2).

By comparing author lists, it was also noted that TRIUMF was listed as a collaborating author on 0.5% of these 428,000 papers. In terms of volume, TRIUMF's most frequent collaborators were with U.S. DOE laboratories, the Italian national laboratory system INFN, and the Helmholtz laboratory system in Germany. In terms of relative volume, TRIUMF was listed most frequently as a collaborator on papers published by the UK Science and technology Facilities Council, the University of Maryland at College Park, Cambridge, and the University of Tokyo.

Science Metrix examined Canadian publishing patterns. The top 30 institutions by volume of publishing in the aggregate of "subatomic sciences" were identified with McGill University, the University of Toronto, and TRIUMF topping the list with roughly 2,500 publications each of Canada's about 16,000.

Figure 3 shows an example of TRIUMF's collaboration network based on the publishing patterns with other Canadian institutions. Note that TRIUMF's member universities figure strongly. TRIUMF is a collaborating author on nearly 14% of these papers with 30%-40% collaboration measured with University of Alberta, University of Victoria, Simon Fraser University, UBC, University of Ottawa, Carleton University, University of Regina, and the Canada Institute for Advanced Research.

Organization	Papers		ARC	ARIF	Collaborations with TRIUMF	
	Score	Trend*			Papers	%
DOE - US Department of Energy	34,605		1.38 ▲	1.09 ▬	577	1.7%
INFN - Istituto Nazionale di Fisica Nucleare	21,766		1.23 ▲	1.09 ▬	540	2.5%
CNRS - Centre national de la rech. sci.	17,686		1.53 ▲	1.24 ▲	197	1.1%
Helmholtz-Gemeinschaft e.V.	17,588		1.33 ▲	1.11 ▲	489	2.8%
Russian Academy of Sciences	14,145		1.21 ▲	1.00 ▬	191	1.4%
CERN - Centre europ. pour la rech. nucl.	11,996		1.48 ▲	1.13 ▲	365	3.0%
Chinese Academy of Sciences	10,687		0.99 ▬	0.99 ▬	87	0.8%
Max-Planck-Gesellschaft	10,400		1.82 ▲	1.22 ▲	192	1.8%
CEA - Commissariat à l'énergie atomique	10,018		1.50 ▲	1.15 ▲	182	1.8%
Joint Institute for Nuclear Research	8,060		1.26 ▲	1.09 ▬	204	2.5%
University of Tokyo	7,908		1.59 ▲	1.17 ▲	350	4.4%
Stanford University	6,009		2.32 ▲	1.27 ▲	68	1.1%
CSIC - Consejo Superior de Investig. Cient.	5,864		1.89 ▲	1.28 ▲	101	1.7%
High Energy Accelerator Res. Org. (KEK)	5,597		1.34 ▲	1.06 ▬	160	2.9%
Harvard University	5,497		2.41 ▲	1.41 ▲	98	1.8%
Kyoto University	5,427		1.28 ▲	1.04 ▬	78	1.4%
Homi Bhabha National Institute**	5,073		1.06 ▬	0.97 ▬	29	0.6%
MIT - Massachusetts Institute of Technology	5,061		2.50 ▲	1.41 ▲	175	3.5%
Université Paris-Sud - Paris 11	4,976		1.73 ▲	1.31 ▲	54	1.1%
University of California, Berkeley	4,565		2.20 ▲	1.36 ▲	79	1.7%
NASA	4,415		1.76 ▲	1.15 ▲	1	0.0%
Osaka University	4,294		1.20 ▲	1.05 ▬	102	2.4%
University of California, Los Angeles	4,284		2.29 ▲	1.40 ▲	108	2.5%
Caltech - California Institute of Technology	4,222		2.37 ▲	1.37 ▲	79	1.9%
Inst. for Theoretical and Experim. Phys. - ITEP	4,209		1.50 ▲	1.26 ▲	94	2.2%
JAEA - Japan Atomic Energy Agency	4,122		0.65 ▼	0.77 ▼	33	0.8%
STFC - Sci. and Techn. Facilities Council	4,119		1.51 ▲	1.24 ▲	358	8.7%
Polish Academy of Sciences	4,106		1.33 ▲	1.14 ▲	43	1.0%
University of Maryland College Park	4,033		2.04 ▲	1.36 ▲	323	8.0%
University of Michigan	4,029		1.91 ▲	1.40 ▲	133	3.3%
UPMC - Université Pierre et Marie Curie	3,942		1.85 ▲	1.34 ▲	105	2.7%
University of Cambridge	3,878		2.07 ▲	1.27 ▲	264	6.8%
University of Oxford	3,817		2.10 ▲	1.36 ▲	121	3.2%
University of London, Imperial College London	3,766		2.04 ▲	1.42 ▲	54	1.4%
Moscow State University	3,762		1.15 ▲	1.01 ▬	37	1.0%
UNIROMA1	3,759		1.65 ▲	1.30 ▲	132	3.5%
CNR - Consiglio Nazionale delle Ricerche	3,748		1.08 ▬	1.08 ▬	9	0.2%
University of Wisconsin-Madison	3,632		1.96 ▲	1.44 ▲	134	3.7%
University of Washington	3,475		2.80 ▲	1.41 ▲	100	2.9%
Princeton University	3,430		3.06 ▲	1.44 ▲	60	1.7%
TRIUMF	**2,303**		**1.48 ▲**	**1.23 ▲**	**-**	**-**
World	**428,848**		**1.00 ▬**	**1.00 ▬**	**2,303**	**0.5%**

