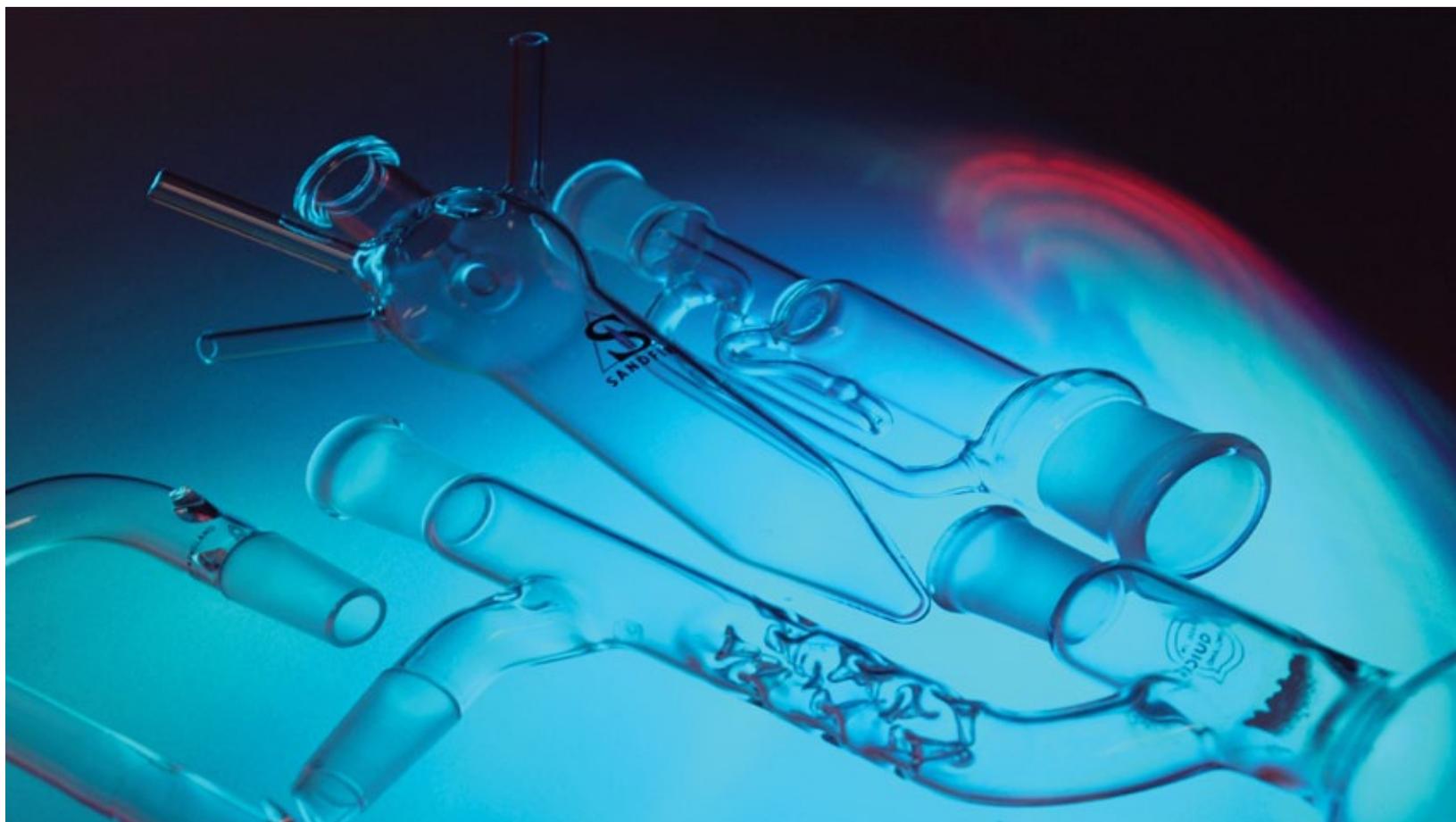


TRIUMF **Scientific Activities Report**

2008 to 2010



TRIUMF

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2008 to 2010



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Cover Photo



Richard Morgan, Scientific Glass Blower

Richard has produced and supplied TRIUMF's radiochemistry and PET programs with custom glassware for over 27 years. His unique works combine scientific specificity, artistic simplicity, and elegant functionality. Richard's studio is located in Gibsons, British Columbia located on the Sunshine Coast.

Photos Back Cover: (right to left)
T2K Event Display
PET Isotope Chemists
TIGRESS Detector

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Mission Statement

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

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

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

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

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

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



Introduction

Director's Preface

Director's Preface

Accelerating Science for Canada

TRIUMF has been busy—not only with operating its main research program and completing key upgrades for improved performance and capability, but also with preparing a new road map for its future. The Five-Year Plan for 2010-2015 was published in mid-2008 and outlined an ambitious vision for the laboratory. The Government of Canada announced its firm support for TRIUMF and for science and technology in Canada as part of the federal budget in early March 2010. In spite of fiscal constraints felt around the world, support for TRIUMF's core operations was renewed for another five years.



This report tells the story of TRIUMF's recent activities and accomplishments. You may note that it appears in a different format; in fact, we have reinvented this document and have designed it to be a resource for our broad community of scientific peers—be they in particle and nuclear physics, chemistry, nuclear medicine, molecular and materials science, accelerator science and technology, or universities, laboratories, and the private sector.

During these past few years, rare-isotope beams from actinide targets in ISAC have become possible (we are presently scheduling our first physics experiments), and the Phase-II upgrade to allow greater acceleration of isotopes in ISAC-II has been completed. A whole spectrum of ions can now be moved past the Coulomb barrier. Similarly, TRIUMF contributions to the Large Hadron Collider and the ATLAS detector, the T2K experiment in Japan, and so on, have all been constructed, transported, installed, and successfully commissioned.

I hope you enjoy learning about what TRIUMF has been up to. None of this would have been possible without the deep commitment of the TRIUMF team and its large community of contributors, patrons, and supporters.
Thank you all!

Yours,

Nigel S. Lockyer
Director

Préfac du directeur

Accélérer la démarche scientifique canadienne

TRIUMF a été bien occupé ces derniers temps - non seulement à exécuter son programme de recherches et à compléter des améliorations cruciales pour accroître son potentiel et sa performance mais aussi à développer un itinéraire possible pour son futur. The plan quinquennal pour la période 2010-2015 a été publié à la mi-2008 et décrivait une vision ambitieuse pour le laboratoire. Dans son énoncé du budget fédéral de Mars 2010, le gouvernement du Canada a réaffirmé un support tangible pour TRIUMF et pour la science et la technologie. Malgré des contraintes budgétaires qui se font ressentir au Canada comme partout ailleurs, le support pour le fonctionnement de base de TRIUMF a été renouvelé pour un autre cinq ans.



Ce rapport décrit les activités et les accomplissements récents de TRIUMF. Vous noterez sans doute le format nouveau qui a été adopté : en fait nous avons repensé ce document de façon à ce qu'il serve de référence pour la grande communauté de nos partenaires scientifiques qu'ils soient en physique des particules ou en physique nucléaire, en chimie, en médecine nucléaire, en science moléculaire ou science des matériaux, en science et en technologie des accélérateurs, ou dans les laboratoires universitaires et dans le secteur privé.

Durant ces dernières années, des faisceaux d'isotopes rares ont été dérivés de cible d'actinides à ISAC (nous venons tout juste de programmer les premières expériences avec ces faisceaux) et une amélioration de l'énergie d'accélération des isotopes à ISACII a été mise en place. Toute une gamme d'ions peut maintenant être accélérée au delà de la barrière coulombienne. Pareillement, les contributions canadiennes au grand collisionneur de hadrons du CERN , à son détecteur ATLAS, à l'expérience T2K au Japon et plusieurs autres ont été construites, transportées, installées et implémentées avec succès.

J'espère que vous aimerez découvrir ce que TRIUMF a accompli. Tout cela n'a été possible que grâce au dévouement de l'équipe TRIUMF et de sa communauté de supporters, mécènes et participants.

Merci à tous,

Nigel Lockyer
Directeur

Introduction

TRIUMF is one of the leading laboratories in the world for studying rare isotopes, and in some instances, is the best. Scientists at TRIUMF are able to study the conditions of supernovae explosions—the deaths of super massive stars—in the laboratory. Using rare isotope beams, researchers can explore the origin of the chemical elements heavier than iron such as copper, silver, and gold. These discoveries will feed into the knowledge base for next-generation nuclear reactors, will help us understand the behaviour of advanced materials under extreme conditions, and will train people for the nuclear industry.

By connecting subatomic physics with research in other areas, TRIUMF will continue to develop and contribute to research in materials and to a world-renowned life sciences program that utilizes medical isotopes combined with positron emission tomography (PET) detectors. TRIUMF's experimental facilities and the core scientific programs of particle and nuclear physics are finding new and crucial applications in the studies of molecular and materials science, as well as nuclear medicine.

With over a thousand users, from international teams of scientists to post-doctoral fellows and graduate and undergraduate students, TRIUMF brings together human talent and sophisticated technical resources.

Photo:
TRIUMF/PET Scanning Facility
using TRIUMF Medical Isotopes at
University of British Columbia hospital



Advancing Knowledge

Subatomic Physics

Molecular and Material Sciences

Nuclear Medicine

Accelerator Physics



Gordon Ball is the head of TRIUMF's Science Division and is an adjunct professor at Simon Fraser University.

Subatomic Physics

Super Allowed Beta Decay

In the recent past we have completed three experiments related to the super-allowed decay program at TRIUMF-ISAC. The devices used for these measurements were the 8π gamma ray spectrometer, its associated ancillary detectors and the GPS 4π gas counter. The purpose of these measurements was to provide valuable high-precision experimental data to obtain precision ft values of $^{26}\text{Al}^m$, ^{18}Ne and ^{19}Ne .

In all three cases, the 8π array was used to measure weak non-analog branches.

S930—Half-life and Branching Ratio Measurements for the Super-allowed β^+ Emitter $^{26}\text{Al}^m$

For the case of $^{26}\text{Al}^m$, the theoretically calculated nuclear structure dependent corrections are the smallest of all the precisely measured super-allowed cases, thus offering least model dependence. Therefore it is important that the ft value of $^{26}\text{Al}^m$ decay be measured with the highest achievable precision. For this experiment, the half-life of the decay was obtained with unprecedented high precision using the GPS gas counter.

The calculated nuclear structure dependent correction for $^{26}\text{Al}^m$ ($\delta C - \delta NS = 0.305(27)\%$ [1]) is smaller by nearly a factor of two than the other twelve precision super-allowed cases, making it an ideal case to pursue a reduction in the experimental uncertainties contributing to the ft value.

Progress in 2008–2010

Measurements of the half-life and super-allowed branching ratio were performed in October 2007 at ISAC I using the GPS1 fast tape transport system

and the 8π γ -ray spectrometer, respectively, as part of an ongoing experimental program in super-allowed Fermi β decay studies. A beam of $\sim 10^5$ $^{26}\text{Al}^m/\text{s}$ was obtained from a SiC target coupled to a surface ion-source, with an order of magnitude enhancement in the ratio of $^{26}\text{Al}^m/^{26}\text{Na}$ provided by TRILIS (TRIUMF Laser Ion Source). Following implantation at GPS1 the movement of the tape to the gas counter was delayed to allow the ^{26}Na activity ($T_{1/2} = 1.07128(25)\text{s}$ [2]) to decay to a negligible level, after which the remaining $^{26}\text{Al}^m$ decays were counted for a minimum of ~ 20 half-lives (see Figure 1). This cycle structure was repeated 2000 times, with the adjustment of various experimental parameters to explore potential systematic effects. A preliminary analysis of these data has shown a statistical precision of $\sim 0.008\%$ representing, by far, the single most precise measurement of any super-allowed half-life to date. A complete analysis of the systematic errors is currently in progress.

Of all the potential non-analog decay branches of $^{26}\text{Al}^m$, only that to the first excited $2+$ level in ^{26}Mg

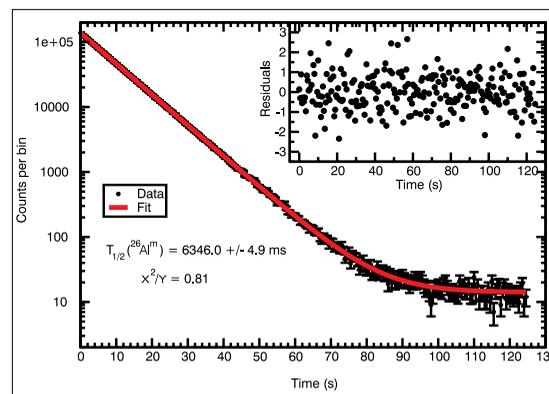


Figure 1: Typical decay curve, with fit, for $^{26}\text{Al}^m$ from one run consisting of ~ 40 cycles.

at 1.81 MeV could have a measurable branching ratio greater than 10^{-6} [3]. Since the contaminant ^{26}Na also decays to this level, each cycle of the branching ratio measurement with the 8π at ISAC-I consisted of saturating the tape with $^{26}\text{Al}^m$, then waiting ~ 20 half-lives of ^{26}Na before beginning the measurement, yielding a ^{26}Na impurity level of $\sim 10^{-5}$. Preliminary analysis indicates that the upper limit on this transition will be reduced from its current value by an order of magnitude.

Ahead in 2010

Combined with a proposed high-precision mass measurement with TITAN (S1073), these half-life and branching ratio measurements will yield a super-allowed ft-value for $^{26}\text{Al}^m$ approximately two times more precise than any of the other super-allowed decays, yielding a new benchmark for tests of nuclear-structure dependent isospin-symmetry breaking corrections and tests of the conserved vector current hypothesis.

The Team

Lead: P. Finlay

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Partnering Labs/Institutions:

National Superconducting Cyclotron Laboratory, Michigan State University, Queen's University, Saint Mary's University, Simon Fraser University, TRIUMF, University of Guelph

S985—Half-life and Branching Ratio Measurement for ^{18}Ne Super-allowed Fermi β Decay

In the second experiment, the beta-decay half life of ^{18}Ne was obtained using the gamma-ray data from the 8π array. A rigorous scheme to correct for pulse pile-up effects in order to extract precision half-lives was employed. This method is a powerful tool to achieve high-precision measurements of half-lives using highly selective gating on the gamma-ray data, thus making beam contamination a minor issue.

Progress in 2008–2010

In June 2008, a measurement of the half-life of the super-allowed emitter ^{18}Ne was performed using the 8π γ -ray spectrometer and the moving tape

collector system. A beam of ^{18}Ne was delivered to the 8π at a rate of $\sim 10^6$ ions/s. The ^{18}Ne ions were implanted into a 40- μm thick aluminum tape for 5 s, following which the beam was turned off for ~ 30 half lives while time data were recorded. The radioactivity on the tape was then moved to a shielded collection box downstream of the array in order to remove the long-lived ^{18}F daughter activity ($T_{1/2} \sim 110$ min) from the centre of the array. These tape cycles were repeated a total of 3100 times over the course of this 2.5 day experiment.

The half-life of ^{18}Ne will be determined using a γ -ray photopeak counting technique that has been recently developed at ISAC [4, 5]. Using the β decay of ^{26}Na as a test of the methodology, it was demonstrated that half-life measurements via γ -ray photopeak counting can be realized with the 8π spectrometer to overall precisions of 0.05% or better even when rate-dependent and systematic losses resulting from detector pulse pileup effects exceed 1.0% [5]. A typical grow-in and decay curve consisting of 175 cycles and gated on the 1042-keV γ -ray that follows 7.7% of all ^{18}Ne β decays is presented in Figure 2.

These data will establish the ^{18}Ne half-life to 0.07% precision constituting the most precise super-

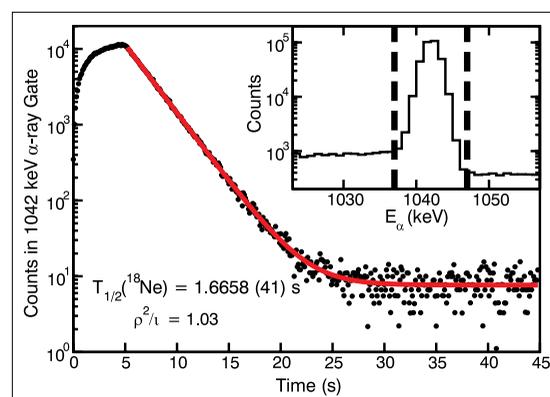


Figure 2: Typical grow-in and decay curve for ^{18}Ne (including corrections for dead-time and pile-up effects) following a γ -ray gate on the 1042-keV transition in the daughter ^{18}F .

allowed half-life measurement performed at ISAC to date with this new technique.

Coincidences between β particles detected in SCEPTAR and rays detected with the 8π provide a powerful tool for β decay spectroscopy and can be performed simultaneously with the half-life measurement. A sample-ray spectrum containing

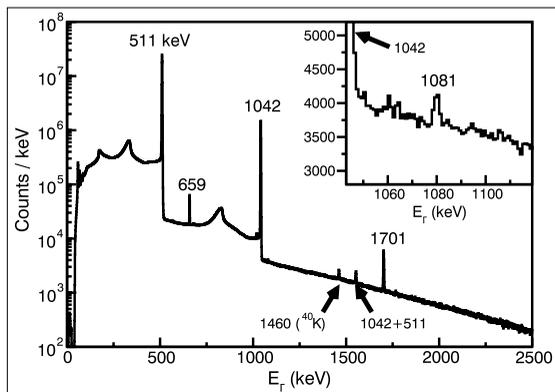


Figure 3: Typical γ -ray spectrum in coincidence with a β particle detected in SCEPTAR with energies labelled in keV. (Inset) The γ -ray transition at 1081-keV follows a weak (2×10^{-5}) first forbidden β -decay branch to the 1.081 MeV state in ^{18}F .

4.5×10^6 counts in the 1042-keV photopeak is shown in Figure 3 and was obtained from the sum of all 20 Compton-suppressed Ge detectors of the 8π spectrometer when in coincidence with a β particle detected in SCEPTAR (SCintillator Electron-Positron Tagging ARray). The 1081-keV ray that follows a previously discovered first forbidden β -decay branch of 2×10^{-5} [6] to the 1.081-MeV state in ^{18}F was also clearly observed (see inset of Figure 3) and demonstrates the sensitivity of these devices to weak decay branches.

These data will be used to extract β decay branching ratios to excited states in ^{18}F with improved precision over previous work.

The Team

Lead: G.F. Grinyer

Members: G.C. Ball, S. Etnenauer, A.B. Garnsworthy, P.E. Garrett, G. Hackman, C.J. Pearson, S.J. Williams; J.R. Leslie; K.L. Green, E. Rand, C.S. Sumithrarachchi, C.E. Svensson

Partnering Labs/Institutions:

National Superconducting Cyclotron Laboratory, Michigan State University; Queen's University, TRIUMF, and the University of Guelph

S1192—Ft Value of the Mirror Nucleus ^{19}Ne

The decay of the mirror nucleus ^{19}Ne provides an excellent opportunity to probe the $V-A$ structure of the weak interaction, which is fundamental to the larger framework of the Standard Model of particle physics. Data from angular correlation measurements and measured Ft values from ^{19}Ne decay have been previously used to set limits on

the probe for exotic interactions such as right-handed and second-class currents that are not included in the minimal Standard Model [7]. In addition, these data can be used to extract the V_{ud} element of the CKM matrix [8], and owing to the relatively low end-point energy of the decay, set improved limits on fundamental scalar interactions (the Fierz interference term) within the weak interaction.

Although the decay of ^{19}Ne is not super-allowed, independent determinations of correlation coefficients from the decay can be used to obtain the Fermi part of the interaction for tests of CKM unitarity. Furthermore, ^{19}Ne beta decay offers an opportunity to probe for right-handed and scalar currents. In these tests of the Standard Model, a precision ft value of the $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$ transition is required to constrain the contributions of exotic interactions beyond the standard model. For this experiment, the half-life of ^{19}Ne was obtained using the SCEPTAR tagging array in the 8π spectrometer as a beta counter. This is the first time that the SCEPTAR plastic scintillator array was used to measure this observable.

Progress in 2008–2010

In 2009, we took data to achieve a high-precision measurement of the ft value of the decay of ^{19}Ne , which currently is limited by the uncertainty in its half-life. Our main experimental objective was to measure the half-life of ^{19}Ne ($T_{1/2} \approx 17$ s) with a relative precision of 0.01% using the SCEPTAR plastic scintillator array. Since this was the first time that SCEPTAR was used for an actual precision measurement, most of our efforts were spent in varying parameters to evaluate the magnitude of various systematic effects. The experiment was divided into three steps.

In the first step, a ^{26}Na beam with an intensity of $\approx 10^6$ ions s^{-1} was implanted onto an aluminized Mylar tape at the centre of the 8π array. (The half-life of ^{26}Na has already been measured to $\approx 0.03\%$ using two independent measurements at ISAC-I.) The decays were registered via beta counting using one half of the SCEPTAR array for a large range of initial rates (by varying the implantation time) to check for rate-dependent systematic effects. Data were registered for ≈ 20 half-lives following the implantation using a multichannel scalar, and were subjected to self-imposed dead times ranging from 5 μs to 28 μs . These data indicated that low rates are crucial to minimize rate-dependent systematic effects.

In the second step of the experiment, which spanned one week, a 37 keV ^{19}Ne beam at $\approx 10^5 \text{ s}^{-1}$ was incident on an aluminum tape in the centre of the array with implantation times ranging from 350 ms to 1.2 s.

In this case, the whole SCEPTAR array was used, such that the trigger rates in each detector ranged from 1 kHz to 4 kHz. Data were registered similarly as before with dead-times ranging from 5 μs to 24 μs . In total ≈ 90 hours of data were collected under varying conditions (such as discriminator settings etc.) to acquire sufficient statistics and test systematic effects. Figure 4 shows the dead-time corrected data and its fit for one such data set.

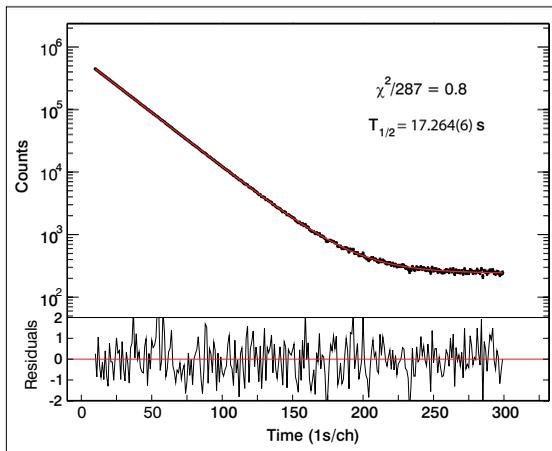


Figure 4: Typical decay curve for ^{19}Ne decay.

In the final stage of the experiment, one 12-hour shift was used to extract weak (forbidden) beta branches from the decay of ^{19}Ne by measuring the gamma-ray intensities using the Germanium detectors.

Detailed data analysis for these data is currently in progress.

The Team

Lead: S. Triambak

Members: R.A.E. Austin, G.C. Ball, G.J. Bangay, L. Bianco, D.S. Cross, M.K. Djongolov, J. Dech, R. D'Entremont, H. Al-Falou, P. Finlay, B. Garnsworthy, P.E. Garrett, K.L. Green, G.F. Grinyer, G. Hackman, R. Kshetri, C. Kierans; K.G. Leach, L. Milovanoic, A.S. O'Hagan, J.N. Orce, M.R. Pearson, E. Rand; S. Reeve, S.K.L. Sjue, C. Sumithrarachchi, C.E. Svensson, E.R. Tardiff, S. Triambak, S.J. Williams; J. Wong

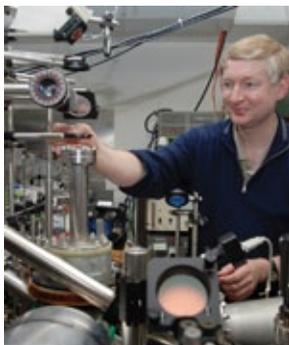
Partnering Labs/Institutions:

Michigan State University, NSCL, Simon Fraser

University, Saint Mary's University, TRIUMF, University of Alberta, University of British Columbia, University of Guelph, and the University of Windsor

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Subatomic Physics

Low Energy Searches

Unaccelerated short-lived isotopes straight from ISAC were used to test several of Nature's fundamental symmetries in the 2008-2010 period. There were five areas of experimentation. Preparation has begun for studies of parity violation in atoms of francium, the heaviest alkali element. A novel method has been developed at TITAN to observe very weak electron capture decays of isotopes stored inside an ion trap. The MTV and RadonEDM experiments use laser-polarized unstable nuclei to search for new sources of time reversal violation, thought to be necessary to explain the excess of matter over antimatter in the universe. The TRIUMF neutral atom trap, by measuring the momentum of all the products of radioactive decay, deduces the momentum of known and unknown weakly interacting particles.

Atomic Parity Violation in Francium

Francium is the heaviest alkali element. So it has a simple atomic system where weak parity-violating interactions between the atomic electrons and the nucleus are enhanced because the atomic electrons have greater probability to overlap the nucleus. All francium isotopes are radioactive, with the longest half-life of 22 minutes. Experiments on the relatively small number of radioactive atoms available, even from projected ISAC yields, require trapping of atoms. The preparation work for the trap-based experiments is mostly happening in the university laboratories of the spokespeople. A plan for locating a temperature-controlled, electromagnetically shielded clean room in the ISAC low-energy area is almost complete. Laser spectroscopy on fast bunched beams from TITAN, which would lead to precision measurements of hyperfine splittings that will be used to extract the hyperfine anomaly to deduce the neutron magnetization distributions, is described

elsewhere in this report (S1010, M.R. Pearson).

Progress in 2008–2010

S1066: Anapole Moment: The nuclear anapole moment is a time reversal conserving, parity-violating, static electromagnetic moment produced by the weak interaction between protons and neutrons. (Anapole means “not a pole”—a whimsical name attributed to Russians.) The only nonzero measurement of an anapole moment was done in the cesium atom, and the result conflicts with experiments using low-energy parity-violating nuclear reactions. Measurements in several francium isotopes would extract isoscalar and isovector weak interactions in the nuclear medium from the sum and difference of neutron and proton couplings. An optical dipole force trap now works at Maryland to hold the atoms at the antinode of a microwave power buildup cavity, with confinement times long enough for the measurement. Two acousto-optic modulators rotate a beam to produce a conservative time-averaged confining potential along both the axial and radial directions. The blue-detuned beams repel the atoms, and the goal is a cage of characteristic size 50 microns that confines but does not perturb them. Figure 1 shows the optical fluorescence image of rubidium atoms 35 ms after turning off the magnetic field and magneto-optical trap beams: a) the cigar-shaped rotating dipole trap; b) the rotating dipole trap together with a 1D blue-detuned standing wave to better confine the atoms. Gravity (g) goes into the paper in the figure.

Ahead in 2010

Work is proceeding at the University of Maryland on the experimental apparatus. A power buildup

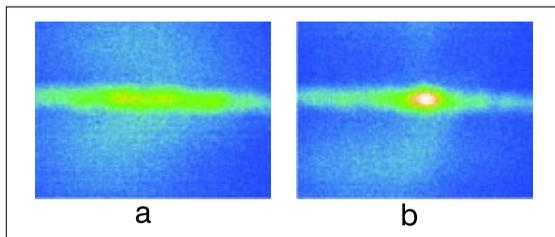


Figure 1: Optical fluorescence image of rubidium atoms.

cavity for microwaves will drive a parity-violating E1 transition between hyperfine ground states. Studies are also proceeding to determine the feasibility of measuring the anapole moment in an isotope chain of rubidium atoms [1].

S1218: Weak Neutral Current between Electron and Nucleon: The existence of a charge-neutral part of the weak interaction was a key prediction of the Standard Model and was discovered in neutrino scattering in the early 1980's. Its strength, determined by a combination of high-energy experiments at CERN and SLAC and the atomic parity-violation measured in cesium atoms in Boulder, is in agreement with the Standard Model prediction to better than 0.5% accuracy. The cesium measurement depends on many-body atomic theory, so tests in another element at similar or better accuracy are important.

The approved experiments for the symmetry program now include a detailed Stark shift-M1 interference experiment to measure the relativistically enhanced M1 in the optical 7S to 8S transition in francium atoms.

Ahead in 2010

Detailed calculations and experimental conceptual design for a full optical atomic PNC measurement in a trap using the same transition are in progress at the University of Manitoba. Work on frequency locking lasers for a rubidium M1 measurement at the University of Manitoba is proceeding.

The Team

Leads: G. Gwinner, L.A. Orozco, M.R. Pearson
Members: S. Aubin, J.A. Behr (TRIUMF), E. Gomez, S.M. Lynam, D. Sheng

Partnering Labs/Institutions:

San Luis Potosi University, TRIUMF, University of Manitoba, and the University of Maryland

Electron-capture branching ratio measurements with a Penning trap for determination of $2\nu\beta\beta$ nuclear matrix elements

A novel method has been developed at TITAN (TRIUMF Ion Trap for Atomic and Nuclear science) in order to observe very weak electron capture (EC) decays of isotopes stored inside a Penning ion trap [2]. These EC decays are especially difficult to measure because of a dominating beta background. These measurements aim towards the determination of transition nuclear matrix elements in $2\nu\beta\beta$ decays. Knowledge of these matrix elements is essential for the theoretical description of $2\nu\beta\beta$ decays. Within this theoretical framework $0\nu\beta\beta$ decays are also described. If this lepton number violating process is observed, thorough understanding of the nuclear transitions is essential to determine the neutrino mass from the half life of the decay. The TITAN EC experiment will provide significant information on nuclear matrix elements in $2\nu\beta\beta$ decays and opens the door to a new field of in-trap-decay spectroscopy.

Progress in 2008–2010

TITAN's electron beam ion trap (EBIT) was connected to ISAC's beam transportation system in 2008. This allowed the injection of both stable and radioactive ions into the EBIT from ISAC. Over a period of several months, operation parameters of the EBIT as well as injection into and extraction from the EBIT were optimized. Ions could be stored for several tens of seconds inside the ion trap without significant losses.

Specialized detectors and mountings were developed and installed to enable effective detection of particles emitted from the radioactive decays of ions stored in the trap. We achieved the detection of beta particles as well as X-rays without contaminating the ultra-high vacuum environment.

All detectors that are inside the vacuum chamber were thoroughly tested prior to installation. Different read-out electronics were tested in order to reach an optimal performance. The signal of the beta detectors was digitized by a tig10 card. This is a card developed at the University of Montreal and is mainly used by the TIGRESS experiment. The X-ray detectors were read out with a DSPEC digitizer manufactured by ORTEC. This combination achieved the highest resolution for the detectors.

In the fall of 2008, radioactive ^{107}In was injected and stored in the ion trap. For the first time X-rays following electron capture events could be clearly identified. The X-ray spectrum was free of any background contribution from betas. The strong magnetic field of the ion trap spatially separated the detection of X-ray and beta particles. This successful experiment showed the feasibility of this new technique. The literature value of the ^{107}In EC branching ratio was reproduced [3].

In the summer of 2009, an experiment with radioactive ^{124}Cs and ^{126}Cs was performed with the goal to determine the EC branching ratios and to test the beta detection system. During the experiment several systematic studies were performed. It was possible to store up to 2×10^5 ions inside the ion trap and observe the EC decay. Figure 2 shows the X-ray signature of ^{124}Cs stored inside the trap. In addition to recording the energies of each beta and X-ray, the detection time was also recorded. Coincidences between X-rays and betas were observed. This observation allows for further reduction of background using off-line analysis techniques.

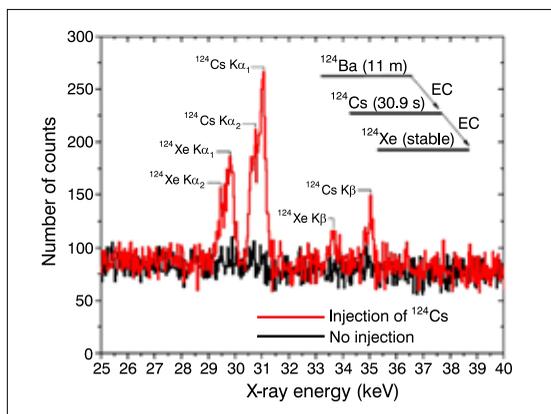


Figure 2: The X-ray signature of ^{124}Cs .

Ahead in 2010

The data analysis of the radioactive beam experiment with Cs is ongoing, and the results will be published. Throughout the year several systematic studies are planned to increase the efficiency of the experiment. Additional low energy Si (Li) detectors will arrive and be tested and installed in the summer of 2010. Later that year, it is anticipated that an experiment with trapped ^{100}Tc will be performed. This will be the first measurement at TITAN to determine the nuclear matrix elements for $2\nu\beta\beta$ decay of ^{100}Mo .

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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 anti-matter. In order to explain why our universe is dominated by ordinary matter, unknown interactions, which violate time reversal symmetry, are required to exist. This experiment searches for violation of time reversal symmetry, which is predicted by models of physics beyond the Standard Model, in a nuclear beta-decay process with the highest precision using a new type of particle position detection device. The MTV (Mott polarimetry for T-Violation) experiment was approved in 2008. First tests at TRIUMF were in 2009, and the final experiment is planned for 2010. This experiment will produce the most precise result on this particular test of time reversal symmetry.

Progress in 2008–2010

The MTV experiment was originally performed at KEK in Japan. After developing a new particle detector that can precisely measure the polarization of electrons emitted from polarized ^8Li nuclei in beta decay processes, a test experiment in 2008 confirmed 10% precision [4–7]. Existence



Figure 3: The MTV experimental setup at ISAC.

of electron polarization perpendicular to its momentum direction is the signal for the violation of time reversal symmetry. A drift chamber, which can detect the position of the electron path with hundreds of thin wires in a gas-filled chamber, was applied as the polarimeter for the first time. The new experiment S1183 was proposed and approved at TRIUMF. The world's highest precision of 0.1% can be expected to be achieved at TRIUMF, thanks to the huge intensity and high polarization of the ^8Li beam produced at ISAC.

The MTV experimental setup was shipped from Japan to TRIUMF in the summer of 2009. The setup is built at a low-energy polarized beam line at ISAC (see Figure 3). In November 2009, the first test experiment was performed with polarized ^8Li beam from ISAC. The ^8Li beam was successfully delivered at up to 10^7 particles per second to the MTV experiment, at around 80% polarization. These numbers should be compared with that of 10^5 particles per second, with 8% polarization at KEK. In addition, performance of the MTV detectors was tested with the high beam intensity, which is a hundred times larger than at KEK. As a result, it is confirmed that we can expect to achieve at least 0.1% precision in the physics data taking planned in 2010. It was also found that there is still room to improve the precision by possibly speeding up the electronics and the detectors. Assuming the improvements, we can then expect to achieve 0.01% precision.

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% promises to explore such new physics signals.

Ahead in 2010

In 2010, we plan to begin data taking and aim to achieve the world's highest precision on this test of time reversal symmetry.

The Team

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S929: Radon EDM

The Radon EDM experiment is a search for evidence of the types of interactions between particles thought to be necessary to explain the abundance of matter relative to antimatter in the universe. The effect of these interactions, as measured at the atomic scale in the form of an electric dipole moment (EDM), would be enhanced by the

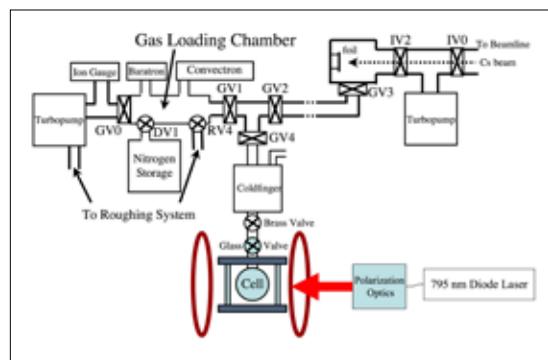


Figure 4: Installation with redesigned coldfinger.

nuclear structure of some radon isotopes. Coupled with the advantages inherent to the use of noble gases in our EDM measurement techniques, radon is a promising candidate for the discovery of a permanent EDM. Such a discovery would be a signal of physics beyond what we currently know about all particles and their interactions.

Progress in 2008–2009

In July 2008, we transported the prototype gas handling and polarization apparatus that had been used in earlier development work at SUNY Stony Brook's Nuclear Structure Laboratory to TRIUMF. We attached it to the ISAC beamline, incorporating a redesigned coldfinger (see Figure 4). The new design allows the noble gas implanted in a thin foil at the end of the beamline to be collected at a cold spot in the vacuum system and provides a smooth path for the jet of nitrogen gas used to push this noble gas into our measurement cell. The polarization apparatus consists of a pair of Helmholtz coils to generate a magnetic field, a spherical glass cell containing a small amount of rubidium, an oven to heat the cell, and a diode laser to polarize the rubidium vapor. Collisions transfer this polarization to the noble gas.

In August 2008, we implanted a beam of ^{121}Cs in a thin zirconium foil, allowed it to decay to ^{121}Xe , and used the gas transfer system to move the ^{121}Xe into the measurement cell along with

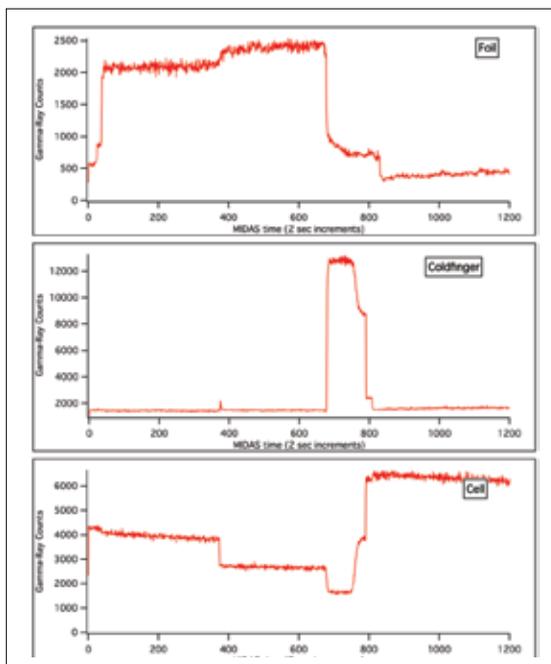


Figure 5: Gamma-ray rates at three location in the vacuum system during the gas transfer process.

about 1 atmosphere of nitrogen gas. High-purity germanium detectors placed at 0° and 90° with respect to the magnetic field direction were used in an attempt to measure a difference in the gamma-ray rates in those directions as the ^{121}Xe decayed. This difference is a polarization signal integral to our method of EDM measurement. There was no statistically significant polarization signal, which we attributed to poor statistics from lower-than-anticipated ^{121}Cs beam intensity as well as flaws in the vacuum system that lowered the achievable polarization.

Improvements were made in July 2009 to the vacuum system to increase the purity of the gas that fills our measurement cell, and automation of some steps in the gas transfer process (see Figure 5) increased the proportion of xenon collected in the foil that made it to the cell, and a new target provided a larger yield of ^{121}Cs for the ion beam. Measurements with stable xenon in the preceding months indicated that the polarization system was capable of polarizing isotopes akin to ^{121}Xe , but the data obtained did not contain a clear polarization signal. We found deficiencies in the polarization system that could account for this.

Yield measurements on a uranium oxide target were performed as part of an experimental program with the goal of allowing the ISAC facility to produce heavy elements such as radon and francium. The energy splitting between opposite-

parity nuclear states in ^{221}Rn and ^{223}Rn , an input for the calculation of the EDM enhancement factors, has never been measured. An electrical short in the target heater module limited our ability to extract the isotopes produced from the target, so our yield of astatine at the 8π apparatus was not enough to ascertain nuclear structure information from the decay of astatine to radon. We were able to demonstrate the production of ^{219}Rn , ^{221}Rn , and ^{223}Rn . The analysis of this data is ongoing.

Ahead in 2010

A systematic effort to optimize each element contributing to the noble gas polarization is under way with the goal of correcting the issues affecting the July 2009 run. This should allow us to be ready to polarize radon during the next actinide target test in addition to studying the nuclear structure of ^{221}Rn and ^{223}Rn using the 8π spectrometer.

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TRIUMF Neutral Atom Trap for Beta Decay

A key experimental feature of the atom trap is that the recoiling nucleus from radioactive decay freely escapes the trap, so its small kinetic energy can be measured. For example, in beta decay, the momentum of the neutrino, otherwise untrackable, can be deduced from the momentum of the other decay products. Neutrinos have no charge and only weak interactions, but they do have a spin, and therefore an intrinsic handedness. The handedness is always aligned with the direction of motion of the neutrino in the Standard Model (SM), which is therefore said to maximally violate the parity (mirror reflection) symmetry. Most new physics beyond the SM would produce neutrinos with the wrong handedness, which would alter their angular distribution with respect to the other particles emitted, or with respect to the initial nuclear spin.

Progress 2008–2010 and Ahead in 2010

S956: Search for Tensor Interactions: A New Method for a Historic Proposal: Parity violation was discovered in nuclear beta decay by measuring the asymmetry in direction of the betas with respect to the initial nuclear spin. Soon after, Treiman realized that the asymmetry in

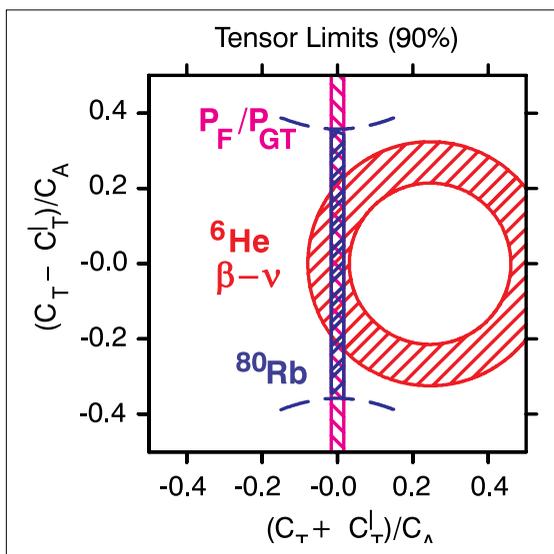


Figure 6: Exclusion plot.

emission of the recoiling daughter nuclei A_{recoil} was just the sum of beta and neutrino asymmetries. A_{recoil} would therefore vanish in spin-changing (Gamow-Teller) decays if the weak interaction had what is now known as its Standard Model form; however, the low-energy daughter nuclei stop in a few atomic layers of material, making direct detection difficult. Since the daughter recoils can freely escape from TRIUMF's neutral atom trap, we used it to measure Treiman's observable. The asymmetry we find in the decay of ^{80}Rb is 0.015 ± 0.029 (statistical) ± 0.019 (systematic), consistent with zero [8]. The experiment could be done an order of magnitude better, although the systematic error comes mainly from theoretical knowledge of the nuclear structure in this region. Figure 6 is an exclusion plot showing our constraints and those of other experiments. The horizontal axis shows the coupling of a tensor interaction to normal left-handed neutrinos, with tight constraints (in magenta) from previous experiments [9]. The vertical axis is the coupling of a tensor interaction to wrong-handed neutrinos, which our A_{recoil} measurement constrains to lie between the two blue, dashed hyperbolas. Our constraint on wrong-handed neutrino couplings is competitive with the best general constraint on tensor interactions from the ^6He beta-neutrino

correlation [10].

S1127: Search for Massive Particles in Isomer Decay: We have continued our search for massive particles emitted in the two-body decay of nuclear excited-state isomers. If a single gamma-ray is emitted, the recoiling nucleus has equal and opposite momentum. If an unknown massive particle were emitted instead of a gamma-ray in isomer decay, then the recoil would have lower momentum.

The recoiling atom in our case has kinetic energy < 2 eV, so it must be photoionized and then accelerated in order to detect it. We have demonstrated photoionization of recoiling atoms from the decay of $^{86\text{m}}\text{Rb}$, but in insufficient quantities to set meaningful limits on massive particles. We are still working to increase the photoionization rate using a power buildup cavity for the Doppler-free two-photon S1/2 to D5/2 atomic transition.

To optimize the photoionization rate, we measured the hyperfine structure and optical isotope shift of $^{86\text{m}}\text{Rb}$, $^{86\text{g}}\text{Rb}$, and $^{81\text{g}}\text{Rb}$. From these we will be able to deduce an atomic physics quantity, the specific mass shift of the D5/2 state. This is a complex two-body momentum correlation over the entire atomic cloud. It is a useful test of many-body atomic theory, and is of interest in alkali-like transitions for astrophysical tests of time variation of the fine structure constant [11].

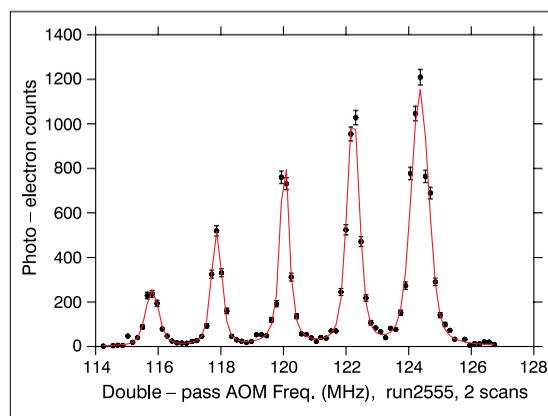


Figure 7: Photoions as a function of laser frequency.

Figure 7, the number of photoions as a function of laser frequency, shows the hyperfine structure. Figure 8 is a textbook “King” plot of one optical transition vs. another in rubidium from which we can deduce the specific mass shift.

S1070: Progress towards Beta-Neutrino

Correlation Upgrade: Our published measurement of the beta-neutrino correlation in ^{38m}K sets the best model-independent constraints on scalar interactions contributing to beta decay. We are working to upgrade this experiment, along

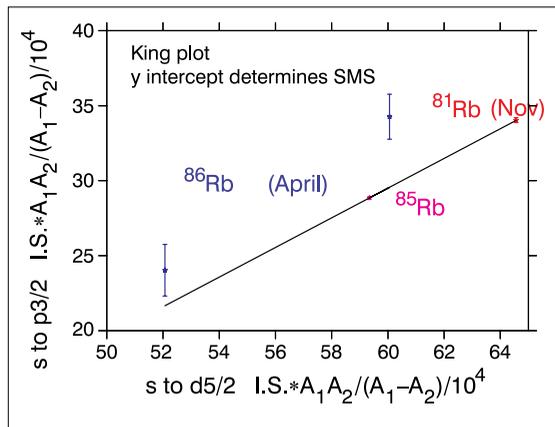


Figure 8: "King" plot of one optical transition vs. another in rubidium.

with a polarized experiment in ^{37}K decay. MCP position readout and electrostatic spectrometer techniques developed in the tensor search and isomer decay will be useful.

S1188: Progress towards Spin-Correlation Upgrade: We published a first measurement of the neutrino asymmetry with respect to the nuclear spin in 2007. We are adding more beta detection solid angle and designing a chamber better dedicated to polarizing the nuclei. The coincidence with atomic shake-off electrons used in the tensor search will help us make clean beta asymmetry experiments by suppressing backgrounds from atoms residing on the walls.

We have demonstrated spin polarization of $98 \pm 1\%$ in ^{37}K atoms and want to improve this in degree and in accuracy of the determination. A group at the University of Manchester has developed a new variation of the magneto-optical trap (MOT) that should be very useful for our polarized beta-decay studies and for future francium atomic parity violation. In both classes of experiments, it is critical to turn the MOT magnetic field off quickly (<100 microsec) so that we can optically polarize and otherwise atomically manipulate our atoms in a field-free region. One main limitation is from eddy currents induced in nearby metal as the magnetic field coils are turned off. In the AC MOT, eddy currents are minimized by sinusoidally varying the MOT magnetic quadrupole field. Eddy currents are out of phase with coil currents, so choosing the right time to turn the coil currents

off can make the eddy currents very small. We are implementing the concept now in a MOT with stable potassium.

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Subatomic Physics

Halo Nuclei

The discovery of the nuclear halo has brought about a renaissance in nuclear physics. In these exotic nuclear forms, one or two neutrons form a low-density large halo around a more compact normal nucleus. Understanding the evolution and consequences of the nuclear halo is presently of great importance. The low-energy, high-intensity, and good quality beams of such neutron-rich nuclei at TRIUMF have given us the opportunity to perform precision studies on these nuclei.

Progress in 2008–2010

Two new measurements and previous experimental results have made a significant contribution to the worldwide study of nuclear halo. Two experiments in particular are at the forefront of this international scientific endeavour. The neutron halo is an unexpected exotic form of nucleus that arises when nuclei have a very large excess of neutrons that makes the last one or two neutrons only attached to the nucleus in a very fragile way. Under such neutron-rich conditions, the properties of nuclei differ much from normal expectations. The experiments at TRIUMF provide us with new information on ^{11}Li and ^{12}Be .

TRIUMF has launched a major program on the most pronounced neutron halo nucleus: ^{11}Li . This program provides a highly sensitive way to study the halo neutron correlation. There are several projects that have made a high-impact in this field. The precise mass measurement of ^{11}Li using the TRIUMF Ion Trap for Atomic and Nuclear science or TITAN Penning trap [1] and the charge radius of ^{11}Li [2] together with the matter radius have helped to define the halo. In the area of direct reactions, using the accelerated beams, the two-neutron transfer from ^{11}Li showed the two neutrons to be strongly correlated [3]. For the first time, signature

of the ^9Li core in its excited state was observed. A recent analysis shows that the observations might be the first direct evidence of phonon mediated pairing in nuclei [4]. The experiment was performed with two beam energies of 3A MeV and 4A MeV. The data for the higher energy is under analysis. The combined interpretation of both data is expected to provide further understanding on the halo neutron-correlation. This experiment also provided an alternative measure of the mass of ^{11}Li [5] that has been found to be consistent with that measured at TITAN.

S1055 ^{11}Li : The loosely bound structure of the halo nuclei suggests that they could be easily polarized. Thus, in the presence of a strong electric field the nucleus might be distorted so that with respect to the centre of mass of the nucleus, the halo neutrons will move opposite to the electric field, while the positively charged core will move in the direction of the field.

The phenomenon of dipole polarizability strongly affects the elastic scattering of halo nuclei on heavy targets, even at energies below the Coulomb barrier, where the nuclear force should not be important. Two effects are relevant: First, Coulomb break-up will reduce the elastic cross sections. Second, the distortion of the wave function generated by the displacement of the charged core with respect to the centre of mass of the nucleus will reduce the Coulomb repulsion, and with it the elastic cross sections.

An experiment was performed at the ISAC II facility, measuring the elastic differential cross section of ^{11}Li on ^{208}Pb at laboratory energies of 2.2 to 2.7A MeV [6]. A reduction of the differential cross sections compared to the Rutherford cross-section was observed and quantified.

The idea behind the experiment is to use a phenomenon of Rutherford scattering and examine how ^{11}Li scattering on lead departs from the well-known predictions. The lead target was chosen for this scattering due to its double magic character and its high Z number ($Z=82$), which guarantees that ^{11}Li -Pb scattering would be dominated by Rutherford scattering if ^{11}Li was a normal compact nucleus. The fact that it is a halo nucleus results in departures from Rutherford scattering, and this deviation can shed light on the nuclear halo. To understand this effect, an elastic scattering experiment was also performed on ^9Li that does not have a halo structure. The data are currently being analyzed. Some interesting preliminary observations show clear signature of breakup at forward angles for ^{11}Li -Pb scattering which is absent for ^9Li -Pb scattering (see Figure 1).

both in the ground state as well as in a long-lived 0^+ excited state, in ^{12}Be was investigated through the $^{11}\text{Be}(d,p)$ reaction for the first time [7]. From angular momentum conservation rules, this reaction is specifically selective to the s -wave content of the 0^+ states in ^{12}Be because since the ground state of ^{11}Be is $1/2^+$. Therefore, the added neutron to ^{11}Be can form a 0^+ state in ^{12}Be only if the neutron is in the $2s_{1/2}$ orbital. The experiment shows that the ^{12}Be nucleus is likely a halo in its excited state and gives new structure information on the ground state. This information is important for understanding the role of nuclear interactions in very neutron-rich nuclei.

This challenging reaction was possible at TRIUMF owing to the newly developed high-intensity ^{11}Be beam. The TIGRESS auxiliary detector system, Bambino, was used to detect the scattered

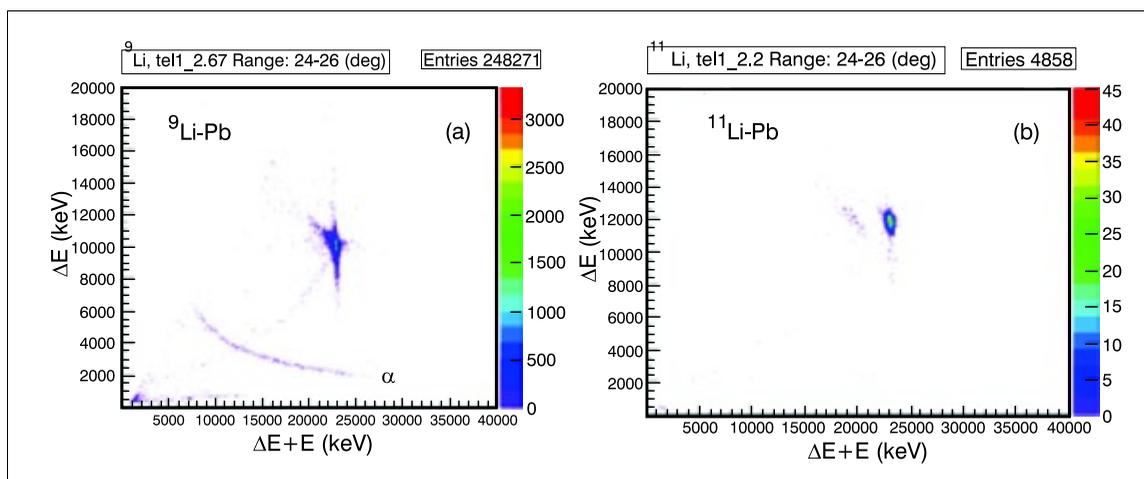


Figure 1: Preliminary data for (a) $^9\text{Li} + \text{Pb}$ scattering at 2.67A MeV (below the Coulomb barrier).

S1065 ^{12}Be : To understand the fundamental reasons behind the evolution from normal to halo structure along the $N=8$ isotones, the study of ^{12}Be is very important. This nucleus in the immediate vicinity of ^{11}Li is the point for onset of breakdown of the conventional $N=8$ magic number. It is understood that the $2s_{1/2}$ orbital unexpectedly intrudes into the p -shell in this region leading to this breakdown. It is the presence of this intruder $2s_{1/2}$ orbital in ^{11}Li that leads to a halo formation; however, the radius of ^{12}Be is not dramatically large like ^{11}Li . It is of interest, therefore, to find out how a stronger pairing between nucleons in ^{12}Be affects the halo formation.

In a recent experiment at TRIUMF, the occupation probability of the neutrons in the $2s_{1/2}$ orbital,

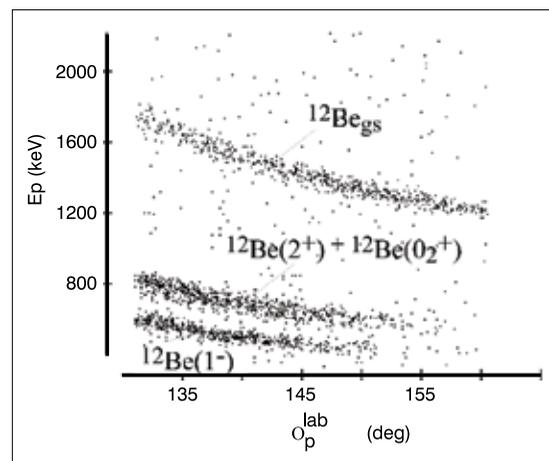


Figure 2: The energy and scattering angle correlation data for protons and ^{12}Be detected in coincidence.

protons and ^{12}Be in coincidence leading to a very clean identification of the specific reaction channel of interest (see Figure 2). The observations show important new information on the *s*-wave configuration of the 0^+ long-lived excited state raising the question whether reduced separation energy in this state induces a halo-like structure in it as opposed to the ground state of ^{12}Be . The ground state spectroscopic factor for the $2s_{1/2}$ orbital is found to be slightly smaller than that reported from knockout measurements. A smaller *s*-wave occupancy in ^{12}Be ground state will be consistent with increased pairing energy.

Masses of the neutron- and proton-rich nuclei provide essential information towards determining the extent of the halo and skin. The TITAN Penning trap facility at TRIUMF has set new standards of high-precision mass measurement. A detailed report on this program with recent results is being presented in a different article in this annual report and is therefore omitted here.

Ahead in 2010

In the coming year, experiments are planned to explore whether the neutron halo leads to new excitation modes. Of special interest is looking for the soft dipole mode, where the oscillation of two halo neutrons against the core nucleus may lead to low-lying dipole resonances. An exploratory search to look for resonance states beyond ^{11}Li will also be launched through one-neutron transfer reactions. Resonant scattering reactions to search for resonance in ^{12}Be are also planned. To extend the power of studying the transfer reactions on neutron-rich nuclei in the upcoming years, we will undertake the development of a new facility with a solid hydrogen target.

The Team

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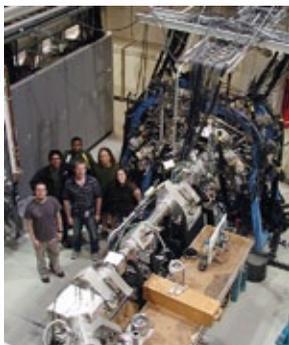
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Subatomic Physics

Structure in Heavy Nuclei

The development of rare-isotope beams worldwide has opened new vistas in nuclear structure research, allowing for the exploration of structure at the extremes of the proton-to-neutron ratio and the isospin degree of freedom. TRIUMF has been very active in this field of research, with the number of dedicated experiments growing and expanding with the development of additional neutron-rich species from an actinide primary target. Research into the nuclear structure of heavy nuclei has been performed predominately using the 8π spectrometer at ISAC and TIGRESS at ISAC-II. A new facility for co-linear laser spectroscopy is being developed.

Coulomb Excitation of $^{21}\text{Na}/^{21}\text{Ne}$ and ^{20}Na

The nuclei ^{20}Na and ^{21}Na are of interest for both nuclear shell structure studies far from stability as well as for understanding the conditions for breakout from the hot carbon-nitrogen-oxygen (hCNO) cycle, one of the main processes that heavy stars use to produce energy, into the rapid proton capture (r-p) process, which is important for explaining the abundances of many neutron-deficient stable isotopes. The hCNO breakout requires reaction sequences that bridge the proton-unbound nuclei ^{15}F , ^{16}F , and ^{19}Na . Two reaction sequences contribute to the flow, though they are predicted to be dominant for different ranges of temperature and density. For higher temperatures and densities (e.g., $T > 0.5$ GK at $\rho = 10^7$ g/cm³), flow is expected to be dominated by the $^{14}\text{O}(\alpha, p)^{17}\text{F}(p, \gamma)^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$ reactions, while for the lower ranges, breakout is expected to be dominated by the $^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne}(p, \gamma)^{20}\text{Na}$ reaction chain. These neutron-deficient Na nuclei were studied by excitation, via the electromagnetic force, of a beam of ^{21}Na and ^{20}Na impinging on a Ti target. This was the first radioactive beam

experiment, performed in 2006, to use the TIGRESS spectrometer for γ -ray detection, and the BAMBINO Si particle detector for detection of the scattered heavy ions.

Progress in 2008–2010

After the experimental data were collected in 2006, new analysis protocols had to be developed and analysis procedures perfected. The main work of extracting the electromagnetic transition strengths, or $B(E2)$ values, for excitation of the first excited state in ^{21}Na , and the first two excited states in ^{20}Na , was performed in 2008. The previous data for ^{21}Na had a highly uncertain $B(E2)$ value of $B(E2; 3/2^+ \rightarrow 5/2^+) = 14 \pm 12$ W.u. In addition to being highly imprecise, the accuracy of the $B(E2; 3/2^+ \rightarrow 5/2^+)$ value in ^{21}Na was questionable comparing to its mirror pair, ^{21}Ne , which has a value of 24 ± 3 W.u. for the corresponding transition. The spectrum for Coulomb excitation from the $3/2^+$ ground state to the first excited $5/2^+$ state is shown in Figure 1 for ^{21}Na , and the $B(E2)$ values were determined by using the $2^+ \rightarrow 0^+$ de-excitation in

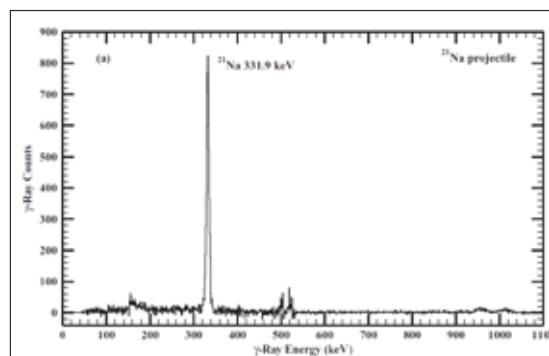


Figure 1: Portion of the γ -ray spectrum observed in the Coulomb excitation of ^{21}Na on a Ti target. A Doppler correction appropriate for the ^{21}Na beam has been applied.

^{48}Ti as a reference. The resulting $B(E2) \uparrow$ values are $131 \pm 9 \text{ e}^2\text{fm}^4$ ($25.4 \pm 1.7 \text{ W.u.}$) for ^{21}Ne and $205 \pm 14 \text{ e}^2\text{fm}^4$ ($39.7 \pm 2.7 \text{ W.u.}$) for ^{21}Na .

The newly-determined $B(E2)$ values were compared with sophisticated nuclear structure calculations using the shell model, and the experimental results indicated that these very neutron deficient nuclei required adjustments in parameters used in the calculations in order to reproduce their transitions rates. By using the effective charges $e_p = 1.5e$ and $e_n = 0.5e$, the $B(E2)$ values produced by the p-sd shell model are 30.7 and 36.4 W.u. for ^{21}Ne and ^{21}Na , respectively. This analysis resolves a significant discrepancy between a previous experimental result for ^{21}Na and shell-model calculations.

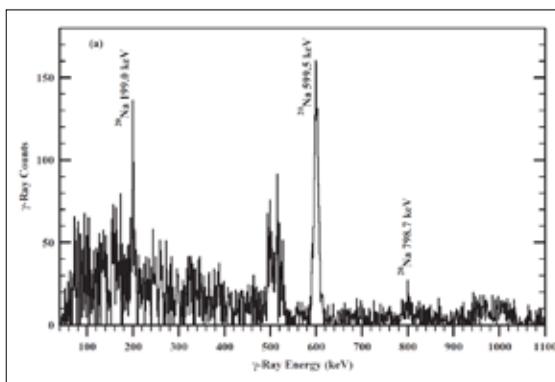


Figure 2: Portion of the γ -ray spectrum observed in the Coulomb excitation of ^{20}Na on a Ti target. A Doppler correction appropriate for the ^{20}Na beam has been applied.

For ^{20}Na , the Coulomb excitation from the 2^+ ground state to the first excited 3^+ and 4^+ states was observed, as shown in Figure 2, and $B(\lambda L)$ values were determined also using the $2^+ \rightarrow 0^+$ de-excitation in ^{48}Ti as a reference. The resulting $B(\lambda L) \downarrow$ values are $B(E2; 3^+ \rightarrow 2^+) = 55 \pm 6 \text{ e}^2 \text{ fm}^4$ ($17.0 \pm 1.9 \text{ W.u.}$), $B(E2; 4^+ \rightarrow 2^+) = 35.7 \pm 5.7 \text{ e}^2 \text{ fm}^4$ ($11.1 \pm 1.8 \text{ W.u.}$), and $B(M1; 4^+ \rightarrow 3^+) = 0.154 \pm 0.030 \mu\text{N}^2$ ($0.086 \pm 0.017 \text{ W.u.}$). These measurements provide the first experimental determination of $B(\lambda L)$ values for this proton dripline nucleus of astrophysical interest.

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Partnering Labs/Institutions:

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Coulomb excitation of ^{29}Na

The success of the shell model applied to atomic nuclei derives its origins from the existence of a set of "magic" numbers corresponding to particularly stable proton and neutron configurations in nuclei along, or close to, the line of β stability. However, for certain exotic nuclei new magic numbers appear while the established ones disappear. A major research program at TRIUMF is the exploration of how the shells evolve as one moves away from the line of stability. Major changes are the locations of the shells that have been linked to the underlying interaction of the valance protons and neutrons, and understanding this mechanism is of vital importance. Nuclei near ^{32}Mg , especially, have been the focus of much research, and the Coulomb excitation of ^{29}Na has been performed in order to understand the boundaries of the region where a major change in shell structure is observed.

Progress in 2008–2010

The Coulomb excitation of ^{29}Na was achieved using a beam of ^{29}Na accelerated using ISAC-I and ISAC-II in August 2007. The analysis work was performed mainly in 2008. Excitation of both projectile and target was observed in the experiment, as shown in Figure 3. Determination of the transition matrix element $\langle 5/2^+ || E2 || 3/2^+ \rangle$ for ^{29}Na was accomplished according to the relative γ -ray yield between ^{110}Pd and ^{29}Na . The experimental result, $|\langle 5/2^+ || E2 || 3/2^+ \rangle| = 0.237(21) \text{ eb}$, is consistent with the prediction of the Monte Carlo shell

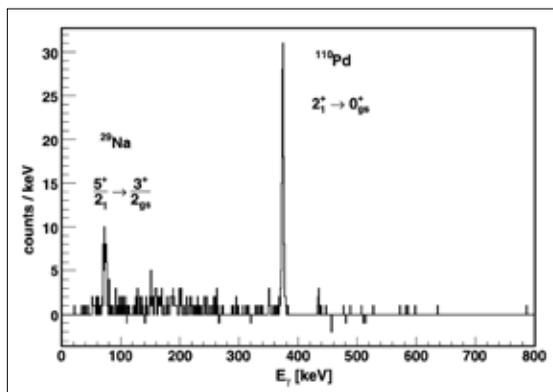


Figure 3: Portion of the γ -ray spectrum observed in the Coulomb excitation of ^{29}Na on a ^{110}Pd target.

model using the SDPF-M interaction of 0.232 eb, which also predicts the correct ground-state spin $I=3/2^+$ for ^{29}Na . This result supports the theoretical conjecture that allows for neutron excitations across the shell gap, resulting in neutrons filling the next major pf shell before completion of the $N = 20$ sd major shell, and that it is a strongly-mixed state comprising a 30–40% admixture of 2p–2h configurations in the wave function. This scenario would imply a narrow sd–pf neutron-shell gap of ~ 3 MeV for ^{29}Na , much smaller than the value observed near stability.

The Team

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Partnering Labs/Institutions:

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Investigation of the Nuclear Structures of the Cd Isotopes

The nature of the neutrino is one of the most pressing issues in subatomic physics today, and can be revealed through the observation of the neutrinoless double β -decay ($\beta\beta(0\nu)$) process. A new class of $\beta\beta(0\nu)$ experiments is underway, including many being constructed at SNOLAB. The neutrinoless double electron capture, ECEC(0ν) process, however, has been suggested to offer a potentially attractive alternative if a resonance condition in the decay Q value can be met. One of the most promising cases for the ECEC(0ν) process existed for the $^{112}\text{Sn} \rightarrow ^{112}\text{Cd}$ ECEC to the fourth 0^+ level at 1871 keV that was within the experimental uncertainty of satisfying the resonance condition of $Q - Q_{\text{res}} = -5.9(4.2)$ keV. Very recent mass measurements using the Penning trap at Jyv skyl  indicated that the $^{112}\text{Sn} \rightarrow ^{112}\text{Cd}$ double EC to the fourth 0^+ level may not undergo a resonant enhancement. However, significant uncertainty, of up to ± 1 keV, remained because of a doublet of levels ($0^+, 4^+$) at 1871 keV in ^{112}Cd . As part of a programme to investigate the nuclear structure of the Cd isotopes, the β decay of ^{112}In and ^{112}Ag was performed in July 2007.

Progress in 2008–2010

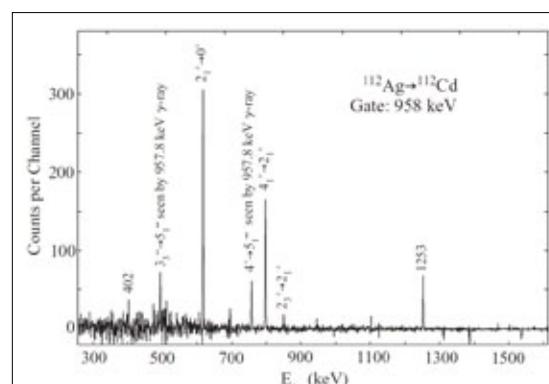


Figure 4: Portion of the γ -ray spectrum in coincidence with a transition feeding the ^{112}Cd 1871-keV 0^+ level observed in the β -decay of ^{112}Ag and ^{112}In .

The analysis of the mass 112 decay data was performed in 2008–2009 at the University of Guelph. The data were sorted into gg coincidence matrices and the decay scheme established using coincident g-ray spectra such as those shown in Figures 4 and 5. The energy of the fourth 0^+ state was accurately determined to be 1871.137(72) keV. Using the recent mass measurement value, the $Q - Q_{\text{res}}$ value is $-5.55(18)$ keV, and it is concluded that the $^{112}\text{Sn} \rightarrow ^{112}\text{Cd}$ ECEC(0ν) process will not receive a substantial resonant enhancement. Further, the experiment revealed the lack of evidence for the 0^+ to two-phonon 2^+



Chris Ruiz is a research scientist at TRIUMF and the leader of the DRAGON program.

Additional authors: Sandrine Courtin, Alison Laird

Subatomic Physics

Nuclear Astrophysics

The experimental nuclear astrophysics program at TRIUMF has seen focused effort on a variety of astrophysical problems, and in the period 2008–2010 emphasis has remained on cutting-edge studies with accelerated rare-isotope beams.

The efforts can be listed in terms of the particular astrophysical scenarios for which they are of importance, namely: nucleosynthesis of gamma-ray emitting radioisotopes in classical nova explosions, the rp-process in Type I X-ray bursts, the s-process and main-sequence stellar burning. Additionally, research has progressed on radiative capture on $^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si}$.

Classical Novae and Gamma-Ray Emitting Radioisotopes

Classical novae—thermonuclear runaways on the surface of a white dwarf in a binary star system—are known to produce a variety of nuclei up to the calcium region via explosive hydrogen burning when they accrete H-rich matter from their companion star. In this case, proton capture reactions are of primary importance in determining the final ejected isotopic abundances from the explosion, including (p, γ) and (p, α) reactions. Prospective targets for gamma-ray astronomy such as ^{22}Na ($t_{1/2}=2.604\text{y}$) and ^{18}F ($t_{1/2}=1.83\text{h}$) are known to be synthesized in quantity in models of novae, and if the characteristic gamma rays from their decay are observed, they would provide a powerful direct look at the inner workings of the explosion and increase our understanding of these cataclysmic, but common, events. To date, no ^{22}Na has been directly observed in any individual novae, despite predictions to the contrary. Part of the problem is that many of the proton-induced reaction rates affecting the ejected abundance of these isotopes are either unknown, or not

measured to sufficient precision. ^{26}gAl ($t_{1/2}=7.1 \times 10^5\text{y}$), a radioisotope which has been observed extensively by gamma ray telescopes, can also be produced by classical novae, and understanding their contribution to the total galactic ^{26}gAl abundance is a similar problem to that of ^{22}Na and ^{18}F .

Progress in 2008–2010

The DRAGON (Detector of Recoils and Gammas of Nuclear Reactions) and TUDA (TRIUMF UK Detector Array) programs have had great past success in studying some of the proton-capture reactions important in these cases, such as the measurement of $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$, $^{21}\text{Na}(p,p)^{21}\text{Na}$, $^{20}\text{Na}(p,p)^{20}\text{Na}$ and $^{26}\text{gAl}(p,\gamma)^{27}\text{Si}$. In the period 2008–2009 this list has expanded with several studies of the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction, which is the single largest source of uncertainty in ejected ^{18}F abundances in novae, and with the first direct measurement of the $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ reaction, which affects the ejected abundances of ^{22}Na and ^{26}gAl . These radioactive beam experiments were all performed with the highest achieved intensities anywhere in the world.

S1195: Resonances in ^{19}Ne with Relevance to the Astrophysically Important $^{18}\text{F}(p,\alpha)^{15}\text{O}$ Reaction

This work was performed by the TUDA collaboration led by spokesperson A. St J. Murphy from the University of Edinburgh. This experiment was originally performed using discretionary time as an alternative to S996 and was later solidified into a full proposal. It was designed to probe higher-lying proton resonances in ^{19}Ne using a simultaneous measurement of resonant elastic scattering and the (p, α) reaction at the TUDA

facility. The purpose was to resolve the question of whether a state predicted by theory exists or not. The state in question, if in existence, could have ramifications for the low-energy cross section of the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction through its interference with lower-lying states of the same spin and parity. The experiment, which took data in 2007, used an isotopically-pure ^{18}F beam of $4 \times 10^4 \text{ s}^{-1}$ incident on a thick (28 mm) polyethylene (CH_2) target which stopped the beam and allowed reactions to occur over a wide range of centre-of-mass energies. Scattered protons and alpha particles from the reactions were detected using a 1 mm thick array of silicon detectors (LEDA). Differential cross-sections for the $^{18}\text{F}(p,p)^{18}\text{F}$ and $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reactions were extracted over an energy range of $E_{\text{c.m.}}=0.6$ –1.6 MeV, and a multichannel, multilevel R-Matrix formalism was used to fit the data from the (p,p) and (p, α) channels simultaneously—the first time this has been performed for these reactions.

Several resonances in ^{19}Ne were observed (see Figure 1), and partial width and spin-parity information was extracted where possible. The properties of a well-known $3/2^+$ state at 7076 keV were found to be consistent with previous measurements. The existence of a previously

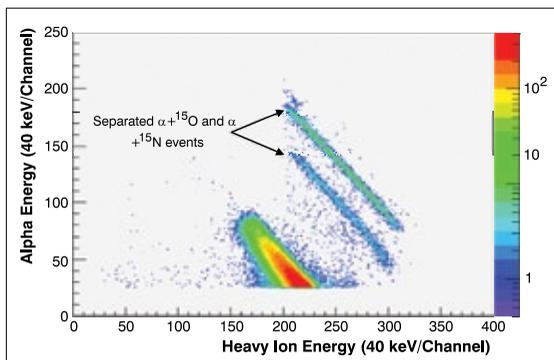


Figure 1: Coincidence events in the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction at $E_{\text{c.m.}}=665$ keV, showing the kinematically separated $^{18}\text{F}(p,\alpha)^{15}\text{O}$ and $^{18}\text{O}(p,\alpha)^{15}\text{N}$ events.

observed $5/2^+$ state at 7500 keV was confirmed, although the widths of this state were found to differ compared to work done elsewhere. A known $(1/2^-)$ state at 7644 keV was also found to be consistent with previous data.

Two new states were observed, a $3/2^+$ state at 7742 keV and a tentatively assigned $1/2^+$ state at 7984 keV. The derived properties of these states suggest that they are too weak to be the state predicted by theory, and will not significantly affect the low-energy $^{18}\text{F}(p,\alpha)^{15}\text{O}$ cross section.

Progress in 2008–2009

A second S1195 run was performed in June 2008, expanding the energy range and running with higher beam intensities (up to $6 \times 10^5 \text{ s}^{-1}$). The data from the first run contains no indication of a candidate proton resonance into the state predicted by theory over the energy range examined.

Ahead in 2010

The June 2008 data is still under analysis, but preliminary indications support the conclusions of the earlier data.

The Team

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Participating Labs/Institutions:

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S996: Nova Observables— ^{18}F Abundance and the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ Reaction

The work was performed by the TUDA collaboration with A.M. Laird, University of York, as spokesperson. The aim of this experiment was to make a direct measurement of the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ cross-section in the astrophysically relevant energy regime in the astrophysically relevant energy regime, a possibility which has been excluded until now due to the unavailability of sufficiently intense ^{18}F beams in the world. ISAC has now achieved the highest ^{18}F intensity, sufficient to make a measurement attempt at these energies.

Progress in 2008–2009

Data were taken at the TUDA facility during the summer of 2008, using a mixed $^{18}\text{F}/^{18}\text{O}$ beam of *average* intensity $8 \times 10^6 \text{ s}^{-1}$ incident on a polyethylene (CH_2) target. The beam was provided using a SiC ISAC target combined with the FEBIAD (Forced Electron Beam Induced Arc Discharge) ion source. The fraction of ^{18}F in the beam was measured using monolithic silicon and photodiode diagnostic detectors and was regularly greater than 50% and reaching $\sim 100\%$ at best. Recoil and scattered products from the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ and $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reactions were detected in coincidence

using segmented silicon arrays (LEDA and MSL S2 type) and were easily resolved from each other due to the difference in reaction Q-value and the superior resolution of the experiment.

Measurements were made at energies of $E_{\text{c.m.}}=665$ keV, 430 keV, 330 keV and 250 keV. A preliminary analysis of the data at 665 keV (see Figure 2) results in a value of the reaction differential cross-section, which is in good agreement with a previous measurement at Oak Ridge National Laboratory. The data at the lower energies is under analysis and will form the Ph.D. thesis of C. Beers at the University of York, UK. The extracted cross-section at $E_{\text{c.m.}}=250$ keV will enable the determination of the sign of interference between the known low-energy $3/2^+$ states. It will, therefore, put a crucial tight constraint on the value of the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction rate at nova temperatures and enable predictions of the ejected ^{18}F abundances.

Preliminary results were presented at the 10th Annual Symposium on Nuclei in the Cosmos, on Mackinac Is., Michigan, Illinois in July 2008.

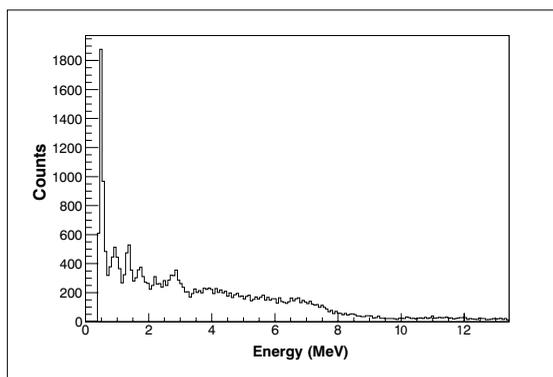


Figure 2: Direct gamma for the BGO spectrum measured at $E_{\text{Lab}} = 1.54$ MeV for the ^{16}O on ^{12}C reaction.

Ahead in 2010

With potential increases in ^{18}F intensity, further measurements of this reaction at the astrophysically-relevant energies may become possible in 2010–2011. The $^{18}\text{F}(p,\gamma)^{19}\text{Ne}$ experiment scheduled to run using DRAGON in summer 2010 will give some indication of the possibilities for this, leading to further beam requests if the intensities are sufficiently improved.

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S810: First Direct Study of the $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ Reaction with a Recoil Mass Spectrometer

This work was performed by the DRAGON collaboration led by spokesperson U. Greife of Colorado School of Mines. The $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ reaction is one of the critical reactions in the transition between the Ne-Na and Mg-Al cycles in nova nucleosynthesis, having a bearing on the ejected abundances of both ^{22}Na and ^{26}gAl .

This reaction had never been measured directly. Only the positions of the few contributing states to the reaction were known to moderate precision from indirect charge-exchange reaction measurements. Strengths of the resonances in question were estimated from theory only, and thus the reaction rate carried a considerable uncertainty, translating into uncertainty in the ejected quantities of ^{22}Na and ^{26}gAl .

Progress in 2008–2009

A ^{23}Mg ($t_{1/2}=11.32\text{s}$) beam was developed for this experiment using a SiC ISAC target, and a resonant laser ionization scheme using TRILIS (TRIUMF Laser Ion Source). During the experiment, peak intensities of $5 \times 10^7 \text{ s}^{-1}$ were delivered to DRAGON. The isobaric contaminant in the beam, ^{23}Na , was present throughout the run in varying quantities, and the ratio of ^{23}Mg to ^{23}Na was closely monitored using a variety of methods, including attenuated beam runs into DRAGON's focal plane ionization chamber, and monitoring of the beam β^+ -decay rate versus total current.

A=24 Reaction products from the $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ and $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reactions were separated from unreacted beam via local time-of-flight measured at the focal plane, in coincidence with prompt gamma rays detected in DRAGON's BGO array surrounding the H_2 gas target. ^{24}Al and ^{24}Mg were separated using ΔE vs E information measured in the focal-plane ionization chamber.

The beam energy of 502A.keV was chosen to cover an energy range where the dominant resonance in $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ was expected, at $E_{\text{c.m.}}=473$ keV. During the experiment, ^{24}Al and ^{24}Mg product nuclei were observed consistent with narrow

proton resonances in the $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ and $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reactions. Those corresponding to the $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reaction were positioned near the centre of DRAGON's gas target, as determined by the distribution of z-coordinates of the highest energy reaction prompt gamma rays (in coincidence with detected recoils). This corresponds to a previously unknown resonance in $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$, although a measurement of this was not the aim of the experiment. The $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ resonance was observed significantly upstream of the centre of the gas target, indicating that it was close to the beam energy, contrary to the suggestions in the literature. Because of this, a special analysis was performed which took into account the effects of the beam energy distribution, the gas target profile, and the BGO response function in order to estimate the correlated values of the resonance energy and strength, E_R and $\omega\gamma$. This results in a 2d probability distribution, shown in Figure 3, which can be used to extract the contribution of this resonance to the $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ reaction rate.

We found that the energy of the '473 keV' resonance in $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ occurs at an energy substantially higher than reported in the literature. Based on this we have re-evaluated the $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ Q-value, and the data from

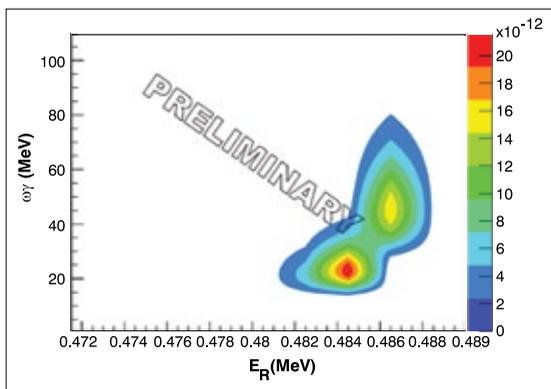


Figure 3: 2d probability density function for resonance strength and energy of the dominant resonance in $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ extracted from the DRAGON data.

several experiments that have reported resonance energy values for this state. We find that by using modern values of the masses of particles involved in these experiments, the resonance energy in the literature shifts up by 9 keV. Our preliminary analysis is in agreement with this value.

Additionally we found a value of resonance strength higher than the shell model estimate,

but consistent within errors, confirming that this resonance is dominant in $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ at nova temperatures. The uncertainty in the reaction rate has thus been drastically reduced, compared to that assumed in nova nucleosynthesis studies.

Ahead in 2010

The results of this experiment have been accepted for publication to *Physical Review C* and will be published in April 2010

The Team

Lead: L. Erikson

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S1027: Measurement of the $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$ Reaction Rate

This work was performed by the TRIUMF-CENPA (Seattle) collaboration, led at TRIUMF by spokesperson C. Ruiz and at CENPA by A. Sallaska and A. Garcia. The $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$ reaction is the direct destruction mechanism of ^{22}Na in novae and therefore greatly influences the ejected ^{22}Na abundance. Although this reaction has been studied substantially, a new state in ^{23}Mg was discovered in a fusion-evaporation experiment where gamma rays were detected, corresponding to a $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$ resonance at $E_p=198$ keV. When compared with the mirror nucleus, this introduced the possibility that the previously unknown resonance would exhibit considerable strength and possibly dominate the reaction rate. A joint TRIUMF-University of Washington effort to measure this resonance was established, based on the fabrication of thick high-quality ^{22}Na implanted targets using the ISAC facility.

Progress in 2008–2009

^{22}Na targets of 300 mCi were fabricated at ISAC in December 2008 using a raster scan implanting at 30 keV into oxygen-free copper plates, and subsequently transported to the Center for Experimental Nuclear Physics and Astrophysics (CENPA) at the University of Washington, Seattle. There, a TRIUMF-designed experimental setup was used in conjunction with the high-quality, high-intensity proton beam at CENPA to measure

all the resonance strengths in $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$ via the detection of gamma rays.

Measurement proceeded until the beginning of summer 2009. The data are under final analysis. Preliminary results indicate that the resonance at $E_p = 198$ keV is not the dominant contributor to the $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$ reaction rate at nova temperatures. New precision measurements have been made of the low-energy resonances which do dominate the reaction rate. This experiment was supported by an NSERC Discovery grant, and will form the Ph.D. thesis of A. Sallaska at the University of Washington.

Ahead in 2010

Data have been analyzed, and the results will be submitted for publication in 2010.

The Team

Lead: A. Sallaska

Members: A.L. Sallaska, C. Wrede, A. Garcia, D.W. Storm, T.A.D. Brown, C. Ruiz, D.F. Ottewell, K. Snover, L. Buchmann, C. Vockenhuber, J.A. Caggiano

Participating Labs/Institutions:

TRIUMF, CENPA (University of Washington)

S1103: (α,p) Reactions in Type I X-Ray Bursts Time-Reversed Approach at ISAC-II

This work was performed by the TUDA collaboration, led by spokesperson M. Aliotta, University of Edinburgh. X-ray bursts (XRBs) are observed as intense emissions of X-rays over very short timescales (typically 1-10 s) and often with recurring periods of hours or days. XRBs are thought to originate from the surface of a neutron star, in a binary star system, accreting material from a less evolved companion. The accretion of matter (generally a mix of hydrogen and helium) significantly increases the surface temperature of the neutron star to a point where thermonuclear fusion reactions ignite. However, because of the electron degeneracy conditions on the surface of the neutron star, such reactions proceed in an uncontrolled fashion, ultimately leading to the nuclear runaway that triggers the sudden emission of intense X-ray fluxes. As the transfer of material from the companion resumes, new flashes of X-rays can be released in subsequent bursts. In order to understand the extreme physics that goes on in these objects, one needs to study the nuclear reactions that occur within. The observation properties of the X-ray

bursts: their time intervals, their luminosity, the shape of the burst of light, all sensitively depend on particular nuclear reactions.

Experiment S1103 aimed at studying the $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$ reaction by time-reversal approach, namely by using a beam of radioactive ^{21}Na onto a CH_2 target, thus investigating the reverse reaction $^{21}\text{Na}(p,\alpha)^{18}\text{Ne}$. The importance of the $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$ reaction relates to the breakout of the Hot CNO cycle that is required to trigger the sequence of reactions leading to the thermonuclear runaway. Despite tremendous experimental effort over the last decade, its reaction rate still remains highly uncertain by astrophysical standard and further investigation is therefore needed.

The experiment was carried out at the TUDA scattering chamber at TRIUMF, using a $^{21}\text{Na}^{5+}$ beam (typical intensities $\sim 10^6$ pps) onto a CH_2 target (~ 500 $\mu\text{g}/\text{cm}^2$). Measurement of $\alpha+^{18}\text{Ne}$ coincidences were performed at six energies ($E_{\text{beam}} = 80.6$ -115.0 MeV) corresponding to an energy range $E_{\text{cm}} = 0.9$ -2.5 MeV for the direct reaction, using a set of silicon strip detector arrays placed at forward angles. Particle identification was achieved by ΔE -E technique for both the alpha-particle detector [Micron, S2 ΔE -E (70, 500 μm , respectively)] and the heavy-ion detector [Micron, CD-PAD (35, 1500 μm , respectively)].

In addition, a couple of shifts were devoted to the investigation of the excited states in the compound nucleus, ^{22}Mg , by using the proton resonant elastic scattering technique. In this case, a thick (~ 105 μm) CH_2 target was used to stop the beam completely. Elastically scattered protons were then detected around zero degrees by a stack of three silicon strip detectors (Micron, W-type) of a total thickness (1500 μm) sufficient to fully stop the most energetic protons (~ 18 MeV).

Preliminary on-line analysis revealed the presence of some relevant resonances in the energy region investigated, however, more conclusive results will be reported once the full data analysis (currently in progress) will be completed.

The Team

Lead: M. Aliotta

Members: M. Aliotta, A. Chen, B. Davids, T. Davinson, H. Al Falou, B.R. Fulton, N. Galinski, D. Howell, G. Lotay, C. Ruiz, P. Salter, S. Sjue, M. Taggart, P. Walden, P.J. Woods

Partnering Labs/Institutions:

University of Edinburgh, University of York, TRIUMF

S1216: The $^{17}\text{O}(\alpha,\gamma)^{21}\text{Ne}$ Reaction

This work was performed by the DRAGON collaboration led by spokesperson A.M. Laird, University of York. The production of heavy elements (heavier than iron) is understood to proceed mainly through the slow (s-) and rapid (r-) neutron capture processes. While there are still significant uncertainties in our knowledge of the r-process, s-process nucleosynthesis is thought to be generally well understood.

One of the remaining uncertainties relates to the impact of ^{16}O on the neutron flux available for the s-process. The abundance of ^{16}O present in these environments as well as its high neutron capture cross-section results in a significant fraction of available neutrons being absorbed through the $^{16}\text{O}(n,\gamma)^{17}\text{O}$ reaction. The subsequent $^{17}\text{O}(\alpha,n)^{20}\text{Ne}$ reaction could return these neutrons back into the environment for the s-process; however, the competing $^{17}\text{O}(\alpha,\gamma)^{21}\text{Ne}$ reaction would bypass this recycling of neutrons. Therefore the role of ^{16}O as neutron poison or merely neutron absorber depends crucially on the ratio between the $^{17}\text{O}(\alpha,\gamma)^{21}\text{Ne}$ and $^{17}\text{O}(\alpha,n)^{20}\text{Ne}$ reaction rates.

There are two theoretical predictions in the literature for this reaction rate ratio, one from Caughlin and Fowler 1988, and the other, based on calculations using the Generalized Coordinate Method, from Descouvemont 1992. These two models differ by roughly a factor 1000 in the astrophysically relevant energy region and this uncertainty impacts the predicted s-process abundances, particularly at low metallicities. There is therefore a need to differentiate experimentally between the two models and constrain the reaction rate ratio.

Data on the $^{17}\text{O}(\alpha,n)^{20}\text{Ne}$ exists in the literature down to around 0.5 MeV centre of mass energy (see NACRE database). Surprisingly however, there is no direct experimental data available on the $^{17}\text{O}(\alpha,\gamma)^{21}\text{Ne}$ reaction. Therefore to allow the $^{17}\text{O}(\alpha,\gamma)^{21}\text{Ne}/^{17}\text{O}(\alpha,n)$ reaction rate ratio to be determined, two experimental measurements of the $^{17}\text{O}(\alpha,\gamma)^{21}\text{Ne}$ reaction were performed in May and November of 2009, using the DRAGON recoil mass separator. A stable ^{17}O beam was delivered to the DRAGON helium gas target and recoiling ^{21}Ne ions identified in the ion chamber positioned at the focal plane. Additional information was provided by the BGO array around the target, and two MCPs located near the focal plane.

The initial run covered the energy region from 1.5 MeV down to 0.78 MeV in the centre of mass. The yield was found to be higher than expected, particularly around 0.8 MeV. This experiment was the first to use the new electron cyclotron resonance (ECR) source on OLIS (delivering around 10^{11} pps to DRAGON). The delivery of such a high-beam intensity, together with the positive results from the initial measurements, prompted a second measurement to push further down into the most astrophysically relevant energy region.

In this second run, a beam intensity in excess of 10^{12} pps was delivered to DRAGON and this allowed the experiment to reach down to 0.6 MeV centre of mass energy. In addition, two measurements were made at higher energies to confirm the yields obtained from the May run. Analysis of the two data sets is in progress and preliminary raw yield information is shown in figure.

Ahead in 2010

Once the excitation function has been extracted, this will be compared with the theoretical predictions, and the appropriate reaction rate included in the astrophysical model to allow the impact of the new rate on s-process nucleosynthesis to be determined.

The Team

Lead: A.M. Laird

Members: A.M. Laird, M. Bentley, K. Chipps, J. Brown, C. Diget, S. Fox, B. Fulton, A. Laird, D. Mountford, A. Murphy, C. Ruiz, M. Taggart

Participating Labs/Institutions:

University of Edinburgh, University of York, TRIUMF

Stars that hydrostatically fuse hydrogen into helium in their cores are called main sequence stars. In addition to the Sun, main sequence stars include the old, metal-deficient stars found in the halo and globular clusters of the Milky Way Galaxy. Knowledge of the rates of the nuclear reactions responsible for the fusion of H into He is required in order to predict the flux of solar neutrinos and the ages of the oldest stars in the Galaxy.

The $^3\text{He}(\alpha,\gamma)^7\text{Be}$ reaction rate represents the largest single nuclear physics uncertainty in theoretical predictions of the fluxes of solar neutrinos. As with nearly every nuclear reaction of interest for main sequence stellar burning, its rate has not been measured at the relevant energies, but only at higher energies where the rate is

larger and measurements feasible. Extrapolation is then required to infer the reaction rate at stellar energies.

While many measurements of this reaction rate have been published, the exact energy dependence is not well known, and theoretical model predictions differ substantially in both shape and absolute magnitude. Hence we have carried out a nuclear-structure-model-independent analysis of modern data employing a Markov chain Monte Carlo algorithm to infer a reliable central value and uncertainty for the rate of the reaction at energies relevant to both solar neutrino production and big bang nucleosynthesis. Subsequently, the first measurement of this reaction rate using a recoil separator was performed; the results above 2 MeV sharply disagree with the only other data set that covers this energy range.

We have therefore decided to carry out a measurement with DRAGON to confirm or refute the recoil separator data and better constrain the reaction rate at stellar energies. This 24-shift proposal was approved by the EEC in July 2009. Measurements will commence in September 2010.

The Team

R.H. Cyburt and B. Davids,

S1151: Lifetime Measurement of the 6.791 MeV State in ^{15}O

This work was performed by the DSL collaboration led by spokespersons B. Davids and N. Galinski of TRIUMF. The ages of ancient stars can be estimated via measurements of their starlight when they exhaust the H fuel supply in their cores and move off the main sequence. In order to do so, the rate of the slowest reaction controlling their energy release, $^{14}\text{N}(p,\gamma)^{15}\text{O}$, must be known. Although measurements of this reaction rate have proven elusive at the energies corresponding to the temperatures of the stars, some of the necessary information can be derived from indirect measurements of the decay properties of states in ^{15}O . In particular, the lifetime of its subthreshold 6.79 MeV state has a strong influence on the reaction rate at low energies. Using the Doppler Shift Lifetimes (DSL) facility at ISAC-II, we have carried out a measurement of the lifetimes of ^{15}O states populated in the $^3\text{He}(^{16}\text{O},\alpha)^{15}\text{O}$ reaction at a beam energy of 50 MeV. This was the first time the DSL facility was operated at ISAC-II. We used a single TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer) detector

to detect the Doppler-shifted γ rays emitted by recoiling ^{15}O nuclei around 0° . High signal/noise data were obtained for all of the states in ^{15}O up to the proton emission threshold and are presently under analysis by SFU Physics Ph.D. student Naomi Galinski.

The Team

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Participating Labs/Institutions:

University of Guelph, University of Liverpool, Université de Montréal, Queen's University, Saint Mary's University, TRIUMF

S1022: $^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si}$ Radiative Capture: Structural and Statistical Aspects of the Gamma Decay

The radiative capture process is the complete fusion of target and projectile to form a compound nucleus which de-excites only by γ -ray emission. Following a recent study of the $^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si}$ resonant reaction at TRIUMF showing hints that, above the Coulomb barrier, the gamma-decay is not only statistical but also structural, we have re-investigated this reaction below the barrier, where the number of open reaction channels is small. The aim of this study was to provide a spin assignment for the resonance and determination of the structural part of its decay. It is of great importance to find the link between resonances in the $^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si}$ radiative capture reaction and the occurrence of molecular configurations in ^{28}Si , which has been debated for a long time.

The radiative capture process induced by heavy ions is a powerful tool to study the interplay between reaction mechanism and nuclear structural effects. Such correlations result from an overlap not only between the entrance channel and the CN states but also between these states and lower lying states. From the connecting γ -transitions, information can be obtained on spins, isospins, and deformations of the populated CN states.

In our previous TRIUMF experiment concerning the $^{12}\text{C}+^{16}\text{O}$ system, we measured a previously

unobserved strong feeding of states around a ^{28}Si excitation energy of 11 MeV [3-5], representing 60% of the decay flux. Interestingly, selective feeding of some low lying states in ^{28}Si indicates a structural character of a part of the gamma-decay.

Progress in 2008–2009

During the 2009 run, the $^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si}$ reaction has been performed at two resonant energies below the Coulomb barrier to get a better understanding of the interplay between the statistical and structural nature of the gamma-decay. The bombarding energies have been chosen below the Coulomb barrier, leading to fewer open decay channels than in our previous study. At these energies, based on our previous spin determinations and on numerical simulations of the full possible decay path, we have estimated that the entrance spins will probably be 0^+ , 1^- , 2^+ or 3^- .

Highly enriched thin ^{12}C targets of $50 \text{ mg}\cdot\text{cm}^{-2}$ have been bombarded by ISAC ^{16}O beams, on resonance at $E_{\text{Lab}} = 16.8$ and 15.4 MeV. The use of the Supernanogan source allowed us to work with beams of 100 to 200 enA intensity, with no

stripper foils. A ^{13}C target has been bombarded to check for an eventual ^{13}C contamination of the ^{12}C targets. Recoiling ^{28}Si nuclei have been identified using the Dragon separator at 0° and the focal plan double sided silicon strip detector. Coincident gamma-rays have been recorded in the associated BGO array.

The analysis of the data of this recent study is under progress by A. Goasduff, PhD student of the University of Strasbourg. Figure 3 shows a preliminary direct BGO spectrum taken on resonance at $E_{\text{Lab}} = 15.4$ MeV. This spectrum shows the following transitions between the low lying states of ^{24}Mg and ^{27}Al from the dominant α and p evaporation channels: 1.01, 1.37, 1.72, 2.21 and 2.75 MeV.

The Team

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Partnering Labs/Institutions:

University of Strasbourg, University of York, TRIUMF



Isabel Trigger is a research scientist at TRIUMF and leads the ATLAS group at TRIUMF; she is also an adjunct professor at the University of Victoria.

Subatomic Physics

The ATLAS Experiment at the LHC

To understand the universe at the most basic level, we need to find out what matter is made of and how it interacts. To probe very small distances, we require very high energies. The Large Hadron Collider (LHC) at CERN is the largest microscope ever built. It is designed to test the Standard Model of particle physics at the high-energy frontier. Only one particle predicted by the Standard Model has not yet been found—the Higgs boson. If it exists, the LHC will be able to produce and detect it. If it does not exist, the LHC will be able to produce and detect whatever it is that is doing the Higgs boson's job generating the masses of all the other known elementary particles. It will be the first accelerator to observe clear evidence of physics beyond the Standard Model. The ATLAS detector[1,2] is the “camera” looking through the LHC microscope.

Progress in 2008-2010

The two years 2008–2009 were exciting and emotional ones for the LHC and ATLAS

collaboration. ATLAS detector commissioning was completed in spring of 2008, when the last section of beam pipe was installed. The cavern was cleaned of all magnetic junk, and ATLAS was tested with cosmic ray data-taking through the summer. In September 2008, the first beams were circulated in the LHC at the injection energy of 450 GeV. The beam guidance and radio frequency (RF) capture went flawlessly, but after only three days of operation there was an unfortunate incident which shut the LHC down for more than a year.

On September 19, 2008, a busbar connection between two superconducting dipoles developed a small resistance and began to warm up. The heat dissipated into the liquid helium keeping the dipoles at 1.9 degrees above absolute zero, and the helium evaporated suddenly, causing a pressure wave which damaged magnets for about a hundred metres in each direction. As well as necessitating repairs, the incident drew attention to areas where improvements could be made in some of the accelerator's monitoring and safety



Figure 1: The ATLAS Tier 1 Data Centre at TRIUMF maintains an unusually compact footprint thanks to liquid cooling.

assurance systems. These were all addressed before the LHC could run again.

The ATLAS collaboration used the year without beams to perform extensive commissioning tests of the detector with cosmic rays. The extended installation time also made it possible to install some additional muon chambers to improve efficiency in the overlap region between the barrel and endcap toroids of the magnet system, to upgrade the inner tracker cooling system, and to repair electronics in many systems. The result is an unprecedented 99.9% of live channels across all subsystems—a remarkable achievement for one of the most complex pieces of electronic equipment ever built.

The TRIUMF ATLAS group increased its central role in commissioning the detector, with Anadi Canepa and Oliver Stelzer-Chilton assuming responsibility for designing and implementing the new Global Monitoring System. This is a framework into which all subdetectors and combined performance groups now plug their own monitoring systems. It also monitors “Global” quantities which check timing and alignment correlations across multiple subdetector systems. This is now the front-line tool in ATLAS for data quality monitoring. The “Global” quantities monitored include physics quantities like the mass spectra of well-known resonances, which allow a quick and effective evaluation of the detector’s calibration. Our post-doctoral work on data quality monitoring for the muon and liquid argon subsystems, which plug into the global framework. We also run a remote monitoring station at TRIUMF, which mirrors the computer desktop visible to a shifter or expert in the ATLAS Central Control Room. This system is currently under evaluation, but should eventually allow shifts to be taken from TRIUMF, cutting our shift-related travel obligations appreciably.

Running with cosmics gave the collaboration almost two years to practise taking data, manning the control room, assessing data quality, processing raw data and distributing it through the international network of Tier 1 and Tier 2 data centres. TRIUMF hosts one of the ten ATLAS Tier 1 centres. The TRIUMF Tier 1 expanded in 2008 and 2009 and now hosts 2.1 PetaBytes (million GigaBytes) of disk, 0.75 PetaBytes of tape, and more than 13000 HEP-SPEC06 of CPU power—half of which was added in autumn 2009 in the form of just 70 dual-quad-core blades from Sun Microsystems.

On November 21, 2009 came the moment of redemption—beams once again circulated in the LHC, in both directions, meaning that both of the LHC’s twin beampipes were once again correctly aligned with all of the thousands of magnets correctly guiding the beams around with submillimetre precision. The beams were then successfully “captured” by the RF system. Within just two days, beams were circulating in both directions simultaneously, and the very first LHC collisions were observed on November 23, at the injection energy of 450 GeV per beam[3].

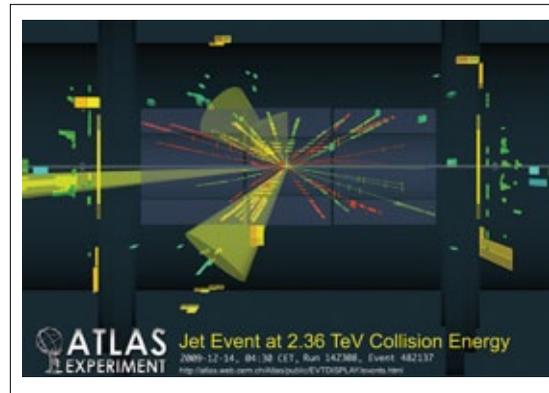


Figure 2: One of the first collision events detected by ATLAS in 2009 at 2.36 TeV. The image shows tracks in the inner detector and energy deposits in the calorimeters.

The next step was testing the acceleration capabilities of the LHC, and on November 30, 2009, the beam energy was ramped up to 1.18 TeV per beam—beating the Fermilab Tevatron’s world record of 0.98 TeV. Accelerated beam collisions were observed for the first time by the ATLAS detector on December 8, and by all of the LHC detectors in the following days. On December 16, the LHC began a few weeks’ shutdown to prepare the machine for higher energy running in February 2010.

Ahead for 2010

The TRIUMF group now includes three graduate students, and is increasing its emphasis on data analysis, building on the commissioning activities of group members based both at TRIUMF and at CERN. The Tier 1 centre continues to be one of the most efficient and reliable in the world as it expands to meet the needs of the data-taking era. The group is also looking to the future, with a request for beam time at TRIUMF to irradiate diamond detectors for a mini-Forward-Calorimeter to instrument a higher-luminosity “Super LHC” allocated high priority in 2010.

The Team

Lead: I. Trigger

Spokesperson: R. McPherson

Members of TRIUMFATLAS group: D. Axen, G. Azuelos, N. Bienvenu, A. Canepa, B. Caron, S. Chekulaev, D. Deatrich, A. de Silva, D. Fortin, D. Gingrich, E. Hill, Y. Ishizawa, V. Kondratenko, L. Kurchaninov, S. Liu, A. Moraes, I. Nugent, G. Oakham, C. Oram, C. Payne, D. Qing, P. Savard, J. Steele, O. Stelzer-Chilton, R. Tafirout, I. Trigger, M. Vetterli, S. Viel, R. Walker, A. Wong

Partnering labs/institutions:

Carleton University, L'université Montréal, McGill University, Simon Fraser University, University of Alberta, University of British Columbia, University of Regina, University of Toronto, University of Victoria, and York University, as well as more than 160 universities and laboratories in 36 other countries

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- [2] ATLAS Collaboration, G. Aad et al., Expected performance of the ATLAS Experiment – Detector, trigger and physics, arXiv:0901.0512 [hep-ex]
- [3] ATLAS Collaboration, G. Aad et al., Charged-particle multiplicities in pp interactions at $\sqrt{s}=900$ GeV measured with the ATLAS detector at the LHC, Physics Letters. B688, Issue 1, 21-42 (2010).

Financial Contribution

Canada has made substantial contributions (worth about \$40Million) to the Large Hadron Collider at CERN through TRIUMF in the course of the last two Five-Year Plans, and hosts Canada's ATLAS Tier 1 Computing Centre.

Akira Konaka is the leader of TRIUMF's particle physics group and is an adjunct professor at the University of Victoria.



Subatomic Physics

The T2K Experiment

The T2K experiment is a study of neutrino oscillation in detail using a neutrino beam directed from J-PARC, a new accelerator in Japan, to the Super-Kamiokande detector 295 km away. The experiment aims to measure the remaining neutrino mixing angle and eventually study CP violation in neutrino oscillation, which will shed light on the matter/antimatter asymmetry of the universe.

Progress in 2008-2010

A proton beam extracted from the accelerator hits a graphite target producing π mesons, which decay into neutrinos. By comparing the neutrino flux at the Near Detector 280m (ND280) downstream from the target, researchers at ND280 and at Super-Kamiokande, 295 km away, can extract precise information about neutrino oscillation. The Canadian group contributed to the design and construction of the remote handling system in the target station and of an optical transition radiation monitor (OTR) right in front of the target that monitors the beam profile (see Figure 1). The

beam line was successfully commissioned with a single magnetic horn at low intensity in April to May 2009. Commissioning with the second and third horns started in November with beam intensities up to 40 kW.

For ND280, the Canadian group contributed the time projection chambers (TPCs) and fine-grained detectors (FGDs). The FGDs serve as the primary target mass for neutrino interactions. Short-ranged particles produced by neutrino interactions are tracked by the FGD itself, while longer-ranged particles penetrate into the adjoining TPCs, determining the charges and momenta of particles produced in neutrino interactions by measuring the curvature of particle trajectories in the magnetic field. They also distinguish electrons, muons/pions, and protons by measuring the rate of ionization energy loss, usually referred to as dE/dx . Both FGDs and TPCs were constructed at TRIUMF and tested in the M11 beam line before being shipped to Japan (see Figure 2). The first neutrino events were observed just before the New Year holiday (see Figure 3).

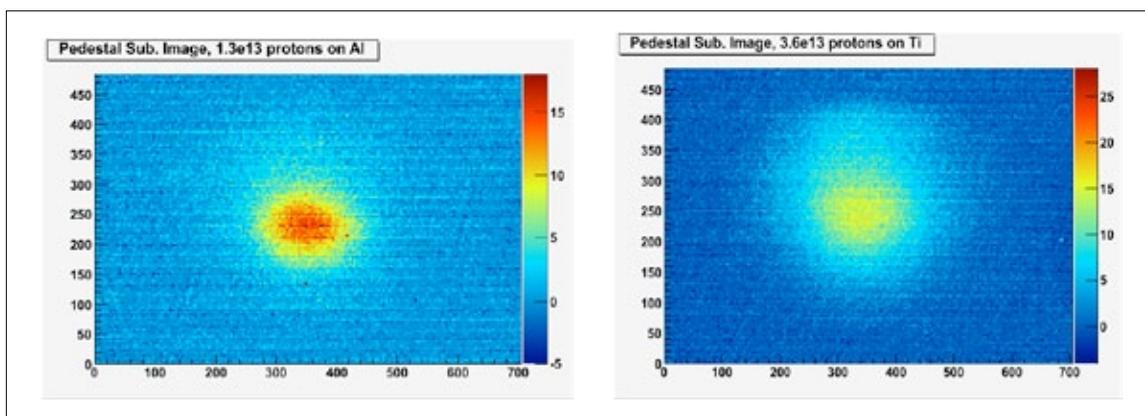


Figure 1: T2K primary proton beam profile at the target observed by the optical transition radiation monitor with Aluminum (left) and Titanium (right) targets.



Figure 2: TPC and FGD at the TRIUMF M11 beam line for test before shipping to Japan.

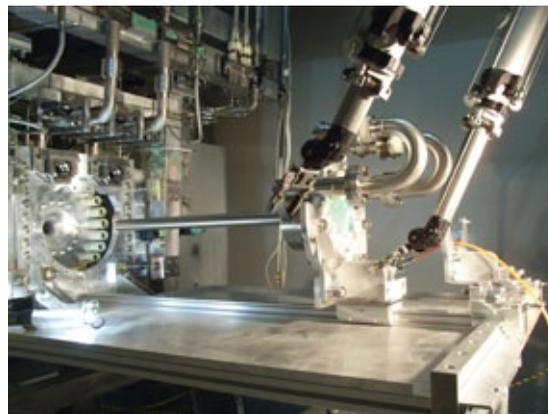


Figure 4: The manipulator system to replace the T2K neutrino production target. The graphite target rod covered by titanium tube is inserted into the horn magnet.