Figure 2: Top 40 global producers of scientific publications (1996-2010 cumulative) in the aggregate of TRIUMF's five research areas. Shown are the output levels and several normalized scores. TRIUMF is shown for reference. Courtesy of Science Metrix.

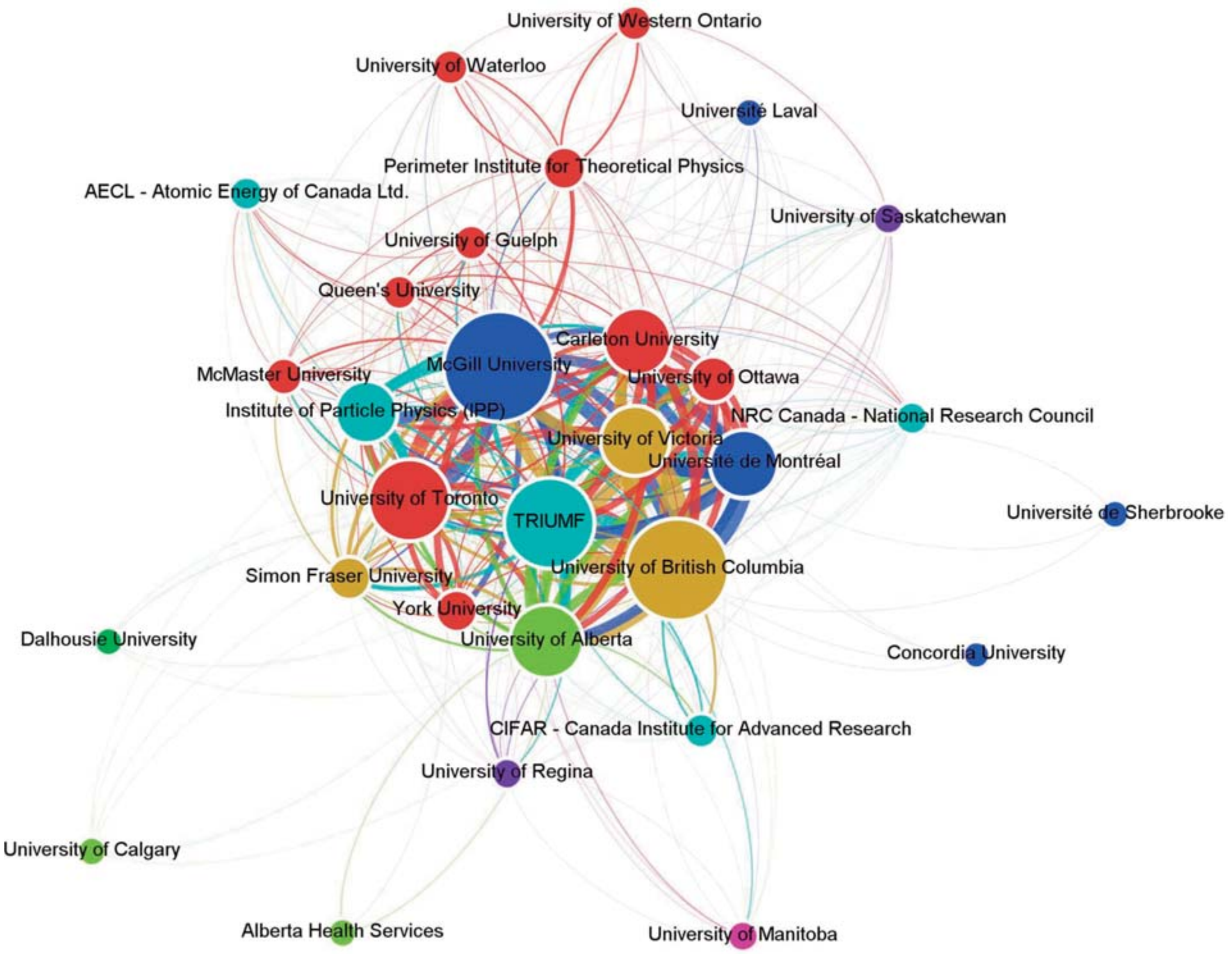


Figure 3: Collaboration diagram for Canadian institutions based on co-authorship on scientific papers 1996-2010 in the aggregate of TRIUMF's five research areas. Courtesy of Science Metrix.