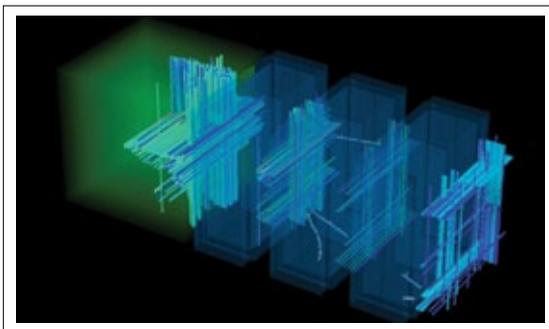


Figure 3: The first neutrino event of the off-axis near detector. Three boxes are the TPC's with observed tracks. The crossed bars are each hit elements of FGD's and downstream electro-magnetic calorimeter.

With an eventual megawatt of proton beam hitting the target, devices in the target station, such as the target and horns, can only be serviced by a full remote handling mechanism. In a 2004 collaboration agreement, TRIUMF committed to supply both a beam monitor station for the final focus beam section upstream of the target as well as a hot cell handling facility adequate for remote target exchange in the horn (see Figure 4). Both of these packages were designed, built and installed by the Remote Handling group. Final installation and equipment commissioning by this group were completed in November 2009. The final full remote handling test in the target station is scheduled for the summer 2010 after the initial physics run.

The OTR monitor is installed immediately in front of the T2K production target. The optical transition (or fluorescence) image is transported using parabolic mirrors to a radiation-hard camera equipped with neutral density filters. Lasers and filament lamps are used to backlight a calibration

foil with precisely machined holes. In April 2009, the proton beam was delivered successfully to the target, and the OTR monitor, with fluorescence ceramic foil, was used for the beam tuning at low intensity. During the November to December run, when the beam intensity increased to 10–40 kW, the OTR light from Al and Ti foils was successfully used to monitor the beam profile.

The Canadian group has led the design and construction effort for the T2K TPC project, which is a collaboration of physicists from Canada, France, Germany, Italy, Spain, and Switzerland. The micropattern gas detectors (micromegas) are produced by a Saclay/CERN collaboration and the electronics are provided by Saclay.

The panels and endplates that make up the inner and outer boxes of the TPC were machined on a large-bed CNC router acquired at TRIUMF through a CFI award. The first TPC module was completed and brought to the M11 test beam area in September 2008. The results from the initial tests indicated that the TPC reached its momentum and dE/dx resolution design goals. Two of the three modules were installed in October 2009, and the third was installed in December. The other aspects of the TPC project, such as gas system, electronics, and survey were completed in December, and the first neutrino events were observed.

The FGD signal light is carried by wavelength-shifting fibre and read out by Hamamatsu Multi-Pixel Photon Counters. The first FGD consists entirely of tracking scintillator planes, while the second alternates scintillator planes with thin layers of water. Comparison of neutrino

interactions between the two detectors will allow the tracker to determine neutrino interaction rates on both carbon and water targets.

During the M11 beam test, the FGD response was measured for protons, pions, muons, and electrons with momenta between 50 and 400 MeV/c. It also offered the opportunity to exercise in full the electronics, slow control, and DAQ system. The test established that the FGD has high light yield for minimum ionizing particles and tagging Michel electrons or stopping muons and pions with very high efficiency.

Both fine-grained detectors were shipped to J-PARC in summer 2009, and final inspection and integration checks were done. They were installed in ND280 in October 2009. The first neutrino event in the FGD was observed in December.

Ahead for 2010

The T2K-Canada collaboration was highly successful in 2008–2009. We constructed and commissioned the detectors, and the first

neutrino events were observed. In 2010, T2K starts its physics run, and after accelerator studies in January and February, the first dedicated run is scheduled from March until June. Canadian members will play leading roles in the operation, calibration, and physics analysis.

The Team

Lead: A. Konaka

Members of TRIUMF T2K group: P. Gumplinger, K. Hamano, R. Helmer, R. Henderson, A. Konaka, K. Mahn, A. Miller, J-M. Poutissou, R. Poutissou, F. Retiere, Tacik, Michel Wilking, Kandy Wong, S. Yen

Partnering labs/institutions:

University of Alberta, University of British Columbia, University of Regina, University of Toronto, University of Victoria, and York University, as well as institutions from 11 countries



Richard Helmer is an engineering physicist at TRIUMF and, as part of the SNO collaboration, shared in receiving the John C. Polyani Award in 2006.

Additional authors: Fabrice Retiere, David Sinclair

Subatomic Physics

SNO and SNOLAB

SNOLAB, located in a mine near Sudbury, Ontario searches for neutrinos, one of the most abundant particles in the universe, and dark matter, whose properties could explain a number of observed cosmological phenomenon.

TRIUMF is involved in three experiments at SNOLAB: EXO, which is searching for neutrinoless double Beta decay in Xenon; DEAP trigger and readout electronics, which are looking for dark matter; and SNO⁺, a new experiment that will take place in the SNO cavity at SNOLAB.

DEAP Trigger and Readout Electronics

The existence of dark matter would explain a number of observed cosmological phenomena, yet its nature remains elusive. DEAP (Dark Matter Experiment using Argon Pulse-Shape Discrimination) is a ball filled with liquid argon,

which would detect weakly interacting massive particles (WIMPs) by measuring the scintillation light they produce when interacting with argon nuclei. It will be located 2 km underground at SNOLAB in Sudbury, Ontario. It is scheduled to start taking data in 2012. TRIUMF is responsible for designing and implementing the trigger and readout electronics for the experiment (see Figure 1).

The scintillation light produced in liquid argon will be detected by up to 264 photomultiplier tubes (PMTs). There will also be up to 96 veto PMTs to detect the Cerenkov light produced in the water surrounding the liquid argon ball. The DEAP background rejection scheme requires identifying every photon detected by each PMT when an interaction occurs in the centre of the ball and within the energy range expected for WIMPs. Such a requirement can only be achieved by separating

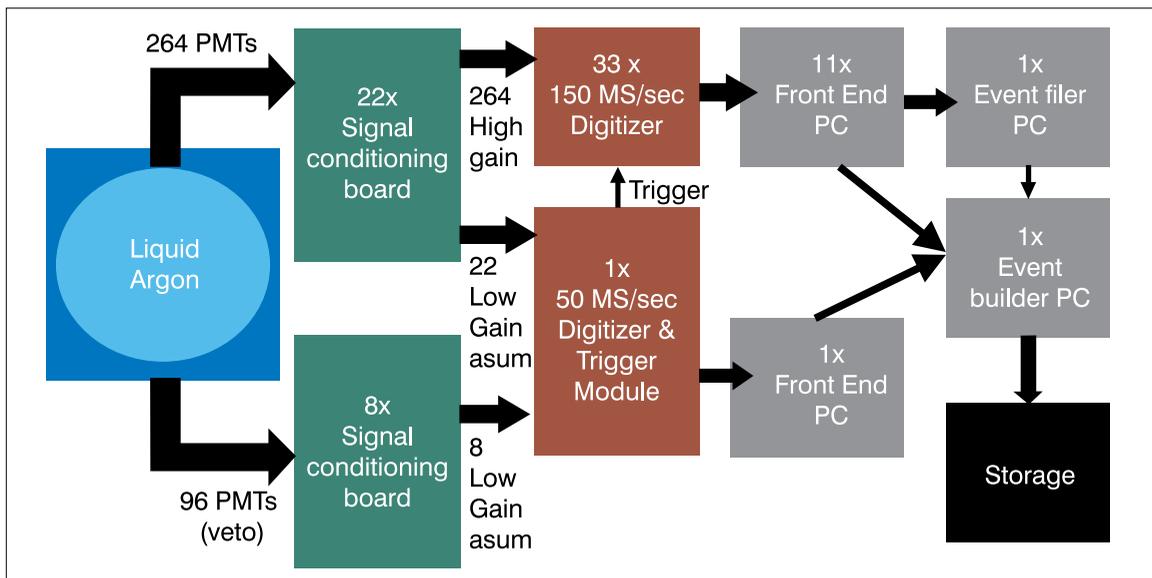


Figure 1: Conceptual design of DEAP trigger and readout electronics.

the photon-induced pulses in time, which requires using digitizers sampling at least at 250 Mega-samples per second (MS/s). Given the event rate expected at DEAP (3.6 kHz), the volume of data produced by 264 digitizer channels running at 250 MS/s is enormous and it is necessary to filter out events in order to keep the data rate under control.

The trigger which performs this filtering is implemented at two different stages: front end and back end. In both cases, the trigger decision is based on a calculation of the total energy deposited (E_{tot}) in argon and the fraction of light emitted within the first 300 ns (F_{prompt}). The information about the veto PMTs is integrated at the front-end trigger level. The front-end trigger system must make a decision within 10 μs , while the backend system can take up to 200 μs .

The front-end trigger system will calculate E_{tot} and F_{prompt} from 24 signals generated by the signal conditioning boards (SCBs).

The SCBs are custom-designed boards that will: 1) decouple the PMT signal from the high voltage, 2) scale and shape the PMT signals to match the 250 MS/s digitizer input requirement, and 3) divert a fraction of the signal from each PMT to generate an analog sum. Each SCB will handle 12 PMT channels. Hence, the analog sum corresponds to the combined outputs of 12 PMTs. The analog signal will be widened to about 200 ns to mitigate the effect of time offset between channels—to minimize the noise and to allow the signals to be processed by a slow digitizer (50 or 65 MS/s).

The back-end electronics, which include reading out the 250 MS/sec digitizers as well as the back-end trigger, are being designed



Figure 2: Picture of the signal conditioning board prototype.

and prototyped at Boston University and the University of Pennsylvania. The 250 MS/s digitizers are commercial V1720 modules from CAEN. The full back-end readout and trigger system will be prototyped in 2010 as part of miniCLEAN, DEAP's sister experiment. The data acquisition system to read out the fast digitizers used in DEAP prototypes is based on the MIDAS system, installed and maintained by TRIUMF DAQ group. A factor-of-five increase in data rate was achieved in DEAP-1 in April 2009 by upgrading the system to use a V1720 digitizer. Such increases in the data rate allowed the experiment to improve, in great measure, the measurement of its background rejection capability.

Ahead in 2010

The DEAP-specific electronics will be designed and implemented by the University of Alberta and TRIUMF. The final SCBs will be designed and built by the University of Alberta (see Figure 2). The DEAP overall trigger design, which was finalized in 2009, will be implemented in 2010 and 2011. The front-end trigger will be implemented by TRIUMF. The design work performed in the last two years at TRIUMF is to be implemented with the hope of detecting first light in 2012, and carry on a WIMP search program for at least 3 years.

The Team

Lead: F. Retière

Members: B. Beltran, M. Boulay, M. Butygov, B. Cai, M. Chen, B. Cleveland, F. Duncan, R. Ford, P. Gorel, Graham, K. E. V. Golovko, A. Hallin, C. Jilings, M. Kuzniak, J. Lidgard, A. McDonald, T. Noble, O'Dwyer, K. Olsen, P. Pasuthip, T. Pollman, W. Rau, F. Retiere, P. Skensved, T. Sonley, M. Ward

Participating Labs/Institutions:

Boston University, Carleton University, Laurentian University, Queen's University, SNOLAB, University of Alberta, and the University of Pennsylvania

EXO – A Search for Neutrinoless Double Beta Decay in Xenon

Neutrinos are thought to be one of the most abundant particles in the universe, similar in numbers to photons, and outnumbering more familiar protons, electrons, and neutrons by a factor of order 10^8 . They are produced in great numbers by the nuclear processes that generate the energy in our sun, and dominate the energy release in supernovae. According to current theories, enormous numbers were created in the

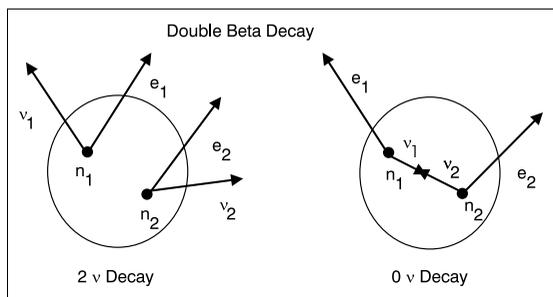


Figure 3: Two forms of double beta decay. On the left, two neutrons simultaneously decay producing two electrons and two neutrinos. In the neutrinoless decay, the two neutrinos are produced but then annihilate each other, returning their energy to the electron.

Big Bang at the start of our universe, however, because they are very hard to study, we know very little about these particles.

Experiments such as SNO have shown neutrinos do possess mass, but the mass scale has not yet been measured. One possible method to fix the mass scale is to observe a nuclear decay process in which a nucleus emits two electrons, but no neutrinos. If this process (known as neutrinoless double beta decay) does occur, the rate is strongly dependent on the mass of the missing neutrinos. Great sensitivity to neutrino masses can be achieved, however, the reaction also requires that the neutrino be its own antiparticle. This property would be unique among the known fermions, but is expected in many theoretical models and might discriminate between classes of models. To date, the process has never been observed and if it occurs at all, the rate must be extremely small. These somewhat paradoxical properties of the decay can be understood by considering the details of the nuclear decay illustrated in Figure 3. There are few nuclear isotopes which are energetically allowed to decay by double beta decay but not allowed to decay by the much faster single decay mode. One of the potential candidates is an isotope of Xe with mass 136. Xenon is an attractive material to use for a search for this decay mode. Like other noble gases it can be made very pure, thus removing internal radioactive backgrounds. In addition, there are no long-lived, radioactive isotopes of xenon. There is a substantial body of knowledge on making detectors out of the noble gases and liquids. Finally, there is the potential to eliminate essentially all of the expected backgrounds by tagging each event with the presence or absence of a daughter barium ion, created at the beta decay location.

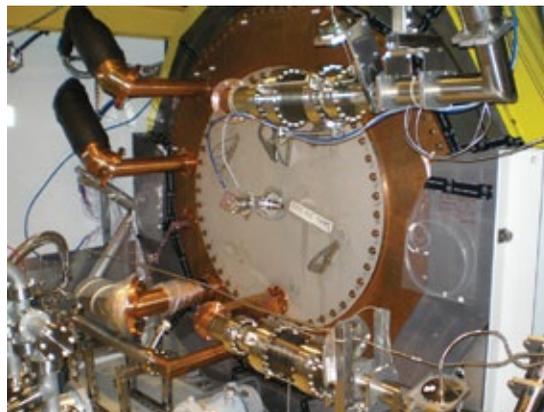


Figure 4: The EXO 200 liquid xenon detector prior to installing the final wall of lead shielding.

Ahead in 2010

EXO is developing two concepts for such a detector. One has xenon in liquid form. A low-background detector of this form has been constructed over the last two years and is currently being commissioned at the WIPP facility in New Mexico. The detector will contain 200 kg of enriched ^{136}Xe making it the largest detector in the world looking for this process. Data taking will start in the summer of 2010. Unless our nuclear models are very wrong, the detector is likely to make the first observation of the two-neutrino decay mode of ^{136}Xe and the neutrino-less decay mode should be observed if the claims of a European group are valid [1]. Figure 4 shows the liquid detector. Much of the engineering support for this detector came from TRIUMF.

A second concept for the detector uses xenon in room-temperature gaseous form. Potential advantages of this form include detection of

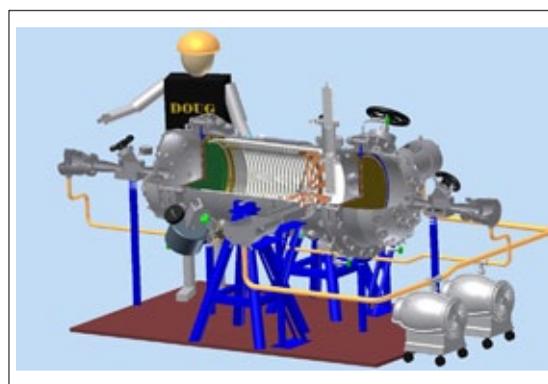


Figure 5: The EXO gas prototype detector is under construction at Carleton. This will be used to test detection technologies for a neutrino-less double beta decay projects.

electron tracks, which eliminates many of the backgrounds, better energy resolution, and the possibility of extracting and identifying the barium daughter. Two research efforts are underway to develop this concept. At Carleton University, a xenon tracking detector is being constructed to study a new form of time projection chamber using electroluminescence. This mode is attractive for our needs because the electroluminescence works without the need for any gas additives. The detector will be large enough to contain electrons of 1 MeV at 1 bar and will operate up to 10 bar. The concept drawing is shown in Figure 5. The components for the detector should be assembled by the end of summer 2010 and commissioning of the system should be complete by the end of 2010.

Critical measurements will include the energy resolution of this type of detector for electrons, electron/gamma discrimination using multi-site selection, and the sensitivity for selecting two-electron events by observing the two Bragg peaks. A second development study has begun at Stanford to look at single barium ion detection. The concept for the study was developed by TRIUMF/Carleton and involves the extraction of ions from a high-pressure gas into vacuum using a technique now common in radioactive beam facilities.

The coming year looks very exciting for the EXO project with first physics data from the liquid detector, completion of the gas prototype, and the possibility of fundamental new science results in the field of neutrino physics.

The Team

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Partnering Labs/Institutions:

Caltech, Carleton University, Colorado State, ITEP Moscow, Laurentian University, SLAC, SNOLAB, Stanford University, TRIUMF, University of Alabama, University of Bern, University of California at Irvine, University of Maryland, University of Massachusetts

SNO+

SNO+ is a new experiment that will take place in the SNO cavity at SNOLAB. The acrylic sphere that

held the heavy water in SNO will be reused, with the water replaced by a liquid scintillator, linear alkyl benzene. In the first phase of the experiment, neodymium will be dissolved in the scintillator, permitting a search for neutrinoless double beta-decay of ^{150}Nd . Later phases, with the neodymium removed, will measure the fluxes of pep and CNO solar neutrinos and the fluxes of geo-neutrinos, neutrino oscillations from several nearby reactors, and search for neutrinos from supernovae.

Besides the acrylic sphere, much of the equipment originally used in SNO will be reused for SNO+. One item that cannot be reused is the universal interface (UI) separating the inside of the acrylic vessel from mine air. Because of more stringent radioactivity requirements, the UI must be sealed to the vessel. The umbilical retrieval mechanism (URM) used to deploy calibration sources into the detector and store them when not in use must in turn be sealed to the UI. Furthermore, much of the original URM was fabricated from aluminum, but because this material is incompatible with linear alkyl benzene, the URM, like the UI, must be fabricated from stainless steel.

Ahead in 2010

Both the original UI and URM were designed and fabricated at TRIUMF and it was natural for TRIUMF to take on these tasks for SNO+. Design of the UI is now complete and fabrication has begun. Design of the URM will commence shortly.

The Team

Lead: R. Helmer

Partnering Labs/Institutions:

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

Reference

[1] Klapdor-Kleingrothaus, H.V. and Krivosheina, I.V. Modern Physics Letters A21 (2006) 1547.



Glen Marshall is a research scientist at TRIUMF and leader of the TWIST experiment.

Subatomic Physics

The TWIST Experiment

The TRIUMF Weak Interaction Symmetry Test (TWIST, Experiment E614) is an experiment that searches for potential deviations from the Standard Model (SM) of particle physics that may be revealed in the decay of muons, particles which TRIUMF is able to produce in abundance. The SM has been very successful at predicting fundamental interactions, but it is widely believed to be only an approximation to a more fundamental theory. Muon decay is theoretically very simple, so simple in fact that it is a common example in university physics textbooks. It provides a well-understood process with the potential to place stringent limitations on physics beyond the Standard Model. The polarized positive muon decay spectrum is described by four parameters that describe the energy and angular distribution of decay positrons. The goal of TWIST is to determine simultaneously three of these parameters ρ , δ , and $P\mu\xi$, to achieve an approximately tenfold improvement in precision compared with results of prior experiments. The main tool is a spectrometer consisting of a high-precision, low-mass, planar detector array in a 2 T solenoidal magnetic field.

E614 was first proposed to the TRIUMF EEC in 1990 but it was not until 1998, with D.R. Gill as spokesperson, that the first substantial funding was obtained from NSERC. In 2000, assembly of the spectrometer was underway in the meson hall and N. Rodning had taken over as spokesperson. The E614 proposal had become an experiment, and was named TWIST. First data was taken in 2002; with the untimely passing of N. Rodning, G. Marshall became the spokesperson. Significant data taking in 2004 and finally in 2006 and 2007 were separated by periods of analysis and improvements to the detector and beam line, with the goal of understanding and reducing

systematic uncertainties. Following the final data taken in 2007, the spectrometer was dismantled, and analysis continued until 2010.

Searching for Nature's Right Hand

Elementary particles such as electrons are labeled as either "right-handed" or "left-handed". A surprising observation is that only left-handed particles seem to feel the weak nuclear force, whereas left- and right-handed particles feel the other fundamental forces equally. This difference, called parity violation, was predicted and observed in the 1950's; and led to a Nobel Prize. It is now a cornerstone of the modern Standard Model of subatomic physics. However, there are strong reasons to believe that this Standard Model is incomplete. "Left-right symmetric" theories explain parity violation by assuming that right-handed particles also respond to the weak force, but we would need to be in a much hotter world—with a temperature well above 10^{15} degrees—for this to be obvious.

The TWIST Collaboration is testing these theories with high-precision measurements of the decay of the muon, a particle that appears identical to an electron in all regards except that it is heavier. The Collaboration has just reported the first improvement since 1966 in the measurement of the energy spectrum of positrons produced in muon decay. This new result agrees with theoretical predictions in which right-handed particles do not feel weak forces. Thus, it is less likely that left-right symmetric theories are the correct explanation for the parity violation of the weak force.

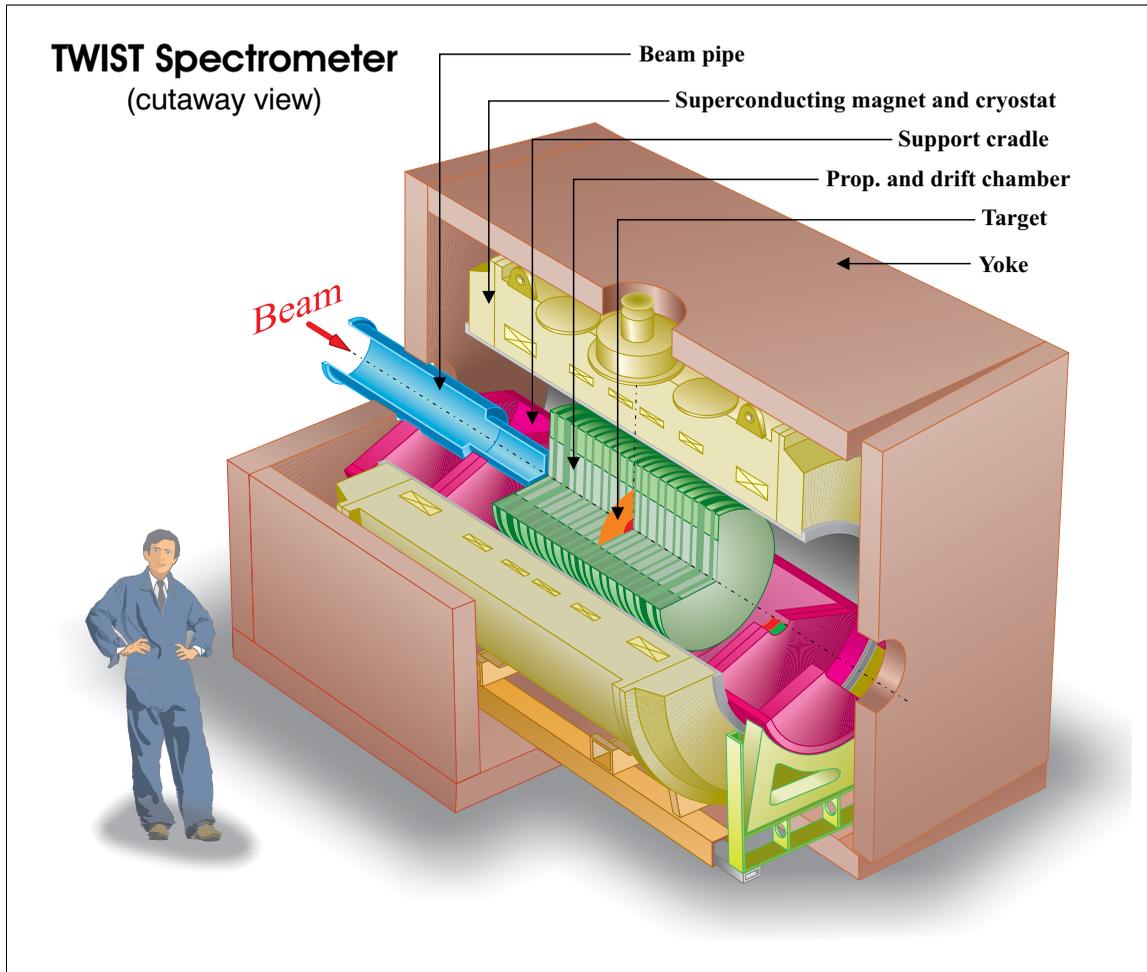


Figure 1: The TWIST spectrometer, showing the detector inside the superconducting solenoid.

Progress in 2008-2010

In 2008, the TWIST group continued analysis of its final high-statistics data sets following the decommissioning of the apparatus in late 2007. Results of intermediate data taken in 2004 were published [1], demonstrating significant progress in the understanding of systematic uncertainties, while motivating many improvements to TWIST's analysis strategies that are critical to the quality of our final results. The precision of the intermediate results is within a factor of two of TWIST's goals for two of the three parameters, ρ , and δ . An exhaustive and detailed evaluation of systematic effects and their uncertainties showed convincingly that the original goals could be achieved with the final data sets for ρ , δ by defining the dominant uncertainties and suggesting ways to reduce them. The TWIST results have been incorporated into the Review of Particle Physics [2] and provide the best constraints on the three decay parameters in the muon particle listings.

Analysis of the final data sets was preceded by a critical review and assessment of previous procedures, stimulating improvements that have led to reductions of several key systematic uncertainties. One example is the drift time calibration in the detector. Space points corresponding to ionization in the planar drift chambers and characterized by the ionization drift times are now calculated from calibrations derived from data rather than from a model based on theory. The same approach was also applied to drift times from simulation, reproducing any bias to a high degree such that it cancels in the comparison. Another example is the energy calibration procedure. It removes small ($\sim 10^{-4}$) differences between data and simulation due, for example, to magnetic field differences, stopping target thickness variation, spectrometer size scale variation, and so on. The kinematic edge of the decay positron distribution near 52.8 MeV is compared in data and simulation in an angle-dependent way. Instead of a fit of both data and simulation to an analytic function, as was done

previously, we now fit the kinematic edge of simulation to data directly.

The leading systematic uncertainties for the asymmetry parameter, P_{μ}^{ξ} , arise from the complexity of accurately simulating the fringe field. There, transverse field components lead to a reduction in the longitudinal component of the spin (along with momentum) and thus to depolarization, i.e., a reduction of P_{μ} . Both the beam characteristics and the magnetic field map must be reproduced in the simulation before the parameter can be extracted from the data by comparison. The reduction of systematic uncertainties to the asymmetry parameter is the greatest challenge, but significant progress has been achieved.

A small set of data was specially taken with the TWIST spectrometer using a negative muon beam to characterize the energy dependence of decay electrons. While this is not sensitive to interactions beyond the SM, it does provide the most precise measurement of the effects on the decay energy of the binding of negative muons in an atom, in this case ^{27}Al . For the first time in such a system, effects were observed that require corrections due to radiative processes. Comparison of data with corrected calculations showed good agreement [3].

TWIST has made extensive use of WestGrid [4] high-performance computing facilities. Our average usage for generation of simulations and for analysis of the data and simulations was 100 CPU's full time. The analysis produces reduced data objects containing momentum, angle, and event characteristics from fitting the helical positron tracks. We typically have 10-15 TB of data and simulation stored on the worker nodes. Our local cluster of 16 dual-CPU nodes at TRIUMF has been utilized heavily for histogramming and fitting the reduced data objects.

Ahead in 2010

Analysis of the final TWIST high-statistics data sets was essentially completed in 2009. The hidden variables that make the analysis "blind" were revealed in early 2010, and final publications and three final Ph.D. theses will be submitted by mid 2010.

The Team

Lead: G.M. Marshall

Members: R. Bayes, J.F. Bueno, Y.I. Davydov, P. Depommier, W. Faszer, M.C. Fujiwara, A. C.A. Gagliardi, Gaponenko, D.R. Gill, A. Grossheim, P. Gumplinger, M.D. Hasinoff, R.S. Henderson, A. Hillairet, J. Hu, D.D. Koetke, R.P. MacDonald, G.M. Marshall, E.L. Mathie, R.E. Mischke, K. Olchanski, A. Olin, R. Openshaw, J.-M. Poutissou, R. Poutissou, V. Selivanov, G. Sheffer, B. Shin, T.D.S. Stanislaus, R. Tacik, R.E. Tribble

Partnering Labs/Institutions:

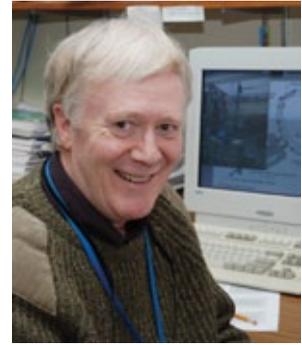
Kurchatov Institute, Université de Montréal, Texas A&M, TRIUMF, Valparaiso University, University of Alberta, University of British Columbia, University of Regina

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- [2] C. Amsler et al. (Particle Data Group), Physics Letters B667, 1 (2008) and 2009 partial update for the 2010 edition. (<http://pdg.lbl.gov/2009/listings/rpp2009-list-muon.pdf>)
- [3] A. Grossheim et al., Decay of negative muons bound in ^{27}Al , Phys. Rev. D80, 052012 (2009) [hep-ex/0908.4270, TRI-PP-09-28].
- [4] See <http://www.westgrid.ca>

Des Ramsay has retired as a senior research scientist at TRIUMF's and is active as an emeritus scientist in a number of TRIUMF projects.

Additional author: Shelley Page



Subatomic Physics The Qweak Experiment

The Qweak experiment at Thomas Jefferson National Accelerator Facility at the Jefferson Laboratory (JLab) will scatter longitudinally polarized electrons from liquid hydrogen and measure the change in scattering probability when the electron helicity is reversed (see Figure 1). This parity-violating asymmetry is proportional to the weak charge of the proton, i.e., the coupling

mixing angle at low momentum transfer to 0.3 % of $\sin^2 \Theta_w$ —a fine measurement in its own right.

Progress in 2008–2010

The main NSERC-funded spectrometer magnet was tested and mapped. The Canadian team installed and calibrated the TRIUMF-designed and built field mapper at MIT Bates (see Figure 2) and performed a full set of magnetic verification measurements. The results indicated that the magnet is performing according to specifications and that the individual coils are positioned

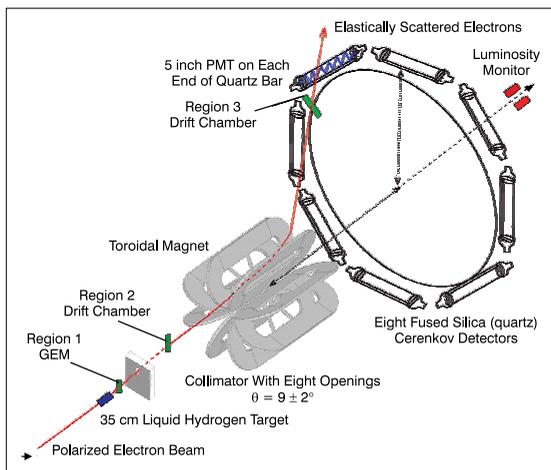


Figure 1: The main elements of the Qweak experiment. (The Regions 1,2, and 3 chambers are only inserted for low-current calibrations runs.)

of the Z boson to the proton. New physics at up to the few TeV scale—for example an extra Z boson (Z'), or supersymmetry (SUSY)—could change this prediction by tens of ppb and would be detectable by a measurement of sufficient accuracy. The Qweak experiment is designed to make just such a measurement, aiming for combined systematic plus statistical uncertainty of 6 ppb. Qweak is complementary to higher energy experiments. For example, Qweak would be sensitive to the sign of the coupling to a Z' , something that the LHC would not be. Qweak will also determine the weak



Figure 2: The Gzero/TRIUMF field mapping apparatus set up at MIT-Bates. The mapper was designed at TRIUMF.

within tolerances (± 2 mm and ± 0.2 deg). The field mapper was shipped from MIT to JLab in January 2010. Once the magnet is re-assembled and surveyed, the Canadian team will set up and calibrate the field mapper and perform another magnetic verification.

Installation of the Qweak experiment in Hall-C at Jefferson Lab started in November 2009 and is still underway. Although there is now very little float left in the schedule, the experiment is still on track to start commissioning in late May 2010.

Collaborators at American Universities and at JLab are working on the other experimental systems. They are also on track for a May 2010 start-up.

All eight diamond detectors for the Hall-C Compton polarimeter were received at the University of Winnipeg, and TRIUMF designed a 48-channel amplifier-discriminator card for use with these detectors. A prototype card was tested, and final production of 10 more cards has been completed. Collaborators at American Universities and at JLab have been working on the other experimental systems. All the collimators have been completed and prototypes of all the tracking chambers have been built and tested. At time of writing, the production of the final chambers was almost complete. The luminosity monitors have been designed and construction is underway.

JLab engineering is handling the beam line, shielding and Hall-C infrastructure. JLab injector group has demonstrated the very fast helicity reversal (up to 1000 spin states per second) requested by the collaboration, and is working on reducing helicity-correlated changes in other beam properties. Many of the custom TRIUMF digital integrators are already in use for diagnostics.

The liquid hydrogen target assembly is nearing completion. It should be ready in time for the run, but the final target checkout will probably be during the initial two weeks of the commissioning run.

A firm end to the running period is set by the JLab shutdown in May 2012 for the 12 GeV upgrade.

Ahead for 2010

Collaborators at American Universities and at JLab are working on the other experimental systems. All the collimators are now complete and are at JLab. Prototypes of all the tracking chambers have been built and tested and production of the final chambers is almost complete. The luminosity monitors are also fully designed and construction is underway.

JLab engineering is handling the beam line, shielding and Hall-C infrastructure. JLab injector group has demonstrated the very fast helicity reversal (up to 1000 spin states per second) requested by the collaboration, and is working on reducing helicity-correlated changes in other beam properties. Many of the custom TRIUMF digital integrators are already in use for diagnostics. First beam is expected in May 2010.

The Team

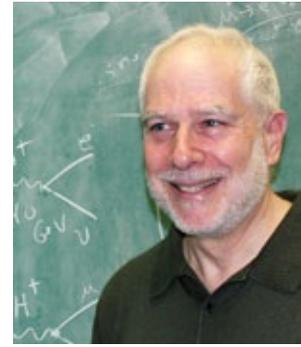
Leads: R. Carlini, S. Kowalski, S. Page

Members: J. Birchall, C. Davis, W. Falk, M. Gericke, E. Korkmaz, L. Lee, S. MacEwan, R. Mahurin, J. Martin, J. Pan, W. D. Ramsay, W. T. H. van Oers, P. Wang

Partnering Labs/Institutions:

Massachusetts Institute of Technology, Thomas Jefferson National Accelerator Facility, University of Manitoba, University of Northern British Columbia, University of Winnipeg. In total there are 25 Institutions (18 American, 4 Canadian, 1 Mexican, 1 Armenian, 1 Croatian) involved in the collaboration

Douglas Bryman holds the J.B. Warren Chair in the Department of Physics and Astronomy at the University of British Columbia and is involved in precision-measurement experiments at TRIUMF.



Subatomic Physics

The PiENU Experiment

The measurement of the branching ratio of

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

pion decays, has provided the best test of the hypothesis of electron-muon universality in weak interactions. The new TRIUMF PiENU experiment aims to improve the precision of the branching ratio measurement by a factor > 5 , confronting the extraordinarily precise Standard Model (SM) prediction of $R_{e/\mu}^{SM} = 1.2352(1) \times 10^{-4}$ to better than 0.1 % and testing the hypothesis of universality to $< 0.05\%$. At that level, new physics beyond the SM may be heralded by a deviation to a wide array of new physics models with pseudoscalar interactions with mass scales up to $O(1000 \text{ TeV})$. Strong limits on the existence of massive neutrinos in the mass region, $< 60 \text{ MeV}/c^2$ will also be determined. We consider massive neutrinos with small couplings to the known leptons so they are potentially exempt from the LEP limit:

Progress in 2008–2010

After development of the extension to the M13 beam line and assembly of the experimental apparatus during 2008, the completed PiENU experiment began operation with an engineering run in the spring of 2009. An initial data set with several times the exposure of previous experiments was acquired in running through November.

Figure 1 shows the PiENU detector arrangement. A 75-MeV/ π^+ beam from the TRIUMF M13 channel with an intensity of up to 100000/s is identified by two plastic scintillation counters and stopped in an active scintillator target. Beam tracking is provided by two 3-plane wire chambers, and two x-y pairs of silicon-strip counters located immediately upstream of the target. Positrons

from $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu\nu$ decays followed by $\mu \rightarrow e\nu$ decays ($\pi \rightarrow \mu \rightarrow e$ decay) are measured in the positron telescope. It consists of an x-y silicon-strip counter, two thin plastic scintillators, a third acceptance-defining wire chamber covering the front of a 48-cm-diameter, 48-cm-long single

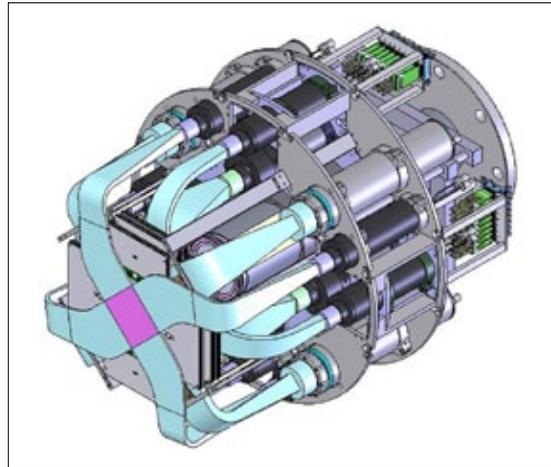


Figure 1: Beam, tracking and target detectors.

crystal NaI(Tl) detector (BINA, on loan from Brookhaven National Laboratory) which provides the primary energy measurement. The fractional solid angle of the telescope is 20%. Two layers of 8.5-cm-thick, 2*25-cm-long pure CsI crystals (also on loan from BNL) surround BINA to capture shower leakage. Analog signals from plastic scintillators, Si strips, NaI(Tl) and CsI detectors are recorded by 500 MHz ADCs (Copper) and 60 MHz ADCs (VF48). A photograph of the setup in M13 is shown in Figure 2.

Simulations using GEANT4 have provided important input for the design of the detector and the experiment. The low-energy response tail of the crystal spectrometer for $\pi \rightarrow e\nu$ events can



Figure 2: PiENU in M13 just prior to insertion.

overlap the energy region of $\pi \rightarrow \mu \rightarrow e$ positrons (< 55 MeV) as a result of shower leakage from the crystals (despite their >19 radiation length coverage). Monte Carlo calculations indicated that the fraction of the low-energy tail events may be as low as 2% of the peak events (comparable which had an order of magnitude smaller solid angle). Pions that decay in flight (DIF) near the target were found to be the major remaining source of the background in the background-suppressed spectrum using the techniques refined. MC calculations showed that measurement of the direction of the beam particles near the target combined with measurements at the entrance of BINA can be used to identify DIF events.

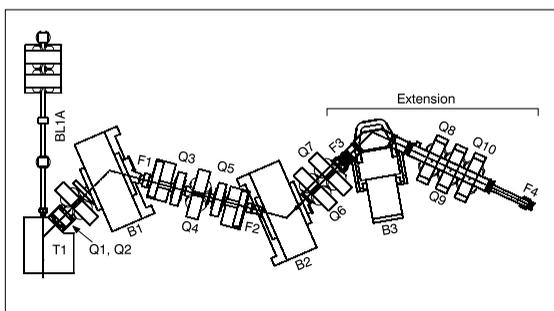


Figure 3: M13 channel extension.

We upgraded and extended the TRIUMF M13 channel shown in Figure 3 described to suppress the positron contamination in the pion beam. A thin foil was inserted at the absorber wheel near F1 resulting in a momentum spread between pions and positrons due to the energy loss difference. The spatial separation of particles at F3 allows a collimator to be placed there to eliminate the positrons. As a result of this development, the TRIUMF M13 channel achieves a pion/positron ratio of >50 . The performance of the extension fully satisfies the requirements of the PiENU

experiment, including providing pion rates up to 100K/s.

The BINA energy resolution was found to be 2 % (FWHM) at 70 MeV including the beam contribution of approximately 1% and the low energy tail response below 75% of the peak value was found to be $<1\%$ for all measured e^+ entrance angles as indicated in Figure 4. Detailed studies

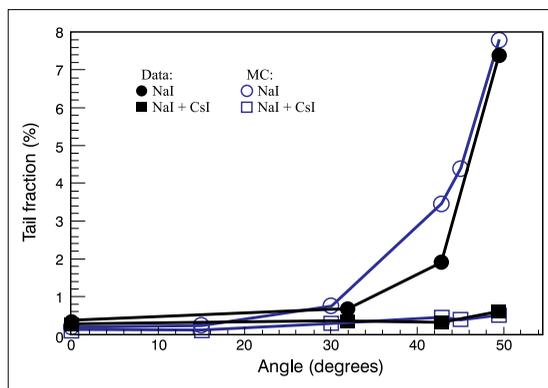


Figure 4: Fraction of tail events below 50 MeV/c.

of the intrinsic BINA response function were also made using 70 MeV (and lower energy) positrons in the beam injected into the crystal. Beside the main beam peak at 70 MeV, two additional structures at 62 and 54 MeV were seen due to photonuclear interactions. These conclusions supported by observations of delayed hits in the CsI ring surrounding BINA as well as from MC simulations including the FLUKA hadronic package. Despite more than 60 years of observations with NaI(Tl) crystals, such effects, which are significant in the quest for ultra-high precision in PiENU have not (to our knowledge), been previously reported.

Ahead in 2010

Measurements made during the first few months of PiENU operation are very promising for suppressing the $\pi \rightarrow \mu \rightarrow e$ events in the background-suppressed spectrum used to determine the low energy tail fraction. The $\pi \rightarrow \mu \rightarrow e$ background has been suppressed by a factor of about five times better than which will result in a highly accurate determination of the tail fraction. PiENU is expected to acquire data during all the available TRIUMF cyclotron operation periods in 2010 and 2011.

The Team

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Members: M. Aoki, M. Blecher, D. Britton, D. Bryman,

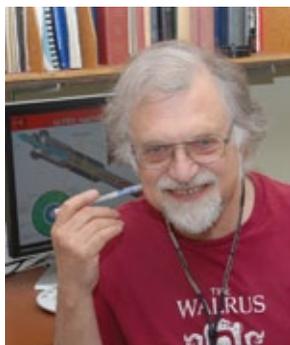
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Partnering Labs/Institutions:

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Subatomic Physics

The ALPHA Experiment

The assumption that reality is invariant under charge-parity time (CPT) inversion means that if an equation involving left handed particles describes a system, then the same equation with right-handed antiparticles and the direction of time reversed will also reflect reality. This symmetry underlies most modern physical theories. Whether this CPT symmetry is exactly conserved is an important experimental question.

The present program aims at developing a trap for antihydrogen atoms which will enable precision measurement of their 1s-2s atomic transition and their ground state hyperfine interval. Measurements of these properties in hydrogen are among the most precise in experimental physics.

Progress in 2008–2010

Because of the reliability of our apparatus and dedication of the on-site collaborators, ALPHA received more than its allocated one-third share of the beam for two six-month runs. The goals set for this period were: upgrading the trap apparatus, commissioning of our Si vertex imaging detector, optimizing anti-hydrogen production in the neutral trap using the annihilation images, investigating charged particle temperatures in the trap, studying the dynamics of p in the neutral trap using the annihilation images, and attempting anti-hydrogen trapping with alternative mixing schemes.

The requirement of very cold \bar{H} imposed very stringent requirements on the cryogenics, electrical noise and alignment of the apparatus. The apparatus was rebuilt and realigned before the 2008 run to lower the temperature substantively inside the cryostat as to simply the apparatus

and increase its robustness. Modifications to the cryogenics allowed an increase in the cold time during runs. High-voltage amplifier noise was identified as a problem and prototype low noise replacements were installed in 2009 on sensitive electrodes.

Sixty percent of the silicon detector modules were available for the 2008 run, and they were arranged to optimize coverage of the mixing region. The imaging detector, together with its electronics and software—a key TRIUMF responsibility—was commissioned and became central to the 2008 studies. The detector performed well, though the missing modules adversely affected the efficiency for reconstructing annihilation vertices. Modifications to the electronics were made at TRIUMF and the University of Liverpool in the spring of 2009 to improve performance and operational protection. The full detector and electronics were commissioned and used in the 2009 run.

The re-engineered trap, working reliably with lower temperatures, resulted in substantial improvements of both the \bar{p} and e^+ intensities. Typically 500000 \bar{p} s were gathered from 8 AD injections and cooled, from which plasmas of 300000 \bar{p} s were produced in the lower-field 1 Tesla mixing region. Positrons were accumulated in an adjacent well, and the potential of this well was gradually raised to mix them with the lowest energy \bar{p} s. We expect to produce lower energy \bar{H} s in contrast to the 2007 run, where the \bar{p} s were injected into the positron plasma at several eV and then cooled by the positrons.

\bar{p} and \bar{H} trapping dynamics: The presence of a strong octupole field is known to compromise the stability of charged particle plasmas, and the

full octupole field was found to decrease our \bar{H} production by about 60%. Annihilation vertices in Figure 1 show a smooth ring of annihilations on the trap wall with no octupole, while the octupole-on annihilations have a component at the edges of the trap. When the \bar{p} are first mixed and the octupole then excited, the annihilation pattern observed reveals that the \bar{p} plasma has expanded radially due to the production of highly excited \bar{H} which then re-ionize in the strong electric fields.

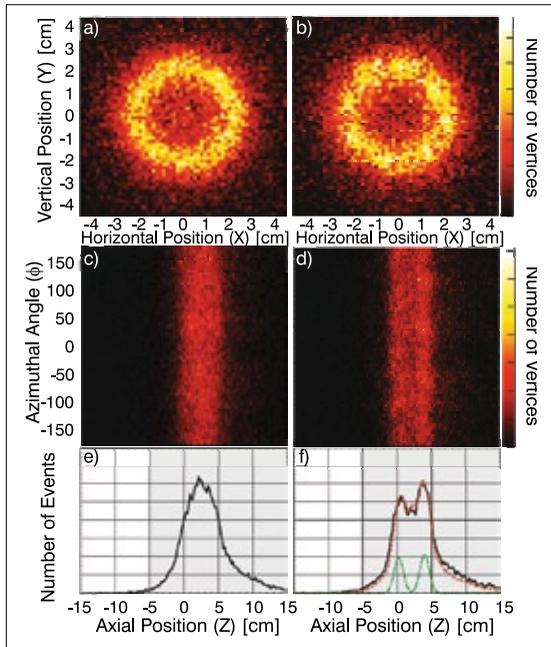


Figure 1: Annihilation vertices observed during mixing without octupole (a,d), with octupole (b,e).

One-component plasmas in equilibrium rotate at a constant angular frequency. Velocities associated with this rotation are of just as much concern as thermal velocities for trapping attempts. In our search for trapped antihydrogen, we varied positron number and density and nested well depths and lengths. Results of these studies on the dynamics of \bar{H} formation have been published.

After transfer to the mixing trap and pulsed-field removal of the electrons, the \bar{p} will have temperatures of $\sim 300\text{K}$ to 1000K . The evaporative cooling method consists of allowing the hottest ones to escape from a gradually lowered potential. Figure 2 shows that the measured \bar{p} temperatures after cooling have reached as low as 10K in very shallow wells. There is a substantial loss of \bar{p} in this process.

Trapping Studies: In 2008, 19 series of trapping runs under different conditions, using a total of 108 caught p and 4 10^6 \bar{H} triggers, were attempted.

Initial e^+ temperatures in the mixing trap were $\sim 1500\text{K}$. Here, annihilations are searched during an octupole quench induced after mixing and then clearing all charged particles. Once the technique for removing the charged particles was refined, no evidence of trapped antihydrogen was seen. Backgrounds, primarily from cosmics, were very low. Much of this parameter space remains to be explored.

In 2009, we performed a first series of 59 attempts with initial e^+ and \bar{p} temperatures of 300K and a 10-second mixing time, using a total of $3.5 \cdot 10^6$ caught \bar{p} and $3.5 \cdot 10^5$ \bar{H} mixing triggers. A second series of 212 attempts, with initial e^+ temperatures reduced to 170K and a 1-second mixing time, used a total of $3.5 \cdot 10^6$ caught \bar{p} and $3.5 \cdot 10^5$ \bar{H} mixing triggers. Results for the yield of trapped \bar{H} from this analysis are expected in early 2010.

Microwave Spectroscopy: In preparation for early measurements of the ground-state hyperfine interval, an innovative cavity compatible with the trap configuration was designed and prototyped at Simon Fraser University, and the transmission of microwaves in the trap has been studied. An elliptical mirror suitable for injecting microwaves into the existing apparatus has been designed at the University of British Columbia and constructed at TRIUMF. Implementation of this Canadian initiative would allow a definitive observation of trapped \bar{H} .

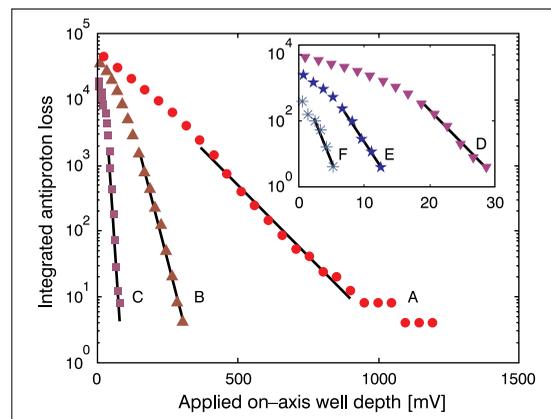


Figure 2: Integrated antiproton loss vs. applied well depth. The series are labeled in order of decreasing temperature (A: 1350K, B: 350K, C: 90K, D: 29K, E: 12K, F: 12K). Solid lines are fits used to determine the temperature.

Ahead in 2010

In 2010, we will upgrade our trap electronics using lower-noise components, which will enable us to

reach lower temperatures for the mixing stage. Improving the numbers that we can trap using the existing apparatus might lead to spectroscopy. In an optimistic scenario for trapping yields, installation of a trapping apparatus that includes microwave resonators and laser access would be possible in 2011.

The Team

Lead: J. S. Hangst (Aarhus)

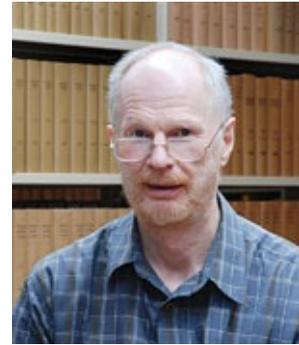
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Members: G.B. Andresen, M.D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P.D. Bowe, E. Butler, C.L. Cesar, S. Chapman, M. Charlton, J. Fajans, T. Friesen, M.C. Fujiwara, D.R. Gill, J.S. Hangst, W.N. Hardy, R.S. Hayano, M.E. Hayden, A. Humphries, R. Hydomako, S. Jonsell, L. Kurchaninov, R. Lambo, N. Madsen, S. Menary, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, D.M. Silveira, , C. So, J.W. Storey, R.I. Thompson, D.P. van der Werf, D. Wilding, J.S. Wurtele, and Y. Yamazaki

Partnering Labs/Institutions:

Aarhus, Auburn University, Berkeley, NCRN, RIKEN, Simon Fraser University, Swansea University, Tokyo University, TRIUMF, Universidade Federal do Rio de Janeiro, University of British Columbia, University of Calgary, University of California at Berkeley, University of Liverpool, University of Rio, and York University

Andy Miller is a research scientist at TRIUMF and leads the detector facility group; he is also a member of the HERMES nominating board and a member of the TRIUMF Science Division safety committee.



Subatomic Physics The HERMES Experiment

HERMES is an international experimental collaboration hosted at DESY, a German national laboratory. Its goal is to study subtle details about how the strongest force known in nature binds together the fractionally charged quarks and electrically neutral gluons to form protons and neutrons (nucleons). In turn, nucleons are bound by “residual leakage” of this force just outside of the nucleons to form atomic nuclei in processes that account for the energy produced in the core of the sun and other stars. HERMES studies how the strong force depends on the orientations of the intrinsic spins of the quarks and nucleons. Led by TRIUMF, Canada made substantial contributions to HERMES in terms of both instrumentation and intellectual participation. The project is now in the end-phase of analyzing the recorded data and publishing scientific papers. What follows are a few highlights among the many preliminary and published results published over the last two years.

Progress in 2008-2010

In 2008, HERMES published results [1] for deeply inelastic scattering (DIS) production of charged kaons (K^+ together with K) from longitudinally polarized deuterium, a heavy isotope of hydrogen in which the nucleus contains both a proton and a neutron. As illustrated in Figure 1, HERMES finds that the unpolarized distribution in strange quark momentum (expressed as a fraction of the nucleon’s momentum in a frame of reference in which it is moving at very high speed, needed because the quark’s internal motion is relativistic) is much softer than was assumed up until now, i.e., such quarks are found typically with lower momentum than expected. Furthermore, HERMES finds that more strange quarks are found with their spins oriented in the same direction as that of the

parent nucleon, rather than opposite, contrary to earlier indications.

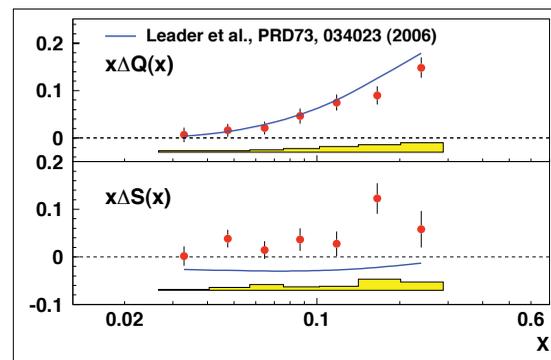


Figure 1: The strange quark momentum distribution from the measured HERMES multiplicity of charged kaons, evolved in each bin to $\langle Q^2 \rangle = 2.5 \text{ GeV}^2$.