TRIUMF's Performance in Relation to International Comparators

In consultation with TRIUMF and the NRC Office of Audit and Evaluation, nine other global laboratories were selected to serve as a reference set for TRIUMF's performance. No single laboratory reproduces the mix of research activities in proportion to TRIUMF, but in each of the five research areas, several of the reference laboratories are fair comparisons to TRIUMF. Note that TRIUMF is smaller in total than many of these laboratories and its program within each field is smaller than the programs at every one of the reference laboratories.

The reference set included:

- Brookhaven National Laboratory (U.S.)
- High Energy Research Organization, KEK (Japan)
- Fermi National Accelerator Laboratory (U.S.)
- Rutherford Appleton Laboratory (U.K.)
- Paul Scherrer Institute, PSI (Switzerland)
- Thomas Jefferson National Accelerator Facility (U.S.)
- National Superconducting Cyclotron Laboratory (U.S.)
- RIKEN Nishina Centre for Accelerator-based Science (Japan)
- Turku PET Centre (Finland)

Including TRIUMF, the ten laboratories studied represent about 31,000 of the world's 428,800 publications in the combined area of the five research fields from 1996-2010. Brookhaven tops the list with about 6,200 publications and Turku PET Centre brings up the rear with about 500 publications. Thus, TRIUMF ranked sixth in terms of output, fourth in terms of ARC score, and third in terms of ARIF score. Table 2 below shows the results in each research field of TRIUMF.

	Particle Physics	Nuclear Physics	Accelerator Physics	Nuclear Medicine	Materials Science
Total Output (10 labs)	19,451	11,465	10,128	3,324	2,249
TRIUMF Output	1,478	1,218	516	241	246
TRIUMF Output Rank	6	4	7	6	5
TRIUMF ARC rank	4	8	2	6	6
TRIUMF ARIF rank	4	4	3	2	7

Table 2. Summary of TRIUMF's scientific publications by research field and relative ranking against the 10 laboratories, as measured by Science Metrix for 1996-2010.

Trends

Science Metrix made an effort to examine trends in TRIUMF's publication patterns. Their analysis did not include any papers published after 2010, which leaves out some of the most interesting developments in particle physics (antihydrogen trapping, the discovery of a Higgs boson) and the recent progress in ISAC-based nuclear physics results (especially the use of actinide targets and TITAN's mass-measurement program).

Science Metrix split the 15 year period 1996-2010 into three five-year periods because the number of papers published annually was below 50 in accelerator physics, materials science, and nuclear medicine, making year-to-year trend analysis difficult. The results shown in Table 7.6-3 are suggestive. TRIUMF's paper output and the perceived impact of its papers is probably on the rise.

		Particle Physics	Nuclear Physics	Accelerator Physics	Nuclear Medicine	Materials Science	Together
Output	1996-2000	512	372	133	69	46	704
	2001-2006	430	416	177	84	60	726
	2006-2010	536	430	206	88	140	873
ARC Score	1996-2000	0.99	1.23	1.02	0.80	1.29	1.08
	2001-2006	2.14	1.81	3.66	0.96	1.04	1.79
	2006-2010	1.65	1.90	2.22	1.84	1.07	1.56
ARIF Score	1996-2000	—	—	—	—	—	—
	2001-2006	1.25	1.23	1.08	1.22	0.95	1.21
	2006-2010	1.24	1.28	1.11	1.41	0.91	1.24

Table 3. Trends in TRIUMF scientific papers 1996-2010 as measured by Science Metrix. Totals may not sum because some papers appear in more than one category; ARIF score is not computed before 2001.

Regarding the top 1% of most-cited publications, increases were observed for TRIUMF in the fields of nuclear medicine, particle physics, and nuclear physics over the 15 year period.

A.6.3 Interpretation

The Science Metrix analysis is insightful and provocative. Several comments and observations are discussed here.

Collaboration

One powerful outcome of the independent analysis is a measure of the degree of TRIUMF's collaboration within Canada and outside the country. Clearly, Canadian universities that are part of the TRIUMF consortium often publish together in the areas of particle and nuclear physics. Additionally, TRIUMF is a collaborating author on many international papers. In terms of the ten-laboratory comparison, TRIUMF papers are some of the most internationally diverse with nearly 25% having more than 5 different countries on the author list. Only Rutherford Appleton Laboratory was more diverse with 40% having 5 or more countries on the author list and most laboratories had more 80% of their papers with 5 countries or less.

The Science Metrix analysis shows that 50% of TRIUMF's papers have more than 10 authors and 18% have more than 100 authors; this is to be compared to the world average in subatomic science of 92% and 1% respectively. As expected, the author list is longest in particle physics and nuclear physics, and shortest in nuclear medicine.