The motion of quarks inside a nucleon can be described not only in terms of their longitudinal momentum fraction, but also their momentum component transverse to the nucleon’s infinite momentum. A few decades ago, in order to explain some perplexing data for collisions between high energy protons, it was hypothesized by D. Sivers that there could be a correlation between this transverse momentum and the transverse direction of the nucleon’s spin (e.g., left or right). The key observable in these measurements is the, e.g., left-right symmetry in the yield of produced mesons, where the target spin polarization is up or down. Figure 2 shows this asymmetry for various types of produced mesons. The experimental discovery of the Sivers effect by HERMES [2] inspired theoretical work that led to the realization that the incorrect proof of its impossibility should be amended to a proof that it should manifest with the opposite sign in

the rare Drell-Yan quark-antiquark annihilation process in proton-(anti)proton scattering. It is

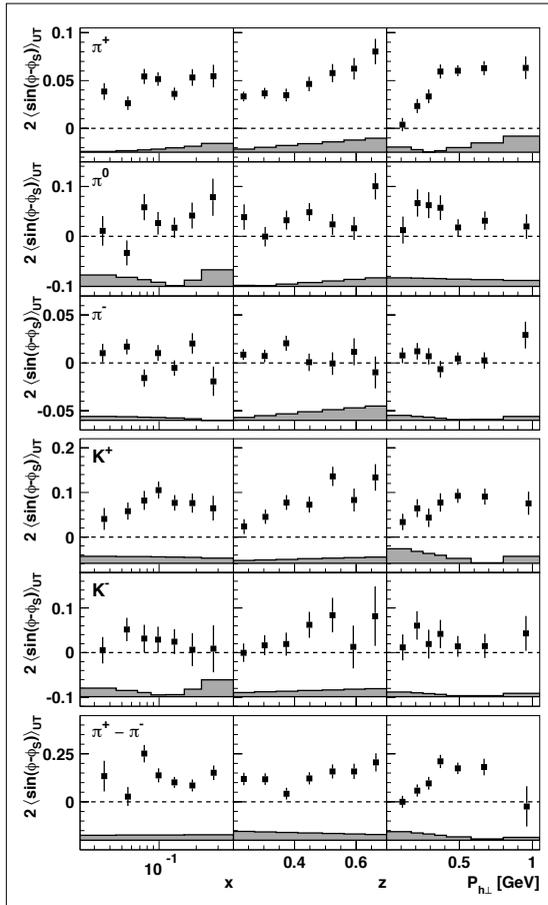


Figure 2: Sivers amplitudes for pions, charged kaons, and the pion-difference asymmetry.

hoped that such Drell-Yan measurements may eventually become technically possible, in order to test this fundamental prediction of our basic understanding of the strong interaction.

A central theme that has pervaded the field of nucleon spin structure for the last two decades is the mystery of how the intrinsic spin of the nucleon ($\frac{1}{2}$ in fundamental units) is “constructed” from the intrinsic spins of the quarks ($\frac{1}{2}$) and gluons (1), and their respective orbital angular momenta about the centre-of-mass of the nucleon. Two decades ago it was discovered, and later confirmed by HERMES and other experiments with high precision, that the net contribution by quark spins is small. There is now also evidence that this is the case for gluons. Hence it is suspected that orbital angular momenta play an important role. Up until 1997, no direct experimental access to this contribution had been identified. Then the field was electrified by the theoretical discovery

that such access could in principle be provided by hard exclusive processes in which exactly one additional particle is produced yet the target nucleon remains intact.

The most transparently interpreted of such processes is the hard exclusive production of real photons, to which a significant and crucial contribution is made by deeply virtual Compton scattering (DVCS) in which a quark absorbs a hard virtual photon and emits an energetic real photon, but remains inside the intact target nucleon. Furthermore, an important contribution to the cross section for exclusive photon production arises from the interference between DVCS and the well-understood Bethe-Heitler process (radiative elastic scattering), giving rise to a rich set of measurable asymmetries with respect to beam charge and spin polarization of beam and target, thereby shedding light on both the magnitude and phase of the DVCS amplitude. HERMES was in the position to pioneer the experimental exploitation of these theoretical discoveries.

In the last two years, two HERMES papers [3, 4] revealed the potential power of such measurements. As illustrated in Figure 3, asymmetries with respect to beam charge and helicity were found to strongly constrain models representing correlations between quark longitudinal momentum fraction and transverse quark position (generalized parton distributions). The statistical uncertainties are indicated by the error bars, and the systematic uncertainties by the lower error bands. Not included is a 2.8% scale uncertainty due to the measurement of the beam polarization. The curves or bands compared to the data represent theoretical calculations based on the available model for the relevant generalized parton distributions that yields best agreement with the data. While the model calculation shown explains the beam charge asymmetries, it is in poor agreement with beam helicity asymmetries. Furthermore, asymmetries with respect to transverse target polarization were shown to have the capability to constrain the contributions of angular momenta of up and down quarks to the nucleon spin. However, the precise quantitative exploitation of this method must await a future generation of experimental facility that is being designed for this type of measurement—the electron-ion collider now under study by Brookhaven National Laboratory and Jefferson Laboratory.

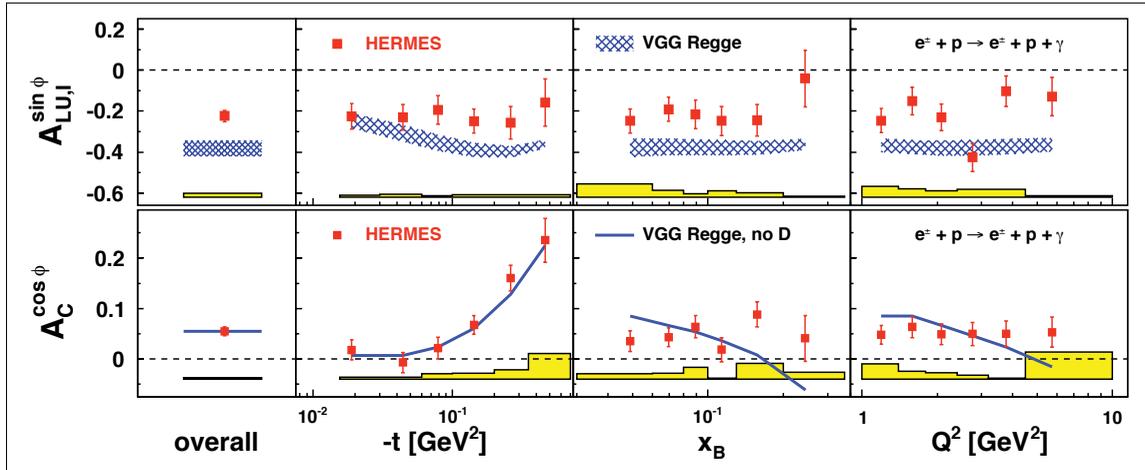


Figure 3: Asymmetries with respect to beam helicity (upper) and beam charge (lower), for DVCS from a hydrogen target.

Arising out of the HERMES program, but not a direct part of it, is a recently published review paper authored by the Canadian group leader together with two others [5]. This paper reviews all of the experimental and theoretical developments of the recent decades in this field, providing simple intuitive pictures and explanations for the various difficult concepts. As it may be argued that a more fundamental understanding is needed to present simple intuitive explanations that are still scientifically correct, this work may be considered to embody many of the intellectual fruits of the Canadian participation in this project.

The Team

Lead: C.A. Miller

Member: S. Yen

Partnering Labs/Institutions:

Twenty-eight collaborating institutes

References

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Subatomic Physics

The G-Zero Experiment

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

Utilizing an alternating right-handed and left-handed polarized electron beam incident on a proton target at Jefferson Laboratory (JLab), the G0 experiment makes use of a superconducting magnet and detector system to measure the rates and momenta of the scattered electrons or the recoil protons. Scattering asymmetries, or differences in the scattering reaction rates using right-handed versus left-handed polarized beams, are observed when parity (or mirror-reflection symmetry) is violated. These scattering asymmetries are sensitive to strange quark contributions. The experiment is challenging because of the small sizes of the typical asymmetries (~5 parts per million, or 0.000005) and the high statistical precision required ($\pm 5\%$, or ± 0.00000025) to achieve adequate sensitivity to the strange quark effects.

The G0 experiment measures the parity-violating asymmetries from elastic electron-proton scattering over a range of momentum transfers [$0.1 < Q^2 < 1.0$ (GeV/c)²], at both forward

and backward scattering angles. A beam of longitudinally polarized electrons is delivered on to a liquid hydrogen (or deuterium) target. From the collision, the recoil protons (forward angle mode) or backscattered electrons (backward angle mode) are then focused thru an eight-sector superconducting toroidal magnet onto arrays of scintillation and Cerenkov detectors (see Figure 1). Much of the detection system and corresponding support structures were prototyped and fabricated at TRIUMF.

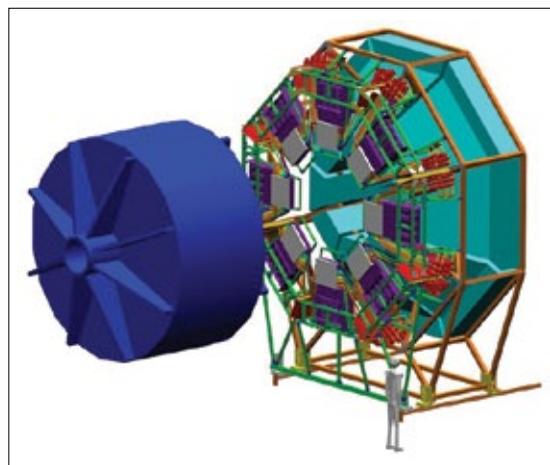


Figure 1: Illustration of the G0 apparatus in the backward configuration, showing the 8-sector toroidal magnet and detector system.

Progress in 2008–2010

Data analysis of the first-phase, the forward angle measurement, was completed and the results published in 2005. Additional physics results, involving transverse beam spin asymmetries data, were extracted from the forward angle data set and have also been published. The second-phase,

the backward angle measurement, completed data-taking in 2007, and the analysis of these data was completed in 2009. Over the summer and fall of 2009, efforts focused on computing the relevant radiative corrections, which needed to be applied before the forward and backward angle results could be combined and the strange quark effects extracted. The final results were extracted and submitted for publication.

Ahead for 2010

Present efforts are focused on the analysis and extraction of additional physics results, involving inelastic electron and pion asymmetries data as well as transverse beam spin asymmetries data at backward angles.

The Team

Lead: W. T. H. van Oers

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Partnering Labs/Institutions:

TRIUMF, University of Manitoba, University of Northern British Columbia, and the University of Winnipeg +15 International: 2 French, 1 Armenian, and 12 American Institutions

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Subatomic Physics

The NPDGamma Experiment

The NPDGamma experiment measures the parity-violating directional gamma-ray asymmetry in the radiative capture of polarized cold neutrons on unpolarized protons in liquid hydrogen, in the reaction $n+p \rightarrow d+\gamma$. The asymmetry is a result of the strangeness-conserving ($\Delta S = 0$) hadronic weak interaction between nucleons, which is a low-energy residual of the weak interaction between quarks. Within the standard model of weak interactions, the charged current contribution to the $\Delta S = 0$ hadronic weak interaction is Cabibbo suppressed and the neutral current terms make contributions to all three isospin channels in the NN interaction ($\Delta = 0, 1, 2$). Based on the current experimental and theoretical status it is not possible to determine the neutral-current, $\Delta I = 1$, part of the hadronic weak interaction.

The goal of the NPDGamma experiment is to measure this part of the hadronic weak interaction in a two-body system where nuclear-structure uncertainties are absent. A modern treatment of the hadronic weak interaction is based on effective field theory, which is the most general description consistent with the symmetries and degrees of freedom of low energy quantum chromodynamics (QCD). In the context of QCD, the description of the hadronic weak interaction involves and provides a window on short-range correlations between quarks. To verify the effective field theory (EFT) approach measurements of parity violation, asymmetries must be made in few nucleon systems, where few-body techniques provide exact nuclear wave functions. The aim of the EFT approach is to calculate the parity violation couplings from first principles, using lattice quantum chromodynamics.

The first phase of the experiment was performed on flight path 12 at the Los Alamos Neutron Science

Center at Los Alamos National Laboratory (LANL) and was completed in 2007. The experiment is currently being installed at the Fundamental Neutron Physics Beam (FNPB) line at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory, Oak Ridge, Tennessee. The experiment utilizes spallation neutrons which are produced from a tungsten (LANL) or liquid mercury (SNS) target by an 800 MeV proton beam pulsed at 20 Hz (LANL) or 60 Hz (SNS). The neutrons are cooled in a cold hydrogen moderator and then delivered to the experiment by a supermirror guide. At LANL, the apparatus was located about 21 metres from the moderator. A schematic of the apparatus is shown in Figure 1. The experiment consists of three neutron beam monitors to

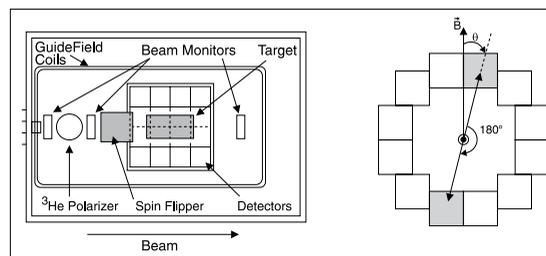


Figure 1: NPDGamma experimental schematic, showing the setup on flight path 12 at LANSCE (left) and one ring of the gamma-ray detector-array (right) (beam into page and B up).

allow in-situ polarization measurements and target monitoring, a helium-3 neutron polarizer, a radio-frequency neutron spin rotator, a 17 liter liquid hydrogen target and an array of 48 CsI(Tl) scintillating crystals to detect the gamma-rays from neutron capture. The experiment is located in a uniform 10 Gauss field, to allow accurate neutron spin transport.



Figure 2: NExperiment cave and beam line (closed) at the SNS.

Progress in 2008–2010

The 2006–2007 first phase data were analyzed, with a result of $A\gamma = (-1.2 \pm 2.1(\text{stat}) \pm 0.1(\text{sys})) \times 10^{-7}$. The first phase was a crucial test of systematic effects to establish the capability of the experiment to reach the goal combined error of 1×10^{-8} . The experiment is currently being installed on the FnpB at the SNS. The experiment beam line, cave and shielding have been completed (see Figure 2),

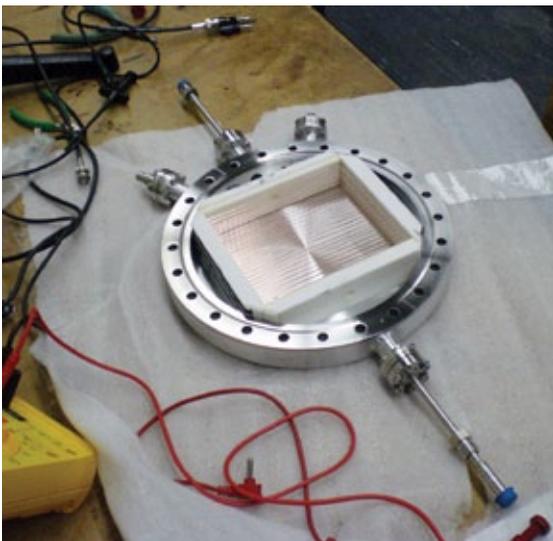


Figure 3: Manitoba neutron beam monitors for the SNS FnpB.

and individual experiment components are ready for installation or are being currently installed. The University of Manitoba group, with support from TRIUMF electronics shop, supplied two new neutron beam monitors, needed to cover the larger beam cross section at the FnpB (see Figure 3).

Ahead for 2010

NPDGamma is expecting first beam for commissioning of the second phase in June 2010.

The Team

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Members: M. Gericke, D. Harrison, R. Mahurin, M. McCrea, S. Page, W. D. Ramsay

Partnering Labs/Institutions:

Arizona State University, Los Alamos National Laboratory, Indiana University, Thomas Jefferson National Accelerator Facility (JLab), University of Michigan, National Institute of Standards and Technology, Hamilton College, University of New Hampshire, University of Kentucky, North Carolina State University, University of Dayton, University of Tennessee, Oak Ridge National Laboratory, University of Manitoba, University of Winnipeg, KEK National Laboratory, Paul Scherrer Institut (Switzerland), Joint Institute for Nuclear Research, Dubna (Russia), Universidad Nacional Autonoma de Mexico, Bhabha Atomic Research Center, Trombay (India).



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Subatomic Physics

TRIUMF's Theory Group

Nuclear Physics and Astrophysics

Nuclear theory has entered an exciting era. This is due to advances on many fronts, including: the development of effective field theory (EFT) and the renormalization group (RG) for nuclear forces; advances in *ab-initio* methods for nuclear structure; efforts to develop a universal density functional based on microscopic interactions; and the application of large-scale computing resources. Combined, these have the potential to provide a unified and systematic description of light to heavy nuclei and matter in astrophysics based on the same interactions and with controlled uncertainties. The following covers the research highlights of the TRIUMF Theory Group in understanding and predicting properties of nuclei, the structure of strongly-interacting matter, and their response to electroweak probes.

Recently, a combination of nuclear and atomic physics techniques has led to the first precision measurements of masses and charge radii of the helium halo nuclei, ^6He and ^8He , with two or four weakly bound neutrons forming an extended halo around the ^4He core. Halo nuclei are particularly challenging for theory because of the extended structure of the wave function. Being neutron-rich nuclei, they present a stringent test for nuclear forces because they probe aspects of strong interactions that are less relevant in nuclei close to stability. Figure 1 shows results for the ground-state energies of helium halo nuclei based on chiral low-momentum nucleon-nucleon (NN) interactions [1]. This combines an RG evolution with the exact hyperspherical harmonics (HH) expansions for ^6He and coupled-cluster (CCSD(T)) theory for ^8He , which have the correct asymptotic behavior of the wave function. The cutoff variation in Figure 1 highlights the importance of three-

nucleon (3N) interactions. For all cutoffs studied, the NN-only results underbind ^8He . Because more attraction is needed for ^8He to describe the

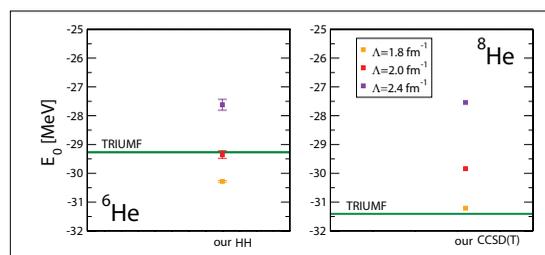


Figure 1: ^6He and ^8He ground-state energies based on chiral low-momentum NN interactions for a range of cutoffs Λ .

experiment, we conclude that the helium isotopes probe 3N effects beyond the overall repulsion observed in calculations for infinite nuclear and neutron matter [2].

The neutron drip-line, which is the limit of neutron-rich nuclei, evolves regularly from light-to medium-mass nuclei except for a striking anomaly in the oxygen isotopes. This anomaly is not reproduced in theories derived from two-nucleon forces. The first microscopic explanation of the oxygen anomaly based on low-momentum 3N forces was presented in [3]. As shown in Figure 2, the inclusion of 3N interactions at next-to-next-to-leading order (N^2LO) or due to Δ excitations leads to repulsive contributions to the interactions among valence neutrons that change the location of the neutron drip-line from ^{28}O to the experimentally observed ^{24}O . This 3N mechanism is robust and general, and therefore expected to impact predictions of the most neutron-rich nuclei and the synthesis of heavy elements in neutron-rich environments.

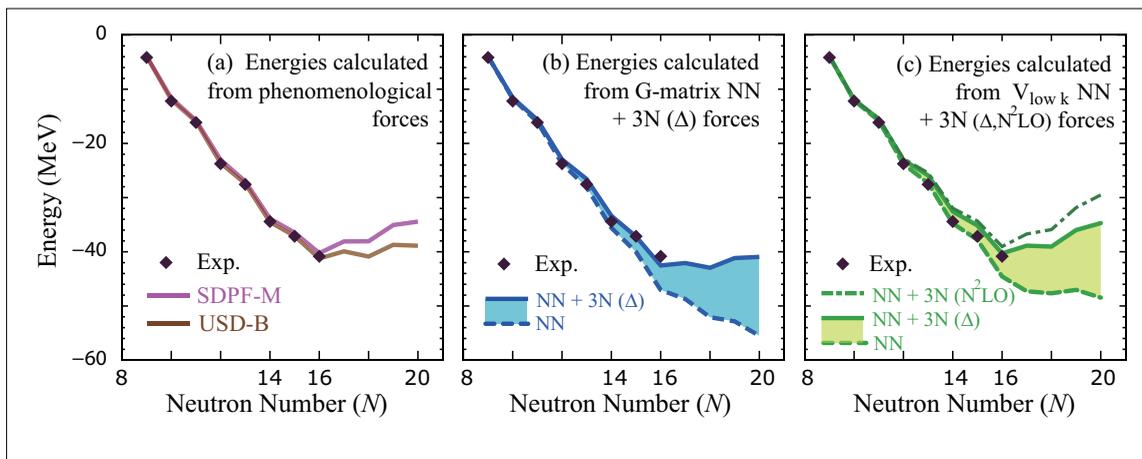


Figure 2: Ground-state energies of neutron-rich oxygen isotopes measured from the energy of ^{16}O . The experimental energies of the bound oxygen isotopes $^{16-24}\text{O}$ are included for comparison. The left panel (a) shows the energies obtained from the purely phenomenological forces. The middle panel (b) gives the energies obtained from 3N forces due to Δ excitations. The right panel (c) presents the energies calculated from chiral low-momentum NN interactions and includes 3N interactions at $N^2\text{LO}$ as well as those due only to Δ excitations. The changes due to 3N forces based on Δ excitations are highlighted by the shaded areas.

We have studied the formalism to include isospin-symmetry-breaking corrections when extracting the up-down Cabibbo-Kobayashi-Maskawa matrix element from superallowed $0^+ \rightarrow 0^+$ nuclear β decay. We have developed an exact formalism and shown that there are no first order isospin-symmetry-breaking corrections to the relevant nuclear matrix elements [4]. Based on this exact formalism, we have calculated the second-order renormalization of the Fermi matrix element due to radial contributions and have shown that radial excitations neglected in the treatment of Towner and Hardy are significant [5]. These are estimated to decrease the isospin-symmetry-breaking corrections. Our results provide a correction term that can be included in existing approaches.

Electroweak reactions are important observables to expand our understanding of nuclear forces. The interaction between nucleons and electroweak probes is accurately known at low energies, making it possible to focus on the hadronic part of the reaction. Exact calculations of cross-sections become prohibitive for more than three reacting particles if direct access to the wave function of all possible final states is required. This can be avoided using the Lorentz Integral Transform (LIT), where the problem is reduced to the solution of a bound-state equation. We have investigated electron scattering on light nuclei, which allows for a detailed study of nuclear properties because energy and momentum transfer can be varied independently. One of our major achievements [6,7] is the study of the longitudinal response

function of ^4He in different kinematical regions, with two-nucleon forces (2NF) augmented by 3N forces (3NF), as shown in Figure 3. We have found a very good agreement with experimental data, where available, and interestingly a strong effect of 3NF (with two different 3N potential models, UIX and TM') at low-momentum transfer, where no experiment exists. Our findings have already triggered new experimental activity at MAMI (in Mainz) and a proposal at JLAB.

Neutrinos play a crucial role for the physics of stellar collapse, supernova explosions, and neutron stars. We have carried out the first calculations [8,9] of neutrino processes based on chiral EFT and RG-evolved interactions, focusing on neutrino reactions involving two nucleons: neutrino-pair bremsstrahlung and absorption, which are key for muon and tau neutrino production in supernovae, and neutrino inelastic scattering. These processes are determined by the spin relaxation rate using a unified approach to neutrino interactions in nucleon matter [8]. In supernova simulations, the standard rates for bremsstrahlung are based on the one-pion exchange approximation to NN interactions. Our calculations based on chiral EFT and RG-evolved interactions show that shorter-range non-central forces reduce the spin relaxation rate and therefore the rate for bremsstrahlung significantly. In addition, the spin relaxation rate sets the scale for energy transfer in inelastic scattering, which is presently not included in simulations. The spin relaxation rates lead to a mean-square energy transfer that is comparable

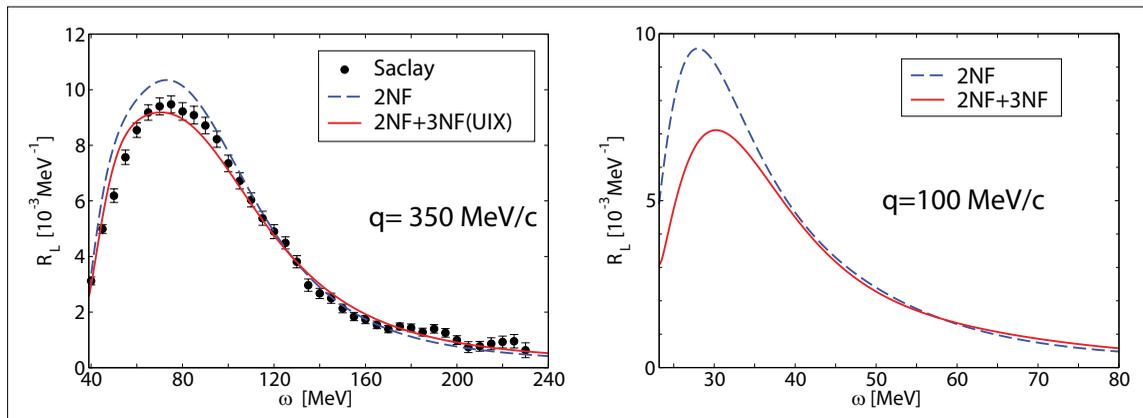


Figure 3: Longitudinal response function of ${}^4\text{He}$ for two values of the momentum transfer q as a function of the energy transfer ω , in comparison with data from Saclay.

to the incoming neutrino energy, indicating that NN collisions may be important for energy transfer in supernovae [9].

Advances in Nuclear Matter Theory

Low-momentum interactions offer the possibility of perturbative nuclear matter [2,10], whereas for hard potentials, the coupling to high momenta renders the Bethe-Brueckner-Goldstone expansion necessarily nonperturbative. Our nuclear-matter calculations based on low-momentum interactions derived from chiral NN and 3N EFT interactions, and fit only to few-body data, predict realistic saturation properties with controlled uncertainties [2]. This is promising for a unified description of nuclei and to develop a universal density functional based on low-momentum interactions, one of the goals of the SciDAC universal nuclear energy density functional project. Neutron matter provides a different perspective from symmetric nuclear matter because only the long-range two-pion-exchange parts of the leading chiral 3N forces contribute [10]. We have also studied in detail the theoretical uncertainties of the neutron matter energy, which provides constraints for the symmetry energy and its density dependence and explored the impact of chiral 3N forces on the S-wave superfluid pairing gap.

Pairing in Nuclei from Low-Momentum Interactions

We have studied S-wave pairing gaps in neutron and nuclear matter as well as the corresponding isospin $T=1$, $J=0$ pairing in finite nuclei on the basis of microscopic two-nucleon interactions [11]. Our results show that pairing gaps obtained

from low-momentum interactions depend only weakly on approximation schemes for the normal self-energy, which is required in present energy-density functional calculations, while pairing gaps from hard potentials are very sensitive to the effective-mass approximation scheme. In a detailed study, we have presented a detailed analysis of partial-wave contributions of nuclear forces to pairing in nuclei, and for $T=1$, $J=0$ pairing, we found that partial waves beyond the standard S-wave channel play an interesting role for the pair formation in nuclei. In addition, we have shown that nuclear forces favor $T=1$, $J=0$ over $T=0$, $J=1$ pairing, except in low- j orbitals [12]. This is in contrast to the free-space motivation that suggests the formation of deuteron-like $T=0$ pairs in $N=Z$ nuclei. The suppression of $T=0$ pairing is because the S-wave strength is distributed on spin-orbit partners and because of the effects of higher partial waves.

Review “From Low-Momentum Interactions to Nuclear Structure”

Our review [13] presents the first overview of low-momentum two-nucleon and many-body nuclear interactions and their use in calculations of nuclei and infinite matter. It summarizes the recent progress in the field thanks to the availability of soft nuclear forces, which makes it possible to obtain convergent calculations across the nuclear chart. Our review discusses the connections to chiral EFT, and clarifies various misconceptions.

Hadron Physics

The hadron physics research undertaken in the Theory Group focuses on the physics of hadrons containing heavy (charm or bottom) quarks.

To study these systems, the methods of lattice quantum Chromodynamics (QCD) are used, which allows for a non-perturbative treatment of interacting quark and gluon systems by numerical simulation.

A major hadron physics project undertaken in the past two years was the calculation of the masses of baryons containing a bottom quark. These systems are interesting because the systematics of the spectrum are sensitive to the details of how quarks interact in QCD. The pattern of the spectrum is determined to a large extent by how the spin-dependent quark-quark interaction depends on quark mass.

In order to get reliable results it is important that vacuum polarization effects associated with light-quark (up, down, strange) quantum fluctuations are incorporated into the lattice QCD simulation. This is a particularly computing-intensive problem, and the study we carried out was possible because we were able to obtain dynamical gauge field configurations containing light-quark vacuum polarization effects from the JLQCD (Japan Lattice Quantum Chromodynamics) Collaboration. Lattice QCD calculations were done at a single lattice spacing (approximately 0.1 fm) so the mass results contain uncorrected lattice-spacing errors which might be a few tens of MeV. Our results [14] for single-bottom baryons are shown in figure 4. The experimental results are shown by the solid bars. The case of the Ω_b baryon

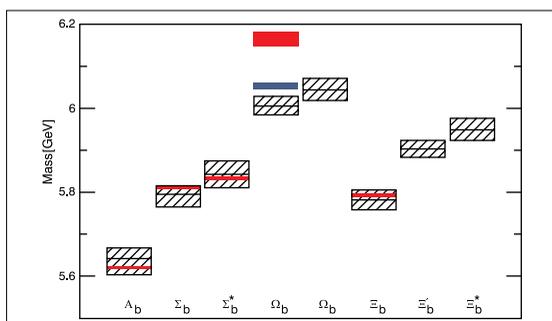


Figure 4: Bottom baryon masses calculated in Lattice QCD compared to experimental values.

is particularly interesting. The D0 collaboration [15] announced their result for the Ω_b mass at the time we were analyzing our results. As can be seen, there is a considerable discrepancy between the calculation and the D0 mass measurement. Agreement between calculation and experimental values in other channels was very good, but the D0 Ω_b result was a puzzle. There is no way to understand why a discrepancy should appear in

only one channel and the lattice QCD approach, being an *ab initio* method, does not have room for ad hoc juggling of the results. Subsequently, the CDF collaboration [16] released their measurement of the Ω_b and may have resolved this issue. Agreement of our calculation with this value is much better, the difference being of the size that might be expected for the uncorrected lattice-spacing errors.

Projects currently underway include the study of radiative transitions in heavy quark systems. One study is concentrating on the decays of bottomonium states (γ , χ_{b0} , χ_{b1} , χ_{b2}) using non-relativistic lattice QCD as the framework with which to describe the bottom quark. This will allow a more detailed test of the higher-order terms of the non-relativistic action than is possible by simply looking at the spectrum.

Another study is looking at the radiative decays of charged and neutral D^* mesons. In this work the recently developed HISQ (highly improved staggered quark) lattice action [17] is used for all quarks in the mass range from up, down, strange, and charm. This lattice action has been very successful in resolving a long-standing discrepancy between the experimentally measured and lattice QCD values of the vector-pseudoscalar spin splitting of charmonium. Our calculation will test the lattice prediction for meson structure over the quark mass range from light to charm.

Particle Phenomenology and Cosmology

Our current understanding of particle physics is incorporated into the Standard Model (SM), which describes all the known particles as well as the strong, weak, and electromagnetic forces. Despite the success of the model in explaining the results of a great number of particle collider experiments, the SM does not fully explain why the weak force is so much weaker than the strong and electromagnetic forces. It cannot account for the dark matter (DM) or the excess of matter over anti-matter in our universe, and it does not provide an origin of the observed neutrino masses and mixings. The activities of the Theory Group are focused on finding solutions to these three major shortcomings of the SM. This research is complementary to several experimental projects at TRIUMF which attempt to discover new physics beyond the SM, in particular those pursued by the ATLAS and T2K groups.

Higgs Physics

The central question about the SM at high energies is “What is the source of electroweak symmetry breaking, which is responsible for making the weak force so much weaker than the other known forces?” In the SM, this breakdown is induced by the Higgs boson particle, the only particle predicted by the SM that has not yet been discovered. We investigated new experimental signals of Higgs bosons when the SM is extended to include supersymmetry, a symmetry that can help put electroweak symmetry breaking on a firm theoretical footing [18, 19, 20]. Supersymmetry can also modify the decay channels of the Higgs compared to the SM. Some of these channels can be challenging to find at high-energy colliders such as the Large Hadron Collider (LHC) at CERN and, therefore, it is important to have an understanding of the full range of possible signals in order to optimize experimental searches for them.

A new potential effect of supersymmetry on decays of the Higgs boson shows the narrow di-photon resonance expected from direct Higgs decays in the SM, as well as a smeared di-photon signal that can arise when the Higgs boson decays significantly to new neutralino particles—predicted by supersymmetry—which then subsequently decay to photons. The smeared supersymmetry di-photon signal provides a new discovery mode for the Higgs at the LHC.

Discrete Dirac Neutrino in Warped Extra Dimensions

We continued our investigation of the Randall-Sundrum (RS) scenario as a theory of flavour, and extended the study from the quark sector to leptons [21]. Dirac neutrinos were implemented in the minimal custodial RS setting via the Krauss-Wilczek mechanism. We demonstrate that by giving explicit lepton mass matrices with neutrinos in the normal hierarchy, lepton mass and mixing patterns can be naturally reproduced at the scale set by the constraints from electroweak precision measurements, and at the same time without violating bounds set by lepton flavour violation. The scenario generically predicts a nonzero neutrino mixing angle Θ_{13} that could be measured at T2K, as well as the existence of sub-TeV right-handed Kaluza-Klein neutrinos which partner with the right-handed SM charged leptons and may be searched for at the LHC.

New Signals of Dark Matter

The SM is unable to explain the dark matter (DM) in our universe. Recent laboratory searches for DM by the DAMA experiments have observed a signal that could be due to DM scattering in their detector. Minimal models of DM are incapable of explaining this signal while avoiding the constraints imposed by null results in other DM searches. We developed new theoretical models for DM involving supersymmetry or RS extra dimensions that can accommodate all direct DM search data simultaneously [22]. These models will be tested in upcoming DM searches such as XENON100 and LUX. The possibility that DM comes from extended RS scenarios involving multiple extra dimensions was investigated [23]. In addition to DM, these constructions predict the existence of many new particles that could lead to striking resonance signals at the LHC.

New Hidden Forces

New forces arise in many extensions of the SM, and in some cases these forces are hidden, acting only very weakly on the known particles. An effective operator approach was used to study the effects of an extra Z' hidden gauge force mediator in polarized Moeller scattering experiments to be conducted at JLab [24]. This low-energy precision measurement is complementary to LHC searches for Z' up to 4 TeV. If found, this measurement can be used to determine the couplings of Z' to the chiral electrons. We studied how a new hidden Z' with a mass on the order of a GeV could arise in the context of supersymmetry [25]. We also investigated the implications of such light hidden force carriers for DM, the LHC, and lower-energy collider signals.

Review of New Physics beyond the Standard Model

We made a comprehensive and modern review of theories of new physics beyond the SM and their potential experimental signals at the LHC [26]. This is the first time the field of LHC-relevant particle phenomenology has been covered in such a broad fashion, and this review is intended to be a useful reference tool as the LHC begins to collect a large volume of data.

Future Plans

In the next year, exciting new data is expected from the LHC, direct and indirect searches

for dark matter, and lower-energy precision measurements. These results will strongly influence the particle phenomenology research of the Theory Group. J. Ng will concentrate primarily on extra-dimensional models and neutrino mass generation. D. Morrissey will focus on potential Higgs boson and related signals at the LHC as well as on developing new theories and methods to probe the nature of dark matter.

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Molecular and Materials Science

Overview of Molecular and Materials Science

The positive muon is one of nature's exquisite and remarkable particles. When implanted into matter, it becomes a microscopic local probe which sensitively interacts with the characteristic electro-magnetic environment unique to the specific atomic and molecular structure of the material under study. At the end of its 2.2×10^{-6} sec lifetime, the muon transmits this information, which is encoded in its spin polarization, to the outside world where it is analyzed to provide a picture or fingerprint of the host's microscopic electronic properties.

The discipline of muon spin resonance/rotation/relaxation, i.e., MuSR or μ SR, can be considered to provide the analogue of an atomic level MRI (magnetic resonance image) of its subject material, leading to its very robust utilization as a research tool in a wide variety of condensed matter and chemical environments.

TRIUMF is the sole source for intense muon beams in the Americas, and is one of only four such facilities in the world. Two of these facilities (J-PARC in Japan and ISIS in the UK) currently provide low-resolution pulsed muons, and the other two (PSI in Switzerland and TRIUMF) deliver high resolution continuous wave (CW) beams. These two complementary methods of muon delivery serve distinct sets of experiments, and in this respect it is only TRIUMF and PSI which serve the global demand for high-resolution muons.

Muon Basics

The five basic aspects of a muon are: its 1e charge of a proton, a large magnetic moment with spin of $\frac{1}{2}$, a mass that is about $\frac{1}{9}$ that of the proton, the aforementioned lifetime of 2.2μ s and, finally, the proclivity to expire by emitting a positron in the direction of its spin polarization. All of these aspects combine to yield an experimental technique whose applicability is very broad. As a bare probe, it resides in the inter-atomic, electron-filled volume and detects the magnetic fields generated by neighbouring nuclei and their associated electrons, i.e., a powerful microscopic

magnetometer. Alternatively, it can acquire a bound electron from the host and transform it into an isotope of hydrogen called muonium, thereby opening up and expanding the field of H chemistry into a range of compounds that would otherwise be unavailable for study.

The mass of the muon is much less than any nucleus so it has relatively high mobility and enhanced reactivity. The rather stately (on a molecular level) muon lifetime and the capability to detect the particles on a sub-nanosecond timescale enable MuSR experiments routinely to extract information within the five orders of magnitude time range from 1×10^{-9} – 100×10^{-6} seconds. The result is a measurement of a broad range of reaction and/or fluctuation rates in either chemical or condensed matter systems.

Whereas muons at TRIUMF are probes into bulk matter, its beta-detected nuclear magnetic resonance (β -NMR) program extends very similar experimental capabilities into the regime of surfaces, sub-surfaces, layers, and interfaces.

Progress in 2008–2010

Insofar as modern electronic devices are engineered around these structures, the emerging potential of this field is clear, and the following pages detail a representative group of experiments in molecular and materials science, namely: high-temperature and related superconductivity, exotic magnetism and quantum phase transitions, industrial basic research for automobile technology, green materials design and physical chemistry, and semiconductors and the new spintronics.

Ahead in 2010

This program is poised to expand its impact on the international molecular and materials science community. The following six sections show how the recent expansion of CMMS infrastructure is facilitating the research capabilities of this program now and in the future.

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Molecular and Materials Science

High Temperature and Unconventional Superconductivity

μ SR is uniquely suitable for the study of superconductivity because it can map out the distribution of super-current induced internal magnetic fields, detect magnetic, superconducting, and non-magnetic phases simultaneously, and follow their relevant dynamical fluctuations. For the high-temperature superconducting materials, this suitability is even more accentuated because the underlying mechanisms responsible for superconductivity are themselves magnetic. The following experiments describe various achievements of this active field of research in 2008 and 2009.

M1138—The Search for Weak Magnetism in Cuprates

One of the foremost questions in the search for an understanding of the microscopic mechanism of high-transition temperature (high- T_c) superconductivity, is the role played by the mysterious pseudogap, which appears in cuprate superconductors at temperatures above T_c . It is widely believed that the mysterious pseudogap region is caused by a “hidden order.” A recent discovery of an unusual magnetic order by polarized neutron scattering below the pseudogap transition temperature T^* of $\text{YBa}_2\text{Cu}_3\text{O}_y$ and $\text{HgBa}_2\text{CuO}_{4+d}$ appears to offer tantalizing clues as to what this order might be. This breakthrough falls on the heels of an earlier finding of another strange magnetic order in $\text{YBa}_2\text{Cu}_3\text{O}_y$ by neutron scattering. Some qualitative features of the magnetic orders are consistent with the cause of the pseudogap being one of two proposed states, distinguished by a unique pattern of current loops in the copper-oxygen (CuO_2) planes that vanish at a quantum critical point (QCP) under the superconducting “dome.” However, this association is controversial because of several

inconsistencies and the failure of key experiments to detect these magnetic orders.

In 2008, zero-field (ZF) μ SR was used to investigate the possible occurrence of loop-current magnetic order in the pseudogap phase of $\text{YBa}_2\text{Cu}_3\text{O}_y$. The experiment included ZF- μ SR measurements on a large $\text{YBa}_2\text{Cu}_3\text{O}_{6.6}$ single crystal in which two types of unusual magnetic order have been detected by neutrons. We observed one type of magnetic order in all samples that did not evolve significantly with hole doping, which is inconsistent with loop-current order. A second type of unusual magnetic order was also observed, but only in the large $\text{YBa}_2\text{Cu}_3\text{O}_{6.6}$ single crystal. The ordered magnetic moment we detected is quantitatively consistent with the neutron experiments. Because μ SR is a local probe, we were also able to determine that this magnetic order is confined to only a small volume of the sample ($\sim 3\%$). This is also not in agreement with loop-current order.

Consequently, our findings do not support theories that ascribe the pseudogap to a state characterized by loop-current order, but instead indicate that dilute impurity phases are the source of the unusual magnetic orders detected in $\text{YBa}_2\text{Cu}_3\text{O}_y$ by neutron scattering.

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M1139—Phase Smearing Test in Boro-Carbide Superconductors near H_{c2} Via the Local Magnetic Field Distribution

Magnetic quantum (dHvA) oscillations are mostly known for their importance in exploring the Fermi-surface of metals; however, as measurements in type-II superconductors have shown in the past decades, this relevance extends to even wider fields than initially imagined. Though a qualitative understanding of the phenomenon of dHvA oscillations in the superconducting state exists, several questions still remain unanswered on a quantitative level. One such question concerns the additional damping of the dHvA oscillation amplitude in the superconducting state.

The additional damping was originally associated with the existence of the superconducting order parameter, but this cannot give a truly quantitative explanation for the observed damping in many experiments. One possible explanation relies on an increase in the inhomogeneity of the magnetic-field distribution while entering the superconducting state, the so called “phase smearing” effect. Determining whether this effect is indeed responsible, even in part, for the additional damping in the oscillation amplitude, is a very important task. If the phase is too weak to account for the observed change, then the existence of additional damping in the superconducting state points towards the need for a new theoretical view of superconductivity under high magnetic field.

MuSR measurements of two different high-quality boro-carbide superconductors have been done near $H_{c2}(T)$ at low temperature. Combined with dHvA measurements and SQUID magnetization measurements, they revealed that the “phase smearing” effect is not responsible for the additional damping seen in the dHvA amplitude.

In the near future, we can use a possible new mechanism to explain the additional damping is correlated to the enhanced disorder in flux-line lattice.

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M1132—Field Induced Magnetism in the Layered Heavy Fermion Superconductor $CeCoIn_5$

The maximum magnetic field strength for which superconductivity exists in conventional superconductors is limited by the increase of energy because of the vortex formation via orbital screening currents. Some 2-D unconventional superconductors replace this limit by higher ones controlled by the increase of energy of the non-magnetic superconducting state with respect to a paramagnetic state, called Pauli-limit. Close to this limit, complex quantum ground states like the Fulde-Ferrel-Larkin-Ovshinnikov (FFLO) superconducting (SC) phase and other modulated SC phases with mixed singlet-triplet order (pair density wave, PDW) coupled to a spin density wave (SDW) magnetic order [2–4], may be present. M1132 examines complex superconducting states which permit the maximum applicable magnetic field strength of a superconductor to increase.

This experiment utilized the M15 DR spectrometer which provides the world’s sole necessary combination of very low temperatures (20 mK) and high magnetic field (5T) to perform this study. A strong diamagnetic shift of the main resonance line is seen for all fields. No additional signal at the normal state paramagnetic position is found proving that a spin-singlet FFLO superconducting state is not realized. Detailed analysis reveals an enhancement of the low-temperature frequency shift for fields between 4.8 and 4.9 T, indicating a coupled mixed singlet-triplet pair density wave and spin density wave order. Incommensurate magnetic order in this regime is further supported by an increase of the static muon relaxation rate at $T = 20$ mK. The nonlinear increase of the internal field distribution in the SC state is in conflict with the linear field dependence of the Ginzburg-Landau paradigm. The strongly enhanced static linewidth around 4.85 T is associated with a field-induced magnetic order inside the SC phase. These findings are consistent with recent neutron diffraction data for H k c. The observed decrease of static linewidth at 5 T external field implies that the additional source of magnetism vanishes simultaneously at the same critical field, which confirms the intimate coupling between magnetism and superconductivity [2–4] in $CeCoIn_5$.

We look ahead to 2010 and publications based on our experimental data.

The Team

Lead: H.H. Klauss

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Partnering Labs/Institutions: Dresden Technical University, LANL, and Simon Fraser University

M1174—Superconductivity in Layered Oxypnictide La(O,F)FeAs

Researchers in the field of superconductivity agree that magnetism clearly inhibits superconductivity because it breaks the spin-singlet pairing of electrons (the so-called “Cooper pairs”) that carry the superconducting current. It is like the “nature abhors a vacuum” idea that superconductivity avoids magnetism. This idea led to a common belief that any materials composed of magnetic elements like iron would have the least potential to serve as good superconductors. Thus, the discovery of an iron oxypnictide superconductor $\text{LaFeAsO}_{1-x}\text{F}_x$ (LFAO-F) with a high critical temperature (T_c) of 26 K (reported in 2008) was a counterintuitive discovery that came as a surprise; the discovery brought this new class of superconducting compounds into focus. The subsequent discovery of an increase in T_c when La was substituted with other rare-earth elements (resulting in a maximum T_c of 55 K) has triggered a broad interest in mechanisms that result in a relatively high T_c on such an extraordinary stage as iron-based compound.

The iron oxypnictides have a layered structure like that exhibited by high- T_c cuprates or copper oxides (see Figure 1), where the conducting Fe_2As_2 layers are isolated from the charge reservoir layers so that the doped carriers (electrons in this case) introduced by the substitution of O^{2-} with F⁻ in the La_2O_2 layers can move within the layers of strongly bonded Fe and As atoms. There is another qualitative similarity between LFAO-F and cuprates: they exhibit superconductivity upon carrier doping of magnetic, pristine compounds. As the undoped cuprates exhibit antiferromagnetism (AF), the mother compound LaFeAsO exhibits the so-called “spin-density wave” state which is similar to the AF state. These observations suggest that there must be a close relationship between magnetism and superconductivity, in

stark contrast to the simple relation of mutual exclusiveness.

At the Tokyo Inst. Tech., researchers, who first discovered LFAO-F, recently revealed that in CaFeAsF , the carrier doping in the Fe_2As_2 layers can be achieved by substituting iron with cobalt, which has one more electron than iron. This was another startling discovery because it was contrary to the common belief that superconductivity is unstable in the presence of inhomogeneity in media that interferes with the coherence of the

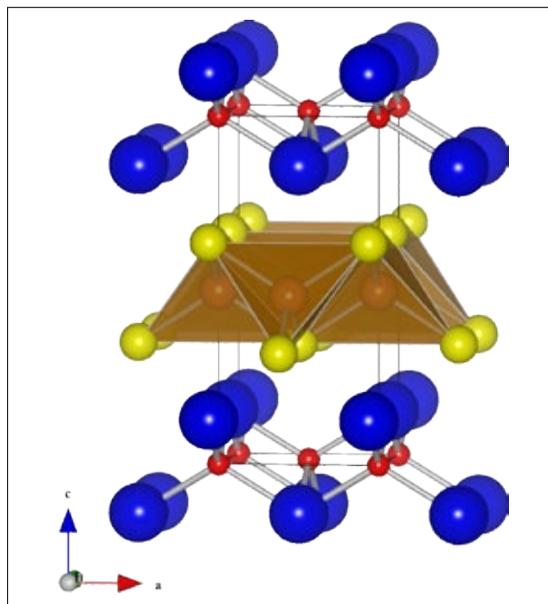


Figure 1: Crystal structure of iron pnictide $\text{LaFeAsO}_{1-x}\text{F}_x$, where the brown, yellow, red, and blue spheres represent iron, arsenic, oxygen (or fluorine), and lanthanum atoms respectively.

Cooper pairs. It has been established that, in the case of cuprates, the direct modification of the conducting layers by chemical substitution does inhibit superconductivity.

Muon spin rotation/relaxation (μSR) is an ideal microscopic probe that is used to study such inhomogeneous matter and is sensitive to both magnetism and superconductivity.

In 2008–2009, the KEK group conducted a muon study involving this Co-doped compound $\text{CaFe}_{1-x}\text{Co}_x\text{AsF}$ and has demonstrated a unique form of coexistence between these two competing electronic states [4]. As shown in Figure 2, the volumetric fraction of the superconducting phase (determined by μSR) increases in proportion to the cobalt content x (that also leads to the decrease of

the magnetic phase fraction), while the density of the superconducting carriers is independent of χ . This result strongly suggests that, as illustrated in

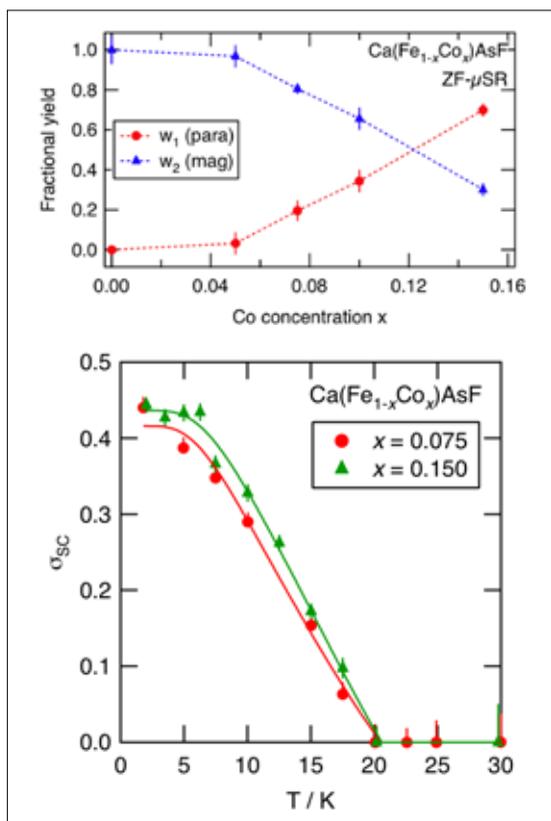


Figure 2: (top) Volumetric fraction of superconducting (“para”) and magnetic phases vs. cobalt content c in $\text{CaFe}_{1-x}\text{Co}_x\text{AsF}$; (bottom) Super-current density (σ_{SC}) vs. temperature.

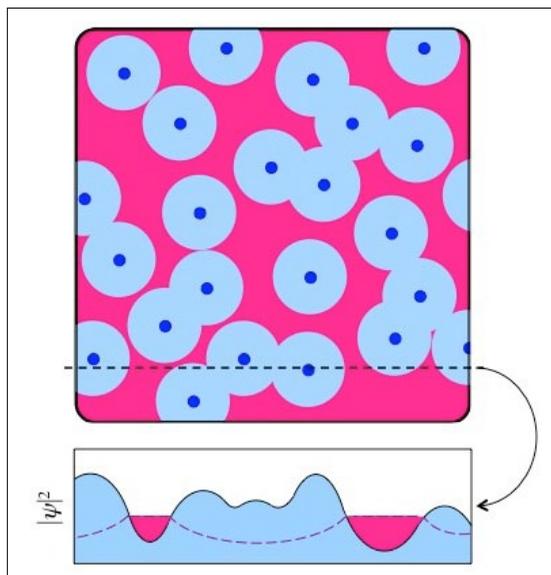


Figure 3: Schematic of the superconducting (SC) phase in $\text{CaFe}_{1-x}\text{Co}_x\text{AsF}$, where the light blue spots represent SC islands around Co ions (blue dots).

Figure 3, the superconducting phase develops in the form of domains or “islands” associated with the cobalt atoms, where each domain has a unique size that is determined by the superconducting coherence length ξ .

Such a form of superconductivity seems to have no counterpart in previously known superconductors, and, therefore, may serve as a highly specific measure to evaluate theoretical models of these superconductors in the year to come.

The Team

Lead: R. Kadono

Members: M. Hirashi, H. Hosono, Y. Kamihara, M.

Miyazaki, T. Takeshita

Partnering Labs/Institutions: KEK-IMSS, TITECH

M1225—Systematic Study of Hole- and Electron-Doped Fe-Based Superconductors with Single Crystals

The recent discovery of the Fe-based layered superconductor has promoted highly intensive research activities. Indeed, superconductivity in $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ occurs even for $x = 1$ [2-4], albeit with T_c much lower ($\sim 3.5\text{K}$) than the optimum ($\sim 38\text{K}$). Competing theories, the multiple fully gapped s_{\pm} -wave Cooper pairing or the nodal-line superconducting symmetry (NSS) scenario have been invoked for the FeAs based systems, whereas in LaFePO the NSS perspective is thought to apply.

MuSR measurements between 2 K and 300 K have been undertaken. For $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ ($x = 0.25$), the temperature dependence of the muon’s relaxation rate, which corresponds to the superconducting gap, is well described by the multiple fully gapped scenario. On the other hand, the impressive observation of a triangular flux-line lattice state in KFe_2As_2 at 2 K suggests the fully gapped scenario, a result inconsistent with the NSS scenario observed by NQR and specific heat.

The work we’ve done in 2008 and 2009 has resulted in many publications; however, more studies are called for. To examine this issue in more detail and understand the mechanism of superconductivity in Fe-based materials, we are planning to perform additional experiments at the temperature down to 20 mK using dilution refrigeration in the next beam time.

The Team

Lead: K. Ohishi

Members: I. Watanabe, Y. Ishii (RIKEN), H. Fukazawa, Y. Kohori, T. Saito (Chiba), K. Yamada, K. Kihou (Tohoku), A. Iyo, C.H. Lee, H. Eisaki, K. Kihou (AIST)

Partnering Labs/Institutions: AIST, Chiba, RIKEN, Tohoku

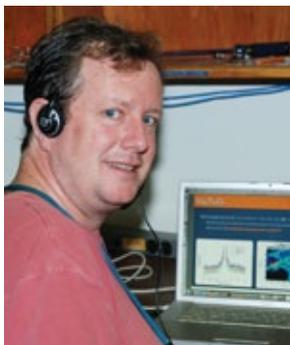
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Molecular and Materials Science

Exotic Magnetism and Quantum Phase Transitions

The study of quantum phase transitions (QPTs) is an emerging theme in current condensed matter physics. These transitions between different ground states at zero temperature as a function of some externally controlled parameter such as pressure, magnetic field, or chemical concentration have received considerable attention. This interest is due to their relevance to high temperature and other exotic forms of superconductivity, as well as unusual finite temperature effects such as non-Fermi liquid behaviour. Categories of systems that are of particular current interest are those that have interactions which are geometrically frustrated and may therefore exhibit so called "spin liquid" ground states. Of course the canonical QPT is that associated with Bose Einstein Condensation (BEC), which in its magnon manifestation is eminently susceptible to MuSR study.

M1079—Spin-Liquid State in the Square-Lattice Antiferromagnet $(\text{CuCl})\text{LaNb}_2\text{O}_7$ and Related Compounds

QPTs occur in the geometrically frustrated square lattice spin system $(\text{CuCl})\text{LaNb}_2\text{O}_7$. In this system, the ratio between the nearest neighbour exchange (J_1) and the diagonal next-nearest neighbour exchange (J_2) can be controlled via chemical substitution or external pressure. Using μSR 's sensitivity to magnetically ordered volume fractions, it is shown that the QPT from a non-magnetic state with a spin gap to a magnetically ordered state is of the first-order type, with phase separation at the phase boundary (see Figure 1).

The Team

Lead: G. M. Luke

Members: Y.J. Uemura and H. Kagayama

Partnering Labs/Institutions: Columbia University, Kyoto University, and McMaster University

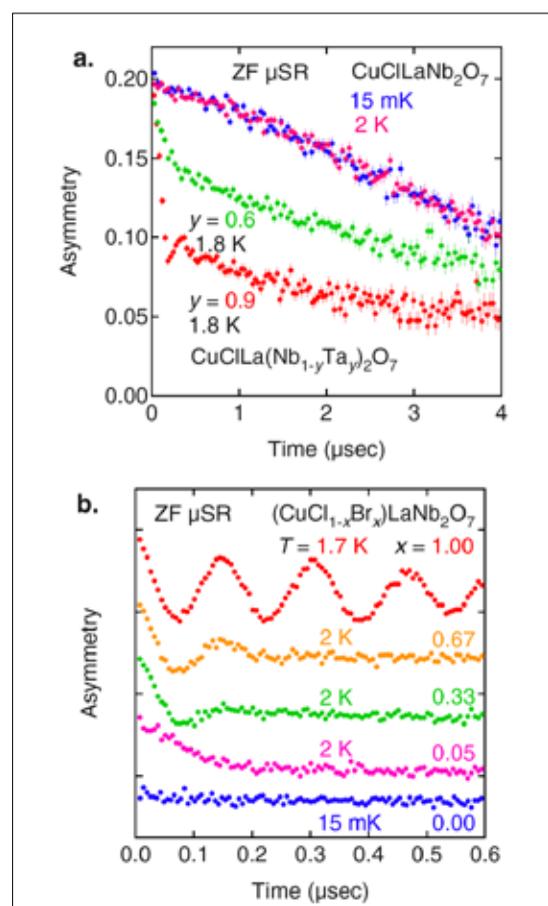


Figure 1: (a) ZF- μSR time spectra in $(\text{CuCl})\text{LaNb}_2\text{O}_7$, demonstrating absence of static magnetism, and in $(\text{CuCl})\text{La}(\text{Nb}_{1-y}\text{Ta}_y)_2\text{O}_7$ showing magnetic order in a partial volume fraction, and (b) ZF- μSR spectra in $(\text{CuCl}_{1-x}\text{Br}_x)\text{LaNb}_2\text{O}_7$ at low temperatures.

M1096—High Pressure μ SR Studies of UGe_2 and M1177—UMGe: Quantum Crossover from Itinerant Ferromagnet to Correlated Paramagnet

The intermetallic compound UGe_2 orders ferromagnetically below approximately 50 K in ambient pressure. Application of hydrostatic pressure results in a reduction of the ordering temperature until a pressure of roughly 15 kbar when ferromagnetism is destroyed in a quantum phase transition to a paramagnetic metallic state. For a range of pressures just less than that needed to destroy ferromagnetism, superconductivity is observed in UGe_2 , apparently within the ferromagnetic state. The combination of high pressure and low temperature make a direct study of the interactions between ferromagnetism and superconductivity difficult. Two related compounds, URhGe and UCoGe, have related structures to that of UGe_2 and order ferromagnetically below 9 K and 2.5 K respectively, then become superconducting at lower temperatures, all at ambient pressure. Work on single crystals grown at McMaster University's Brockhouse Institute for Materials Research has confirmed the presence of ferromagnetism in these materials (see Figure 2).

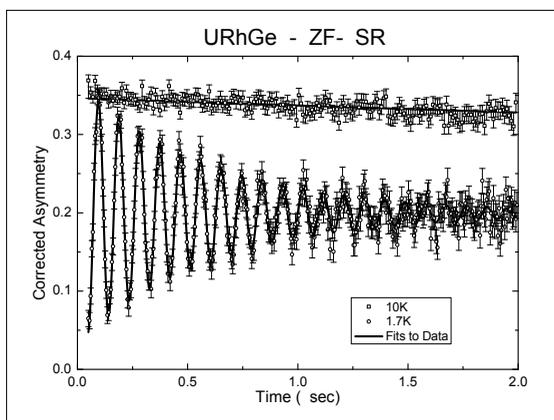


Figure 2: The μ SR relaxation signal at 10.5 K shows no sign of an oscillation, whereas that at 1.8 K clearly shows a precessing polarization which indicates a spontaneous magnetization in this compound.

The Team

Leads: M1096: G.M. Luke; M1177: G.M. Luke
Members: M1096: E. Baggio-Saitovitch, T. Goko, A. Huxley, S.R. Julian, Y.V. Sushko, Y.J. Uemura; M1177: Y.J. Uemura, C.R. Wiebe

Partnering Labs/Institutions: M1096 and M1177: CBPF Rio, Columbia University, McMaster

University, University of Edinburgh, University of Kentucky, and University of Toronto

M1139— μ SR Studies of Magnon Bose Condensation in $Pb_2V_3O_9$

Recently, it has been found that spin systems can enter a state which can be described as a BE condensate of magnons. In zero-field, two spin $\frac{1}{2}$ antiferromagnetically coupled ions have a non-magnetic spin singlet ground state; however, applying an increasing magnetic field lowers the energy of the triplet state until it reaches a crossover point and becomes the ground state. The presence of further neighbour interactions gives a band of triplet excitations that cause the formation of a “crossover” band, and the magnetic Hamiltonian of the system can be mapped onto that of interacting bosons with a Bose Einstein

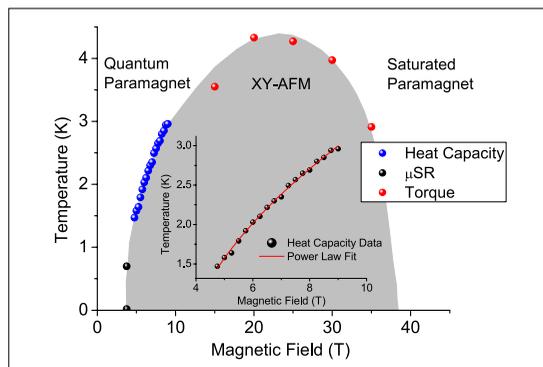


Figure 3: μ SR studies of Magnon Bose Condensation in $Pb_2V_3O_9$.

Condensation (BEC) ground state. In the spin system, the BEC manifests itself as a magnetically ordered state, but most of these BEC of magnon states occur at fields far above the current mSR capabilities, except in the $Pb_2V_3O_9$ material (see Figure 3). As such, high transverse field mSR measurements of single crystals of $Pb_2V_3O_9$ have been carried out. The data, via the direct observation of the magnon signature, has been combined with high field torque magnetometry and heat capacity measurements to determine the magnetic phase diagram of $Pb_2V_3O_9$.

The Team

Lead: C.R. Wiebe
Members: I.A. Afflek, G.M. Luke, Y.J. Uemura, K. Yoshimura

Partnering Labs/Institutions: Columbia University, Florida State University, Kyoto University, McMaster University, and University of British Columbia



Jun Sugiyama is a research scientist at Toyota Motor Company's Central R&D Laboratories in Japan.

Molecular and Materials Science

Industrial Research for Automobile Batteries and Energy Storage

The world is facing a “paradigm shift” regarding the power source for automobiles, from a fossil powered internal combustion engine to an electric motor using batteries and/or fuel cells. In order to achieve the shift smoothly and quickly, several huge technological barriers need be overcome, mainly by the development of new materials for the components of batteries, fuel cells, and electric motors. μ SR techniques extract unique information on materials and provide oracles for the guiding principles related to new materials development.

M1049—Spin State Transition in $RECoO_3$ ($RE=La, Pr, Nd$ and Sm)

M1049 seeks to clarify the spin-state transition temperature of the well-known perovskite-type compounds $RECoO_3$ ($RE= La, Pr, and Nd$). The spin state of the Co ions in $LaCoO_3$ is known to vary with temperature from a low- T to a high- T high state via an intermediate spin state. As a result, $LaCoO_3$ is insulating at low- T , but metallic at high- T . Because the metallic behaviour is significant for an electrode material, it is pertinent to study the spin-state dynamics of the Co ions in the related materials. Although the spin-state transition for $LaCoO_3$ is well investigated by several conventional techniques, using such methods for the other (rare earth) $RE CoO_3$ is very difficult due to large magnetic moments of the RE ions. Combining the muonic Knight shift obtained in a high transverse field (TF) with the dc-susceptibility data, the spin-state transition temperature (T_{SS}) was measured and found to increase monotonically as the average ionic radius of the RE ion is decreased. Our measurements demonstrate that TF- μ SR is a unique technique to detect the spin-state transition in compounds with large 4f moments through the change in microscopic magnetic environments at T_{SS} [1].

To further elucidate the change in T_{SS} with the ionic size, high-pressure TF-spectrum measurements are planned for 2010.

M1161—Complex Phase Diagram of $Ca_{1-x}Na_xV_2O_4$

The goal of M1161 in 2008 and 2009 was to elucidate the magnetic phase diagram of the solid solution $Ca_{1-x}Na_xV_2O_4$ with $0 \leq x \leq 1$. In the $Ca_{1-x}Na_xV_2O_4$ crystal lattice, the V_2O_4 double-chains, which are formed by a network of edge-sharing VO_6 octahedra, align along the b -axis to make an irregular hexagonal one-dimensional (1D) channel. Because the Ca/Na ions locate at the centre of the 1D channel, this compound has potential technological applications as a solid-state ionic electrolyte for future batteries. Recent work indicates that μ SR is an optimal technique to determine the diffusion coefficient of Li for such materials, including magnetic ions [2].

Prior to embarking on the Na-diffusion measurements at high T , their low- T magnetic nature was measured down to 1.8 K. Static antiferromagnetic (AF) order is observed for the metallic compounds with $x \geq 9.3/12$ as well as for NaV_2O_4 and insulating CaV_2O_4 . A variety of phases were also found to appear as a function of x and/or temperature (see Figure 1a). Employing a precise analysis of the zero-field μ SR spectrum at ambient pressures, the pressure dependence of the static AF order suggests a temperature dependent rearrangement of spin order on the V_2O_4 chain in the metallic compounds [3]. These findings naturally lead to the question of the ground state and ionic diffusion for the related compounds. Continued work on an expanded range of target materials— $CaFeO_2$ -type $NaMn_2O_4$, $LiMn_2O_4$ and hollandite-type $K_2V_8O_{16}$ and $Rb_2V_8O_{16}$ —is the focus of a new proposal (M1184).

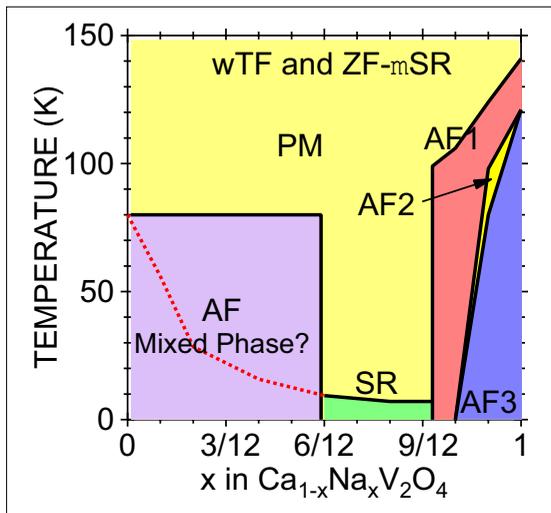


Figure 1a: The phase diagram determined by both wTF- and zero-field (zf-) μ SR. PM means paramagnetic phase, AF and AF₁ static antiferromagnetic ordered phases, and SR short-range AF ordered phase. A red broken line represents the T at which the normalized weak TF asymmetry is 0.5.

M1175—Search for H- μ -H bond in Hydrogen Storage Materials

The nature of the “hydrogen bond” between μ^+ and anions has been heavily investigated since the discovery of F- μ -F in fluoride crystals, such as LiF, NaF, CaF₂, and BaF₂. F- μ -F systems are also found in organic polymers, like Teflon and Nafion, and it has been concluded that F- μ -F configurations are ubiquitous μ SR phenomena in compounds containing F ions. This circumstance suggests that similar hydrogen-bond systems occur with other anions.

In 2008–2009, during the search for high-capacity hydrogen storage systems, we investigated the thermodynamic properties of borohydrides [M(BH₄)_n]. Experimental data have been acquired for five different powder samples below ambient temperature. Zero-field μ SR measurements indicate the formation of the H- μ -H system in LiBH₄, NaBH₄, KBH₄ and Ca(BH₄)₂, but not in Mg(BH₄)₂. The data indicates that the amplitude of the H μ H signal ($A_{H\mu H}$) varies with the electronegativity (χ_p) of Mⁿ⁺ (see Figure 1b). This happens because, when χ_p of Mⁿ⁺ is small, [BH₄]⁻ will be more negative and result in increased electron density around the H⁻ ions and the concomitant increase in $A_{H\mu H}$. Since the thermodynamic stability of M(BH₄)_n also depends on χ_p , $A_{H\mu H}$ is thought to be a microscopic indicator for the stability of M(BH₄)_n [4]. To observe the hydrogen-desorption reaction in M(BH₄)_n and related materials, we need to maintain them in

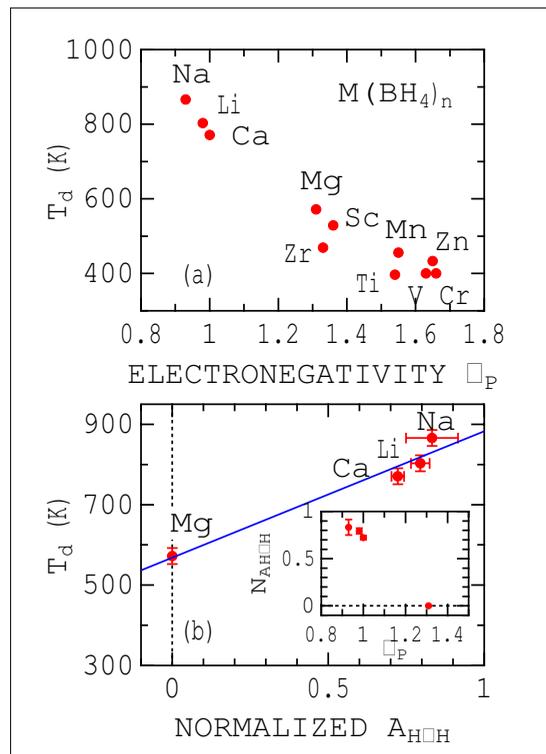


Figure 1b: The relationship between (a) hydrogen desorption temperature (T_d) and electronegativity (χ_p); and (b) T_d and Normalized $A_{H\mu H}$. The inset of (b) shows the relationship between normalized $A_{H\mu H}$ and χ_p .

the vicinity of their desorption temperature (T_d). In 2010, we plan to make such high- T measurements using a specialized high-pressure cell that can control the desorption reaction.

The Team

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Partnering Labs/Institutions: KEK, PSI, Toyota Central R & D Laboratories, Inc., TRIUMF, University of Alberta, and University of British Columbia

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Molecular and Materials Science

Green, Materials Design and Physical Chemistry

Flem's chemical reaction rates lie at the heart of many research interests, not only in the field of chemistry itself, but in related pursuits in biology and biochemistry and in chemical engineering, at both the university and industrial levels. Many of these reactions involve complex mechanisms of many reaction steps and to help understand the complex dance that nature has choreographed, it is important to study key elementary steps in these mechanisms. In these endeavours, comparisons between theory and experiment play a vital role.

M1051—Mu and Muoniated Free Radical Formation and Reactivity in Ionic Liquids

Ionic liquids have opened up new perspectives for use as extraordinary solvents in some areas of chemistry. In 2008–2009, this work contributed to an understanding of free radical reactions as well as intermolecular interactions and dynamics in ionic liquids (see Figure 1). In particular, we have demonstrated that the free radical formation is significantly enhanced in ionic liquids (IL) as compared to molecular solvents [1].

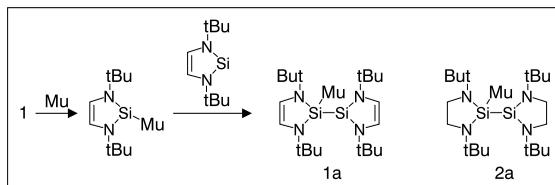


Figure 1: Green chemistry: enhanced free radical formation in phosphonium ionic liquid is clear and dramatic.

This understanding prompted additional studies on the comparison of reaction kinetics of transient intermediates with different IL solutes. As well, it has opened the field of radiation chemistry

in phosphonium ionic liquids, a prelude to the understanding of IL reaction dynamics that are important for the development of applications in radioactive materials processing within the industry of nuclear energy production.

In 2010 and beyond, a future effort on kinetics in ionic liquids, as well as intermolecular interaction in ionic liquids, will provide information on the intermolecular interactions between CO_2 and ionic liquids as well as its reaction kinetics in ionic liquids. These will have implications in CO_2 capture, using ionic liquids, and in the field of free radical polymerization in ionic liquids.

The Team

Lead: K. Ghandi

Members: C. Alcorn, J. Clyburne, P. Cormier, R. Robski

Partnering Labs/Institutions: Mount Allison University and Saint Mary's University

M1172—Muoniated Radicals Formed from Unsaturated Silicon, Germanium and Tin Compounds

The reporting period, 2008–saw continuing work on M945 (muonium addition to carbenes). We investigated the chemistry of radicals derived from unsaturated silicon, germanium, and, in particular, tin compounds because of their trend to form coupling products. MuSR spectroscopy is a new method for studying organometallic radicals, giving important structural and chemical bonding information which, at present, cannot be studied by any other methods. To date, MuSR spectra have been observed for divalent compounds of Si and Ge (silylenes and germlyenes) as well as a compound containing a $\text{Si}=\text{C}$ double bond.

For the silylenes, the muon hfcs measured are 235 and 155 MHz, which are far lower than the values predicted for these species by DFT (density functional) calculations. To explain this discrepancy, we proposed that the initially formed silylene-Mu adducts react with other silylene molecules to produce the muoniated disilanyl radicals (see Figure 2). Additionally, the primary radical adduct between a silylene and muonium

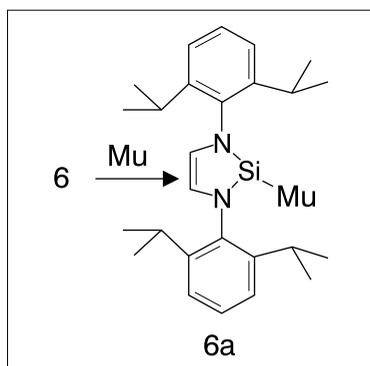


Figure 2: Scheme 1: Coupling of muoniated radical with silylene.

has been detected for the first time and confirmed using LCR (level crossing resonance) with the ^{14}N . This was made possible by introducing bulky substituents close to silicon and thereby preventing the conversion of the primary radical into the secondary disilanyl.

In 2010, further work will measure the reaction rates when other substituents at different positions of the silaimidazole ring are used. Ultimately, we plan to study many other unsaturated compounds, first within the group 14 elements, and later for many other main group and transition metal organometallic compounds.

The Team

Leads: P. Percival and R. West

Members: J.-C. Brodovitch, A. Mitra, B. McCollum

Partnering Labs/Institutions: Mount Royal University, Saint Mary's University, Simon Fraser University, University of Wisconsin

M1131 and 1268—Reactions in Supercritical CO_2

Supercritical carbon dioxide is considered a “green solvent,” and understanding the free radical chemistry in supercritical CO_2 can help to design new environmentally friendly processes to produce chemical compounds and polymers.

In 2008–2009, these experiments reported the first, and to date the only, detection of any reactive free radical by any technique in supercritical carbon dioxide [2]. The results of this work also imply that hydrogen atoms react with alkenes in a broad range of thermodynamic conditions, which is a first step of their polymerization. We also observed how slight changes in the temperature or pressure of the supercritical CO_2 allow the free radical reactivity to be “tuned,” which in turn provides a means to control such reactions.

Finally, it has been suggested that reaction with alkyl radicals might be used as a method of CO_2 capture [3]. This work concludes that for supercritical water at < 400 bar and < 100C such reactions could not be used for this purpose.

The Team

Leads: K. Ghandi and D. Arseneau

Members: M1131: J.-C. Brodovitch, J. Clyburne, B. McCollum, A. Mitra, P.W. Percival, R. West; M1268: J.-C. Brodovitch, J. Clyburne, P. Cormier, B. McCollum, A. Mitra, P.W. Percival, R. West

Partnering Labs/Universities: M1131 and M1268: Saint Mary's University, Simon Fraser University, and the University of Wisconsin

M931—Polymer Materials Design

Metal-cyanide coordination polymers, particularly those based on the dicyanoaurate(I) and tetracyanoaurate(III) building blocks, have a wide variety of potential applications as vapochromic or magnetic sensors, birefringent components and negative thermal expansion materials.

A new series of isostructural polymers of the form $\text{M}(\mu\text{-OH}_2)_2[\text{Au}(\text{CN})_2]_2$ ($\text{M} = \text{Cu}, \text{Ni}, \text{Co}, \text{Fe}, \text{Mn}$), incorporating the cyanometallate unique motif of the aqua-bridged chain $\text{M}(\mu\text{-OH}_2)_2\text{M}$, has been synthesized. Such motifs determine the physical properties of the material, and mSR used in conjunction with SQUID magnetometry can study how their magnetic properties change as a function of transition-metal magnetic moment.

The Cu/Ni/Co systems all show ferromagnetic coupling; the Cu(II) system orders at 200 mK, and the Ni(II) and Co(II) systems form a spin-glass state in zero-field at low temperatures, as do the antiferromagnetically coupled Fe(II), Fe(III) and Mn(II) systems. These data indicate that the one-atom aqua-oxygen bridge between metals and the interchain hydrogen bonding, via the hydrogen

atoms of the bound water, plays a key role in mediating magnetic exchange [4]. Additional μ SR work on the analogous $M(\text{H}_2\text{O})_4[\text{Au}(\text{CN})_4]_2 \cdot 4(\text{H}_2\text{O})$ ($M=\text{Mn}, \text{Co}, \text{Ni}$) and the partially dehydrated $\text{Cu}(\text{II})$, has been carried out to clarify their magnetic phase behaviours, with the latter exhibiting ordering. Also, given that the hydrogen-bonding in the $M(\mu\text{-OH}_2)_2[\text{Au}(\text{CN})_2]_2$ systems are critical factors in the observed magnetic behaviour, the dehydrated anhydrous analogues, of the form $M[\text{Au}(\text{CN})_2]_2$, have also been measured.

The data examined to date suggest that completely different magnetic behaviour compared to the hydrated analogues has been observed. Such combined studies are critical to furthering our understanding of magnetic interactions and ordering in these molecule-based magnetic materials, a future step towards designing coordination polymers with useful magnetism-based applications.

The Team

Lead: D. Leznoff

Fundamental Reactions

M1097—The $\text{He}4_\mu$ Atom and a Study of the $\text{He}4_\mu + \text{H}_2$ Reaction

The simplest reaction is the $\text{H} + \text{H}_2$ “exchange reaction.” The effect of isotopic mass on this reaction, a field of study known as “kinetic isotope effects” (KIEs), has had a long history since the discovery of deuterium (D) by Harold Urey in 1932, most recently exemplified by a detailed comparison of experiment with accurate theory for the $\text{H} + \text{D}_2$ and $\text{D} + \text{H}_2$ reactions. However, H and D atoms differ by only a factor of 2 in mass. Because of its radioactivity tritium, despite its mass of 3 amu, has not found widespread use beyond studies of its “hot atom” reactivity [5]. So it has fallen to nuclear science and in particular muon science to extend the H-atom isotopic mass scale. The lightest H atom is muonium ($\text{Mu}=\mu^+e^-$, mass 0.114 amu). The goal of M1097 was to extend the range of isotopic mass to the heaviest H atom, neutral muonic He, $\text{He}4_\mu$ (4.11 amu), in a first-ever measurement of its chemical reactivity, the $\text{He}4_\mu + \text{H}_2 \rightarrow \text{He}4_\mu\text{H} + \text{H}$ reaction. Comparisons with Mu then allow for an unprecedented range of KIEs, a factor of 36 in isotopic mass.

In 2008–2009, three different calculations were carried out (see Figure 3) on the highly accurate

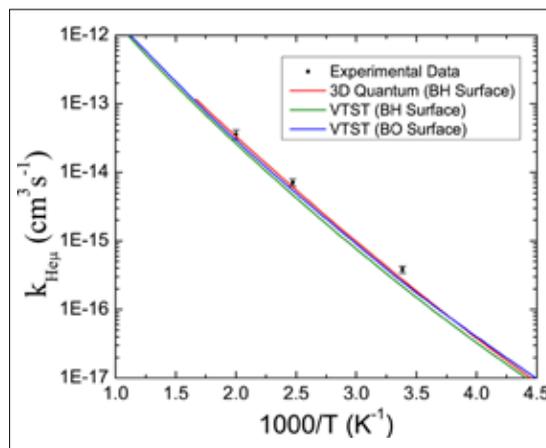


Figure 3: Arrhenius plot of the thermal rate constants for the $\text{He}4_\mu + \text{H}_2$ reaction at 295, 405 and 500 K. The solid lines shown are from theoretical calculations on the highly accurate “CCI/BH” potential surface: 3D quantum scattering calculations (red line) and VTST calculations on both the BH (green line) and Born Oppenheimer (blue line) surface.

complete configuration reaction (CCI) surface [6]. The most accurate are expected to be the 3D quantum rates on the Born-Huang (BH) surface, which include mass corrections to the Born-Oppenheimer (BO) surface (red line). Variational transition state theory (VTST) calculations were also carried out on the BH surface (green line) and on the BO surface (blue line).

The fully quantum calculations agree well with experiment at the two highest temperatures but, interestingly, fall noticeably below at 295 K. In contrast, the VTST calculations fall well below experiment at all temperatures (note the log scale) and particularly on the BH surface, pointing to an inherent failing in these calculations. Not shown is the comparison with $\text{Mu} + \text{H}_2$ [7], which is four orders of magnitude slower at 295 K, in contrast to $\text{D} + \text{H}_2$, which has the same rate constant [6].

Muonic helium is formed by negative muon capture on helium, which then undergoes charge exchange with dopant NH_3 to produce the neutral atom. In order to minimize competitive μ^- capture on the H_2 reactant, high He pressures and hence backward μ^- beams on the M9 beam line were required. Preliminary studies of the $\text{He}4_\mu + \text{H}_2$ rate at 295 K were reported [8], from beam time in spring 2008.

Additional data were taken in the fall of 2008 and in the spring of 2009, at 295 K and at 405 K and

500 K, allowing us to complete this experiment. A summary of the results is shown in the Arrhenius plot in Figure 3 above, comparing them with theory [6,8].

A joint publication is being submitted to the Journal of Chemical Physics.

The Team

Lead: D.G. Fleming

Members: D.J. Arseneau, J.H. Brewer, O. Sukhorukov

Partnering Labs/Institutions: University of Alberta and University of British Columbia

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Molecular and Materials Science

Semiconductors and Spintronics

M938, M1088, M1199, M1221, M1222, M1253, and M1254—Muons, Magnetic Polarons and Spintronics

Semiconductor electronics has so far been based on the transport of charge, while storage of information has mainly relied upon magnetism (the collective interactions of spins). A new discipline known as spintronics proposes to exploit the strong mutual influence of magnetic and electrical properties, which promises new types of devices and computer technologies.

One mechanism for such phenomena involves the concept of magnetic polarons (MP)—microscopic clouds of magnetization, each composed of a single charge carrier strongly coupling its neighbouring magnetic ions through an exchange interaction. MPs determine many of the electrical, magnetic, and optical properties of some materials. In spite of the importance of this quasiparticle, it has eluded direct observation until now.

In 2008–2009, these experiments utilized the positive muon as both a donor centre and/or a local magnetic probe to respectively generate and detect the MP. Specifically, once embedded in an MP, the muon's hyperfine (HF) interaction with the localized electron results in a splitting into two precession frequencies analogous to those of muonium ($\text{Mu} = \mu^+e^-$) [1,2] that lead to the determination of the HF coupling, the spin, and ultimately the size of the MP. Studies have been carried out in several magnetic semiconductors as well as in other materials where the MP's presence was hitherto unrecognized.

Magnetic Polarons in Magnetic Semiconductors

An electron in the conduction band is normally a free carrier and contributes to the conductivity of the medium. Localizing such an electron reduces this contribution but raises its kinetic energy and

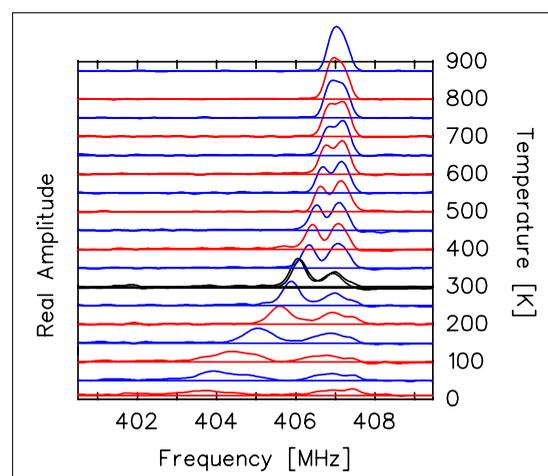


Figure 1: Temperature dependence of the frequency spectrum of the MP in the magnetic semiconductor SmS in a transverse magnetic field (TF) of $H=3$ T, showing that the hyperfine splitting between the two muonium-like lines increases with decreasing T (and increasing H) until it levels off below about 150 K.

is therefore unlikely unless some local interaction lowers its energy at least as much. A familiar example is the attractive Coulomb potential of a positive donor ion. A less obvious example is the decrease of the electron-mediated exchange energy when a number of magnetic ions with weak direct coupling experience a strong indirect ferromagnetic (FM) coupling. This interaction increases with the local electron density, so it favours localization and can be sufficient to

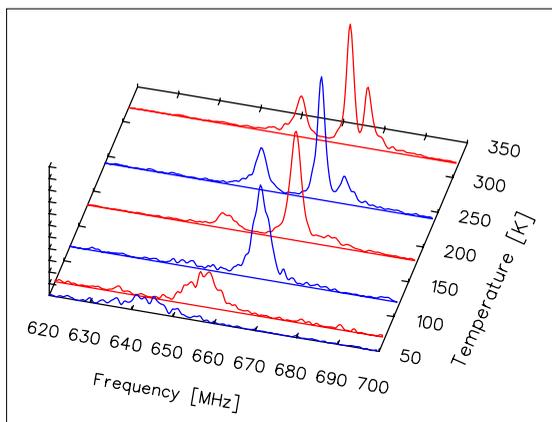


Figure 2a: Temperature dependence of the frequency spectrum of the MP in the magnetic semiconductor EuS in a TF of $H=5$ T. Again, the MP hyperfine splitting increases with decreasing T until the Curie temperature of EuS, below which the binding effect of the FM exchange interaction is lost and the MP disappears.

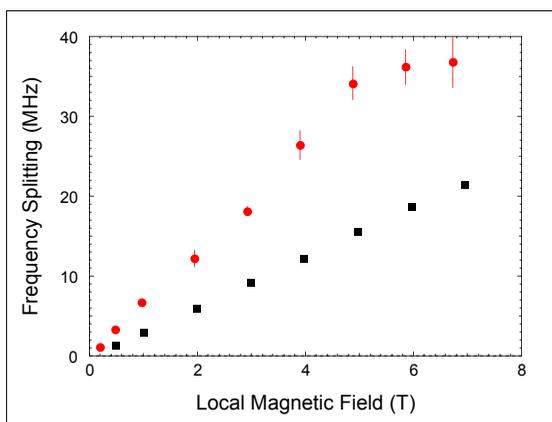


Figure 2b: Magnetic field dependence of the MP hyperfine splitting in EuS at $T=300$ K (black squares), where it increases linearly with field H , and at $T=90$ K (red circles) where it saturates above 5T at $A=37 \pm 3$ MHz, telling us that the MP has a spin $S=36 \pm 4$ and a radius $R \approx 0.3$ nm at 90 K.

autolocalize an electron into an FM “droplet” on the scale of the lattice spacing in an antiferromagnetic (AFM) or paramagnetic (PM) “sea”. This metastable quasiparticle is called a magnetic polaron (MP) and despite its obvious fundamental interest, all experimental evidence for its existence prior to this work have been indirect because “ q -space” techniques, such as neutron scattering, normally detect atomic-scale entities only when they are arranged into a periodic lattice. Small, randomly dispersed MP are invisible to such tools, but they can be positively identified by a local magnetic probe: i.e., the μ^+ .

Spin Polarons in Magnetically Frustrated Metals

Frustrated magnetic systems and their associated spin fluctuation dynamics have been the focus of extensive research for many years. Disorder, competing antiferromagnetic (AF) interactions, and certain lattice symmetries sometimes create situations in which the system energy of the spins has no unique minimizing configuration. This so-called frustration promotes exotic electronic and magnetic behaviour by preventing the formation of a conventional ordered state down to very low temperatures. Recently there has been growing interest in the interplay between itinerant and local moments in geometrically frustrated $5d$ transition metal $A_2B_2O_7$ systems, which are typically metallic because the $5d$ orbitals are much less localized than $3d/4d$ electrons. Indeed, the interaction between these itinerant carriers and the local electrons is believed to be the cause of the unique electronic and magnetic properties of such $5d$ pyrochlores.

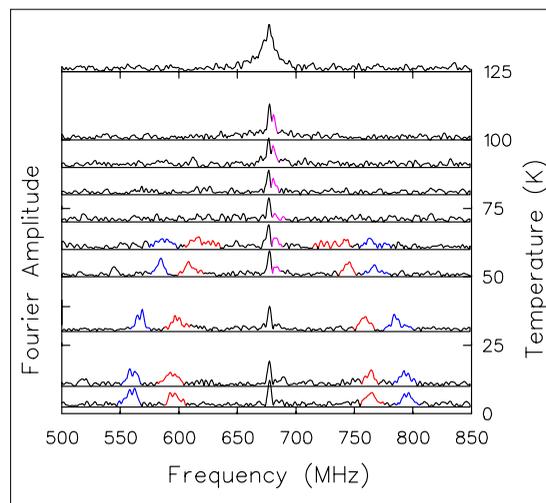


Figure 3a: Temperature dependence of the μ SR frequency spectrum in $Cd_2Re_2O_7$, at 5 T. At low T two sets of SP lines are observed with splittings independent of field above about 1 T, corresponding to an SP with a characteristic radius of about 0.15 nm. Above about 60 K, this state gives way to a larger, weaker SP with a radius of about 0.5 nm, similar to those seen in magnetic semiconductors.

Such a material is $Cd_2Re_2O_7$, which undergoes a metal-insulator transition (MIT) to become a “better” metal with no well-defined magnetic order when cooled down below 200 K. The high-temperature phase is described in terms of a “moderately correlated metal” with a carrier mean free path on the order of the atomic spacing.

Our μ SR data on this material yield specific spectroscopic evidence for electron confinement into spin polarons (SP).

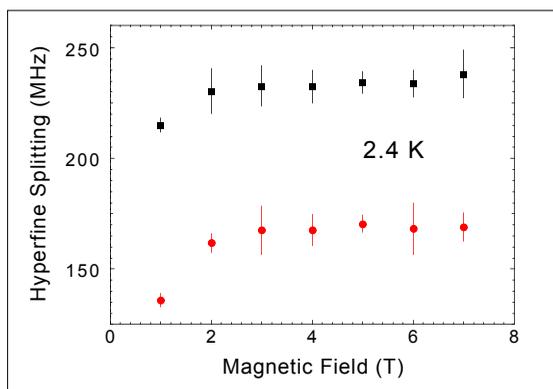


Figure 3b: T Magnetic field dependence of SP splittings in $\text{Cd}_2\text{Re}_2\text{O}_7$, at $T=2.4$ K. Note that the splitting saturates at relatively low field, unlike in magnetic semiconductors.

These measurements constitute the first direct observation of muonium-like states in a good metal. It is made possible by the double virtue that, within the bound SP state created by the exchange interaction, the muon itself can “fall” into

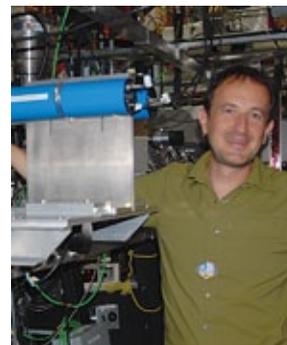
a muonium-like bound state whose relaxation rate and lifetime are prolonged by the SP’s suppression of the “spin-flipping” and Coulomb-shielding behaviour of the normal metal conduction electrons. The muon is therefore only an observer; the SP must be present before the muon arrives, as originally predicted by de Gennes in 1960 [3].

Given the current understanding that the MP/SP is present (and can be directly observed via HTF- μ SR) in a wide variety of magnetically frustrated, disordered or AF materials, these experiments seek to widen their scope to see how many different phenomena might yield to the explanatory potential of magnetic polarons. Heavy fermion (HF) metals (the MP is, in effect, an HF) as well as other types of highly correlated electron (HCE) systems, such as the magnetic parent compounds of high temperature superconductors (HTSC) and other materials, are of great current interest. Preliminary results are already very promising.

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Andrew MacFarlane is a professor of chemistry at the University of British Columbia and leader in the field of β -NMR.



Molecular and Materials Science

Studying Interface Layers with β -NMR

All electronic, magnetic, and structural properties of a material are altered near an interface between two materials, and such alterations can persist over the (atomically large) length scales of nanometers to microns. In the world of shrinking electronic devices, the role of such interfaces becomes ever more significant; famously illustrated by the unanticipated discovery of the giant magneto resistance (GMR) phenomena and its subsequent revolutionary impact on modern information technology. Experimental techniques to extract depth-resolved information across such boundary layers are very sparse, and to that end TRIUMF's variable energy, high luminosity, spin-polarized ^8Li beam provides a unique resource to conduct detailed magnetic resonance studies in the vicinity of such interfaces. The technique is called beta-detected nuclear magnetic resonance, or simply, β -NMR.

In 2009, and looking forward to 2010, two basic themes will be actively pursued: M1153 will delve into the study of the normal metal—superconductor interface, and M1176 will focus on the non-equilibrium spin distributions resulting from the injection of polarized electrons into an $\text{EuO}_{1-x}/\text{Si}$ bi-layer film.

M1153—Microscopic Investigations by β -NMR of Proximity Effects in Metal Superconductor Bilayers

Although this experiment examined the Ag/Nb interface in 2008–2009, related earlier work, M1041 on pure Nb [1] proximal and vortex disorder effects [1,2], predated it. Fundamentally, M1153 explores the properties of superconductor (S) normal metal (N) interface. The reciprocal influence of the two metals is characterized by the respective appearance and weakening of

the superconductivity in N and S [3]. This proximity effect is characterized by spatially varying properties, i.e., in the density of states, superfluid density, and supercurrents, and thus is clearly related to the underlying variations in the superconducting order parameter.

Measurements have been performed on several AgNb bilayers with Ag thickness between 30 nm and 120 nm. The Nb thickness in all cases was sufficient so that the $\sim 9.1\text{K}$ T_c of the Nb is close to the bulk value. Figure 1a shows the observed β -NMR resonance curves at 20G of ^8Li in the Ag overlayer. Below the critical temperature of the bilayer, the resonance is diamagnetically shifted, reflecting the presence of induced superfluid density and supercurrents in the otherwise normal metal Ag. The main focus of M1153, however, is to study the spin relaxation which originates from the fluctuating superconducting order parameter. These fluctuations occur on a time scale too short to be observed with low-energy- μSR , so β -NMR is

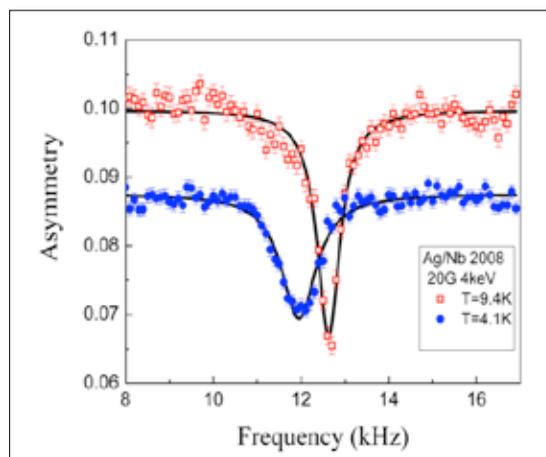


Figure 1a: Resonance from ^8Li in Ag above and below the critical temperature T_c of the Ag(40nm)/Nb(270nm) bilayer.

essential for this measurement. Figure 1b shows a dramatic peak in the observed spin relaxation rate of ^8Li in the Ag overlayer, which is attributed to a critical slowing down of the induced superconducting order parameter.

These measurements are the first direct use of NMR relaxation to detect such order parameter fluctuations and will, no doubt, lead to future studies.

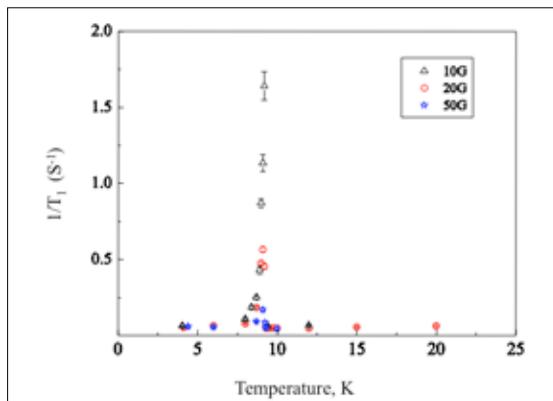


Figure 1b: The $1/T_1$ relaxation rate as a function of temperature in an Ag(40nm)/Nb(270 nm) bilayer.

The Team

Lead: E. Morenzoni

Members: K.H. Chow, R. Kiefl, W.A. MacFarlane

Partnering Labs/Institutions: PSI, University of British Columbia, and the University of Alberta

M1176— ^8Li Investigation of Spin Transport through Ferromagnet-Semiconductor

M1176 investigates a semiconductor/ferromagnet interface to gain an understanding of the means to manipulate electron spins and transport them within a heterostructure [4,5]. Such capabilities are required in the quest to combine the information processing power of semiconductor devices with the data storage capabilities of magnetic structures, thereby addressing a “Holy Grail” of current spintronics research, i.e., the controlled injection of polarized spins from a magnetic overlayer into a semiconductor. The specific goal of M1176 is to make use of depth-resolved β -NMR to investigate the model heterostructure $\text{EuO}_{1-x}/\text{Si}$.

EuO is a rare example of a ferromagnetic semiconductor, where strong indirect exchange interactions between the localised Eu^{2+} ions are mediated by charge carriers. Below its Curie temperature, EuO has only one occupied majority spin band and hence is a source of

spin-polarized electrons which can be injected into the semiconducting Si substrate. MBE procedures are now able to produce high quality impedance matched thin films of EuO_{1-x} ($x < 0.1\%$) on n-type (001) doped Si substrates and β -NMR measurements on a relevant heterostructure (5 nm Ti / 10 nm amorphous Si / 30 nm EuO_{1-x} / 0.516 nm SrO / n-type (As) Si (001)) are herein reported [4].

Stopping distribution simulations determine that a 28 keV ^8Li implantation energy yields an implantation depth of 170 nm with 70 nm range straggling, well inside the doped Si substrate. With the magnetic field parallel to the heterostructure surface and the easy axis, a single sharp resonance line comparable to that of intrinsic silicon is observed at high temperatures. Lowering the temperature below the EuO_{1-x} ordering transition $T_c = 69$ K results in a dramatic 25-fold increase in the linewidth (see Figure 1c). Below 70 K, the increase tracks the bulk magnetization (or order parameter) of the EuO_{1-x} . Understanding the increase in the linewidth at low temperatures within the Si substrate is essential. It could be due to a distribution of Fermi contact interactions with polarized electrons or, alternatively, dipolar fields from the Eu moments. In general, any source nonuniformly magnetised layers, i.e., from magnetic domain formation, grain boundaries, or interface roughness, would cause a strongly depth-dependent line broadening in an adjacent layer.

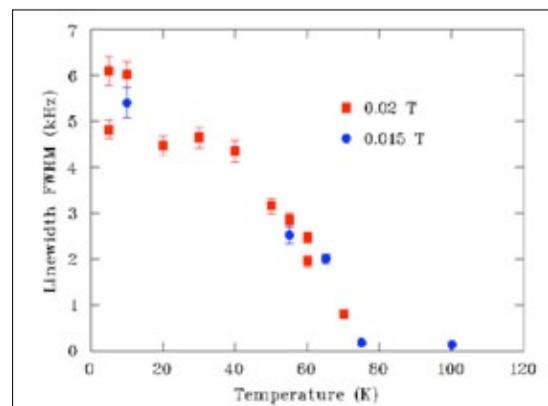


Figure 1c: Variation of resonance linewidth in the doped Si layer of a $\text{EuO}_{1-x}/\text{Si}$ heterostructure as a function of temperature.

To help sort out these potential effects, the future experimental arsenal will be augmented with a capability to apply an electric potential across the heterostructure, giving the experiment a tuneable means to control and hence detect the presence of polarized spin injection into the Si semiconductor.

The Team

Leads: S. Dunsiger and G.D. Morris

Members: P. Boeni, K.H. Chow, R. Kiefl, W.A. MacFarlane, J. Mannhart, E. Morenzoni, D.G. Schlom, A. Schmehl

Partnering Labs/Institutions: Augsburg University, Cornell University, PSI, TU Munich, University of Alberta, University of British Columbia.

M1198—Research for Nuclear Reactors

The Canadian National Program on Generation IV Energy Technologies is a program of research and development established to fulfill Canada's commitment to the Generation IV International Forum (GIF). The GIF nations have agreed to collaborate on development of "next generation" nuclear power systems, and Canada has committed to work on the Supercritical-Water-Cooled Reactor (SCWR). Atomic Energy of Canada Limited (AECL) specializes in pressurized water-cooled nuclear reactors (PWRs), but their existing fleet of CANDU and MAPLE reactors operate at lower temperatures than a SCWR. Thus, a major technology gap exists, and among the needs identified is research on materials, corrosion, radiolysis, and water chemistry under supercritical conditions.

M1198 and its principals have specifically received funding for the latter area, i.e., to conduct studies of muonium kinetics in supercritical aqueous solutions, gather information concerning water radiolysis transient products, and thereby provide kinetic data which can be used to test relevant models for reactions in SCWRs. This research effort builds on the previous work of Mu in aqueous solutions, which clearly delineates markedly non-Arrhenius kinetics insofar as the rate constant goes through an extremum as the water conditions approach the critical point [6].

Recent studies using D₂O solutions show reaction rates that differ remarkably from their light water analogues. Should these data be confirmed, developing an understanding of the underlying causes will become an important aspect of the work. Also, similar to the earlier studies, it is again verified that extrapolating low-temperature data in the vicinity of the solvent triple point will lead to fundamentally incorrect values concerning the relevant reaction rates.

Collaborative discussions with AECL personnel and other groups involved in the GIF project

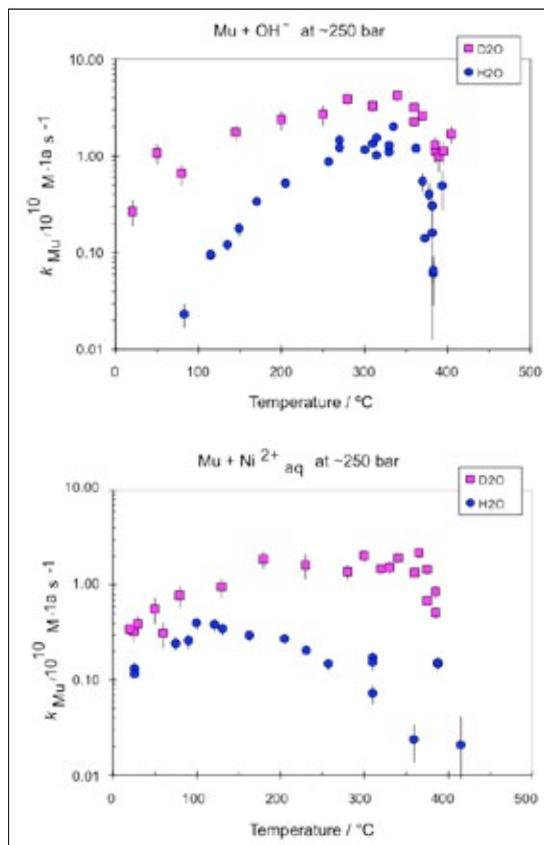


Figure 1a,b: Preliminary reaction rate constants of Mu in heavy water.

have concluded that the 300–450°C range is of particular interest, and to that end, future plans include kinetic studies of Mu reactions with ammonia, oxygen, and hydrogen in aqueous solutions within this temperature range.

Since current knowledge about the kinetics of aqueous reactions in the temperature range 300–650°C is so sparse, almost any new data will be valuable in focusing the issues.

The Team

Leads: P. Percival, K. Ghandi

Member: J.-C. Brodovitch

Partnering Labs/Institutions: Mount Allison University, Simon Fraser University

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Additional authors: Mike Adam, Jean-Michel Poutissou

Nuclear Medicine

Overview of Nuclear Medicine

Changes to Support Growth

The year 2007 saw the operation of the TR13 cyclotron move to the Accelerator Division where the TR13 would receive better operational support. Then, in 2008, the Life Sciences Program moved from the Science Division to its own Nuclear Medicine Division to create a structure which will better allow the nuclear medicine program to grow and diversify by reaching out to the oncology community at the British Columbia Cancer Agency (BCCA) and to link to industrial partners like MDS Nordion, Inc. The main scientific activity will remain centered on neurology through the Pacific Parkinson's Research Centre (PPRC) headed by Dr. J. Stoessl. The strengthening of that operation was accomplished at the University of British Columbia (UBC) via the creation of the PET Imaging Centre with Dr. V. Sossi at its head.

Facility Improvements

The Division's priority in 2008–2009 was to consolidate the core program by strengthening the infrastructure and personnel that will support the radiochemistry activities delivering routine tracers to TRIUMF's partners. The cyclotron enclosure and targetry work were spearheaded by C. Hoehr and the lab upgrade was guided by P. Schaffer. The effort, which was coordinated by Dr. M. Adam, involved enclosing the TR13 cyclotron in a separately controlled environment, refurbishing and improving the $^{11}\text{CH}_4$ production target and chemistry unit, and replacing the ECAT scanner with a GE Advance one. Upgrades of one radiochemistry laboratory are currently planned to form a single production environment modeled on the requirements of the proposed good manufacturing practices for positron emitting radiopharmaceuticals. A new radio chemist

was added to the team in August 2009, and arrangements were made to get scanner support via the TRIUMF detector group.

These changes seemed to have paid off because we can report a substantial increase in deliveries of tracers to UBC and with fewer lost scans. At the same time, we delivered FDG to the patients of the BCCA; typically 108 scans every two weeks all year around.

Research and Development

The second aim of the Nuclear Medicine Division is focused on research and development (R/D) efforts to link with new partners. (Dr. P. Schaffer is coordinating this part of the program.) Activities have been developed with the BC Cancer Agency (for ex-EF5 tracers) and with MDS Nordion through a new R/D agreement and support from NSERC's CDR program for the development of metallic (Ga,Cu, and In) based tracers. A contract is also in place with MDS Nordion for the construction of a Radiochemistry Research Laboratory in the basement of the MHESA. This facility will be a joint laboratory that will eventually contain four hot cells to be used for the development of new radiotracers.

The construction of UBC's Centre for Comparative Medicine, located across the street from TRIUMF, provides another opportunity for forming new research collaborations. We have been working with Dr. Chris Harvey-Clark to include a PET imaging suite and an underground pneumatic transfer line that will conveniently allow us to deliver tracers.

Medical Isotopes

The worldwide crisis in the supply of the ^{99m}Tc SPECT agent raised the opportunity to consider nonreactor-based production of ^{99}Mo for which TRIUMF and its partners have obtained proof-of-principle funding. This opportunity, as detailed in the TRIUMF Five-Year Plan 2010–2015, argued

that the visibility of the Nuclear Medicine program would be very important in establishing the societal relevance of TRIUMF. This report will attempt to showcase the main activities of the new Nuclear Medicine Division during 2008 and 2009 and will look forward to exciting plans for the future. Many of those plans involve collaboration with agencies also devoted to nuclear medicine.

The Team

Lead: J.M. Poutissou

Deputies: M. Adam, P. Schaffer



Mike Adam is a senior research scientist at TRIUMF, deputy head for core programs of the Nuclear-Medicine Division, and an adjunct professor of chemistry at the University of British Columbia.

Nuclear Medicine

Collaborative Research with MDS Nordion, Inc.

TRIUMF has been collaborating with MDS Nordion on medical isotope production for over 30 years. The relationship has included licensing of medical isotope production knowledge from TRIUMF, operating three small cyclotrons, and using a low-energy proton beam from the main TRIUMF cyclotron to enable MDS Nordion to supply heart imaging isotopes. A 1995 report by the US Institute of Medicine's Committee on Biomedical Isotopes cited the TRIUMF-MDS Nordion relationship as a model of public-private partnership, one that could be emulated in the United States. In addition, TRIUMF and MDS Nordion won the Natural Sciences and Engineering Research Council of Canada (NSERC) 2004 Synergy Award for Innovation for their outstanding university-industry partnership.

Building on this solid foundation of synergic efforts, MDS Nordion and TRIUMF have elevated the relationship to a new level. The signing of a Memorandum of Understanding (MOU) in September 2008 was the first step along this path. The purpose of the MOU was to establish a framework for collaboration between the two organizations. The objectives were to acknowledge the importance of their strategic collaboration, to establish the parameters of their working relationship, and to facilitate commercialization of promising new radiological agents for imaging, diagnosis, and treatment of disease.

The medical area of focus within the collaboration is oncology, but other disease areas may be pursued as well. The collaboration has been named "The Centre of Excellence in Radiomedicine, collaboration between TRIUMF, and MDS Nordion." Under the umbrella of the MOU, specific projects will include activities necessary to carry out research and development

of radiological agents. The two major activities are anticipated to be collaborative research projects in radiochemistry and radiopharmaceutical research and infrastructure for radiochemistry research involving constructing and equipping modern laboratory facilities suitable for conducting the research.