TRIUMF reports that it is "involved" in about 70% of Canada's NSERC-supported subatomic physics research. Comparing this value with the co-authorship rate of 30%-40% for the major Canadian universities, it seems that TRIUMF's involvement is perhaps half intellectual and half technical and engineering infrastructure (as in, TRIUMF helped build detectors at SNOLAB but is not a scientific co-author). This observation is not unexpected.

Impact

TRIUMF appears to consistently rank in the upper half of an international peer group of ten laboratories. Recent results from ATLAS, ALPHA, and ISAC will probably boost TRIUMF's relative performance, and of course, when ARIEL is full on line, the laboratory should advance significantly.

Apart from output numbers, the other criterion of interest is the rate of citation of articles. Web of Knowledge was used to find the 30 most highly-cited articles in TRIUMF's entire history (since the first TRIUMF-authored publication in 1972), and among those published since 2010, during the present Five-Year Plan. The most highly cited publication with TRIUMF authorship, with over four thousand citations, is "GEANT4 – a simulation toolkit" published in NIM A506 in 2003; GEANT4 is also responsible for the sixth-most-cited article. In second place, with over 1,900 citations, is a review article on "The Bonn-exchange model for the nucleon-nucleon interaction" from Physics Reports (Review section of Physics Letters) 149 (1987). Twelfth, thirteenth and sixteenth place are also nuclear theory papers. Third, with 1,300 citations, is the SNO publication of "Direct evidence for neutrino flavour transformation" from PRL 89 (2002). SNO accounts for five of the thirty top-cited TRIUMF papers. BaBar and HERMES each account for two. The ATLAS Higgs Boson discovery paper from 2012 is in eleventh place overall, with just under 500 citations. Seventh, ninth and tenth places are held by papers on μSR and high-T_c superconductors. In fifteenth place, with about 450 citations, the most cited nuclear-medicine paper from TRIUMF describes a 3D image reconstruction technique. Seventeenth is a multiple-authored nuclear astrophysics review paper on solar fusion cross-sections from 1998.

If only papers published since 2010 are considered, the ATLAS Higgs boson discovery paper from 2012 is in first place with nearly 500 citations, followed by the T2K observation of electron neutrino appearance with over 400. Twelve of the thirty most-cited papers are from ATLAS, and seven are from CDF. The SNO low-threshold analysis, with just under 100 citations, fills 13th place, with nuclear theory papers on three-body forces and chiral effective field theory in the 16th, 17th and 22nd positions. A particle physics theory paper is the 21st most cited (over 60 citations), and hadronic physics theory papers are 23rd and 28th. The 2010 ALPHA paper on antihydrogen trapping, with nearly 60 citations, rounds out the list in 25th place.

The citations records, both short- and long-term, imply that TRIUMF's highest publishing impact comes from its participation in high-profile collaborative projects with a global scope. The Theory Group also continues to produce high-impact papers. Individual experimental nuclear physics papers appear to accumulate significant numbers of citations over longer time periods: a 1982 paper on nucleon-nucleon phase shifts has been cited 150 times, while none of the experimental nuclear results published since 2010 has more than a dozen citations so far.

Materials Science

TRIUMF's productivity in materials-science papers has increased dramatically over the 15 year period. This result reflects the increasing international profile of the Centre for Molecular and Materials Science driven by several factors: the emergence of β-NMR as a characterization technique, the retention of a facility-outreach coordinator for this program, and new muon beam lines with world-leading capabilities.

Summary

The Science Metrix study is tantalizing. The trend data is inconclusive without the recent three years, and the challenge of measuring the bibliometric impact of a small laboratory on the international stage is clear (in some areas, with less than 50 papers published per year). The methodology used seems robust and appropriate; cross-checks with Thomson-Reuters Web of Knowledge reveal similar volumes of publications with some enhancements.

The results suggest that TRIUMF is a key element of Canadian research and perhaps at a stage of transition; the results of such a bibliometric study five years from now will be interesting indeed.

A.7 STUDENTS AND TRAINEES

At TRIUMF one of our primary goals is inspiring the next generation of scientists and giving them a place where they can apply and develop the skills that they learn in University, while also contributing to TRIUMF's primary capacity as a research institution. In keeping with these goals every year TRIUMF hosts over a hundred graduate students as they conduct research here. Below is a list of the Theses that these students have created while working here.

THESES - 2008

M.Sc.

K. Leach, *High-Precision Measurement of the Superallowed Beta Decay Branching Ratio of 38mK* (University of Guelph, MSc)

P. Lu, *Monte-Carlo Simulations of Positron Emission Tomography based on Liquid Xenon Detectors* (University of British Columbia, MSc)

M. Porter-Peden, *Transfer reactions with radioactive beams: simulations and design of experimental setups*, (Colorado School of Mines, MSc)

C. Tunstall , *Cross section measurements for the 12C+12C fusion reaction at low energies*, (University of York, MSc)

J. Wong, *Design Study of DESCANT - DEuterated SCintillator Array for Neutron Tagging*, (Guelph, MSc)

Ph.D.