Research Progress in 2008-2010

The first project to materialize under the MOU involves a tripartite collaboration among MDS Nordion, TRIUMF, and UBC's Department of Chemistry. The project is entitled "Enabling Technologies for Metallic Radioisotopes in Nuclear Medicine" and is co-funded by NSERC and MDS Nordion. The project has a projected three-year lifespan and was initiated in March 2009. The researchers propose to develop the chemistry to incorporate both positron emitting tomography or PET imaging and gamma-ray emitting radioisotopes for single proton emission computed tomography or SPECT imaging into biological molecules such as peptides, proteins, oligonucleotides, carbohydrates, and fatty acids and then to evaluate their biological properties as potential imaging or therapy agents.

During 2008, the focus of the project was on the synthesis of chelates and the characterization of their complexes with gallium. The results have significantly surpassed expectations by pinpointing a chelate that shows anomalously high affinity for gallium. This chelate, and several closely related ones, are currently being investigated further to determine the optimal method of linking them to biological molecules.

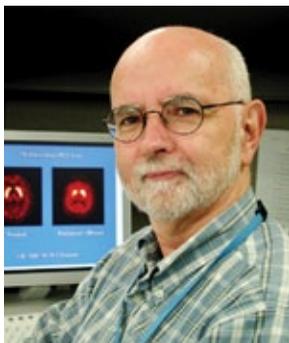
The second project to materialize under the MOU involves the planning and construction

of a Radiochemistry Research Laboratory (RRL) in the basement of the Meson Hall Extension Service Annex (MHESA). The agreement to refurbish two rooms in the MHESA basement was signed on October 30, 2009 and represents a collaboration between MDS Nordion and TRIUMF to carry out activities on the use of radioisotopes, radiochemistry, and radiosynthesis, as well as *in vitro* and *in vivo* biological characterization and imaging for the purposes of development of radiotracers for preclinical and clinical molecular imaging used for the diagnosis and assessment of biological function and disease. The project is co-funded by MDS Nordion and TRIUMF, with contributions of the former designated mainly for equipping the laboratory and those of the latter

for providing the infrastructure. The RRL will be jointly operated and occupied by both partners, with approximately 50% of the availability devoted to joint research. A gating meeting has been held for the project. Recommendations of the gating committee are being addressed and we expect that construction of the laboratory will begin during the spring of 2010.

Ahead for 2010

While isotope production by MDS Nordion and TRIUMF continues to supply a significant fraction of the medical isotopes used in Canada and abroad, researchers from the two organizations have set out on a path that will build on their current relationship and develop new uses for isotopes in radiological agents for disease imaging, diagnosis, and treatment.



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Nuclear Medicine

Collaborative Research with UBC

Earth and Ocean Sciences:

The radio isotopes of copper $^{64}\text{Cu}/^{67}\text{Cu}$ were first requested in 2003 to investigate the physiological role of Cu in microscopic algae, phytoplankton. Marine phytoplankton account for only 1% of the plant biomass on earth; however, they are responsible for ~50% of global net photosynthesis, and thus play an important role in controlling atmospheric CO_2 levels. Because insufficient Fe inputs restrict phytoplankton growth in ~30% of the global ocean, we need to have a better understanding of how the ocean affects the global C cycle, so it is essential to elucidate the physiology of Fe-limited phytoplankton. In the last 17 years, research on elucidating Fe nutrition and acquisition mechanisms in phytoplankton has revealed that Cu, a redox-active trace element, is essential for the growth of open ocean phytoplankton, especially if experiencing Fe limitation. The UBC-TRIUMF collaboration made the first measurements of Cu requirements by diatoms grown under various Fe and Cu levels using $^{64}\text{Cu}/^{67}\text{Cu}$. Researchers have shown that some isolates have high Cu requirements when subject to Fe-limitation, as Cu is a co-factor of putative ferric oxidases that facilitate Fe uptake under low Fe. However, they have also demonstrated that oceanic species have an extra Cu requirement (over and above the Cu demand associated with their high-affinity Fe transport system). Using metalloproteomics, the collaboration is presently elucidating the physiological roles of Cu in phytoplankton and hope to reveal substitutions of Cu for Fe in various biochemical pathways that would allow phytoplankton to lower their Fe requirements in low Fe environments. In addition, researchers are investigating Cu acquisition mechanisms when Cu levels are not toxic [1].

In September 2006, the team participated in a cruise in the Northeast Pacific, from Sidney (BC) to 700 nautical miles in a Northeast direction. This oceanic area is the focus of the oldest time series program in the world oceans (Line P, 50 years) and encompasses waters with high and low Fe concentrations. Plankton Cu requirements and uptake kinetics were investigated, with MDS-Nordion and TRIUMF providing 2 mCi of ^{67}Cu for the cruise. In addition, Katie Gagnon (SFU & TRIUMF) built a sea-going gamma counter for use onboard the vessel. A manuscript describing our field findings was recently published (see Ref. 2).

Department of Pathology (Diabetes):

Type 1 diabetes mellitus (T1DM) results from destruction of pancreatic β -cells. Islet transplantation is an attractive approach for treating T1DM patients, but there is a massive loss of islets during and after transplantation. Dipeptidyl peptidase-4 (DPP-IV) inhibitors have been introduced as therapeutics for type 2 diabetes (T2DM). They partially act by blocking degradation of the incretin hormones glucagon-like peptide-1 (GLP-1) and glucose-dependent insulinotropic polypeptide (GIP), thus increasing circulating levels of active hormones. The incretins are released during a meal and potentiate glucose-induced insulin secretion. In addition to their insulinotropic actions, GLP-1 and GIP also promote proliferation and survival of islet β -cells, and DPP-IV inhibitors exert similar effects in T2DM models. The objective of the study was to establish whether DPP-IV inhibitor treatment prolonged survival of transplanted islets in an auto-immune NOD model of T1DM and to track islet loss using PET.

Effects of the DPP-IV inhibitor MK0431 (Sitagliptin) on glycemic control and functional

islet mass in NOD mice were determined with metabolic studies and microPET imaging using a PET reporter gene (PRG)/probe (PRP) system previously developed by the group. Treatment of NOD mice with MK0431, prior to and post islet transplantation, resulted in prolongation of islet graft survival, as determined by PET scanning and glucose tolerance tests, whereas post-treatment alone showed only small beneficial effects. Subsequent studies demonstrated that MK0431 pre-treatment resulted in decreased infiltration of T-lymphocytes (insulinitis) in diabetic NOD mice and reduced *in vitro* migration of isolated splenic CD4+ T lymphocytes.

Treatment with MK0431 therefore reduced the effect of auto-immunity on graft survival partially by decreasing the homing of CD4+ T cells into pancreatic β -cells³.

Department of Botany:

In an ongoing collaboration with Drs Unkles and Kinghorn at St Andrews, Scotland, the collaboration has demonstrated that disruption of both high-affinity nitrate transporters (nrtA and nrtB) prevented growth of the fungus on nitrate and that $^{13}\text{NO}_3^-$ uptake was completely absent. Yet the fungus was able to grow on nitrite, signifying a discrete nitrite transporter (nitA), in addition to the capacity of nrtA and nrtB to absorb nitrite. Using ^{13}N , the team was able to characterize the nitrite transporter, which has now been cloned and turns out to be a tetramer of around 127 kD. The sensitivity of $^{13}\text{NO}_2^-$ detection allowed us to measure nitrite influx at concentrations as low as 250 nM; no evidence of sigmoidal kinetics that might indicate co-operativity among subunits was observed.

Four asparagines (N122, N173, N214, and N246) are highly conserved among prokaryotic nitrite transporters. Modifications of these residues may result in a complete loss of the capacity to grow on nitrite depending upon the amino acid substitution. Examining the uptake of $^{13}\text{NO}_2^-$ in these mutants, it was typically observed that hyperbolic kinetics disappear in mutants unable to grow on nitrite, and is being replaced by linear concentration dependence. pH studies indicate that this linear flux is partly due to nitrous acid (HNO_2) permeation. With respect to the role of the NRT3 genes in nitrate transport in *Arabidopsis thaliana*, researchers have generated antibodies against the high-affinity nitrate transporter nrt2.1 and nrt3.1, a second protein that is essential for nitrate transport. Using two-dimensional

chromatography, it has been demonstrated that nrt3.1 and nrt2.1 exist as a single (possibly dimeric) complex in the plasma membrane. The presence of a discrete nitrite transporter in *Arabidopsis thaliana* is similar to the case in *Aspergillus* where the higher plants also appear to possess a discrete nitrite transporter. Both nitrate transporters also transport nitrite. Using double mutants lacking nitrate transporters (*nrt2.1 / nrt2.2* mutants), researchers have characterized nitrite transport in the *nrt2.1 / nrt2.2* double mutants using $^{13}\text{NO}_2^-$ and are attempting to clone the gene responsible for this transport using T-DNA mutants, and by rescuing the *Aspergillus* mutant using a plant cDNA library. This will enable the group to generate knockout mutants and examine $^{13}\text{NO}_2^-$ influx.

Department of Chemistry:

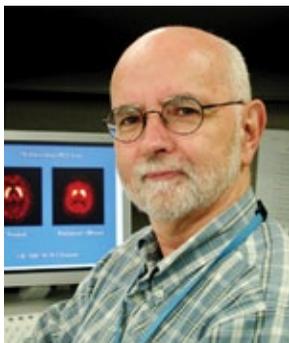
Having the Chemistry Department involved brings in more basic scientists into the project, which allows us to be more creative in the radiochemistry. This ultimately, will allow us to make radiopharmaceuticals that we could not make otherwise.

Three collaborative projects, LS-53, LS-56, and LS-72 were very productive again during the reporting time. LS-53 was completed this year and produced five publications. Experience gained in LS-53 has now been transferred to LS-90, the collaborative radiometal project with MDS Nordion. The collaborative project with Professor Perrin, LS-56, has resulted in six publications on the topic of conjugating F-18 molecules to biomolecules such as Oligonucleotides and peptides. LS-72 is a collaborative project with Professor Withers and focuses on the development of F-18 imaging agents that can be used to image lysosomal storage diseases in children.

From 2008–2009, the collaboration successfully labelled a fluorosugar that binds to the enzyme that is used in replacement therapy. A publication on this has now been submitted to PNAS.

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Nuclear Medicine

PET-based Collaborations with Pacific Parkinson's Research Centre

For nearly 25 years, the TRIUMF Radiochemistry team has worked in conjunction with the UBC PET Team to provide a world-class research environment for the study of neurodegenerative diseases, focusing primarily on Parkinson's disease (PD) although in recent times the interest has expanded to include psychiatric disorders and dementias.

Progress in 2008–2009

It should be noted before a discussion of progress that there was a major disruption in the supply of radiotracer for the Pacific Parkinsons Research Centre (PPRC) imaging program which lasted from late summer 2007 until early spring 2008; however, significant progress has been made despite the disruption.

Demonstration of VMAT2 binding sensitivity to dopamine levels

It had previously been shown that patients with dopa-responsive dystonia (DRD) have elevated DTBZ binding potential values (de la Fuente-Fernandez *et al.*, 2003). As DRD is characterized by dopamine depletion in the context of a structurally normal nigrostriatal pathway, with presumably empty vesicles, this result suggested that vesicular dopamine and DTBZ molecules compete for VMAT2 sites. We have now confirmed this prediction in patients with PD by showing that DTBZ binding decreases after levodopa administration.

Identification of age-specific patterns of neurodegeneration in Parkinson's disease

Using the data set corresponding to a multi-tracer, 8-year longitudinal PET study (Nandhagopal *et*

al., 2009), younger subjects (age of onset, 35 years) were found to endure substantially more nigrostriatal dopamine damage than older subjects (age of onset, 70 years) before the first PD symptoms appear. Thus, at symptom onset, DTBZ binding had decreased by 74% in younger subjects and by only 55% in the older group ($p < 0.05$). In addition, the rate of progression of neurodegeneration, as estimated by DTBZ binding, was substantially greater in older subjects. Thus, for example, during the first year after symptom onset, the corresponding rates of neurodegeneration were 5.2% vs. 3.6%, respectively ($p < 0.05$). Extrapolations of the exponential decay curves for each tracer (DTBZ, MP, and FD) indicate that the presymptomatic phase of the disease is significantly longer in the younger PD group (for DTBZ, 25 vs. 10 years; for MP, 15 vs. 10 years; and for FD, 8 vs. 4 years).

Our results suggest that the neurodegenerative process in PD first affects the vesicular compartment (DTBZ binding) and then progresses to involve other components of the nigrostriatal dopamine terminal. Remarkably, this pattern of neurodegeneration was observed not only in younger subjects (35 years) but also when the average age of onset for the entire data set (53 years) was considered. By contrast, in the older group (70 years), the decay of DTBZ and MP occurs simultaneously, which likely reflects lack of compensatory mechanisms.

Testing the genetic vs. environmental influences in Parkinson's disease by PET. Using a multi-tracer PET approach (including DTBZ and MP), researchers are currently studying subclinical dopamine changes in healthy parents of probands pertaining to three different types of pedigrees: 1) Pedigrees type A, in which the proband and one

of the proband's parents have PD (no other first-degree relatives should have PD); 2) Pedigrees type B, in which only the proband has PD (i.e., none of the proband's parents is affected); and 3) Pedigrees type C (control group), in which both probands and parents are free of PD.

Taking into account that, according to post-mortem studies, the risk of PD in the general population is 10% (i.e., 10% is the prevalence of cases with incidental Lewy body state in the general population) the following two hypotheses are being tested:

Hypothesis #1: PD is a genetic disorder with an autosomal dominant pattern of inheritance with incomplete penetrance. If this hypothesis is correct, the expected risk of PD in the healthy parent of pedigrees type A should be the same as in the general population (i.e., it was the affected parent who passed on the PD gene to the affected child/proband). Naturally, the same risk (10%) applies to healthy parents of pedigrees type C (control group). By contrast, the risk of PD in healthy parents of pedigrees type B must be 50% (i.e., the PD gene was necessarily passed on to the affected child/proband by one of the parents). Hence, if hypothesis #1 is correct, the subclinical dopamine lesion is predicted to be greater in healthy parents of pedigrees type B, compared to healthy parents of pedigrees types A and C.

Hypothesis #2: PD is a genetic disorder with an autosomal recessive pattern of inheritance. In this case, healthy parents of pedigrees types A and B should share the same risk of PD (50%; i.e., healthy parents must carry a mutant allele). Consequently, if hypothesis #2 is correct, healthy parents of pedigrees types A and B should have greater subclinical dopamine damage than healthy parents of pedigrees type C (control group).

Environmental influences will be inferred whenever the PET results do not fit with these two genetic hypotheses. For example, the observation that healthy parents of pedigrees type A have the greatest dopamine lesion would certainly favour environmental causation of PD. It should be noted that 1) there is no evidence to suggest that other patterns of inheritance may be at work in PD; and 2) previous studies have shown that PET with DTBZ and MP are able to detect subclinical dopamine changes, for example in asymptomatic carriers of PD mutations (LRRK2, parkin) [1,2].

Table 1 - GE Advance Scanning Statistics

	2009
Total Scans Conducted	106
Total Scans Lost	2
Lost to: -patient	1
-chemistry	1

*Scanner was commissioned in April 2009

Table 2 - ECAT Scanning Statistics

	2008
Total Scans Conducted	101
Total Scans Lost	13
Lost to: -patient	10
-chemistry	3

*Scanner was decommissioned in December 2008

Table 3 - HRRT Scanning Statistics

	2008	2009
Total Scans Conducted	156	122
Total Scans Lost	23	61
Lost to: -patient	14	46
-rabbit line	4	0
-chemistry	0	5
-scanner	5	10

Table 4 - MicroPET Scanning Statistics

	2008	2009
Total Scans Conducted	277	169
Total Scans Lost	7	18
Lost to: -scanner	3	6
-cyclotron	3	1
-chemistry	0	8
-scanner	1	2
-conflict with patient scan	1	2

Scanners: The imaging core supports three scanners. TRIUMF supplies support for the maintenance of these scanners and the results from 2008–2009, are detailed below and in Tables 1 through 4.

GE Advance scanner. This scanner was installed in March 2009 to replace the 18-year-old ECAT953B scanner. Phantom and patient cross-over studies have been performed to assess the resolution/quantification difference between the ADVANCE and ECAT data.

HRRT scanner. This scanner has been performing well, and after implementing and testing Inki Hong's (S. Korea) version of the image reconstruction algorithm, the time required for data reconstruction has been reduced to ~12 min/frame. Several instrumentation related papers have been published [3-5] and a physics and astronomy student (K. Cheng) has completed his Ph.D. work on the improvement of scatter correction for the HRRT data. Efforts are currently directed towards devising methods to estimate the accuracy of realignments of HRRT dynamic data sets [6] and accuracy of attenuation correction. The physics/methodology related studies are NSERC funded (V Sossi).

MicroPET- Focus 120. Being able to study human disease in animal models has been an extremely important part of fundamental research into human health. Just as functional imaging using PET has advanced research in living humans, being able to perform similar studies in the living animal enables researchers to examine the impact of therapies in the living animal, serially over time. The scatter correction

for the transmission data has been developed (resulting in a Ph.D. thesis of another physics and astronomy student, E. Vandervoort, and 2 additional publications). Another physics and astronomy student (G. Topping) completed his M.Sc. thesis, investigating analysis methods best suitable for dopaminergic imaging in rats. ¹¹C-methylphenidate (MP) Scatchard studies in rats and DTBZ⁺ Scatchard studies in mice are being currently performed (combination of Core and NSERC funding). Methodological results from these studies are being used in all studies related to the dopaminergic system performed on the microPET.

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Jean-Michel Poutissou is head of TRIUMF's Nuclear Medicine Division and former Associate Director of TRIUMF.



Nuclear Medicine Collaborations with BC Cancer Agency (BCAA)

Clinical Program

The clinical program has been running continuously since its inception in 2005, providing an invaluable service to oncology patients in British Columbia. Over the past 12 months, 2,917 adult and 130 pediatric oncology patients from across BC underwent clinical FDG PET/CT scans at the Vancouver Centre. These studies continue to be performed under two Clinical Trial Applications (CTAs) with Health Canada utilizing ^{18}F produced on the TR13 cyclotron, and FDG synthesized at the BCCA's temporary production facility at TRIUMF. One scanning day was lost due to a problem with the PET/CT scanner, and 3.5 days lost due to problems with the FDG synthesis module. No scanning days or portions thereof were lost due to unscheduled cyclotron downtime.

Research Program

Several active in-house and sponsored clinical trials used FDG PET/CT scans for therapy planning or response monitoring. For other radiopharmaceuticals, eighteen ^{18}F -DOPA scans were performed using radiopharmaceutical synthesized at TRIUMF—3 clinical (neuroendocrine tumour evaluation) and 15 as part of a radiotherapy related clinical trial in recurrent brain cancer (see Figure 1). Nine ^{18}F -EF5 studies were performed as part of a clinical trial evaluating hypoxia in non-small-cell lung cancer and represent the first clinical trial utilizing this radiotracer in Canada.

Researchers at BCCA, TRIUMF, and UBC have been very successful at securing research grants in oncology through competitive grant funding agencies, including the Canadian Institutes for Health Services (CIHR) and the Natural Sciences and Engineering Research Council of Canada

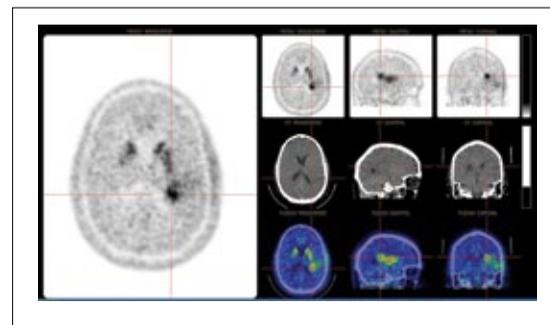


Figure 1: Example of brain tumour imaging using (^{18}F - DOPA) FDOPA.

(NSERC). The projects that have been funded are: new proposals on radiolabelled peptides for cancer imaging (CIHR, total \$570,210), the use of [^{18}F]FES to predict response to therapy (NIH, total \$429,850), the development of cyclotron production for technetium isotopes (NSERC/CIHR, total \$1,304,395), the development of new ^{68}Ga radiotracers as alternatives to Tc99m probes (NSERC/CIHR, total \$429,593 and \$445,437), novel methods for radiolabelling cancer-seeking pharmaceuticals (CCSRI, \$373,892), and development of therapeutic and diagnostic agents targeting carbonic anhydrase IX for breast cancer (CIHR). Other probes based on radiolabelled antibodies have also been tested in animal experiments (see Figure 2 for an example of HER2/neu imaging by Don Yapp *et al.*).

These successes illustrate the strong synergy that exists between researchers at BCCA, TRIUMF, and UBC. They have also emphasized the need to expand our research infrastructure for cancer research both at BCCA and TRIUMF to meet the needs of a growing field.

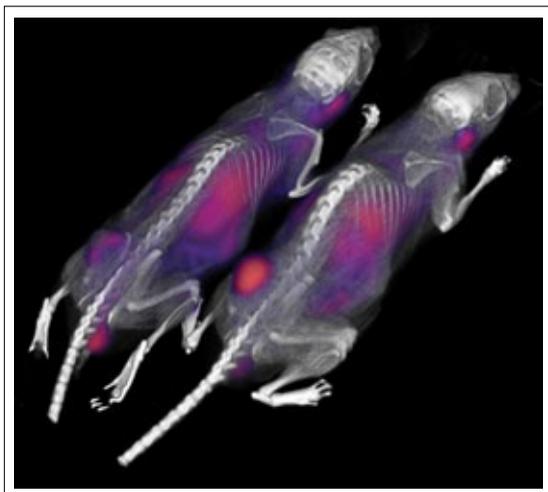


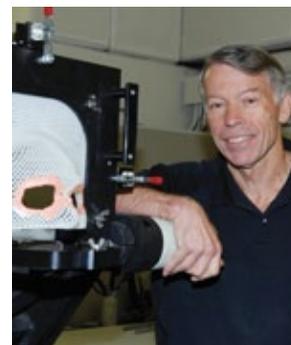
Figure 2: HER2/neu protein expression imaged in a mouse breast cancer model with ^{64}Cu -labelled herceptin.

Ahead for 2010

With the new cyclotron facility opening in early 2010, besides ^{18}F FDG, ^{18}F FDOPA, and ^{18}F JEF5 currently available from TRIUMF, we plan to provide ^{18}F NaF, ^{18}F FES, ^{18}F FLT, and ^{18}F FECh for clinical studies within one year after the opening of BCCA PET Centre, with operations beginning sometime in July 2010. In addition, we will also explore the potential of ^{18}F -labelled regulatory peptides such as bombesin, substance P, and neuropeptide Y for early diagnosis and characterization of cancer. New funding from NSERC and CIHR for alternative isotopes for medical imaging will provide support to develop new targets and processing methods for cyclotron-based technetium production. The \$1.3M grant, which was awarded for use over two years and involves five institutions across Canada, involves François Bénard and Tom Ruth, co-principal investigators, plus co-applicants Paul Schaffer and Stefan Zeisler.

Ewart Blackmore is retired head of TRIUMF's Engineering Division and now oversees the proton therapy program with the BC Cancer Agency.

Additional author: Douglas Bryman, Thomas J. Ruth



Nuclear Medicine

Nuclear Medicine and Proton Therapy Facilities

The nuclear medicine facilities comprise the TR13 cyclotron (reported elsewhere) and two radiopharmaceutical production laboratories, one quality control laboratory, and one research laboratory. The UBC hospital has three PETs used primarily by the Pacific Parkinson's Research Centre (PPRC). A 2.5 km underground pneumatic transfer line connects the TRIUMF radiopharmaceutical laboratories with the UBC PET imaging suite. Located at the TR13 cyclotron is a small clean room containing a hot cell used by BCCA for the production of FDG.

Extensive planning has occurred for a new Radiochemistry Research Laboratory to be located in the basement of the MHESA. This facility will be a joint laboratory with MDS Nordion that will eventually contain four hot cells to be used for the development of new radiotracers.

We are in the planning stages to upgrade one of the existing radiochemistry laboratories to better allow us to meet the Good Manufacturing Practices requirements for the production of positron emitting radiopharmaceuticals. This effort involves upgrading the interior of the existing hot cell, installing a second hot cell, and installing a laminar flow hood. Room alterations will also provide a cleaner environment with better air quality and restricted access. Only materials and personnel involved in the production of the radiopharmaceuticals will be allowed in this area. The addition of the second hot cell will allow both ^{11}C and ^{18}F tracers to be produced in this laboratory.

Status on the Synthesis of Radiotracers for PET Scanning

The PET group at TRIUMF continues to supply the PPRC with radiotracers for scanning with PET imaging. In addition, [^{18}F]DOPA and [^{18}F]EF5 are now sent to BCCA for scanning with PET/CT. There are currently three production personnel supplying the requested tracers using two hot cells and a total of 12 different radiotracers are produced routinely. A new in-house methyl iodide system began routinely producing [$\text{C}11$] methyl iodide in July 2009.

Table 5 - Total Number of Deliveries for 2008 and 2009

	2008	2009
UBC PET Program	503	555
Others*	71	71
Development Runs	191	201
Radiochemistry Runs	129	77

*BC Cancer Agency (not including FDG), Botany, Chemical Engineering Earth and Ocean Sciences

Table 6 - Distribution of Deliveries to UBC for 2008 and 2009

	2008	2009
Patient*	208	239
MicroPET	197	155
Shared Patient*/uPET	54	20

*Includes all subjects scanned on large scanners

Proton Therapy Facility

Between January 1, 2008 and December 31, 2009, the Proton Therapy Program, led by E.W. Blackmore and C. Hoehr, treated 15 patients during five scheduled treatment sessions each year. This brings the total number of patients treated at TRIUMF to 145. This number is less than the 14 patients treated in 2007 alone, but considered a statistical fluctuation (average per year: 9.7 ± 3.6). Figure 3 shows the number of patients per year since the start of treatments in 1995. Treatment is carried out using a modulated beam of 74 MeV protons with the dose delivered over 4 daily fractions, each taking about 2 minutes.

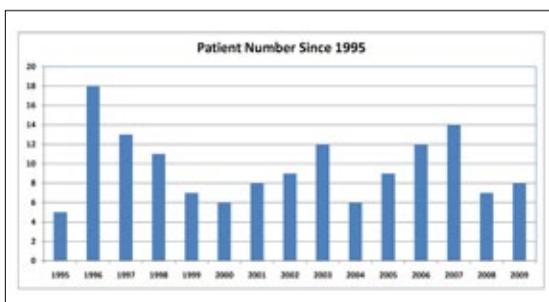


Figure 3: Number of patients treated with protons per year since 1995.

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 4). These clip positions are then compared to the desired locations determined by the treatment planning

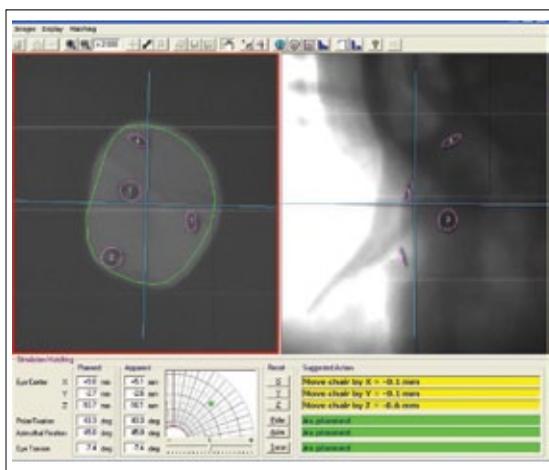


Figure 4: Digital X-ray image, lateral and axial. This patient had four metal clips inserted around the tumour. The software is used to match the expected position of the clips (purple circles) with the actual clip position in the X-ray image, thus aligning the patient.

program. The patient chair is then moved to correct for any errors.

Since the beginning of TRIUMF treatments the 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 two years. The solution that has been selected is a digital X-ray camera based on a CMOS image sensor manufactured by Rad-icor Imaging. This camera has an active area of 5 cm by 5 cm with 1024 by 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.

Liquid Xenon Detectors for PET

This work is led by D. Bryman of UBC. PET allows physicians to non-invasively examine the biochemical functioning of organs. Molecular imaging promises to foster translation of developments in cell and molecular biology into improved health care. PET relies on advanced detector technology and on radiolabelled tracers. The Fluorine-18 labeled glucose analog FDG is an invaluable tool for oncology used to image metabolic activity. PET has proven valuable in early detection, staging, treatment planning, and follow-up, all of which can lead to improved patient outcomes and lower health care costs. PET is also used extensively in psychiatry and neurology for diagnosis and research of disease.

Researchers are developing liquid xenon (LXe) detectors for PET which aim to achieve systems with higher sensitivity than conventional PET systems and better spatial resolution, reaching the sub-mm level in all three dimensions without parallax errors. In addition, due to faster time response (useful for reduction of random coincidences), and superior energy resolution, the LXePET system may produce images of higher overall quality. Because each energy-depositing interaction can be precisely recorded, application of LXe gamma-ray detectors as coincidence Compton cameras for PET is also practical.

Many areas of PD study would benefit substantially from the availability of LXePET. Prominent potential applications would be *in vivo* studies involving 1) subregional analysis of neurochemical changes in

animal (genetically modified) models of PD; and 2) subregional detection of gene expression studied using labelled oligonucleotides. The improved sub-mm imaging provided by LXePET would have a major impact in mice brain and cancer model imaging. The superior resolution and sensitivity would allow quantifying tracer distribution in extremely small brain structures

In 2008, we received a three-year award from the highly competitive Canadian Health Research Program (CHRP) jointly sponsored by NSERC and CIHR. The goal of this project is to construct and test a proof-of-principle system consisting of two sectors of an LXe microPET ring. The infrastructure for the LXe lab in which this work is being performed has been provided by the Laboratory for Advanced Detector Development (LADD), a Canada Foundation for Innovation project of UBC, the University of Montreal, and TRIUMF. Expertise in relevant technologies and techniques, including detector engineering and construction, cryogenics, electronics, real-time computing, as well as in experimental and clinical PET research, has been available through collaboration of TRIUMF, UBC, and the BC Cancer Agency.

LXe charge and light measurements using a prototype detector confirmed important aspects of the LXe detector performance, and cooling, purification, and control systems were evaluated [1]. Scintillation light was detected with large area avalanche photodiodes while ionization electrons were collected on an anode instrumented with low noise electronics after drifting up to 3 cm. Operational conditions were studied as a function of electric field. The anti-correlation of light and charge was observed and used to improve the energy resolution (see Figure 1); energy resolution

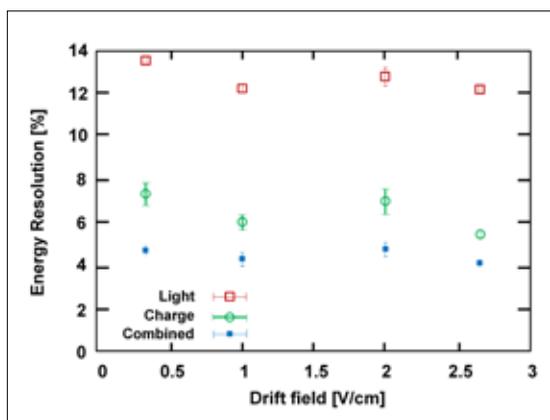


Figure 1: Energy resolution from charge and light measurements in an LXe prototype as well as the combined resolution for different drift fields.

< 10% (FWHM) was achieved.

The relationship between scintillation light and ionization signals was also investigated. Based on these results, a combined energy resolution of <3.5% (or < 8% FWHM) is anticipated in a detector configuration suitable for applications to PET. Further improvements are foreseen in purification and low noise electronics. The expectations for performance under operating conditions for PET also include sub-millimeter 3-D position resolution from the charge signal, timing resolution < 1 ns from scintillation light, and the ability to reconstruct Compton scattering events. Spatial location of events obtained from the prompt distributed light signals will be used to reduce the ambiguities of associating the scintillation light and charge at high levels of activity.

The reporting period saw the assembly and test of a prototype PET ring sector which fits in the existing 8.5 l cryostat. It includes a high-precision time projection chamber for measurements of ionization energy and coordinates a 32 channel APD array for scintillation measurements. The system employs liquid state purification and a pulse tube refrigerator for cooling to reduce LN2 consumption. In addition, we are well into the design of the full ring cryostat system that will house two or more sectors for coincidence PET studies. Simulations of the proposed LXe PET system, focusing on Compton scattering reconstruction and light collection issues, were also performed.

The group continues to develop and refine simulations of the expected performance of the LXe PET system involving Compton reconstruction and imaging studies. Light signals in our detectors for PET are important for triggering, initial localization, and ultimate energy measurements. Therefore, researchers studied techniques to localize the positions and determine the energies of gamma-ray interactions in liquid xenon gamma-ray detectors using only the isotropic scintillation light emission at 175 nm. GEANT4 Monte Carlo simulations were used to generate data observed by the photo-detectors when a specified number of photons were emitted from various locations within the chamber.

Reconstruction algorithms were developed to take the photo-detector data as input and return the energy and position of the interaction. For position reconstruction, neural network algorithms were used. The neural network model was developed

and tested for regions of the chamber that are most critical for position reconstruction. How well this network reconstructs input from localized interactions was studied and energies ranging from 300 keV to 511 keV including effects of avalanche photo-diode (APD) noise emerged. The network provided position reconstruction of individual interactions to within a volume of radius approximately 0.9 cm including APD noise. Photon sources involving Compton scattering and effects of light scattering and absorption on the walls of the chamber were also investigated.

system, and a computer control system. Several mechanical configurations were pursued to meet the requirements to house an annular array of 12 detector segments. This annulus of detector segments, surround by a double wall bore, will be built from thin-wall stainless steel. PET users will have access to a 10 cm diameter bore running completely through the cryostat in which to place specimens to be imaged. Preliminary thermal heat load, and mechanical stress calculations were carried out, and detailed design work is proceeding. Construction of the cryostat and detectors will take place in 2010.

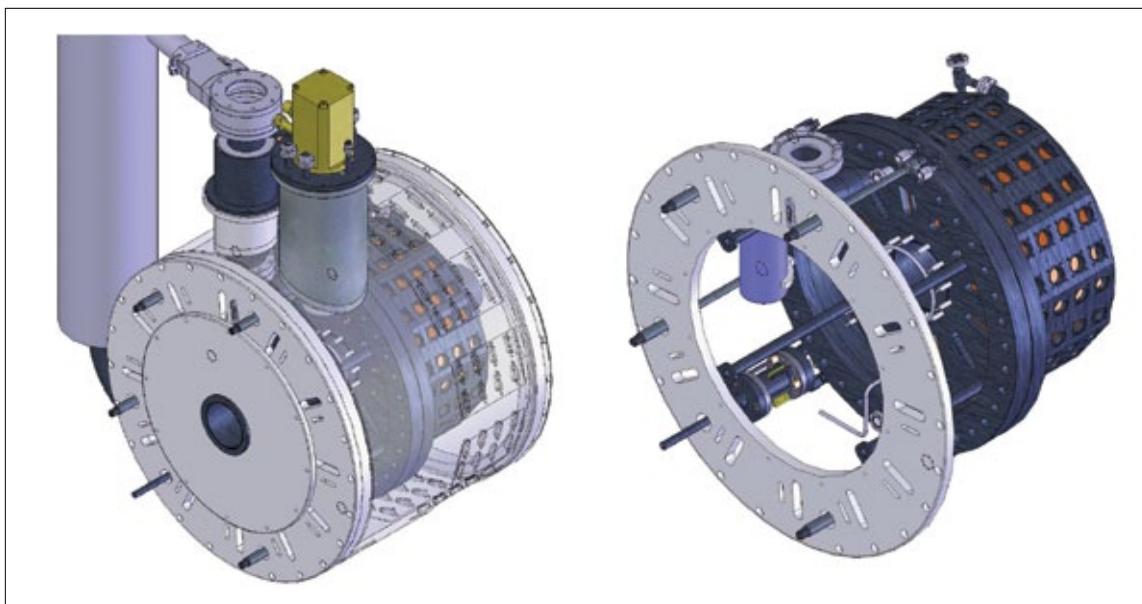


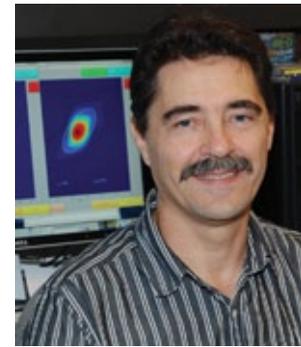
Figure 2: Design of the LXePET outer vacuum vessel (left) and inner cryostat vessel (right).

The full ring PET detector system employs a cryostat (see Figure 2), consisting of a vacuum vessel surrounding a thermally isolated inner vessel, which holds the gamma-ray detector elements immersed in LXe. In addition, the system includes a gas handling system, a gas recovery

Reference

[1] P. Amadruz *et al.*, *Simultaneous reconstruction of scintillation light and ionization charge produced by 511-keV photons in liquid xenon: Potential application to PET*. Nucl. Instr. Meth. Phys. Res., A607 668–676 (2009).

Richard Baartman is a senior scientist and beam physics group leader at TRIUMF.



Accelerator Physics

Accelerator physics activities in 2008–2009 focused on developing capabilities for the cyclotron and its extracted beam lines. Work began in earnest on design and specification for the superconducting electron linac (e-linac).

We focused on increasing intensity and improving stability as well as preparing for an additional high intensity high-energy extracted beam. A major refurbishment activity still underway is the replacement of the vertical injection beam line. We used this opportunity to improve on the original 35-year-old design. We have been designing our first major electron accelerator: a 50 MeV, 500 kW e-linac. Because the parameter space of possible configurations has many dimensions, a genetic optimization algorithm has been used. During this reporting period, we also collaborated on beam studies for CERN and participated in the commissioning of the large hadron collider (LHC). Lastly, we have given many of the lectures in a graduate-level course on accelerator physics at the University of British Columbia.

Progress in 2008–2009

Cyclotron

We provided beam dynamics support and overall coordination of experiments to develop the cyclotron for the future. We had foreseen that there will be an additional rare-isotope beam production line (BL4N), besides the existing BL1A (mainly for muSR), BL2C (for medical isotopes), and BL2A (existing RIB line). With total output on four lines together possibly reaching as high as 400 μA in the future, exploration of intensity limits was pursued.

As H-stripping rises sharply with beam energy, we can reduce activation by lowering BL1A and 2A

energies from 500 MeV to 480 MeV. A tune was developed for 480 MeV running and performs satisfactorily with surface muon flux measured and found to be down by only $\sim 3\%$.

A related issue was the extraction of three simultaneous beams at high energy. As RIB targets must run at near maximum temperature, it is important to stabilize the beam current to about 1%. When sharing beams, very small changes in the circulating beam can result in large ($\sim 10\%$) changes in extracted current. In beam experiments, it has been demonstrated that the two intended beam lines, because they are 120 degrees apart and the radial tune is 1.5, do fluctuate in phase. Thus stabilizing one will also stabilize the other, and this has indeed been experimentally confirmed. Presently, the current is stabilized by feeding back the measured, extracted current in BL2A in a loop, which adjusts the duty factor of the 1 kHz pulser. Another method would be to reduce the radial fluctuations in the cyclotron beam by compensating the 3/2 resonance, and experiments have been performed to demonstrate the feasibility of this technique.

Considerable effort went into interpreting the centre-region measurements carried out after the fall 2009 shutdown. Work concentrated on determining the cyclotron's phase acceptance and transmission with/without bunching, and the possibility of improving cyclotron performance by using the radial flags to restrict the phase acceptance of the injected beam.

ISIS

The design of the optics of the new vertical section is complete, and a design note has been released. The technique used was to calculate the 3D beam envelopes (six-phase space dimensions), including

space charge, axial magnetic field, and acceleration at the dee gaps in the cyclotron. The calculation is first order only but contains all the relevant physics of that order: in the cyclotron it includes electric focusing, the gap-crossing resonance, and the radial-longitudinal coupling effect of space charge. Because of the coupling effects in the spiral inflector, and the weak magnetic focusing on the first few turns, it is impossible to match the injection line to the cyclotron optics; a factor-of-five growth in emittance is predicted, and this agrees with measurements taken in the past on the existing configuration. Space charge limits the achievable beam current in the cyclotron because it drives the vertical incoherent tune to zero; the design's goal is to achieve 500 μA , and the present studies and past performance indicate that this is feasible.

Secondary Channels

The PIENu beam line (M13) was tuned and performed according to expectations. The M9 beam line design was optimized, while the M20 design was adjusted to the developing engineering constraints.

Primary Beam Lines

We performed Monte Carlo simulations on BL1A to derive the beam losses for the re-design of the so-called "collimator B." G4Beamline is a beam transport extension of GEANT4. A complete 3D software model of BL2A has been assembled in G4Beam line including all primary elements up to and including the RIB target. The advantage of this approach is that all particles down to the ppm level can be included, which is essential because extraction via stripper foil creates a few ppm of very large-angle scatters that impinge upon the beam pipe. As well, the window and final target pattern can be included and the resulting activation pattern calculated. The work was presented as an invited talk at the 2009 International Computational Physics Conference (ICAP09). Comparison of the losses and activation with measurements has begun.

A new primary line, BL4N, was designed to supply the protons to the proposed new RIB target. This was designed with a collimator in the front end to reduce spills throughout the line compared with BL2A. As well, the beam was made impervious to the fluctuations commonly occurring in the cyclotron's extraction stripper foil by compensating the cyclotron's dispersion.

ISAC

Optics were designed for the following beam lines: Charge State Booster loop, GRIFFIN, IRIS, and TUDA2/HERACLES. As well, we redesigned the optics matching into the high-resolution mass separator to achieve higher resolution and better reproducibility.

e-Linac

During the design phase of e-linac, we developed a framework for modeling and optimizing beam dynamics in order to explore optimal working parameters and define the operational envelope subject to realistic constraints. The core of this program consisted of beam dynamics modeling tools integrated with a multiple-objective genetic optimization engine. Computation was carried out on WestGrid [2] to take advantage of its massive parallel processing capability. Additional infrastructure and functionalities were developed to enable more general optimization over multiple modeling modules, to characterize the robustness and tolerance of solutions through parameter space scanning, and to efficiently process massive optimization data into physically interpretable results. This package proved a powerful tool not only for obtaining optimal design solutions but also for deciding between competing design options (such as machine configuration, choice of hardware, etc.) guided by well-reasoned criteria. The genetic multiple-objective approach proved capable of finding truly global solutions not easily accessible otherwise which, in the process, revealed intricate interplay between parameters and allowed further understanding of underlying physics and provided valuable guidance for better designs.

Beam-dynamics-dictated solutions, including machine layout, hardware, and operating parameters were obtained for the e-linac, meeting or exceeding specs for both the 16 pC/bunch photo-fission and the 100 pC/bunch light source applications. Tolerances of operating parameters were also obtained as part of the baseline design.

CERN and Other International Collaborations

CERN

For the superconducting linac proposed at CERN as part of an upgrade to the large hadron collider (LHC), we performed simulations to determine the effects of the higher order cavity modes on the beam's stability. Our work was backed up by calculations made by our CERN colleagues and

will be used to decide on the design of the higher order mode dampers.

For the beam–beam calculations for LHC, we finalized the grid-multipole (hybrid FMM) model in our parallel code COMBI and performed timing trials for increasing numbers of bunches and interaction points. Performance results showed good scaling and only a modest uplift over a soft-Gaussian model. This work was reported in a 2009 Particle Accelerator Conference (PAC09) paper and also in a CERN co-worker’s talk at ICAP09. Furthermore, we obtained analytical results for the effect of parasitic beam–beam encounters on smear of the emittance. Combined with previous six-track calculations, this result helped CERN to decide against the dipole-first interaction region scheme for improvement of luminosity. Both results were reported at the Chamonix 2009 meeting. Finally, one of our members participated in the LHC commissioning runs for three weeks in November 2009.

Fermilab

An optics design was made for a 550 MeV/c two-stage separated kaon beam for the P996 collaboration at Fermilab which aims to measure 1000 rare decays of the kaon into a pion and two neutrinos.

J-PARC

Adjustments were made to the optics design of the 800 MeV/c kaon beam at J-PARC because of additional engineering constraints.

Ahead in 2010

During the next year, we will be participating in the commissioning of the new vertical section of the injection line. Following that, and as part of our next five-year-plan, we hope to complete the design and commission the e-linac.

The Team

Lead: R. Baartman

Members: Yu-C. Chao, J. Doornbos, F. Jones, S. Koscielniak, D. Kaltchev, Yi-N. Rao, L. Root

Partnering Labs/Institutions:

CERN, Fermilab, J-PARC, TRIUMF

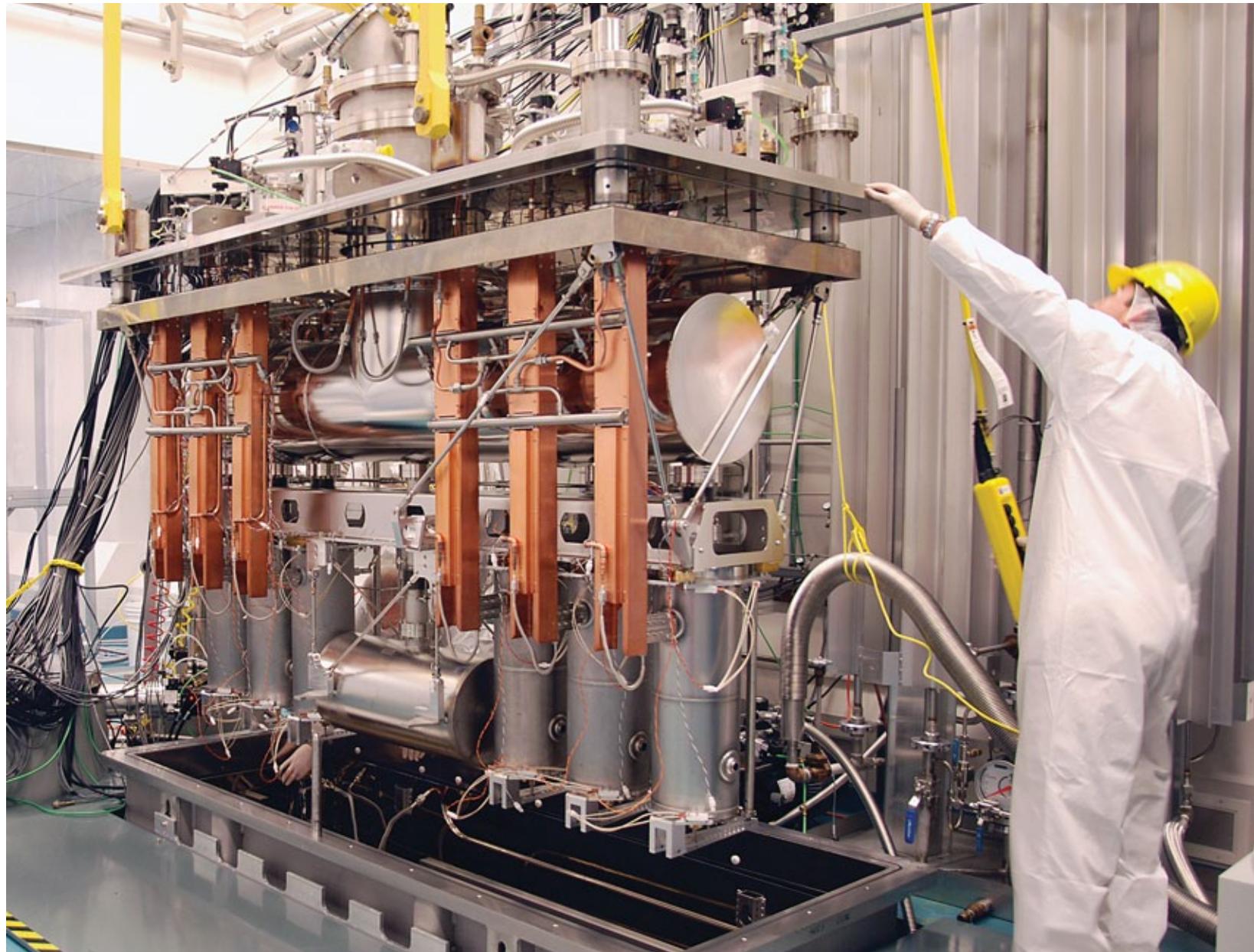
Introduction

TRIUMF's highly skilled staff represent a key asset for Canada in the pursuit of national objectives in science, technology, and innovation. People provide the expertise to build, maintain, and operate facilities at TRIUMF and elsewhere. Technologists have skills that simply are not available elsewhere in Canada, and in some cases are very uncommon worldwide. In addition to supporting the TRIUMF program, these highly qualified personnel are a unique resource for all Canada. TRIUMF's expertise, in areas like accelerator and detector development, is sought out by international collaborators who, in return, contribute their expertise to TRIUMF.

This section is a comprehensive description of TRIUMF's physical resources — the accelerators, beam lines, detectors, and other facilities. On site, TRIUMF has five cyclotrons (three operated by MDS Nordion), three linear accelerators, and a multitude of beam lines.

Between 2008 and early 2010, TRIUMF performed upgrades and development to beam lines and targets. As Canada's premier laboratory for accelerator science and technology, part of TRIUMF's mission is the stewardship and development of the next generation of accelerators. TRIUMF has advanced several projects fulfilling these goals: field-focused alternating gradient accelerators, superconducting radio-frequency technology, and a collaboration with India's Variable Energy Cyclotron Centre.

Photo:
ISAC-II Accelerator Hall
Superconducting Linear Accelerator Cryomodule



Providing World-Class Tools

Existing Accelerator Facilities

Detector Development and Support

Next Generation Accelerators



Jamie Cessford is the Manager of Accelerator Operations at TRIUMF, and leads the Cyclotron Operations group.

Existing Accelerator Facilities

520 MeV Cyclotron Operations

The Accelerator Operations Department operates the three major beam delivery facilities at TRIUMF—the 520 MeV cyclotron, the ISAC rare-isotope beams (RIB) facility, and the TR13 PET isotope cyclotron. This section discusses 520 MeV cyclotron operations. The following two sections discuss ISAC facility operations, and TR13 cyclotron operations.

The 520 MeV has four independent extraction probes with various sizes of foils to provide protons to up to four beam lines simultaneously. Beam line 1A routinely delivers protons at 500 MeV to two target systems. The beam power ranges from 50 to 75 kW. The first target, T1, services three experimental channels; one of which is used for the T2K project. The second target, T2, services two μ SR experimental channels. Downstream of T2 is the 500 MeV facility, which produces strontium that is used in medical imaging generators and the thermal neutron facility.

Beam line 1B separates from BL1 at the edge of the cyclotron vault and provides international users with the proton irradiation facility (PIF) that mimics space radiation for testing computer chips. The BL2C (70 to 116 MeV) line is used for the proton therapy program (PT) to treat choroidal melanomas (eye tumours) and proton irradiation of rubidium to produce strontium for medical imaging generators. BL2C is also used to provide lower energy protons to the PIF users.

BL2A provides 500 MeV proton beams at up to 50 kW to the on-line ISAC target that produces exotic radioactive ion beams for a host of experiments.

Beam line 4 is capable of delivering protons of energy from 180 to 520 MeV, albeit at only 5 kW. It was last used as a production facility in 2000 for

the parity violation experiment. Other significant experiments on this beam line include charge symmetry breaking and TISOL (TRIUMF Isotope Separator On-Line), the predecessor to the ISAC facility.

The facility operates 24 hours a day, 7 days a week, with a major three-month shutdown from January to March and a one to two week mini-shutdown in September.

Facility Operation - 2008 Totals

The cyclotron ran for 5,009 hours or 92.1% of the 5,438 hours scheduled. Our annual fall mini-shutdown ended in early September, and our winter shutdown began on December 21, 2008. The major downtime for the running period was diagnostics, accounting for 41% of the total 455 hours. Most of the 186 hours of diagnostic downtime was due to the failure and repair of the Extraction 1 probe. The RF was in second place with nearly 25% of the downtime.

Beam line 1A ran for 3,638 hours or 90% of the 4,044 hours scheduled and received a charge of 375 mAh or 93% of the 403 mAh scheduled. The BL1A triplet temperatures were well behaved all year. During the fall shutdown, 1AQ14 and 15 were flushed.

Beam line 1B delivered beam to the proton irradiation facility for two weeks.

The 2C1 line was used for proton therapy (5 sessions of 7 patients) as well as for 9.5 weeks of Proton Irradiation Facility operation. BL2C4 ran for 3,015 hours or 93% of the scheduled 3,242 hours and also received 96% of the scheduled charge (177 mAh of the scheduled 184 mAh).

BL2A delivered 3201 hours of beam to either the east or west target stations, or 78% of the scheduled 4,100 hours. BL2A received 163 mAh or 80% of the scheduled 203 mAh. Both 2A2 and 2A3 had excellent fourth quarter hours and charges at 95% of scheduled.

The total extracted beam was 715 mAh, which was 103 mAh more than what was delivered in 2007.

Facility Operation - 2009 Totals

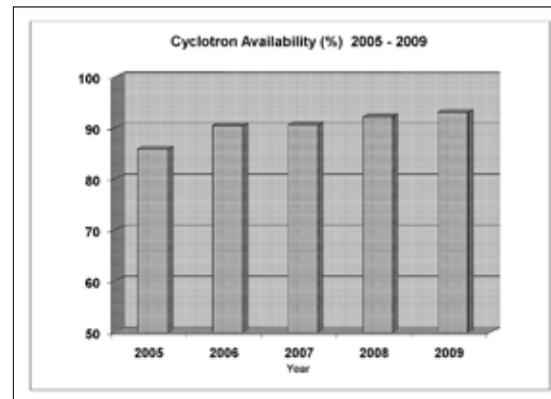
The cyclotron ran for 5,368 hours or 93.0% of the 5,769 hours scheduled. Our annual fall mini-shutdown started in early September and our winter shutdown began on December 22, 2009. The major downtime for the running period was vacuum, accounting for 50% of the total 381.4 hours. Most of the 191 hours of vacuum downtime was due to the failure and repair of the RF coupling loop feedthrough. The feedthrough failed after another leak opened up while the vacuum interlocks were inactive. The RF was in second place with nearly 14% of the downtime.

Beam line 1A ran for 3988.5 hours or 95.5% of the 4178 hours scheduled and received a charge of 457 mAh or 100% of the 457 mAh scheduled. The BL1A triplet temperatures were well-behaved all year, with 1AQ15 needing a flush in mid-August. Beam line 1B delivered beam to the proton irradiation facility for two weeks.

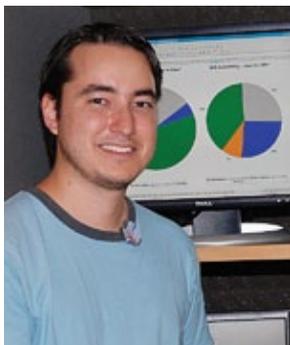
The 2C1 line was used for proton therapy (6 sessions of 9 patients) as well as for 9 weeks of Proton Irradiation Facility operation. BL2C4 ran for 3,109 hours or 91.6% of the scheduled 3,396 hours and also received 98.6% of the scheduled charge (211 mAh of the scheduled 214 mAh). This was a record year for charge delivered to BL2C4.

BL2A delivered 3,732.4 hours of beam to either the east or west target stations, or 74% of the scheduled 5,057 hours. BL2A received 139.8 mAh or 76% of the scheduled 184.3 mAh. BL 2A3 had very good numbers with hours and charges near 95% of scheduled time.

The total extracted beam was a record 808 mAh. This is 93 mAh more than what was delivered in 2008.



History of cyclotron availability and uptime.



Jonathan Aoki is a senior accelerator operator at TRIUMF.

Existing Accelerator Facilities

ISAC Facility Operations

ISAC (Isotope Separator and ACcelerator) is a world-class facility specializing in the production and acceleration of rare isotope beams. Stable Ion Beam (SIB), produced by the Off-Line Ion Source (OLIS) and the two online target stations (ITE and ITW), is generally used as a pilot beam during the setup of Rare Isotope Beam (RIB) to experiments. With protons on target, RIB can be extracted from one of the two online target stations.

SIB and RIB can be transported to low-energy experiments or accelerated to high-energy experiments to a maximum of 40MeV. High energy beam delivery is achieved by utilizing a combination of room-temperature and superconducting accelerators.

ISAC experiments are scheduled throughout the year, excluding the Winter Shutdown period (several months beginning in December) and the Fall Shutdown period (1-2 weeks in September).

Beam Delivery for 2008

The 2007 winter shutdown ended during the second week of April 2008. The active beam schedule spanned April to December, and then resumed again on March 18, 2009 after the 2008 shutdown.

In 2008, 3,277 hours (71% of the scheduled 4,615 hours of ITE/ITW beam time) of RIB was produced and made available for use at ISAC. This included experimental runtime, development shifts, and overhead (such as start-up and tuning time). In addition, 5,602 hours of stable ion beam (SIB) were available for use from the OLIS (off-line ion source).

During the August actinide target run, ISAC remained idle for 295 hours (2A beam was requested off but was scheduled and available). If we were to re-label the actinide "idle" time as uptime, the beam availability at ISAC rises to 77%. During this period, ISAC logged 750 hours of downtime; significantly more than usual. Of this, 576 hours were due to the failure of two ion sources (Ta #24 and SiC#18). If we eliminate this downtime, less than 4% of the scheduled beam time was lost due to other failures in ISAC. This number would be more in line with the performance of previous years and would have put us in the range of our availability goals. It should be noted that during the fourth quarter of 2008, beam was available for 92% of the scheduled beam time.

August 29, 2008 marked the first time that an actinide target (UO₂#1) was run in ISAC. The target received approximately 300 μ Ah of protons, during which an extensive set of yield and safety measurements was carried out. In preparation for the run, upgrades were made to the radiation safety system. An improved ITM gas sampling system was installed, and an alpha CAM (continuous air monitor) was put in place. Filters were also installed in front of various IMS and ILT backing pumps to monitor the possible spread of contamination in the LEBT beam line during the actinide target run.

Installation and commissioning of the new multi-charge ion source (MCIS) at OLIS spanned most of 2008. Numerous commissioning benchmarks were reached, including the first observed plasma in November, and the first beam accelerated through the ISAC-I DTL in December.

Commissioning of the new charge-state booster (CSB) continued through the year. In November,

a major benchmark was reached when $80\text{Rb}14+$ was successfully charge-bred and accelerated through the DTL

The following experimental facilities also received beam from April 1, 2008 to December 21, 2008: 8π (S984, S985); $\beta\text{NMR}/\beta\text{NQR}$ (M1040, M1041, M1153, M1176); DRAGON (S810, S1027, S1122); RADON EDM (S929); SEBT2 (S1104, S1151); TIGRESS (S1069, S1105, S1209); TITAN (S1158, S1066); TRINAT (S1127); TUDA (S996); and Yield (S841).

Major Jobs in 2008

The PLC-based ISAC nuclear exhaust ventilation monitoring system was commissioned in March 2009. It works independently of the existing distributed digital control (DDC) system and serves as a redundant indicator of the status of the nuclear ventilation.

Significant modifications to target module #3 (TM3), the west Faraday cage, and the west target pit were required to prepare for the upcoming June 2009 west target FEBIAD (forced electron beam induced arc discharge) run. TM3 work started in April 2008 and carried on through the 2008 winter shutdown. The old electron cyclotron resonance source tray was removed, and the module was fitted with a FEBIAD source. Faraday cage and target pit work were carried out whenever access to the areas was possible (both are exclusion areas during 2A proton beam delivery). Preparation for the west target FEBIAD run is ongoing.

To meet Varian specifications, the mounting hardware on all ISAC turbo pumps was inspected and upgraded where necessary. By the end of 2008, the mounting hardware on all ISAC turbo pumps was up to specification, with the exception of the DTL turbo pumps. Administrative procedures were put in place to prevent access to the DTL cage during the operation of the pumps. To address safety concerns, the 2000 l pump in the polarizer section was replaced with a 1000 l pump.

Beam Delivery for 2009

The 2008 winter shutdown ended during the third week of March 2009, so the active beam schedule spanned March to December.

For 2009, 3,446 hours of RIB were produced (68% of the scheduled 5,057 hours of ITE/ITW beam time) and made available for use at ISAC. This includes experimental runtime, development shifts, and

overhead (such as start-up and tuning time). In addition, 6,244 hours of SIBs were available for use from the OLIS.

During this period, ISAC logged 961 hours of downtime. Extraction electrode issues and the failure of the TM4 shutter during the September Ta#29 run-period resulted in 78 hours of downtime. The high power zirconium-carbide target (ZrC#4), coupled with a FEBIAD ion source was scheduled to run in June. The modifications required to use the FEBIAD ion source (mounted in target module 3) in the west target station were not completed on time, and the run had to be cancelled. This accounted for 396 hours of the downtime total.

Although the UO2#2 FEBIAD run-period in November was delayed (resulting in 185 hours of downtime), the ion source (mounted in target module 3) was successfully operated in the west target station in December—a significant achievement. If we eliminate the downtime due to these target and ion source issues, it can be seen (Figure 3) that less than 6% of the scheduled beam time was lost due to other failures in ISAC.

In collaboration with the CERN EURISOL target development group, ISAC tested and irradiated a prototype Al_2O_3 target in the east target station in March 2009.

In September, a leak in the window between the 2A beam line and the west target station was discovered. The window was replaced, but the scheduled target run (ZrC#4) had to be cancelled. ISAC ran its second actinide target (UO2#2) in December 2009. The target saw $426\mu\text{A}\cdot\text{hrs}$ of protons. Similar to the first actinide target run, an extensive set of Yield measurements was carried out, as well as periodic radiation safety measurements.

During development on an experimental $4\text{He}2+$ “alpha” CUSP source it became possible to make a mass measurement at MEFT. This required operating the RFQ at $A/q=2$ —an historic first that was achieved in December 2009.

The following experimental facilities received beam from March 18, 2009 to December 21, 2009: 8π (S823, S1215); $\beta\text{NMR}/\beta\text{NQR}$ (M1042, M1153, S1155); DRAGON (S1216, S1219); MTV (S1183); TIGRESS (S1107, Test); TITAN (S1073, S1112, S1148); TRINAT (S1127); TUDA-II (S1103, S1147); Yield (S841); and Yield EURISOL (S1149).

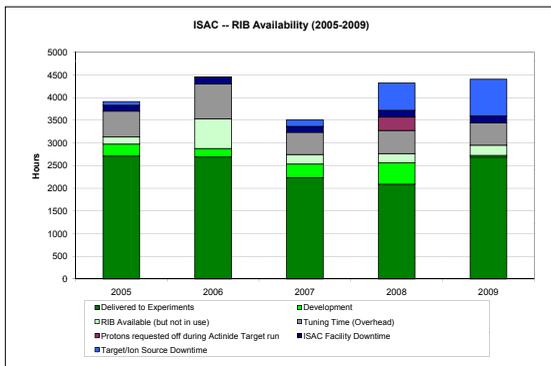


Figure 3: ISAC - RIB availability 2005-2009

Major Jobs in 2009

To meet Varian specifications, the mounting hardware on all ISAC turbo pumps was inspected and upgraded where necessary. Following the upgrade of the remaining three DTL turbo pumps in September, the mounting hardware on all ISAC turbo pumps was up to specification.

ISAC's current monitor system was commissioned in November. The system, which is in compliance with the ISAC-II safety report, allows the delivery of approved ion beams with energies greater than 5 MeV/u into the ISAC-II experimental hall.

Cornelia Hoehr is the TR13 operations coordinator for the PET program, and also leads the proton therapy program.



Existing Accelerator Facilities TR13 Cyclotron Operations

The TR13 is the smallest cyclotron at TRIUMF, accelerating H⁺ ions to 13 MeV. It is located in the meson hall Extension and produces isotopes which are primarily used for the production of medical isotope tracers. The main programs supported are the Pacific Parkinson's Research Centre and the BC Cancer Agency.

Progress in 2008 - 2010

We are pleased to report that 2008–2009 were two very productive years, without significant downtime. Between January 1, 2008 and December 31, 2009, the TR13 Operations group delivered activity to 21 approved experiments. The different isotopes with their half lives are ¹³N (9.97 min), ¹¹C (20.36 min), ¹⁸F (109.77 min), ⁵⁵Co (17.53h), and ⁵⁶Co (77.3 d). A total of 2,804 different runs were carried out, adding up to 28,100.1 μAh of beam delivered. The amount of beam delivered for production and development per target is shown

Target Material	Target #	Product	Delivered Beam (μAh)	Scheduled Beam (μAh)	Efficiency (%)
¹⁸ O/ ¹⁶ O ₂	EA	¹⁸ F-ND ₂	455.6	394.1	118
Fe foil	FC	⁵⁵ Co	0.8	0.8	100
Ni foil	FC	⁵⁵ Co	5.5	5.0	110
¹⁸ O/ ¹⁶ O ₂	FD	*	3,467.3	3,356.5	108
Ar/F ₂	FD	¹⁸ F/F ₂	436.2	403.5	108
¹⁸ O/ ¹⁶ O ₂	DB	¹⁸ F	3,5699.9	3,5590.0	101
N ₂ /H ₂	DD	¹³ N/ ¹³ C	8199.1	6754.1	82
Production Total			26274.4	24594.0	107
¹⁸ O/ ¹⁶ O ₂	EA	¹⁸ F-ND ₂	45.6		
N ₂ /O ₂	FC	¹³ C/ ¹³ O ₂	308.9		
¹⁸ O/ ¹⁶ O ₂	FD	*	226.4		
Ar/F ₂	FD	¹⁸ F/F ₂	68.3		
¹⁸ O/ ¹⁶ O ₂	DB	¹⁸ F	6.5		
N ₂ /H ₂	DD	¹³ C	538.2		
Ar			531.8		
Development Total			1828.7		

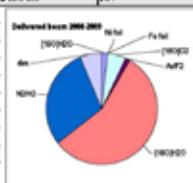


Table 1: Beam delivered in 2008-2009. The scheduled beam excludes runs cancelled by the user:
* This is the so-called “two shoot” method of producing [¹⁸F]F₂. The irradiation of [¹⁸O]O₂ produces ¹⁸F and the irradiation of Ar/F₂ recovers the [¹⁸F]F₂ from the target.

in Table 1. The table also indicates the scheduled versus delivered beam.

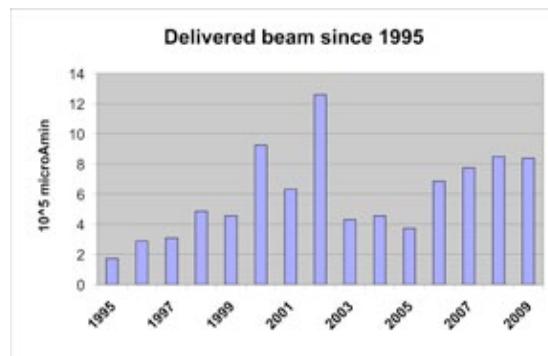
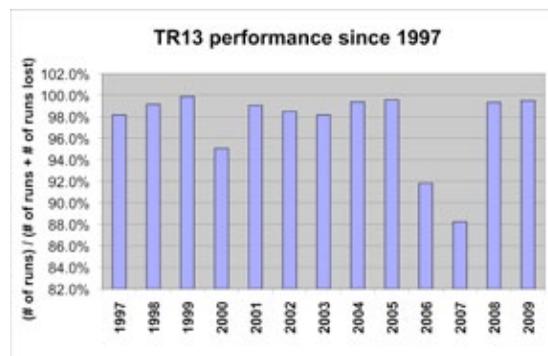
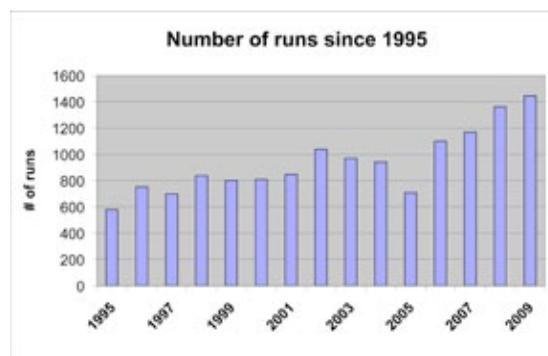


Figure 1: TR13 performance since 1995-1997. The numbers of lost runs in 1995 and 1996 are not available.

Figure 1 shows the number of runs, delivered beam, and performance in comparison to earlier years. A clear increase in the number of runs can be seen. In 2008, we lost only nine runs, and in 2009 only 5 runs, because of problems at the TR13 cyclotron and the rabbit line used to send the tracer to the University of British Columbia hospital. These statistics show 99.5% reliability for the TR13 and the rabbit line combined for both years.

TR13 Enclosure:

The biggest project by far in 2008–2009 was the design and installation of an enclosure around the TR13 cyclotron. Figure 2 shows that this enclosure has its own ventilation system and functions like a fume hood. All activity produced inside is



Figure 2: Enclosure around the TR13 cyclotron (in blue).

confined. The new structure ensures independent operation of the cyclotron from the rest of the meson hall extension. Its design was approved in the fall 2008, its installation started in January of 2009, and it was fully commissioned in the summer of 2009.

Target Development:

A new target was installed and tested to produce $[^{11}\text{C}]\text{CO}_2$. The starting material in the target is a mixture of N_2 and 0.5% O_2 . Aluminum, tantalum, and niobium were tested as target body materials. The niobium target body yielded the highest amount of activity (92% of the theoretical yield).

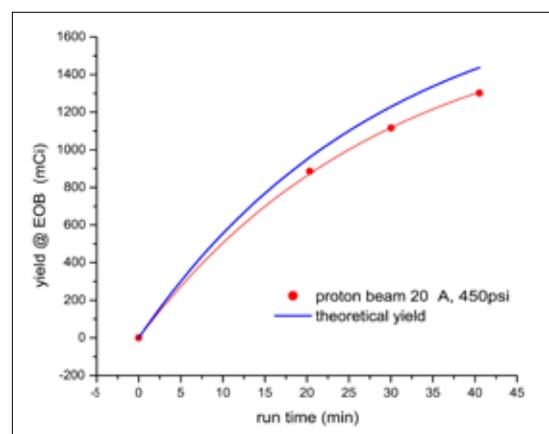


Figure 3: Yield measurement of $[^{11}\text{C}]\text{CO}_2$ with niobium target body. Proton beam current is $20\ \mu\text{A}$, the pressure in the target during irradiation is 450 psi.

Robert Laxdal is a research scientist at TRIUMF, a deputy of the Accelerator Division, and is the head of the superconducting radio Frequency (SFR) development and projects group. Bob is also project leader for the Phase II upgrade of ISAC-II.



Existing Accelerator Facilities

ISAC-II Accelerator and Beam Line Upgrades

Energetic particle beams enable much of modern research in the physical sciences. Electrons, protons, and other charged nuclei that are accelerated to high velocity serve as probes for studying the broad range of matter: from new materials, to molecules, to quarks. In all existing and planned ISAC-II facilities, beams are accelerated in evacuated tubes by the powerful electric fields in travelling waves. In linear accelerators (linacs), these 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).

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. Micro-particles of other metals from machining, or absorbed gases during welding, can 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 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 B.C. 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.

Progress 2008-2010

The energy of the ISAC-II superconducting 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 facility has been 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 in April 2010.

The first experiment to use the new accelerating energy at TRIUMF was "Lifetime measurement of 6.791 state in 15O". In April 2010, the first beam was accelerated by the SCC cryomodules with a maximum energy of 9.6 MeV/u for 16O5+. After stable running overnight, the gradients were pushed significantly in the SCC modules achieving a final energy of 10.8 MeV/u.

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.

Ahead for 2010

TRIUMF is now moving forward with the acceleration of rare isotopes to higher energies, allowing nuclear physics studies beyond the Coulomb barrier. Superconducting radio-frequency (SRF) technology is at the leading edge and rapidly expanding; laboratories around the world are lining up to incorporate it into their future projects.

The world market for these devices is expected to grow, quite dramatically, well into the next decade.

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.

There is international interest in developing this technology and building industrial capacity to engineer and construct these machines. As the number of companies capable of producing these cavities is quite limited at present, demonstration of a Canadian capability assures the country a share of the global market.

Friedhelm Ames is a research scientist at TRIUMF, and is the group leader for ISAC Facility Support.



Existing Accelerator Facilities

Charge-State Breeder

The degree of acceleration for an ion depends on its overall electric charge and its mass. For ions with mass greater than 30 amu, substantial acceleration is only possible if the charge state of the ions injected into the accelerator is increased (usually controlled by removing additional electrons). This process is called charge breeding or charge-state breeding. Increasing the energy to which rare isotopes (called ions or radioactives when they are ionized to give them net electrical charge) can be accelerated at ISAC-II enables new classes of nuclear-reaction experiments.

Progress in 2008–2009

In order to avoid further losses from stripping after the radio frequency quadrupole (RFQ), the mass-to-charge ratio should be below $A/Q = 7$ to meet the acceptance of the drift tube linac (DTL) and the ISAC-II superconducting linear accelerator. To increase the charge state of ions, an electron cyclotron resonance (ECR) ion source (14.5 GHz PHOENIX from Pantechnik) configured as a charge breeder has been set up. Singly charged ions can be captured inside the plasma of the source and transformed into highly charged ones before they are extracted. Following successful off-line tests it was moved to the ISAC facility and installed in the mass separator room during the shutdown period in 2008 and the following maintenance cycle.

After completion of the set-up, a first test run was performed in November 2008 culminating in the first acceleration of charge-bred radioactive ions. A beam of singly charged ^{80}Rb ions from an on-line Ta target and surface ion source was directed into the charge breeder. The extracted $^{80}\text{Rb}^{14+}$ ions were transported to the RFQ and accelerated to an energy of 150 keV/u. The efficiency for the charge-state breeding at this time was about 1%.

During 2009, several periods of running time were used for further optimization and final commissioning with both stable and radioactive ions. In addition to the ISAC on-line ion sources, a test ion source has been used. The test source is integrated into the beam line leading up to the charge breeder and can deliver singly charged Cs ions from a surface source. It allows the set-up of the ion optical elements and the optimization of the breeding process independent from the on-line sources. A maximum efficiency of 2.4% for the charge-state breeding of stable Cs^{21+} was achieved with this source. During the 2009 running period, a failure in the on-line target ion source systems restricted the use to only beams from surface ion sources, both from the west and east target station equipped with Ta or Nb targets.

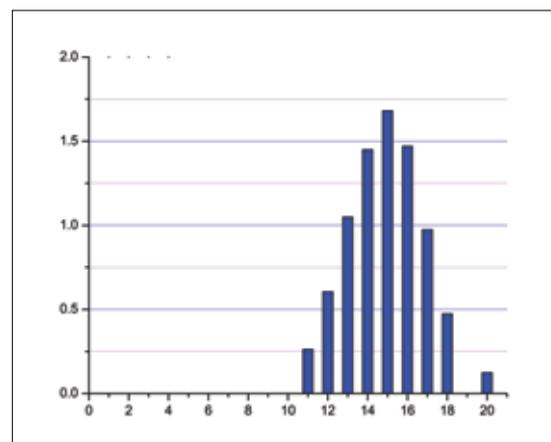


Figure 1: Efficiency for the charge state breeding of ^{76}Rb ions from a high power Nb target / surface ion source from ITE as function of the charge state. 3.8×10^6 singly charged ions have been injected into the charge breeder source.

Ahead in 2010

Radioactive ions charge bred so far are: ^{46}K , ^{64}Ga , ^{76}Rb , ^{80}Rb , ^{122}Cs , and ^{124}Cs . Figure 1 shows the efficiency measured as the ratio of the extracted number of ions to the number of injected ions

for different charge states of ^{76}Rb . Although the maximum efficiency of 1.7% is already close to the value obtained at the off-line tests, further optimization will continue to improve this number and extend the range of isotopes to those with shorter half lives and different elements.

Syd Kreitzman is the CMMS Facility group leader at TRIUMF and the technical advisor to the TRIUMF Condensed Matter EEC.

Existing Accelerator Facilities

M9 and M20 Beam Line Upgrade

TRIUMF is one of only four facilities worldwide to provide muon beams for research in the fields of materials and molecular science. Indeed, the wide applicability of muon-spin rotation (μ SR, where the R can stand for rotation, resonance, or relaxation) to significant areas of condensed matter physics and physical chemistry has prompted the Canadian science community and the research agencies (NRC, CFI, BCKDF, and NSERC) to support an expansion of TRIUMF's infrastructure for its Centre for Molecular and Materials Science (CMMS) Facility. Completion of these new muon beam lines (M9A in 2010; M20 in 2011) will enable the provision of state-of-the-art μ SR capabilities to a widening user community allowing for the utilization of this technique in the service of their own specific fields of research. TRIUMF's β -NM/QR (beta-detected nuclear magnetic/quadrupolar resonance) Facility, which provides analogous experimental capabilities for surface and interface materials science, continues to upgrade the efficiency of its operations with the introduction of advanced (multiple) sample handling ultra high vacuum methods.

New M9A Muon Beam Line

TRIUMF supports the development of M9A, a new surface muon beam line which deploys next generation technologies both in the beam delivery infrastructure and at the final measurement spectrometer. The layout of this channel is shown in Figure 1. Two salient devices contribute to the beam line's high performance [1], the fast electrostatic kicker and the achromatic Wien filters/spin rotators. The kicker has the capability to turn on within 250 ns of a detected muon thereby preventing any subsequent muons from entering the beam line and compromising the measurement.

This Muons On REquest (MORE) capability, first proposed by TRIUMF [2] and later implemented at PSI [3], allows the standard experimental time window of 8–10 μ s to be doubled thereby increasing the measurement's sensitivity to small changes and subtle effects by over an order of magnitude.

Modern muon beam lines must have the dual capability of removing contaminating particles and precessing the beam polarization so that they become perpendicular to the beam direction; the latter enabling the important task of very accurate beam injection into a high magnetic field. Both functions can, in principle, be actualized with the use of a Wien filter, a device with crossed electric and magnetic fields. For the purposes of beam cleansing a modest device is sufficient but to accomplish 90° spin rotation very high voltages are required, and doing so efficiently and robustly is a particularly difficult technical challenge. The Wien filter design in M9A confronts the electrostatic complexities with an innovative design restricting vacuum fields to < 65 KV/cm. Equally unique is TRIUMF's utilization [4] of a split rotator configuration, in which an intervening aberration cancelling triplet allows the transmitted luminosity to be unimpaired.

The final distinct aspect of the M9A beam line concerns its "working end" which is comprised of magnet-spectrometer sub-systems which provide the sample environment and a detector array which transforms the information embedded in the muon's decay signature into a very detailed picture of the electromagnetic environment and correlations relevant to the material under study. Specifically, the M9A magnet is an advanced design, 3 T, large bore, superconducting split solenoid which provides 1 ppm high field

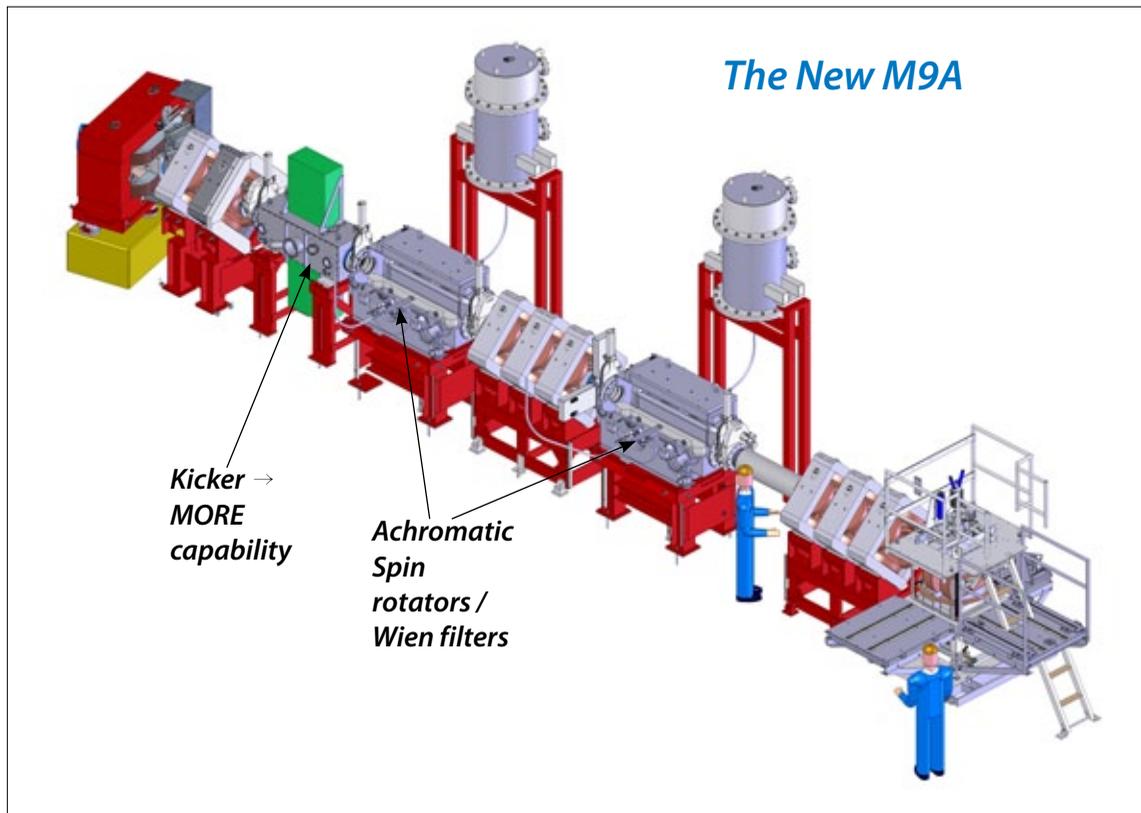


Figure 1: Rendering of the new M9A muon beam line section (downstream of the B2 dipole).

homogeneity, 3-axis zero field compensation, and a “magic T” room temperature bore to enable optimal low- and high- field geometries.

Upgraded M20 Muon Beam Line

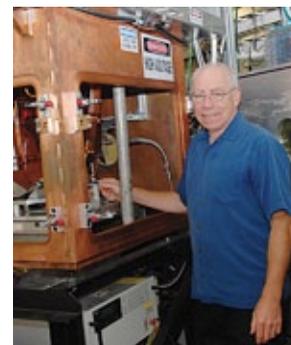
As of early 2010, the M20 upgrade project, in its advanced design stages, was awarded contracts for all major devices. Before this upgrade, the channel’s utility was limited by relatively low luminosity because it was originally envisioned for purposes other than 4.1 MeV surface muon transport. Moreover, it contained a conventional single-element, low-efficiency spin rotator. In keeping with M9A developments, the upgraded M20 is designed for high luminosity, utilizes an appropriate version of a dual achromatic Wien

filter/spin rotator, and incorporates further MORE capability [5]. Specifically, the new M20 will allow for a simultaneous use of the MORE leg with the conventional leg, thus further enhancing the productivity of the beam line.

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- [3] See <http://lmu.web.psi.ch/facilities/more.html>
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- [5] J. Doornbos, Design notes by Jaap Doornbos at <https://documents.triumf.ca/docushare/dsweb/View/Collection-4215>

Pierre Bricault is the Target/Ion Source Development group leader at TRIUMF and an adjunct professor with Université Laval.



Existing Accelerator Facilities

Actinide Target Development

Until recently, the ISAC facility at TRIUMF has been limited to the use of targets with $Z \leq 82$ and, by extension, to the production and delivery of rare-isotope beams (RIB) with atomic masses less than about 170. Other facilities use targets of actinide compounds to produce heavier and more neutron-rich isotopes of scientific interest for their experimental program. Furthermore, such targets could be used for the production of RIB by photofission using an electron linac driver in combination with a conversion target. As a result, the use of actinide targets at ISAC and the projected Advanced Rare Isotope Laboratory (ARIEL) facility is a key part of TRIUMF's current Five-Year Plan. [1]

Progress in 2008–2010

ISAC was initially limited to the use of targets with $Z \leq 82$ as a condition of TRIUMF's operating license. TRIUMF worked with the Canadian Nuclear Safety Commission (CNSC) to amend the license to include restricted use (low proton beam intensity) of actinide-based target materials as a first step towards routine operation. A safety analysis report which addressed the specific characteristics of actinide targets was submitted to the CNSC in January 2008, and the Commission approved a first test in August.

The test, consisting of two separate stages, began on August 29 with a proton beam current of $1 \mu\text{A}$. The first stage comprised $100 \mu\text{Ah}$ of proton beam on target and was intended to study the potential migration of activity through the target and rare-isotope beam line vacuum systems as well as to review the additions to the ISAC radiation monitoring system and other infrastructure. In the second stage, an additional $196 \mu\text{Ah}$ of protons beam were put on target, and RIBs generated with

a surface ion source were transported to the ISAC experimental hall for yield measurements.

The results of the first test were compiled and a final report submitted to the CNSC in June 2009. A license amendment was granted in November [2] allowing a second low-current run to take place in December 2009. During this run $426 \mu\text{Ah}$ of proton beam—at currents of up to $2 \mu\text{A}$ —were put on target. Yield measurements of RIB from a FEBIAD ion source focused on the neutron-rich isotopes of the noble gases Ar, Kr, Xe, and especially Rn. RIBs were also delivered to the 8π spectrometer on a trial basis. Data from this run are still being analyzed.

Ahead in 2010

Based on the experience of the previous runs, improved target material compounds are currently being developed. The next actinide target run at ISAC is expected in late 2010.

The Team

Leads for ISOL Target Group: P. Bricault, M. Dombisky, P. Kunz
Lead for Beam Delivery Group: C. Morton

References

- [1] Five-Year Plan 2010—2015: Building a Vision for the Future, M. McLean and T.I. Meyer, editors-in-chief, TRIUMF (2008).
- [2] <http://nuclearsafety.gc.ca/eng/commission/pdf/2009-11-19-Division-TRIUMF-CMD09-H125-Edocs3459234.pdf>



Keerthi Jayamanna is a research scientist at TRIUMF, and works in the ISIS Development group.

Existing Accelerator Facilities

OLIS Development

The Off-Line Ion Source (OLIS) was originally built to provide pilot beams for the beam line network under construction at ISAC prior to 2000. It had a single ion source driven by a microwave generator. As more types of isotope beams became available, interest began to arise in using OLIS beams for their own sake in nuclear physics experiments. A surface ion source was proposed and built to serve this function. Accommodating it together with the existing ion source required a multi-headed vacuum box—the cornerstone of OLIS today (see Figure 1)—and a major reworking of the OLIS high voltage cage, marking the second generation of this facility. The surface source proved capable during beam development and was used for several production beams, notably select alkaline metal beams delivered for the polarizer, β -NMR and DRAGON facilities. A commercial Supernanogan ion source was purchased, prepared and installed over 2007 and

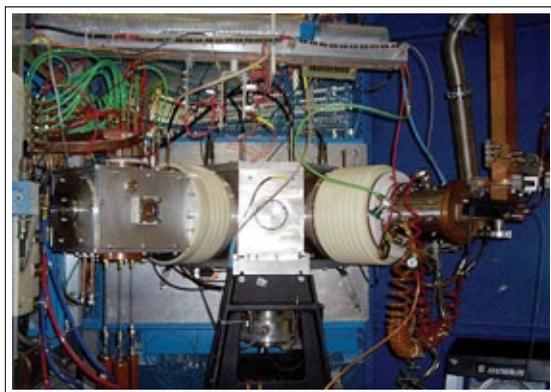


Figure 1: OLIS 3-way vacuum box.

2008, to add multi-charge capabilities to OLIS. This marked the facility's third generation, and greatly expanded the range of beams possible from OLIS, particularly from the heavier elements

of the periodic table. The Supernanogan and the preexisting microwave and surface ion sources play an important role at ISAC because they are used to provide pilot beams for accelerator tuning and specific beams for experiments.

A proposal was made to enhance OLIS to handle multi-charge beams. A commercial Supernanogan ion source from Pantechnik was purchased and fitted. This ion source is capable of producing many of the beams previously produced in the microwave ion source, affording the luxury of a backup ion source in the event of failure. It is also capable of producing multiple (electric) charge states of the same ion, making it a versatile and desirable ion source. This source is mounted onto a removable cart, which can be docked outside of the OLIS high voltage cage during maintenance (see Figure 2).

Progress in 2008–2010

The Supernanogan [1] source was tested for the first time in November 2008. The first multi-charge ion beam was produced and confirmed on December 2, 2008. Completion of fittings and controls occurred over the January 2009 shutdown period. First commissioning followed. The first beam sent to a scheduled experiment occurred on May 23, 2009. Since then, this ion source produced the majority of scheduled beams from OLIS [2].

At the end of the 2009 beam schedule, an ion source development was undertaken at OLIS using a custom CUSP ion source to generate a ${}^4\text{He}^{2+}$ "alpha" beam. Although this was primarily a feasibility study, it set a milestone at ISAC. This was the first filament-type ion source ever used at ISAC. It produced a beam of $A/q=2$, which was sent through the radio frequency quadrupole

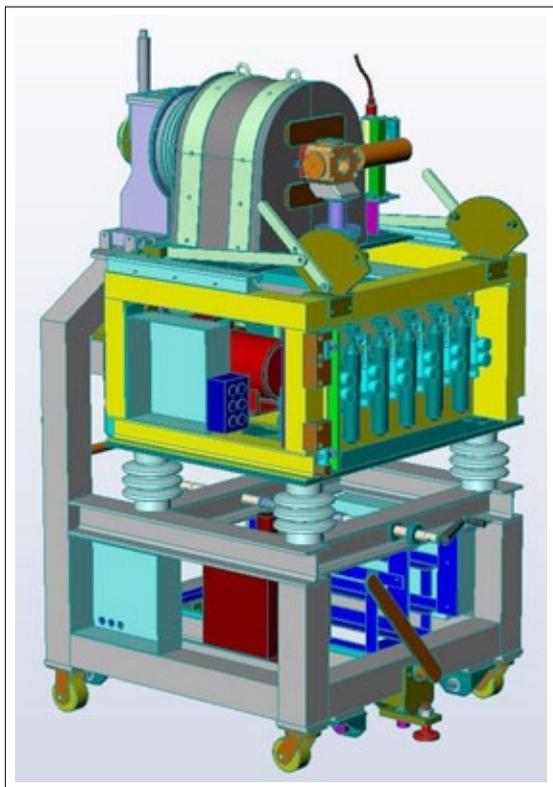


Figure 2: Supernanogan ion source and cart.

(RFQ) accelerator on December 18, 2009, setting a new acceptance record for that accelerator.

Over the summer of 2008, a system was developed and implemented to monitor and stabilize the OLIS separator magnet field. The initial motivation for this effort was to enable the magnet to separate out many of the closely spaced beams from the Supernanogan.

Over the reporting period of 2008 and 2009, the following beams were produced and delivered from OLIS. In 2008: $^{16}\text{O}^{2+}$, $^{18}\text{O}^{1+}$, $^{21}\text{Ne}^{1+}$, $^{22}\text{Ne}^{2+}$, $^{23}\text{Na}^{1+}$, $^{24}\text{Mg}^{1+}$, $^{27}\text{Al}^{1+}$ and $^{33}\text{S}^{2+}$; and in 2009: $^{12}\text{C}^{1+}$, $^{12}\text{C}^{3+}$, $^{16}\text{O}^{2+}$, $^{16}\text{O}^{3+}$, $^{16}\text{O}^{7+}$, $^{16}\text{O}^{8+}$, $^{17}\text{O}^{3+}$, $^{17}\text{O}^{6+}$, $^{18}\text{O}^{1+}$, $^{18}\text{O}^{2+}$, $^{18}\text{O}^{4+}$, $^{20}\text{Ne}^{1+}$, $^{20}\text{Ne}^{2+}$, $^{21}\text{Ne}^{1+}$, $^{22}\text{Ne}^{2+}$, $^{25}\text{Mg}^{1+}$, $^{27}\text{Al}^{1+}$ and $^{33}\text{S}^{5+}$. Emittance of $^{16}\text{O}^{+3}$ is shown in Figure 3.

Ahead for 2010

A heater ion source is presently being fitted to the Supernanogan plasma chamber. Once completed and tested, it will be able to produce beams from solid materials that can be compacted and evaporated at a controlled rate, much like the surface ion source. Later, a sputter source will also be fitted, so that metal ion beams can be produced as well.

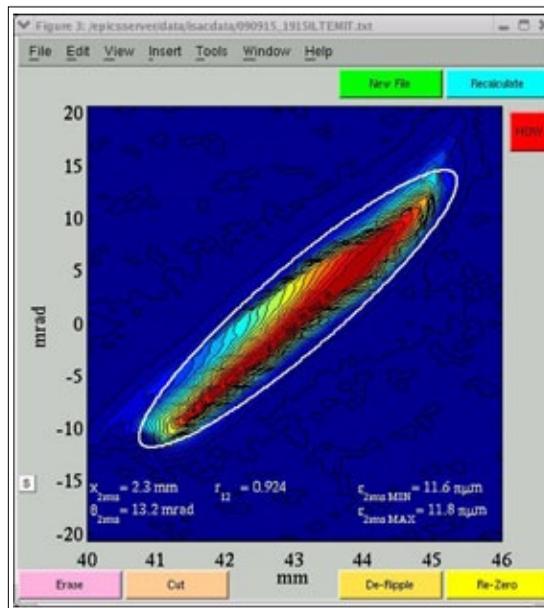


Figure 3: $^{16}\text{O}^{3+}$ Emittance scan 10π mm-mrad at 90%.

Late last year, OLIS was used as a test stand for a developmental ion source intended for helium beams. This source was removed again after completion of the tests. Future tests such as these are anticipated.

It is expected that the majority of beams from OLIS will be provided from the Supernanogan ion source. Standard beams are planned for 2010, as well as enriched sulphur, magnesium, and germanium beams. The former beams can be made in either available ion source, whereas the heavier beams require the Supernanogan. Both heater and sputter source development with the Supernanogan are planned prior to delivering these beams.

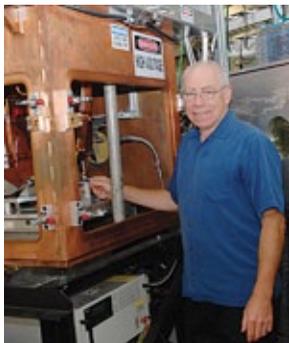
The Team

Lead: K. Jayamanna

Members: Geoff Wight, Ray Dubé, Damien Gallop

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- [2] Magee, M., and G. Wight et al., Supernanogan ion source delivers first beams, *TRIUMF Current Events* (July 24, 2009).



Pierre Bricault is the Target/Ion Source Development group leader at TRIUMF, and an adjunct professor with Université Laval.

Existing Accelerator Facilities

Ion Beam Development

During the design study of the EURISOL facility, four generic classes of high-power targets were studied: refractory and molten metals, oxides, and carbides. Over the past two years, TRIUMF contributed to the development of an oxide target made of stacked Al_2O_3 on Nb composite discs. The EURISOL team utilized the high-power target container, which was developed at ISAC-TRIUMF [1].

The target stack itself was made, loaded, and outgassed at ISOLDE and then shipped to TRIUMF. A new forced electron beam induced arc discharge (FEBIAD) ion source was developed for this test. It has a cold transfer line to remove the non-volatile contamination. The 500 MeV proton beam was shaped in size and intensity to match the EURISOL power density. The target prototype operated at 25 μA with a peak at 30 μA for a total of 3174 μAh over nine days.

Introduction

The rationale for this test came from the ongoing EURISOL-DS project aimed at developing the next generation of European ISOL-type, rare-isotope facility. The EURISOL reference design is based on a 1 GeV proton beam with a multiuser facility operating several target stations in parallel. The target station comprises a 4 MW dual Hg converter-fissile target and three 100 kW direct target stations [2].

We present in this report the development and the on-line tests of the oxide target. These tests constitute the basis for validation of tools required for the design of a high-power oxide target.

ISOL Direct Targets

Today, ISOL (isotope separation on-line) direct targets are operated at kW dissipated power levels, except for a few refractory metal foils and composite graphite-carbide targets developed at ISAC-TRIUMF. These targets are operated up to 100 μA and 70 μA , respectively [3]. Routine operation of targets at 100 kW poses several problems including heat dissipation, and material and target container integrity over extended periods.

Oxide targets are particularly difficult to operate because they have a low thermal conductivity and a low operating temperature, which ranges between 1000 and 1700 K. The low operating temperature makes the radiative heat exchange practically inefficient.

Target Container Design

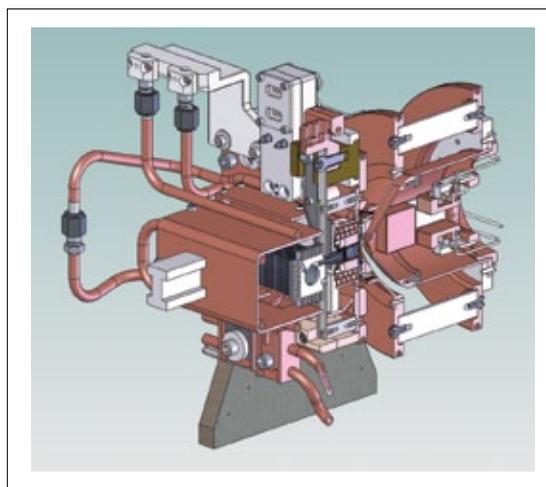


Figure 1: A section view of the target ion source assembly in use at ISAC.

Figure 1 shows a schematic of the target/ion source for the FEBIAD assembly. The proton beam comes from the right at a normal angle with respect to the heavy ion beam axis. The high-power target is made of a tantalum tube and tantalum radial fins. The oxide/Nb discs assembly are inserted into the tantalum container. The vapour migrates toward the FEBIAD ion source to produce the rare-isotope beams. The high-power target developed at ISAC utilizes the radiative cooling towards a water-cooled heat shield. The addition of fins on the tantalum container enhances the effective emissivity to 0.92 [1].

Composite Refractory Metal Foil and Oxide Discs
The target material was developed at CERN. To improve the effective heat conductivity, and the mechanical properties of the target, a composite structure was used, with the oxide layer supported onto a Nb foil. This is a technique similar to the one used for our carbide/graphite composite target [4]. In this case the Nb foil replaces the graphite sheet. The porous alumina is 1 mm thick and 15 mm in diameter. The alumina discs were brazed onto Nb foils with a 100 μm reactive brazing alloy (86.2 Ti, 10.2 Al, 3.6 V).

On-line Tests at ISAC Using the TRIUMF 500 MeV Cyclotron

The EURISOL oxide target test was approved for 24 shifts by the EEC as experiment S1149 and received proton beam from March 22–31, 2009. The oxide target discs provided by the EURISOL collaboration were inserted into the high-power target container provided by TRIUMF and then mounted onto the ISAC target module equipped with a FEBIAD ion source. The FEBIAD ion source was developed at TRIUMF using the same concept used at GSI by R. Kirchner [5] and at ISOLDE-CERN by Sundell [6]. Figure 2 shows a section view of the TRIUMF FEBIAD ion source using a cold transfer line to purify the neon beams.

During the test, the beam intensity on target was increased gradually while selected isotope yields were monitored. Because the heat comes from the proton beam interaction with the target material, it is of prime importance to monitor the proton beam profile during the entire run. We maintained a beam size profile at FWHM of 6 to 6.5 mm. Figure 3 shows the resulting yields obtained for different neon isotopes and incident proton beam intensity. The release performance of the target improved with proton beam intensity by more than a factor of 10. This can be understood simply when

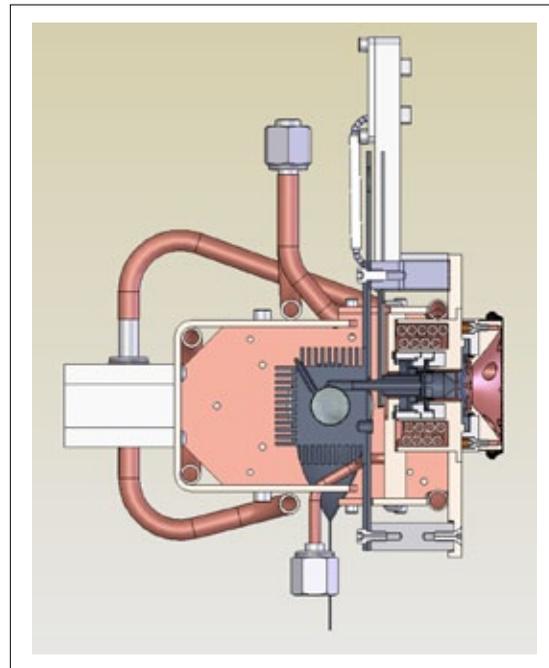


Figure 2: Section view of the new FEBIAD ion source using a cold transfer line.

one realizes that the target material reaches its optimum temperature at 25 μA .

Discussion and Outlook

This test demonstrated that the composite $\text{Al}_2\text{O}_3/\text{Nb}$ target can operate reliably up to 25 μA . Looking at the yield for neon isotopes as a function of the half-life, the release seems to be faster for the alumina/Nb than with the SiC/graphite foil. We have more than a factor 4 for the oxide compared to the SiC/gr for the short period.

One of the limiting factors of the $\text{Al}_2\text{O}_3/\text{Nb}$ is the brazing material that was used to bind the alumina

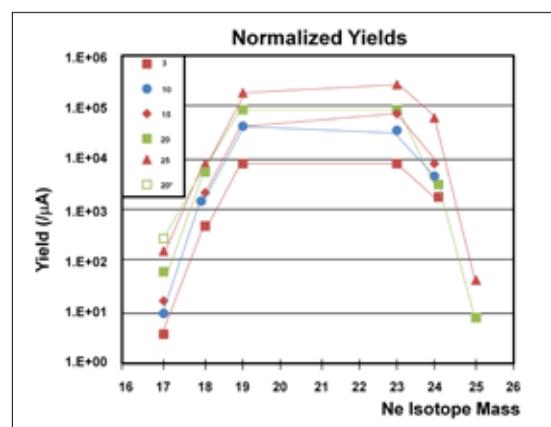


Figure 3: Neon isotope yield normalized to 1 μA as a function of the incident proton intensity.

disc onto the Nb foil. The other limiting factor is the alumina thickness, which is about 1 mm. We can remove these issues by reducing the alumina thickness and simply casting the alumina onto Nb foil and then treating with heat in situ. Samples of casted alumina directly on Nb shows that we can reduce significantly the alumina thickness, ~ 0.1 mm compared to 1 mm.

The Team

Lead: P. Bricault

Members: F. Ames, P. Bricault, R. Catherall, M. Dombbsky, S. Fernandes, T. Stora

Partnering Labs/Institutions:
CERN-ISOLDE, TRIUMF

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Andy Miller is a research scientist at TRIUMF and leads the Detector Group; he is also a member of the TRIUMF Science Division Safety Committee.



Detector Development and Support

The mission of TRIUMF explicitly identifies the detection of particles as a core competency of the laboratory. The Detector Group comprises the core of this expertise. The team includes the Detector Electronics, Facility, and Development groups. This section provides an update on activities and progress since 2008.

Progress in 2008–2010

Detector Electronics

The Detector Electronics group made crucial contributions to the PiENU, Medical Imaging, and ATLAS projects as well as selected nuclear physics experiments.

PiENU: The design of the experiment (described elsewhere) was completed in 2008, and the majority of the sub-detectors were manufactured by April 2009. These are scintillator detectors, which are used to detect charged particles and stopped pions, with wire chambers and silicon strip detectors to measure charged-particle positions, and a calorimeter to measure energies of the positron or photon from the pion decay. All scintillator detectors, wire chambers, and silicon strip detectors were built by the TRIUMF Detector Facility. Refurbishing of the calorimeters was done with strong support of the facility's experts, and the front-end amplifiers for the silicon detectors were designed, manufactured, installed, and commissioned by TRIUMF's Detector Electronics Group. The readout and signal acquisition system for the calorimeters, silicon strips, and wire chambers is based on the VF48 (pulse amplitude digitizer) and VT48 (time digitizer) modules developed initially for the KOPIO experiment.

Medical Imaging with Liquid Xenon: The TRIUMF Detector Group is active in developing an innovative technology for medical imaging based on a liquid xenon (LXe) gamma detector. In 2008–2009, a prototype detector was built, and tests started in fall 2009. The detector is a full-size sector (1/12 of a wheel) of a small animal positron emission tomograph (microPET). The front-end and readout electronics that were built by the group were successfully commissioned. In parallel, the DEG has started design of the full 12-sector microPET cryostat and detector. Conceptual design of the new cryostat was done in the fall of 2008, and its 3D model is being developed.

New techniques of light detection in LXe were investigated, and an optimized layout of photodiodes was proposed. A new concept was developed for detection of LXe ionization signals based on a single printed-circuit board recording events in two dimensions. The advantage of this approach is that no wire lattice is needed in the module design, which simplifies the assembly and guarantees reliable operation. 3D modelling of the chamber is in progress.

ATLAS Detector Upgrades: The TRIUMF Detector Group is collaborating in two ATLAS calorimeter upgrade research and development projects: high-rate tests of the existing liquid argon (LAr) calorimeters and development of a warm forward calorimeter. In 2008–2009, two beam tests of small prototype LAr detectors were performed at the ATLAS high-rate facility of IHEP in Protvino, Russia. Technical expertise and manpower for these tests were partly provided by the Detector Electronics group.

In 2008, ATLAS Canada initiated an international collaboration to develop a new radiation-hard

calorimeter for the forward region of the ATLAS detector. The leading technology chosen for this detector is based on diamond sensors, while an alternative technology could be a moderate-pressure noble-gas ionization calorimeter. For initial tests and for measurements of radiation hardness, several types of diamond sensors were selected and purchased. Instrumentation for characterization of diamond detectors was prepared and samples were tested with α and β sources. Another arrangement for radiation tests and qualification is being prepared.

Nuclear Physics Experiments: In the fall of 2008, the Detector Group developed and prototyped two low-noise preamplifiers for the new SHARC silicon detectors and for the QWEAK diamond tracker. Both amplifiers are based on an upgrade of a design previously developed for the LXe PET sector and for the PIENU silicon-strip detectors. The first batch of SHARC boards was manufactured and used in a 2009 run, while the first batch of QWEAK amplifiers is being tested.



Figure 1: The inner box of a T2K TPC after assembly and gluing in the facility's large clean room. The top, bottom and sides of the inner box are Cu/G10/Rohacell/G10/Cu laminate with the copper milled on our large router to produce field strips. The outer TPC box panels are Al/Roha/Al laminates.



Figure 2: A view of a T2K TPC inner box assembled into the outer box in the clean room; one of the twelve sets of MicroMegas readout electronics is installed for testing.

Detector Facility

The Detector Facility had one major project during 2009: the Tokai to Kamioka (T2K) experiment at J-PARC in Japan. The Canadian T2K group and the TRIUMF Detector Facility were responsible for the design, construction, testing, and installation of the five large tracking chambers that serve as the core for the "Near Detector" located only 280 m from the neutrino production target.

The tracking chambers were of two types: time projection chambers and a fine-grained detector.

Time Projection Chambers: Of the first type are the three large high-precision gaseous time projection chambers (TPCs) for tracking charged particles, each $\sim 2 \times 2 \times 1$ m. For the first time, they employ MicroMESH Gaseous Structure (MicroMegas) electron sensors, which were supplied by European collaborators. Figures 1-3 are photographs of a T2K TPC. After years

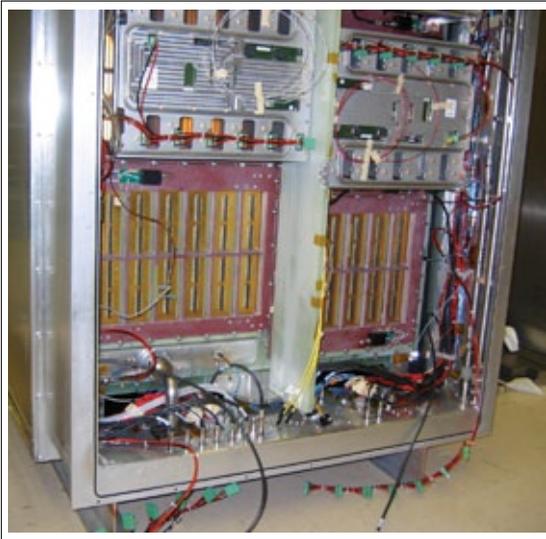


Figure 3: A zoomed view of a T2K TPC with two sets of readout installed.

of design and prototyping, the first production TPC was finished in 2008 and was moved to the TRIUMF M11 beam line for beam tests in early May 2008. This TPC stayed in M11, with more readout electronics being added for testing and DAQ development until mid-November 2008. The production and testing of the rest of the TPCs in the facility took place in the latter half of 2008 and early 2009.

Fine-Grained Detector: The second type of tracking chamber is the fine-grained detector (FGD), two of which serve as active targets for the neutrino beam produced by the J-PARC accelerator complex. These FGDs are $\sim 2 \times 2 \times 0.3$ m, and there are two types. The first type is made from fifteen XY layers of polystyrene scintillator material. Each XY layer consists of two layers of 10×10 mm scintillator bars with a single axial hole and co-extruded TiO_2 outer coating. The light produced by each of these $\sim 6,000$ scintillator bars is collected by a wavelength-shifting fibre and fed to a new type of optical sensor used here for the first time—the Multi-Pixel Photon Counter (MPPC). Figures 4 and 5 are photographs of the first FGD. The second type of FGD is called “passive water” and consists of seven XY layers alternating with six 30-mm-thick water layers. Each water layer consists of an extruded polycarbonate panel (commercially available) that has its ends sealed with epoxy. A subatmospheric-pressure water circulation system was designed and built so that small leaks will not cause water to drip out into the containing darkbox.