M. Bowen, *Radiolabelled Carbohydrate Conjugates: Studies of Alzheimer's Disease Therapeutics and Tumor Imaging* (University of British Columbia, PhD)

Bertrand Brelier, *Etude de la production associée ZH/WH, H -> avec le détecteur ATLAS* (University of Montreal, PhD)

L. Erikson, *Experimental Developments for the Study of Explosive Nucleosynthesis in Stars* (Colorado School of Mines, PhD)

A. Gorelov, *Positron-Neutrino Correlation Measurements in the Beta Decay of Magneto-Optically Trapped ^38mK Atoms* (Simon Fraser University, PhD)

J. Ives *The Measurement Of The Rare Decay K-Plus To Pi-Plus, Neutrino, And Anti-Neutrino* (University of British Columbia, PhD)

Z. Ke, *A cooler ion trap for the TITAN on-line trapping facility at TRIUMF* (University of Manitoba, PhD)

J. Lefebvre, *Interplay between structure and properties in dicyanoaurate-based coordination polymers* (Simon Fraser University, PhD)

B. M. McCollum, *Exploring chemical reaction mechanisms using a light "isotope" of hydrogen* (Simon Fraser University, PhD)

R. P. MacDonald, *A precision measurement of the muon decay parameters rho and delta*, (University of Alberta, PhD)

G. MacDougall, *μSR and Susceptibility Studies of the Normal State of Unconventional Superconductors*, (McMaster University, PhD)

R. S. Naik, *Studying fusion reactions for effect of PCN on heavy nucleus formation and for nuclear structure effects*, (University of Oregon, PhD)

J. Paulo Idàrraga, *Vector Boson Scattering at High Energy at the LHC*, (University of Montreal, PhD)

M. Smith, *A mass measurement of the short-lived halo nucleus 11Li with the TITAN Penning trap spectrometer*, (University of British Columbia, PhD)

M. Subramanian, *Lifetimes of States in 19Ne above the 15O+alpha Threshold*, (University of British Columbia, PhD)

Dipl. Ing

A. Teigelhoefer, *Grating tuned Ti:Sa-Laser for Spectroscopy at Rydberg and auto-ionizing atomic states*, (Fachhochschule Oldenburg, Dipl. Ing)

THESES - 2009

M.Sc.

H. Bazid, *Recherche d'un neutrino lourd avec le détecteur ATLAS au LHC,* (University of Montreal, MSc)

C. Champagne, *Characterizing and Optimizing the TITAN facility from Energy Spread Determinations with a Retarding Energy Field Analyzer,* (McGill, MSc)

G. Demand, *Development of a Novel Algorithm for Nuclear Level Scheme Determination,* (Guelph, MSc)

M. Fujihara, *Synthesis and investigation of novel magnetism in new geometrically frustrated material Fe2(OH)3Cl,* (Saga University, MSc)

A. Gaudin, *Drift speed and gain measurements in the T2K time projection chambers,* (UVic, MSc)

K. Green, *Nuclear Structure of 112Cd Through Studies of Beta Decay ,* (Guelph, MSc)

N. Ito, *Improvements of COPPER 500-MHz Flash ADC for PIENU Experiment,* (Osaka, MSc)

T. Williams, *Studies of the Ferromagnetic Superconductors URhGe and UCoGe,* (McMaster, MSc)

Ph.D.

J. P. Carlo, *The magnetic phase diagrams of (Ca,Sr)2(Ru,Ti)O 4 and iron pnictide systems revealed by muon spin relaxation,* (Columbia, PhD)

M. Egilmez, *Magnetotransport and magnetoresistive anisotropy in perovskite manganites,* (University of Alberta, PhD)

I. Fan, *Muonium dynamics in Si and Ge under photoexcitation,* (University of Alberta, PhD)

J. Ferland, *Potentiel d'observation de la Technicouleur à l'aide de l'expérience,* (University of Montreal, PhD)

J. Lavoie, *Production of Pure Ion Beams by Laser Ionization and a Fast Release RFQ,* (Universite Laval, PhD)

D. Lebhertz, *Modes de décroissance des réactions de capture radiative résonnantes des collisions 12C+12C et 12C+16O,* (Strasbourg, PhD)

P. Mumby-Croft, *TACTIC - A New Detector for Nuclear Astrophysics,* (University of York, PhD)

J. Rodriguez, *Study of the dipolar Ising system LiHoxY1-xF4 using muon spin rotation/ relaxation,* (McMaster, PhD)

H. Saadaoui, *Magnetic properties near the surface of cuprate superconductors studied using Beta-Detected NMR,* (UBC, PhD)

M. Schumaker, *Coulomb Excitation Structure Studies of 21Ne, 20,21Na,* (Guelph, PhD)

E. Tardiff, *Towards a Measurement of the Electric Dipole Moment of 223Rn,* (University of Michigan, PhD)

M.Phys.

H. Dare, *Use and adaption of a Fortran-77 code to determine the lifetimes of states in 19Ne,* (University of Surrey, MPhys)

Dipl.Phys.

A. Voss, *Investigation of Rydberg Atom Ionisation in Hot Cavities for Application in Resonant Ionisation Laser Ion Sources,* (TU Braunschweig, Dipl.Phys.)

THESES - 2010

M.Sc.

J. Bangay, *Nuclear Structure of 110Cd Studied with Beta Decay of 110In and (n,n'gamma) Reaction ,* (Guelph, MSc)

A. Desilets-Benoit, *Effet de la symétrie sur la supraconductivité de LaRhSi3 et la frustration magnétique du SrRE2O4 (RE = Dy ou Ho),* (Montreal, MSc)

A. Geisheimer, *The chemistry and applications of tetracyanoaurate(III) as a building block in heterobimetallic coordination polymers,* (SFU, MSc)

S. Hirota, *Development of the room temperature muonium generatorfor the muon magnetic dipole moment measurement at J-PARC,* (Tokyo, MSc)

K. Yoshihara, *R&D studies of Muon Polarimeter for J-PARC E06 T-Violation Experiment,* (Tokyo, MSc)

Ph.D.

R. D. Bayes, *Measurement of the decay parameter rho and a search for non-Standard Model decays in the muon decay spectrum,* (UVic, PhD)

J. F. Bueno, *A direct measurement of pmu xi from muon decay,* (UBC, PhD)

B. Ross. Carroll, *Muonium in Silicon Germanium Alloys,* (Texas Tech, PhD)

A. Aczel, *Studies of Bose-Einstein Condensates in Magnetic Insulators,* (McMaster, PhD)

C. Beer, *Low energy measurements of the 18F(p,α)15O cross section,* (University of York, PhD)

M. Brodeur, *First direct mass measurement of the two and four neutron halos 6He and 8He using the TITAN Penning trap mass spectrometer,* (UBC, PhD)

M. Hagihara, *An extensive study of geometrically frustrated series M2(OH)3X,* (Saga University, PhD)

A. Hillairet, *Measurement of the delta and eta muon decay parameters,* (UVic, PhD)

K. Yamada, *Search for Massive Neutrinos in pi+ -> e+ nu Decay,* (Osaka, PhD)

D.Eng.

K. Mukai, *Synthesis and Characterization of Lithium Cobalt Nickel Oxides for High-energy Density Lithium-ion Batteries,* (Osaka City, DEng)

THESES - 2011

M.Sc.

C. Clements, *Simulations of a High-Resolution Micro-PET System based on Liquid Xenon,* (UBC, MSc)

A. Close, *Beta decay and beta-delayed neutron emission of 100Rb and its daughter nuclei,* (University of Surrey, MSc)

E. Hill, *The Cosmic Muon Flux in the ATLAS Detector at the Large Hadron Collider,* (UVic, MSc)

W. Huang, *μSR studies of high Tc superconductors: Effect of vortex lattice disorder on TF-μSR measurements of the magnetic penetration depth and nuclear contribution to the ZF-μSR relaxation spectrum,* (SFU, MSc)

R. Nandanavanam, *Investigations on the contribution of the AtNRT2.6 gene to nitrate transport in Arabidopsis thaliana ,* (UBC, MSc)

E. Rand, *GEANT4 Simulations for the Radon Electric Dipole Moment Search at TRIUMF ,* (Guelph, MSc)

D. Storey, *A view screen beam profile monitor for the ARIEL e-linac at TRIUMF,* (UVic, MSc)

H. Zhu, *Electric Field Calculation And Ionization Signal Simulation In Liquid Xenon Detectors For Pet,* (UBC, MSc)

Ph.D.

T. J. Parolin, *Using low-energy ^{8}Li beta-detected NMR to probe the magnetism of transition metals,* (UBC, PhD)

E. Boros, *Acyclic Chelates for Imaging with Radiometals,* (UBC, PhD)

T. Brunner, *In-Trap Decay Spectroscopy for ββ Decays,* (TUM, PhD)

M. Fujihara, *Synthesis and investigation of novel magnetism in new kagome and tetrahedral lattice compounds,* (Saga University, PhD)

M. Hiraishi, *Superconductivity and Magnetism in Fe-based Superconductors Probed by Muon Spin Rotation/Relaxation,* (Tokyo, PhD)

C. Malbrunot, *Study of Pi->e nu decay,* (UBC, PhD)

M. Miyazaki, *Pseudogap State of (Bi,Pb)2201 Studied by Muon Knight Shift,* (Tokyo, PhD)

Dipl. Phys.

B. Eberhard, *The TITAN cooler Penning trap for short-lived highly charged ions; investigations for nested trap applications and fast electrode switching,* (University of Mainz, Dipl.Phys.)

THESES - 2012

M.Sc.

R. Dunlop, *High-Precision Branching Ratio Measurement for the Superallowed Beta+ Emitter 74Rb,* (Guelph, MSc)

L. Evitts, *Optimising SPICE: Spectrometer for Internal Conversion Electrons,* (University of Surrey, MSc)

H. Heggen, *Radiofrequency quadrupole laser ion source (RFQ-LIS) for isobar suppression,* (TU Darmstadt, MSc)

S. Ito, *Time Spectrum Analysis for the Precision Measurement of pi+ -> e+ nu Branching Ratio (Japanese),* (Osaka, MSc)

B. Jigmeddorj, *Nuclear Structure Study of 110Cd Through Internal Conversion Electrons,* (Guelph, MSc)

A. Kobayashi, *Development of a muon polarimeter for the J-PARC T-violation search experiment,* (Tokyo, MSc)

T. Munsie, *Studies of the Low Temperature Behaviour of CoNb2O6,* (McMaster, MSc)

S. Reeve, *Determining the Transmission Efficiency for 3He(alpha,gamma)7Be in DRAGON,* (SFU, MSc)

O. Shelbaya, *Laser spectroscopy of rare Rubidium isotopes and development of data analysis software at TRIUMF,* (McGill, MSc)

A. Teigelhoefer, *Astatine and Yttrium laser spectroscopy for RIMS applications,* (University of Manitoba, MSc)

J. Turner, *Characterization of Diamond Sensors for use in ATLAS Calorimeter Upgrades,* (Carleton, MSc)

A. Zamanpour, *Measurement of the ttZ production cross section in the three lepton final state with 13.0 fb−1 of* $\sqrt{s} = 8$ *TeV pp collision data collected by the ATLAS detector,* (MSc)

Ph.D.

P. S. Fernandez, *Synthesis and Biological Activity of Chloroquine Ferrocenyl Conjugates for the Treatment of Malaria,* (UBC, PhD)

J. F. García, *Analysis of breakup channel of the reaction 11Li+208Pb at energies around the Coulomb barrier,* (PhD)

M. M. Hossain, *Absolute value of the magnetic penetration depth and field profile in the Meissner state of exotic superconductors Yttrium barium copper oxide and Co-doped pnictide,* (UBC, PhD)

M. Cubero, *Estudio de dispersión de 9Li y 11Li sobre un blanco de 208Pb a energías en torno a la barrera coulombiana,* (PhD)

S. Ettenauer, *First Mass Measurements of Highly Charged, Short-lived Nuclides in a Penning Trap and the Mass of 74Rb,* (UBC, PhD)

P. Finlay, *High-Precision Half-Life and Branching-Ratio Measurements for the Superallowed Beta+ Emitter 26Alm,* (Guelph, PhD)

A. Goasduff, *États intrus dans les noyaux de la couche sd : de 1p-1t à np-nt dans les isotopes de Si,* (Strasbourg, PhD)

J. Guo, *Copper requirements and acquisition mechanisms in marine phytoplankton,* (UBC, PhD)

T. Kong, *Feasibility test of exotic particle searches in the decay of trapped rubidium isomers,* (UBC, PhD)

P. Salter, *Time-reversed measurement of the 18Ne(a,p)21Na cross-section for Type I X-ray bursts,* (Edinburgh, PhD)

V. Simon, *Measurements of neutron-rich Rb and Sr nuclides for nuclear astrophysics and the development of a novel Penning trap for cooling highly charge ions,* (University of Heidelberg, PhD)

D. Smalley, *Multi-nucleon transfer reaction studies of 6He on 12C using the SHARC and TIGRESS arrays,* (Colorado School of Mines, PhD)

Q. Song, *Beta-detected NMR of* Li^+ *in spintronic materials,* (UBC, PhD)

A. Voss, *Nuclear ground state moments of radioactive Lithium and Francium Isotopes probed via zero-field Beta-NQR and collinear laser spectroscopy,* (Manchester, PhD)

G. Wilson, *Investigating the evolution of the nuclear magic numbers via single-neutron transfer populating 26Na,* (University of Surrey, PhD)

A.8 LEADERSHIP TEAM

As of September 2013 and during the search for TRIUMF's next director, TRIUMF is led by a Leadership Team empanelled by the Board of Management. This team is chaired by James D. Hanlon as Chief Executive Officer / Chief Administrative Officer.

Remy Dawson

Head, Engineering Division

Mr. Remy Dawson's career has reflected his wide ranging interests and capabilities. He has worked in both science and industry, with particle detectors, commercial cyclotrons, linear accelerators, medical devices, and print industry capital equipment and software. Prior to rejoining TRIUMF six years ago, Dawson was a key driver in developing the team, the business strategy, and the products that became market leaders in the newspaper print industry worldwide. At TRIUMF, Dawson has made core contributions to development of the Quality Management System and project management and is currently Engineering Division Head and co-leader of the ARIEL project. Dawson is a registered Professional Engineer and has a B.Sc. in Mechanical Engineering from the University of Alberta.

James D. Hanlon

Head, Business & Administration Division

Mr. James "Jim" Hanlon has worked in the field of Research Administration for 26 years, five years in the for-profit sector and 21 years in the non-profit sector. Prior to working in research administration, Hanlon worked in a number of financial and administrative positions in the manufacturing and distribution business. He is also Secretary to the TRIUMF Board of Management and President and CEO of Advanced Applied Physics Solutions, Inc. He has a BA in Economics from the University of Ottawa and holds a Certified Human Resources Professional (CHRP) designation.

Reiner Kruecken

Head, Science Division

Dr. Reiner Kruecken joined TRIUMF in early 2011 from the Technical University of Munich where he held the chair (C4) for Experimental Physics of Hadrons and Nuclei. He is now also a Professor of Physics and Astronomy at UBC. Kruecken received his Ph.D. in nuclear physics from the University of Cologne in 1995. After a postdoctoral fellowship at Lawrence Berkeley National Laboratory he moved to Yale University in 1997 where he was an Assistant Professor at the Physics Department and the A.W. Wright Nuclear Structure Laboratory until he moved to Munich in 2002. His current research interests are in the area of the structure of exotic nuclei and nuclear matter, nuclear astrophysics, as well as applications of nuclear physics methods to radiation biology and medicine.

Lia Merminga

Head, Accelerator Division

Dr. Lia Merminga is Head of the Accelerator Division at TRIUMF, Canada's National Laboratory for Particle and Nuclear Physics. She joined TRIUMF in June of 2008 after sixteen years at Jefferson Lab, where she worked first as a staff scientist and later as the Director of the Center for Advanced Studies of Accelerators. Prior to joining Jefferson Lab, she worked at SLAC from 1989 to 1992. Merminga received her Ph.D. in physics from the University of Michigan in 1989. Her research interests include advanced accelerator systems and nonlinear dynamics, with a recent focus on the design and development of energy recovery linacs and their applications to high-power free-electron lasers, synchrotron radiation sources, and electron-ion colliders for nuclear and particle physics. She is a fellow of the American Physical Society (APS), serves on the U.S. High-Energy Physics Advisory Panel, and is past chair of the APS Division of Particles and Beams.

Paul Schaffer

Head, Nuclear Medicine Division

Dr. Paul Schaffer graduated from the University of British Columbia in 1998 with a B.Sc. in both chemistry and biochemistry. He earned his Ph.D. at McMaster University. His doctoral work focused on the design and synthesis of technetium and rhenium chelates as potential new radio-imaging or radiotherapy agents. Schaffer then became a Research Scientist at the McMaster Nuclear Reactor. In 2006, Schaffer entered the private sector as a Lead Scientist at General Electric Global Research in upstate NY. There, he was responsible for developing novel radiotracers for GE Healthcare. He came to TRIUMF in 2009.

Henry Chen

Chief Financial Officer

Mr. Henry Chen came to TRIUMF in 2011.He is an alumnus of the UBC Faculty of Commerce and holds the Certified Management Accountant designation. To TRIUMF, he brings 27 years of experience in financial management within the profit and not-for-profit sectors. His industry experience includes public sector finance (BC government), retail and wholesale distribution, hospitality management, and most recently, managing the financial and business affairs of a not-for-profit society working with UBC.

Timothy I. Meyer

Head, Strategic Planning & Communication

Dr. Timothy Meyer came to TRIUMF in late 2007 from the U.S. National Academies in Washington, D.C., where he served as an expert in science and public policy as a senior program officer at the Board on Physics and Astronomy. He earned his Ph.D. in experimental particle physics from Stanford University in 2002. In 2010, Meyer chaired a strategic communications review of the U.S. DOE's premier plasma and fusion science laboratory managed by Princeton University. In 2011, he was recognized by Business in Vancouver news magazine as one of the "Top 40 under 40" among Vancouver professionals. In 2013, Meyer became the inaugural TRIUMF Scientist in Resident at Emily Carr University of Art + Design.

Anne Trudel

Manager, Environmental Health & Safety

Dr. Anne Trudel's career has spanned many different areas at TRIUMF. Having completed her doctoral studies in low energy nuclear physics in 1987, she joined the nucleon charge exchange program then underway at TRIUMF under the direction of Peter Jackson and Otto Hauser. From there her interest in detectors lead her to work on a transition radiation detector that was designed, built, and commissioned as part of TRIUMF's contribution to HERMES. In 1996, in order to remain closer to home while raising children, she joined the radiation protection group as Health Physicist. It was a natural fit, capitalizing on her expertise with detectors and applying it to the protection of health and safety in the work place.

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