Figure 4: The first T2K FGD being assembled in the large TRIUMF clean room. Each of the fifteen XY-layers of scintillator is lifted onto the assembly jig with a vacuum lifter. Then the top, bottom and sides of the aluminum darkbox are assembled around it.

All the TPCs and FGDs were shipped to Japan in 2009 as follows: TPC #0 and FGD #1 in June, FGD #2 in July, TPC #1 in August, and TPC #2 in November. All have now been successfully installed in the experiment and commissioned. The first cosmic events were seen in both FGDs on October 19, 2009. The first TPC cosmic events were seen on December 18, 2009, and in all three TPCs on January 21, 2010. Since then, the surrounding



Figure 5: The T2K FGD darkbox after being rolled out of the clean room and rotated to the vertical on the jig. After being lifted off the jig, the front and back covers are installed, and the FGD is ready to move to M11 for installation of the electronics and beam testing. For shipment to Japan, the electronics and covers are removed and the FGD is rotated back to horizontal on the same jig.

1000 ton magnet has been closed and the first neutrino candidate events have been seen. There is still some work remaining to optimize the performance of the FGD and TPC readout and data acquisition system, but for the detector facility the project is essentially complete. It is considered a huge success for the T2K group and TRIUMF.

Large-Table Router: In 2009, the 3 x 3 m Router Facility played an essential part in the construction of the T2K TPCs and T2K FGDs. It was heavily used to machine the TPC inner and outer box composite panels and endplates. Machining inner box panels required critical work to meet the high tolerances. The cutting of the field strip patterns was the most difficult. The router was also used to scribe the nominal locations for the hundreds of aluminized dots and strips on the TPC central cathode, which serve as targets for an ultraviolet laser for generating fiducial signals. The router was also used to survey their final locations, so that each TPC half would have a calibrated pattern to correct for electronic and magnetic field distortions in the experiment. The router was also used to machine the FGD XY layers and the darkbox front/back covers.

T2K Gas System: While the TPCs and FGDs were being fabricated, assembled, and tested, a parallel facility effort was the T2K gas system for the TPCs. This gas system is large and complex and has two parts. The first part is a one-pass, 15 L/min CO₂ system for the three outer box volumes, while the second is a 30 L/min, mixed, recirculated and purified argon/CF₄/isobutane system for the three TPC inner boxes. Tight pressure matching ($< \pm 0.1$ mbar) between the inner and outer volumes was required. Controlling the system during operation and chamber flushing required a complex control system.

This gas system was the major effort of Robert Openshaw and Marielle Goyette during 2009 (and earlier years). Figure 6 shows a photograph of the gas system during testing in the TRIUMF MHESA facility, filling eight racks. The system was installed and commissioned at J-PARC in late 2009 and is operating very successfully.

Scintillator Shop: During 2009 the heavily used Scintillator Shop continued to function as the machining centre for the facility. In addition to a wide variety of scintillators fabricated for μ SR, approximately 50% of the effort was on fabricating pieces for the T2K project. Other large efforts in the shop were for the PiENU and Liquid Xenon



Figure 6: The TPC gas system being tested at TRIUMF before shipment to J-PARC.

projects.

In 2009 the Detector Facility staff worked closely with the PiENU group to complete the installation of the wire chambers and scintillation detectors. This is a complex set of nested detectors with very tight clearance tolerances. The coordinated use of 3D modelling by the Design Office and Detector group was essential for the successful installation

Also in 2009, Grant Sheffer coordinated the installation of the GE Advance PET medical scanner for the Pacific Parkinson's Research Centre at the UBC Hospital. In the fall of 2009, Dr. Sheffer attended an intensive five-day training course for the maintenance of this scanner. He will continue to work closely with TRIUMF's Division of Nuclear Medicine to ensure this scanner is properly maintained.

Detector Development Group

While the T2K FGD was being constructed, a program aimed at characterizing multi-pixel photon counters (MPPCs) was launched in order to understand their impact, if any, on the FGD performance. Little information was available about the MPPC response because they had never been used before in a physics experiment. In T2K, MPPCs are used to detect the light emerging from 1 mm-diameter, 2 m-long, wavelength-shifting fibers. MPPCs are pixilated Geiger-mode avalanche photo-diodes. In other words, they convert a photon into an electrical signal—a charge of about 10^6 electrons.

The number of photons hitting the device is measured by counting the number of pixels that avalanche. The response eventually saturates at large light levels due to the nature of the Geiger-

mode avalanche, because it is impossible to know how many photons hit the same pixel at the “same” time. MPPCs were chosen to equip the T2K scintillator detectors because they are insensitive to magnetic field, unlike photomultiplier tubes that have been used for decades; however, known nuisances (dark noise, after-pulsing, cross-talk, and saturation) had to be characterized in order to understand how to operate and calibrate the devices and process their signals. TRIUMF spearheaded this work within the T2K Near Detector collaboration. A paper about after-pulsing was published in 2008 by the TRIUMF group. A complete paper summarizing the characterization of the MPPC response to low light level (less than 100 photons) is about to be submitted by the T2K photosensor group. A third paper about the response to more than 100 photons is being prepared by Imperial College in London and TRIUMF.

As the MPPC characterization effort for T2K reached maturity, a program was started to investigate using MPPCs for other applications. The MPPC characterization effort has led to the conclusion that MPPCs provide significantly better performance than PMTs provided that they

are operated and calibrated with care. At TRIUMF, MPPCs are starting to be used in a number of experiments where they outperform PMTs (for example, yield station, muSR). MPPCs are serious contenders to equip the next generation PET scanners, especially because they are insensitive to magnetic field and allow simultaneous operation of PET and magnetic resonance imaging (MRI).

In 2009, a test facility was assembled to investigate the use of T2K MPPCs to instrument a $1.5 \times 1.5 \times 30$ mm³ LSO crystal; the most widely used scintillating crystal in new PET scanners. While the length (30 mm) of the crystal was too long to allow optimum energy and timing resolution, the project was successful in two ways: 1) high-speed electronics, optimum for MPPC readout, was developed; and 2) the T2K MPPC simulation program was reconfigured to handle scintillation light from LSO crystals, which allowed the interpretation of the data in detail. Furthermore, this work, and the work done at several other institutions, show that MPPCs are expected to significantly improve the performance of future PET scanners and allow operation in an MRI magnet. The next step is to demonstrate this expectation by building a complete prototype.

The Team

Leads: R. Henderson, L. Kurchaninov, A. Miller, F. Retiere



Robert Laxdal is a research scientist at TRIUMF, a deputy of the Accelerator Division, and is the head of the Superconducting Radio Frequency (SRF) development and projects group. Bob is also project leader for the Phase II upgrade of ISAC-II.

Next Generation Accelerators

As Canada's premier laboratory for accelerator science and technology, part of TRIUMF's mission is stewardship and development of the next generation of accelerators. Between 2008 and early 2010, TRIUMF advanced several projects fulfilling these goals: field-focused alternating gradient accelerators, superconducting radio frequency technology, and a collaboration with India's Variable Energy Cyclotron Centre.

Field-Focused Alternating Gradient Accelerators

TRIUMF has historical prowess in the field of cyclotron accelerators as evidenced by the designs of medical isotope producing cyclotrons that have come from TRIUMF as well as the main 500 MeV cyclotron itself. On a more general level, cyclotrons are part of a broader family of accelerators which use magnetic fields to confine, accelerate, and recirculate charged particles. With fixed magnetic fields, modulated radio frequency, and pulsed beams, FFAGs operate in the same mode as synchrocyclotrons and, like them, allow higher pulse rates and larger acceptances (and therefore higher intensities) than synchrotrons.

TRIUMF has begun collaborations with the British Accelerator Science and Radiation Oncology Consortium (BASROC) on a major international project to build a complete hadron therapy facility using a Non-Scaling Fixed-Field Alternating Gradient synchrotron (NS-FFAG). This project has the potential for radiotherapy in the treatment of cancer, and TRIUMF has established an intellectual property agreement with BASROC. The device would provide beams of much higher intensity than what is currently available for many applications, including medical isotope production, cancer therapy, industrial materials

processing, energy production and subatomic physics.

Superconducting Radio Frequency Technology

Accelerators use electromagnetic fields to add energy to charged particles. The electromagnetic fields at microwave frequencies are typically produced in resonating structures called cavities and precisely timed bunches of particles pass through the structures to absorb energy from the fields. The next generation of accelerator technology uses superconducting materials to fabricate the radio-frequency cavities in order



Figure 1: Three cryomodules in the ISAC-II vault.

to minimize energy losses on the surface of the cavity. TRIUMF has become a world leader in the development and deployment of so-called superconducting radio frequency (SRF) accelerator technology. For instance, the ISAC-II accelerator (described elsewhere) relies on SRF cavities to accelerate beams of rare isotopes for fundamental studies of nuclear structure and dynamics.

An important new laboratory was opened that adds to the technical infrastructure supported

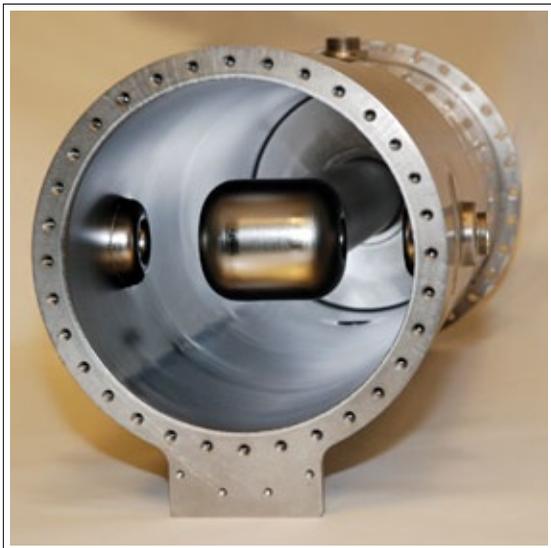


Figure 2: The cavity is fabricated from pure niobium. When cooled to near absolute zero, it becomes a superconductor and the electromagnetic fields can be produced with almost no power loss for high efficiency acceleration.

by the SRF group at TRIUMF. The Chemical Etching Laboratory is used to superclean ultra-pure niobium, both prior to welding during the cavity fabrication process and after the cavity is complete. In the new lab, a potent and precise mix of strong acids is safely employed to remove a thin layer of niobium and any foreign material from the niobium surface. Each part that needs to be welded is placed in the acid bath for 15-20 minutes. Some sub-assemblies may require several etching steps



Figure 3: Director Nigel Lockyer and Bikash Sinha, Director of the India-based VECC, sign a collaboration agreement between their laboratories in August 2008.

depending on the number of welds required. In addition, the completed cavity is further etched for about two hours to further clean and polish the niobium surface. The new lab allows for the safe handling of the acid and maintains the acid at a cool temperature that is required for optimum results. The new infrastructure greatly expands the technical capability of the SRF group.

The group has also transferred the technology of cavity fabrication to a local company PAVAC Industries. The company has recently manufactured twenty cavities for the ISAC-II heavy ion linac. Further, the capability allows TRIUMF to grow SRF research and development to other cavity types for other future accelerators or fundamental research. PAVAC is now able to bid on other accelerator projects in the global market.

TRIUMF has joined the TESLA Technology Collaboration (TTC), a worldwide consortium that has taken on the responsibility to oversee the many technical issues of constructing the proposed future accelerator known as the International Linear Collider (ILC) using SRF technology. TRIUMF's membership in the TTC provides at least two important benefits. Firstly, it can provide Canadian businesses with a seat at the table among companies involved in the industrialization of such a large technical initiative. Secondly, TRIUMF can take advantage of the global design initiative to bolster lab infrastructure and accelerator capability. As TRIUMF contributes to this international collaboration, it can bring back the knowledge and expertise in building local infrastructure for electron accelerators, which TRIUMF can use to further its own research.

VECC

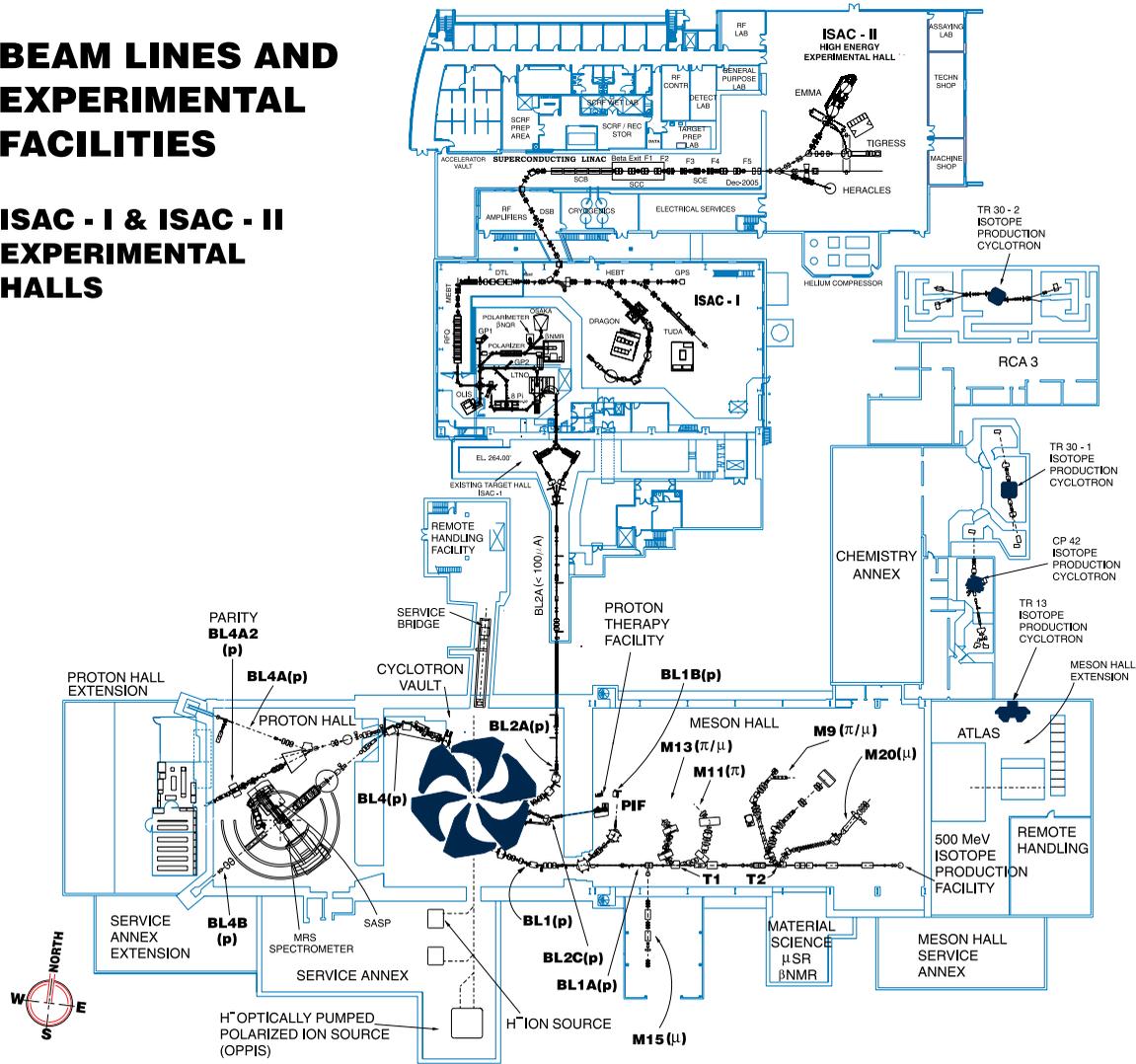
TRIUMF has signed an umbrella Memorandum of Understanding with the Variable Energy Cyclotron Centre (VECC) in Kolkata, India, for collaboration in accelerator and rare-isotope beam physics. This agreement frames the current \$6.26 million activity (equal contributions from both parties) which focuses on the development of the initial 10 MeV section of a 50 MeV electron linear accelerator for producing rare isotopes for physics and medicine. The linac is composed of superconducting radio frequency resonators as described above, The main component of the 10 MeV accelerator is the injector cryomodule (ICM). As part of the MOU two ICMs will be constructed and fully tested at TRIUMF. After testing, one will be exported and shipped to India for installation and commissioning at the VECC laboratory.

The ICM element would form the first of 2-3 stages of an electron accelerator of perhaps 50 MeV and several hundred kilowatts of beam power. In mid-2009, the Canada Foundation for Innovation funded the development and construction of such an SRF electron accelerator at TRIUMF through a \$52 million proposal led by the University of Victoria. The collaboration with VECC

will expedite the first phase of work. It is expected that VECC would be able to complete the design and construction of an electron accelerator of their own in India (likely using Canadian suppliers for the high-technology components) after collaborating with TRIUMF on building an ICM. The collaboration would continue as the devices become operational and the research program begins.

BEAM LINES AND EXPERIMENTAL FACILITIES

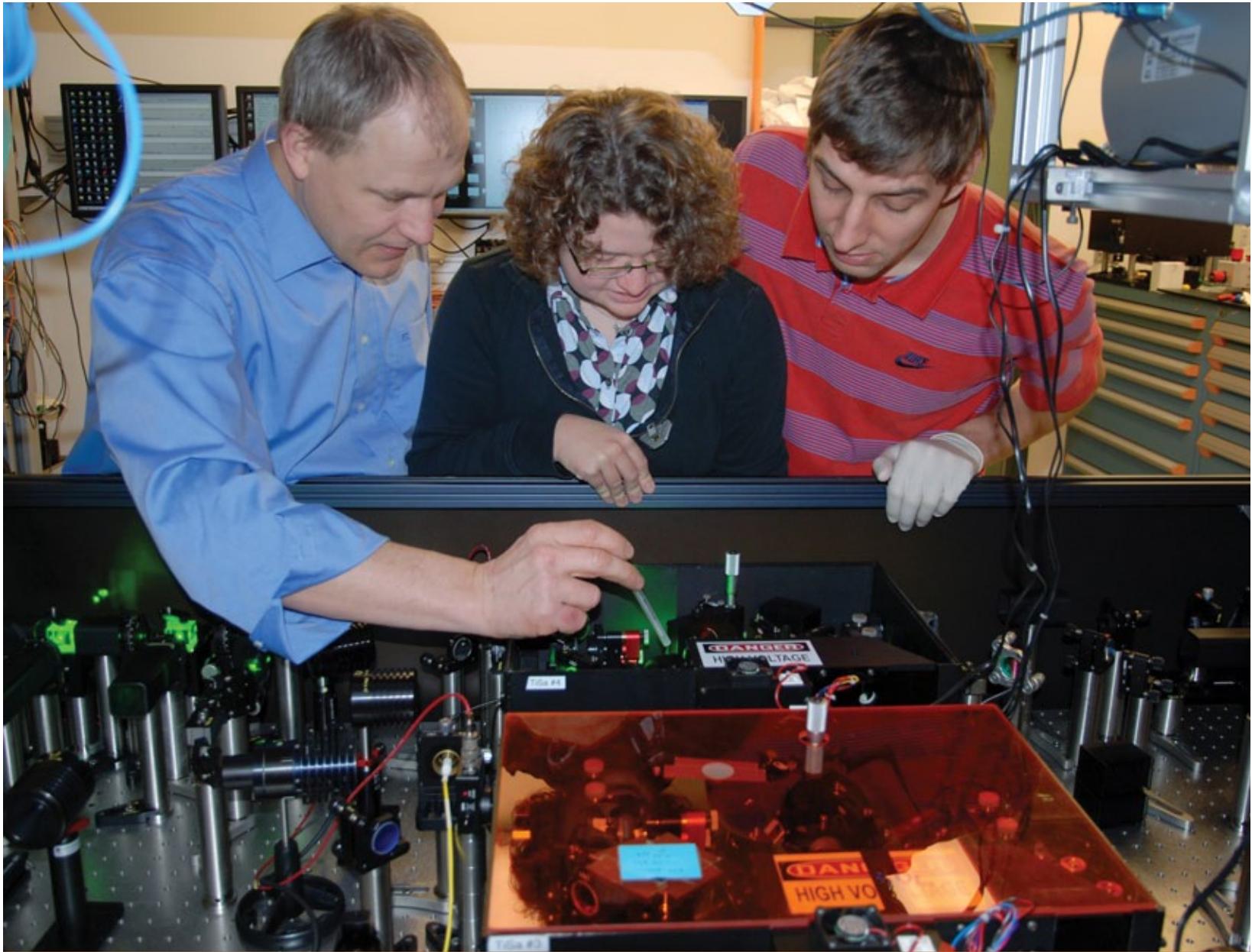
ISAC - I & ISAC - II EXPERIMENTAL HALLS



Map of the TRIUMF site and experimental facilities circa 2008-2010 including the five different cyclotrons on site and the linear accelerators in use for accelerating beams of rare isotopes. The ISAC-II experimental hall is the latest addition.



Photo:
TRIUMF scientist Jens Lassen
working with students at the laser ionization lab.



Creating Future Leaders

Education and Outreach



Marcello Pavan is the Outreach Coordinator for TRIUMF and an instructor for first year physics at UBC.

Education and Outreach

TRIUMF is recognized as an outreach and student training leader in Canada. Outreach offers students, teachers, and the general public different levels of engagement with TRIUMF, from visiting our web site to taking part in experiments. With outreach, part of the Strategic Planning and Communications (SPC) office, TRIUMF has leveraged the skills of SPC undergraduate co-op students to increase the value of our outreach, conference, communications, and educational initiatives.

TRIUMF is amongst the largest employers of undergraduate students in Canada, attracting students from university co-operative education programs across the country. In 2008, TRIUMF employed 64 undergraduates from six provinces, while in 2009 we attracted 51 students from eight provinces. In addition, the TRIUMF Summer Research Award offers five scholarships every year to an undergraduate student from each of Canada's five regions (Atlantic, Quebec, Ontario, Prairies, and B.C.) for summer research work.

The undergraduates are offered activities to enhance their experience, including social events, weekly lectures, a Presentation Skills Workshop (with UBC) and the Summer Student Symposium, where students give 10 to 15 minute talks 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.

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 \$3000 award and a six-week work term at TRIUMF, and attracts ~90 applications from the top high school physics

students across British Columbia. In 2008, Darien Niamir from West Vancouver and Sen Mei from Penticton worked, respectively, with Graeme Luke (μ SR) and Jens Lassen (laser ion source). In 2009, Anffany Chen from Vancouver and Jeremy Johnson from Victoria worked, respectively, with Pat Walden (ISAC TUDA) and Graeme Luke (μ SR) (see Figure 1).



Figure 1: 2009 High School Fellowship winners Jeremy Johnson and Anffany Chen (far left and right, respectively) with aboriginal intern Dylon Martin (in red) posing with Accelerator Division Head Lia Meringa.

One measure of the program's success has been the high return rate of Fellows as undergraduate students. Of the eight students eligible to return as co-op students, five have returned for summer placements.

The Vancouver School Board (VSB) and the University of British Columbia (UBC) established a working group dedicated to improving aboriginal educational opportunities, which TRIUMF joined in 2008. Our first pilot project brought a Manitoba aboriginal high school student, Dylon Martin

Year	2006	2007	2008	2009
Public				
# Guests	428	471	444	524*
# Tours	99	138	141	146
Science				
# Guests	920	669	607	1071
# Tours	51	44	40	52
Students				
# Guests	586	806	718	540
# Tours	24	43	30	25
VIPs				
# Guests	133	160	333	290
# Tours	42	42	63	66
TOTAL				
# Guests	2067	2106	2102	2425
# Tours	216	267	274	290

Table 1: Guests and tours over four years.

(see Figure 1) to TRIUMF for a six-week work experience in the summer of 2009. The goal was to inspire Dylon with a breadth of science outside his normal experience, and 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 (see for example <http://www.triumf.ca/research-highlights/student-stories/dylons-corner-where-physics-medicine-collide>). The project was considered a big success, and has attracted keen interest from the VSB/UBC working group.

The Saturday Morning Lecture Series, hosted annually with UBC Physics and Astronomy, offers free public lectures in the TRIUMF auditorium, 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 proven popular, averaging 60-80 attendees, but recently, attendance has increased dramatically, filling the auditorium for most of the 2008-2009 and 2009-2010 series. Guests come mainly from Vancouver, the North Shore, and Richmond, and consist of about 80% high school students and 20% adults. If the popularity continues to grow, the lectures will need to be moved to a larger venue in 2010-2011.

The outreach program is creating the Physics in Action educational videos series. These videos relate and demonstrate how high school physics concepts are manifested at TRIUMF. The first pilot video (on relativity) was a low-budget offering, and in 2006 TRIUMF was granted funds by NSERC PromoScience to create three new high-quality 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. The video's scope was far bigger than anything yet 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.

The TRIUMF public tour continues to attract over 2,000 people per year to the lab (see Table 1). Attendance has increased steadily over the years, with 2009 attracting the most ever. A slight drop in student attendance was more than made up by an increase in general public tours and scientific tours associated with conferences.



Figure 2: TRIUMF's 40th Anniversary Open House August 8th, 2009 attracted over 1300 guests of all ages to a day of self-guided tours, demos, food, and fun.

The largest recent public outreach event was undoubtedly the 40th Anniversary Open House on August 8th, 2009, where over 1,300 enthusiastic guests took part in self-guided tours and physics demos, and enjoyed free food and children's activities (see Figure 2). The event was very well received with repeated calls heard to "do it again soon". The Open House also demonstrated TRIUMF's community spirit—around 100 staff volunteered their time and energy to make the event a big success.

In 2009, TRIUMF paired with students from Emily Carr University and began the Artists in Residence Program. The program—spear-headed and continued by the SPC team's co-op students—exists to generate a broader interest in the imaginative and inspirational side of scientific inquiry through the impressions of visiting artists. During the creative process, members of the SPC team visited Emily Carr, and students made a number of visits to TRIUMF exploring the links between science and art. Inside of their studio class "Black Holes and other Transformations of Energy," students created unique pieces with their preferred mediums; everything from paintings, to sculptures, to digital pieces. In an opening celebration, TRIUMF's ISAC-II atrium was transformed into a studio space, where the work

remained on display for a number of weeks. To open the display, the students and researchers were invited to an evening event, where the students came to share their experiences with the researchers.

Ahead for 2010

Activities during the Open House revealed the appeal of using video to showcase TRIUMF and its message. Consequently the Outreach group is planning to deploy in a number of flat-panel screens around the site to display slide shows and videos describing TRIUMF, its history, and our science to laboratory visitors.

Work on the third Physics in Action video (on radioactivity and its uses) began in early 2010.

Based on past experience and careful project planning, the video is expected to be completed in mid/late 2011.

The Artists in Residence program was embraced fully by the students and researchers, and will only continue to grow. In 2010, similar projects are already planned with Simon Fraser University and Emily Carr students, as well as a photo walk where local photographers will be invited to capture the lab creatively with images.

TRIUMF outreach has made great strides in the past few years exploiting synergies from the SPC team and co-op students, and we can look forward to more good work in the months and years ahead.



TRIUMF is both for scientists and for the public. Public tours, educational programs, and outreach activities in the schools help engage young minds in promising futures in science, technology, engineering, and medicine. Here, students examine scale models of TRIUMF in the main lobby.

Introduction

Working in partnership with universities, governments, and industry, TRIUMF is conducting revolutionary research in the areas of subatomic physics and nuclear medicine for the benefit of all Canadians and others around the world that will result in ground breaking scientific, economic, and social outcomes.

Photo:
AAPS technician Keith Ladouceur
working on the MoRe Ion Source.



Generating Entrepreneurial Opportunities

Commercialization and Knowledge Transfer



Tim Meyer is the head of Strategic Planning and Communications at TRIUMF and part of the senior management team.

Commercialization and Knowledge Transfer

TRIUMF is strongly committed to undertaking high impact research and delivering value above and beyond the cultural and intellectual benefits of pure research. The chief objectives of the Five-Year Plan have been selected not only because of the opportunities they afford for scientific excellence, but also because of their potential for economic impact, their contribution towards commercialization of research, and their ability to attract top talent to Canada as well as retain it.

New Technology Transfer Structures and Mechanisms

Two new developments are shaping TRIUMF approaches to generating and exploiting entrepreneurial opportunities: the success of TRIUMF's proposal for a federally seeded Centre of Excellence for Commercialization and Research (CECR) and the formation by the Board of Management of a Private Sector Advisory Committee to advise the director on relevant issues.

In autumn 2007, TRIUMF submitted a proposal to the inaugural competition of the federally funded Centre of Excellence for Commercialization and Research program. In February 2008, the Minister of Industry announced that TRIUMF's proposal was one of 11 selected for seeding funding in the amount of \$15 million each. Advanced Applied Physics Solutions (AAPS) was organized, incorporated, and began operations as a stand-alone, not-for-profit company. The mission of AAPS is to improve the quality of life for people around the globe by developing technologies emerging from worldwide subatomic physics research, including TRIUMF research.

The creation of AAPS provided TRIUMF the opportunity to re-evaluate its models, best mechanisms, and best practices for the transfer of knowledge and technology to business and medical communities. AAPS has become a major partner in the exploitation of TRIUMF's technologies. However, AAPS may not always be the best vehicle, so TRIUMF has maintained the option to partner with other companies and organizations that have the best expertise or opportunity to develop and market new and evolving technologies.

During the 2008–2009 fiscal year, the Technology Transfer Division was disbanded in favour of a Technology Transfer Panel. Chaired by Dr. Nigel Lockyer, TRIUMF's current director, the panel consists of senior scientific, engineering, financial, and administrative staff. The panel's mandate is to review all proposals for technology transfer activities, to determine the best partner for exploiting the technology, and to enter into appropriate agreements that will ensure that technologies are developed and marketed in the best interests of Canada. The Technology Transfer Panel reports on its activities to the TRIUMF Board of Management Technology Transfer Committee.

Decisions made by the new panel have required a change to TRIUMF's traditional reporting methods on the 2006–2010 Business Development Targets which had been used to evaluate TRIUMF's technology and knowledge transfer success in the Five-Year Plan 2010–2015. In 2008–2009, TRIUMF adopted many of the Canadian universities' technology and knowledge transfer practices, including that of not patenting technologies on "spec". Technologies will now be patented only when a development and marketing partner can be identified. Rather than annually reporting

totals of licenses, patents, and other agreements, TRIUMF will report at the end of each Five-Year Plan and will report only those licenses and other agreements that are active and viable.

The TRIUMF Board of Management Technology Transfer Committee provides advice to the Technology Transfer Panel on a variety of technology transfer and commercial activities and assists in the development of policies related both to technology and knowledge transfer and TRIUMF's commercial activities. Members of this committee are drawn from the TRIUMF Board of Management, industry, commercialization experts, and TRIUMF staff.

The Private Sector Advisory Committee advises the TRIUMF director on matters relating to strategic commercial opportunities that may be available to TRIUMF. Members of this committee represent business interests from the major regions of Canada and thus ensure that commercial opportunities available throughout Canada can be pursued. The 12 members of this committee are drawn from Canadian industry, the federal and provincial governments, the TRIUMF Board of Management, and TRIUMF administration. The full complement of members is being recruited for this committee at the time of this writing.

Leading the Nuclear Medicine Revolution

As outlined in the Five-Year Plan 2010–2015, the core thrust of TRIUMF's entrepreneurial programs is the development, commercialization, and market penetration of new advanced nuclear-medicine technologies. Several activities in this area are outlined here. They illustrate two unique and critical features of TRIUMF's approach to commercialization: (1) identifying and working with key partners to exploit existing business knowledge to reduce barriers to market entry (i.e., don't go it alone in getting a new product to market; instead, choose strategic industry partners); and (2) frame product development as well as business relationships in terms of phases, each step designed to add competence and confidence in the collaboration.

MDS Nordion, Inc., TRIUMF, and the University of British Columbia are collaborating on 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. This partnership is expected to accelerate

innovation, which could provide the opportunity to commercialize new nuclear medicine products. TRIUMF and MDS Nordion, Inc. are collaborating on the development of a laboratory space at TRIUMF, including hot cells and related equipment, which will allow TRIUMF scientists and MDS Nordion, Inc. scientists to work side by side developing new radiotracers for diagnosing and treating disease.

TRIUMF's expertise in isotopes, accelerators, and the chemistry of nuclear medicine has contributed significantly to national Canadian priorities. Recent history has highlighted the global importance of medical isotopes, particularly molybdenum-99 (Mo-99) which is used to produce technetium-99m (Tc-99m), which is used in 80% of the world's nuclear medicine procedures. This isotope is chiefly produced by two ageing nuclear reactors, one in Chalk River, Ontario, and the other in the Netherlands. Considerations about safety and maintenance have jeopardized the supply chain for Mo-99. TRIUMF, in collaboration with the University of British Columbia, and AAPS, along with support from Natural Resources Canada, convened a panel of 20 experts to study the feasibility of producing Mo-99 via photo-fission using a high-power electron accelerator rather than the traditional approach using weapons-grade uranium in a nuclear reactor. The Task Force's report was published in November 2008 and concluded that the potential for success was sufficiently compelling to make a laboratory "end to end" demonstration the next step.

TRIUMF developed the concept as Zero-Enriched Uranium Molybdenum-99 (ZEUM) under a Memorandum of Understanding with MDS Nordion, Inc.; the phased development plan called for a demonstration of the technology in 2013 followed by construction of a pilot plant for preliminary production of commercial product in 2015. Guided by the advice of the Task Force, TRIUMF prepared a submission to the Government of Canada's Expert Review Panel on Medical Isotope Production in July 2009. The Expert Review Panel released its report in early December 2009 and acknowledged the growing importance of diversifying the supplies of Mo-99 and noted the key role that accelerator-based technologies could play in this regard.

TRIUMF senior research scientist Thomas J. Ruth co-lead a proposal for development of technetium-99m production using cyclotrons with BC Cancer Agency's François Bénard, to the NSERC/CIHR program on Alternative Radiopharmaceuticals

for Medical Imaging. The \$1.3 million award was announced in November 2009 as one of seven nationally funded projects; the TRIUMF/BCCA project was the largest grant and includes partners from Edmonton, Sherbrooke, and London, Ontario. Conventional medical cyclotron machines are already being used to produce radioisotopes for many diagnostic procedures. Finding alternatives to reactor produced medical isotopes is vital to staying ahead of the supply curve and meeting the health needs of patients; producing technetium radioisotopes from cyclotrons could be a safe, reliable, and cost-effective alternative to using material produced in nuclear reactors. It is expected that this research will lead to clinical studies within two years to validate the new production methods.

Deputy Division Head of Nuclear Medicine Paul Schaffer has been leading a series of discussions with GE Healthcare on a number of fronts. TRIUMF hosted a visit from GE's global research team that examined opportunities for next-generation cyclotrons and advances in radiochemistry.

Next-Generation Accelerators with Superconducting RF Technology

A second thrust in TRIUMF's entrepreneurial program is the application, commercialization, and deployment of next-generation accelerator technology using superconducting radio-frequency (SRF) cavities. This technology allows very high-power accelerators to be designed and constructed with reduced operating costs.

TRIUMF developed expertise in this global technology and has successfully transferred it to a local company, PAVAC Industries, Inc., in Richmond, BC. PAVAC and TRIUMF are one of only five teams in the world capable of working with this technology. PAVAC has used its new expertise in SRF cavities to contribute to the design and future manufacturing of components for TRIUMF's electron linear accelerator project. More importantly, TRIUMF's partnership with the VECC laboratory in India on SRF technology has introduced PAVAC to Indian markets and vice versa. Through these connections, PAVAC has sold two of its \$3 million electron-welding units to India in the past year. Furthermore, PAVAC has been contacted by several U.S. procurement teams to participate in a qualification process for bidding on future U.S. contracts to supply SRF cavities for several new accelerator projects in the U.S. PAVAC will build a prototype cavity for CERN's 700 MHz

Superconducting Proton LINAC (SPL) project as a qualification to compete for the many cavities eventually required for the SPL.

PAVAC is working to develop another commercial application of SRF technology for remediation of noxious elements in flue-gas emissions of power plants; the technology would use small accelerators with SRF technology to provide high-power beams to remove NO_x and SO_x. This technology is the subject of a new Cooperative Research and Development proposal being prepared for the Natural Sciences and Engineering Research Council.

This string of successes illustrates how an intentional partnership and good understanding between two organizations can have a transformational impact.

Other Selected Partnerships and Results

In addition to these core thrusts, TRIUMF continues to identify new partnerships and opportunities for expanding the economic impact of its science and technology. Several examples from 2008–2010 are discussed here.

TRIUMF has a decades-long relationship with the BC Cancer Agency (BCCA). TRIUMF operates Canada's only proton beam cancer therapy facility. The treatments are for relatively rare cancers of the eye called "choroidal melanomas", and "iris tumours". During 2008–2009, seven patients were treated, bringing the total number of patient treatments to 137 since we began in 1995. The BCCA has acquired its own TR13 cyclotron but the cyclotron cannot be installed and operational until the building to house it is complete. TRIUMF and the BCCA entered into the second year of an agreement to supply BCCA with fluorine-18 and FDG needed for its PET/CT scanners.

On Thursday, September 17, 2009, Dehnel Particle Accelerator Components and Engineering, Inc. (D-Pace) was recognized as a Canadian Innovation Leader by the Government of Canada. Mr. Drew de Kergommeaux, Director–Pacific Region, NRC, presented the company with a Canadian Innovation Leader Certificate (CIL) in acknowledgement of its role in researching, developing, supplying, and commercializing products and services for the international commercial accelerator industry, linking scientific research to commercialization, jobs, and economic growth. Also in attendance were Mr. Bruce Hardy,

local NRC Industrial Technology Advisor and D-Pace institutional collaborator Dr. Neil Coburn, Dean of Arts & Sciences, Selkirk College.

D-Pace—a TRIUMF spin-off company—was founded in 1995 by Dr. Morgan Dehnel after he completed his doctoral studies at TRIUMF and the University of British Columbia. Based in Nelson, BC, this technology firm specializes in complete beam line system designs and charged particle transport systems, as well as components for cyclotrons, ion implanters, and linear accelerators. In 2001, D-Pace began the successful commercialization of TRIUMF-licensed ion source, target, and detector technologies and now sells them internationally.

TRIUMF's proton and neutron irradiation facilities provided beam-test services to 29 different companies, laboratories and university groups—many of them several times—during the 2008–2009 fiscal year. Of these users, eight came from Canada, six from the United States, and five from Europe. Canadian users included the Canadian Space Agency (CSA), MacDonald Dettwiler, Microsat System Canada, Honeywell Canada and several universities.

For several of the companies, including the CSA, TRIUMF provides an essential service in qualifying the equipment for radiation exposure during space missions. The ability to qualify equipment for radiation exposure is now extending into the aircraft industry for Honeywell, Boeing and a consortium of United Kingdom companies. The largest user of beam time during 2008–2009 was a company testing networking equipment for ground level applications where even the low flux of cosmic ray neutrons is causing errors or damage to their sophisticated equipment.

The beam hours provided to the users and commercial revenue generated were about 40% more than the previous year.

Throughout these past two years, TRIUMF's relationship with AAPS, Inc. has taken shape. TRIUMF regularly provides technical and engineering staff and support to AAPS to fulfill its commitments to AAPS's success. The specific nature of these activities is described in the AAPS annual reports, and is not detailed here.

Introduction

As a national laboratory supported primarily by public funds, TRIUMF has a responsibility for effectively managing its activities to ensure optimal results for Canada. To do so, TRIUMF has a lean administrative team that provides coherent structure, guidance, and accountability to the diverse portfolio of science, technology, and innovation activities. Although the specific results and course of research are by definition uncertain, TRIUMF uses a variety of mechanisms to assure quality management, project and program effectiveness, compliance with regulatory standards, and overall safety. Above all, TRIUMF's commitment is to excellence.

In this chapter, updates to TRIUMF's management structure and tools are outlined. For instance, new business procedures, expanded stakeholder participation via advisory and oversight committees, enterprise-wide project management tools, and a comprehensive quality management system have been rolled out.

Photo:
Quality Assurance Meeting,
Rolf Keitel, Aziz Ahmad (Canadian Light Source), Nigel Lockyer



Managing for Excellence

Administrative Structure

External Relations

Portfolio Management

Quality Assurance



Shirley Reeve is Chief Financial Officer at TRIUMF and Treasurer of TRIUMF Accelerators, Inc.

Ensuring Accountability and Performance

TRIUMF is funded by the Government of Canada, but is owned and operated as a joint venture by a consortium of Canadian universities. This governance structure—which is unique in Canada and perhaps in the world—has been and continues to be a very successful model for operating a national facility such as TRIUMF. The organizational and administrative structure of TRIUMF is shown in Table 1.

During the five years ending March 31, 2010, TRIUMF's value to the Canadian and university physics community grew and the joint venture membership grew accordingly. L'Université de Montréal, the University of Manitoba, Guelph University, Queen's University, and York University all applied for, and received, permission to join the joint venture as full members. The University of Calgary and the University of Regina applied for associate membership in the joint venture, a prelude to applying for full membership.

The TRIUMF Board of Management meets quarterly and is responsible for the financial and administrative affairs of TRIUMF. The Board of Management is made up of two voting representatives from each full member university and two private sector representatives. 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.

TRIUMF's operations are funded by the Government of Canada on the basis of Five-Year Plans put forward by TRIUMF. Funding flows to TRIUMF through a "Contribution Agreement" between the National Research Council of Canada (NRC), who provides the oversight and accountability for the funding, and the full members of the TRIUMF Joint Venture. 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. At March 31, 2010 TRIUMF's Statement of Work obligations for the 2005–2010 Five-Year Plan and their status are shown in Table 2. All Tasks were successfully completed.

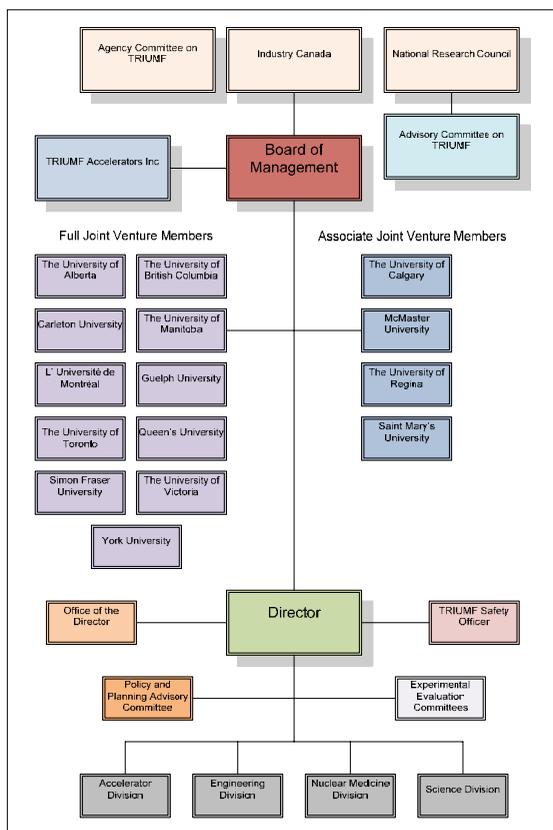


Table 1: TRIUMF Organizational Structure at March 31, 2010.

	Task	Status
1	Completion of 20 medium Beta accelerator cavities	Complete
2	Completion of 20 high Beta cavities	Complete
3	Completion of accelerator cooling system	Complete
4	Commissioning of one experimental location to provide unique exotic beams to approved high profile experiments	Complete
5	Commissioning a total of 3 experimental locations to provide unique exotic isotope beams to approved high profile experiments by the end of 2009	Complete

Table 2: NRC Contribution Statement of Work for five years ending March 31, 2010.

Monitoring the laboratory's performance is a joint responsibility of the Agency Committee on TRIUMF (ACT), represented by Industry Canada, Natural Sciences and Engineering Research Council (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 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 IPRC for the 2005–2010 Five-Year Plan took place at TRIUMF between September 24 and 26, 2008. The 11-person committee, chaired by Dr. Rolf-Dieter Heuer, the Research Director of DESY, examined three key aspects of TRIUMF: its relevance to the Canadian research community as well as Canadian industrial and commercial interests; TRIUMF's success in meeting its objectives; and the excellence of its activities and researchers. The IPR committee also reviewed the Five-Year Plan proposed for 2010–2015 to identify potential opportunities and new directions for TRIUMF.

In 2008, the Office of the Director was established, replacing the Administration Division. The TRIUMF Division Heads report to the TRIUMF Director through the Office of the Director as well as the administrative departments of finance, supply chain management, human resources, general administration, and security. In addition, the Office of the Director takes full responsibility for quality assurance, environment, health and safety, and communications and outreach. The Office

of the Director, also oversees the Experiments Evaluation Committees (EECs), the Policy and Planning Advisory Committee (PPAC) and the Safety Management Committee. In addition, this Office has operational, maintenance and required upgrade responsibility for the radioisotope production cyclotron facilities (ATG) operated on behalf of MDS Nordion Inc. and acts as liaison with MDS Nordion Inc., and Advanced Applied Physics Solutions Inc. (AAPS), which are located on the TRIUMF site.

TRIUMF has recognized the growing importance of Nuclear Medicine on site and across Canada. The Life Sciences group, previously a part of the Science Division, was renamed Nuclear Medicine and established as a separate TRIUMF division.

A critical focus for the Office of the Director from 2008–2010 was the development and presentation of the 2010–2015 Five-Year Plan (www.triumf.ca/about-triumf/message-director/five-year-plan), a project that involved TRIUMF staff and the Canadian physics community.

The Government of Canada announced its support for TRIUMF in Budget 2010, awarding TRIUMF \$222.3 million in operating funds, to be administered via the NRC Contribution Agreement, over the full five years requested. TRIUMF's core funding is ensured to March 31, 2015. While the funding level is identical to what was provided in the last Five-Year Plan, TRIUMF recognizes that the current fiscal climate provides challenges for everyone and the funding provided for the five years indicates confidence in TRIUMF, the laboratory's plans and a belief that the laboratory will continue to contribute to Canada's future.

TRIUMF's operating costs are funded by a contribution from the federal government through the NRC. In addition, TRIUMF scientists are eligible for grants from NSERC, and Canadian Institutes for Health Research (CIHR). TRIUMF can be a partner

	\$000	\$000	\$000	\$000	\$000	\$000
	TOTAL	2009-10	2008-09	2007-08	2006-07	2005-06
National Research Council	228,500	44,000	43,500	51,500	45,500	44,000
Natural Sciences & Engineering Research Council	28,889	6,588	5,971	6,375	5,267	4,688
Canada Foundation for Innovation	9,259	1,946	1,115	1,868	2,406	1,924
Western Economic Diversification	919	919	0	0	0	0
MDS Nordion Inc	19,955	4,350	4,371	3,939	2,772	4,523
Affiliated Institutions	8,266	2,191	2,092	1,815	1,084	1,084
Advanced Applied Physics Solutions Inc	2,200	1,166	1,034	0	0	0
Commercial Revenue	8,793	2,338	1,530	1,711	1,486	1,728
General	1,364	61	175	461	417	250
	308,145	63,559	59,788	67,669	58,932	58,197

Table 3: TRIUMF Funding 2005-2010

in large infrastructure projects supported by the Canada Foundation for Innovation (CFI) and the British Columbia Knowledge Development Fund (BCKDF). TRIUMF's funding, ending March 31, 2010, see Table 3.

Other receipts include:

Affiliated Institutions: Reimbursements for expenditures incurred by Canadian and international laboratories and institutions while working at TRIUMF.

MDS Nordion Inc.: Reimbursements for expenditures incurred by TRIUMF on behalf of MDS Nordion Inc.

Advanced Applied Physics Solutions (AAPS): In 2008 TRIUMF was one of eleven recipients of the first Government of Canada's Centre of Excellence awards for Commercialization and Research (CECR), and TRIUMF incorporated the not-for-profit company AAPS to receive the funding. TRIUMF provides services to AAPS, who then reimburses TRIUMF for the costs incurred.

Commercial Revenue: Income earned from royalties and commercial activities undertaken by TRIUMF.

General: Interest income

The TRIUMF staff supported by the NRC contribution work on a wide variety of projects and activities for the TRIUMF internal science program and in support of Canadian scientists performing science at laboratories in Canada and around the world.

The demand for TRIUMF's scientific, engineering, and technical expertise is very high. In 2009

TRIUMF undertook the development and implementation of a comprehensive Project Management system, which tracks employees' efforts and the financial resources allocated to the various projects. This new system will make the best use of TRIUMF's human resources and meet as many needs as possible with the resources available. The allocation of the NRC-funded staff for the year ending March 31, 2009, see Table 4.

TRIUMF has approximately 350 employees paid from its operating funds, and approximately 150 term appointments funded through grants or affiliated institutions.

All employees are reviewed for performance on an annual basis, and salary increases and promotions are based on performance.

During this Five-Year Plan, TRIUMF developed a salary administration scheme for the Technician Category of employees which offers more flexibility when hiring and when recognizing performance or considering promotions. This "Job Family" system moves away from an automatic career progression system to a pay for performance system. There are now salary ranges appropriate and unique to the various technician groups.

TRIUMF has a very strong student program and hires some 30 summer students per year in addition to approximately 10 university co-op students hired each term.

TRIUMF has established an on-line office where users and visitors can contact the Visitor Services

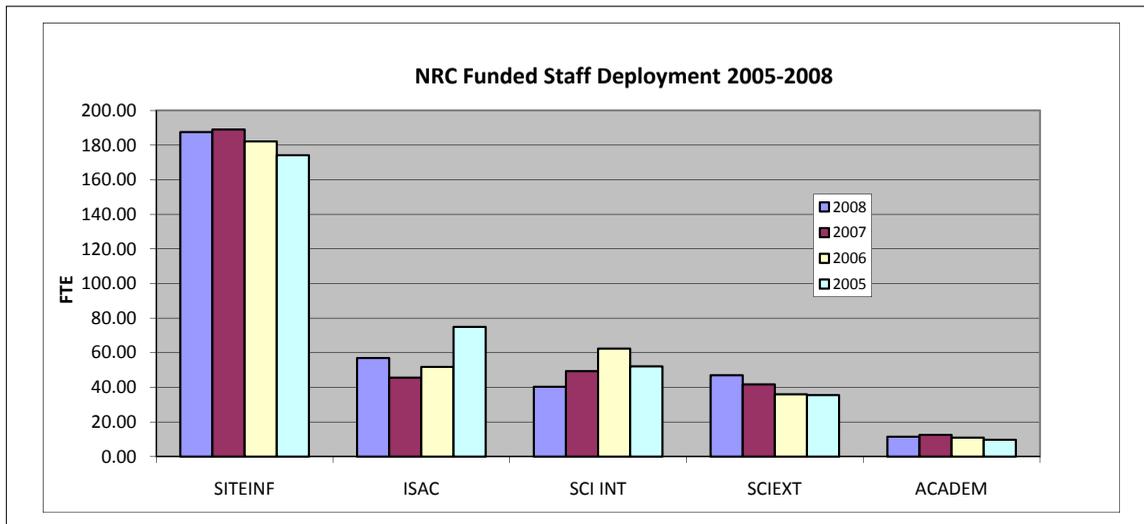


Table 4: Deployment of NRC-funded TRIUMF staff.

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.

TRIUMF had approximately 425 long-term visitors in 2008, 300 of whom came from 17 countries outside of Canada.

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. Security guard coverage continues between 6:00 pm and 6:00 am on working days with 24 hour coverage on weekends and statutory holidays. All vehicles accessing the site behind the security fence are required to acquire a permit before entering the site.

All buildings used by TRIUMF are owned by the University of British Columbia as they sit on university land. The Canadian Universities Reciprocal Insurance Exchange (CURIE) provides insurance coverage for all TRIUMF buildings and their contents. TRIUMF maintains full insurance coverage, including third-party liability coverage of \$50M.

Over the last two years the office of Environment Health and Safety (EH&S) has worked to complete corrective actions for the directives and action items stemming from inspections carried out

around the license renewal of 2007. The programs inspected were: emissions; environmental monitoring and waste management; radiation protection; fire protection; and security. All action items have been closed except for a few associated with the fire protection program and the requirements for compliance with NFPA-801. The first draft of the fire hazard analysis is undergoing revision to include greater detail for the methodology and a more complete inventory in those areas of the laboratory where there could be a significant fire hazard. Pre-incident plans are also being drafted to better coordinate with the response of Vancouver Fire & Rescue Services.

A separate task force, the Quality Implementation Panel, has been addressing the directives and action items of the quality assurance program inspection and a summary of progress with those action items is provided below.

All the regulatory program corrective action plans are on track for completion before the mid-term license hearing scheduled for fall 2010.

As part of the non-conformity resolution process, terms of reference were established for the Safety & Quality Assurance Oversight Panel. The panel is chaired by the manager of EH&S and includes division heads and group leaders with operational responsibility for safety on site. It is responsible for reviewing all matters of safety on site on a regular basis, and for verifying that corrective action implemented for identified nonconformities has been completed and addresses root causes. Terms of reference were also updated for the TRIUMF Accident Prevention Committee (TAPC).

TAPC is the provincially mandated employer-employee safety committee that carries out monthly site inspections, reviews deficiencies, and raises these to nonconformities if they require addressing at a higher level.

An amendment to the CNSC Accelerator Operating License to permit irradiation of targets at ISAC with atomic number greater than 82 ($Z > 82$) was obtained in August 2008 to perform a test irradiation with an actinide target and 2 mA proton current. New instrumentation was put in place for monitoring potential airborne alpha-emitting contaminants both within the ISAC target hall and also for the nuclear ventilation exhaust from the ISAC facility. The test irradiation was completed in September 2008. A report of the successful completion of the test along with a request for a license amendment for ongoing low-current irradiation of actinide targets was submitted to the CNSC in the spring of 2009, and a license amendment was issued in November 2009. Prior to the license amendment, and as part of our ongoing commitment to provide in-depth protection, TRIUMF upgraded the hot cell nuclear ventilation to include charcoal filtration. A subsequent irradiation of an actinide target was carried out successfully in December 2009.

To address the 2006 CNSC QA Audit the TRIUMF Quality Manual and the TRIUMF Standard Operating Procedures (TSOPs) have been updated, reviewed and released. Each group at TRIUMF has produced a Group Manual that describes the specifics of how they have implemented the requirements of the TSOPs. Internal assessments of each group also began in 2008 and internal audits in 2009 to assist groups in implementing TRIUMF's Quality Assurance program.

The design and maintenance processes for all accelerator safety systems have been formalized in

a Safety Systems Group Manual that supplements the generic TRIUMF Standard Operating Procedures (TSOPs). Part of the work has involved registering devices that are routinely calibrated or tested in a new TRIUMF web-based Calibration Database. The database put the calibration status for approximately 300 monitors in an auditable form.

Major upgrades of three ageing 520 MeV facility radiation safety subsystems are well under way. The Central Safety System (for access control and machine protect), RMS1 System (for Beamspill monitors) and RMS2 System (for Residual, Neutron and Air monitoring) are all to be upgraded for reliability and maintainability. The same design approach was used in all three system upgrades: CAMAC I/O modules and field wiring will be retained, but old microprocessors will be replaced with new, flash-based linux systems.

The beam lines in the Proton Hall have been declared decommissioned, and the work required to remove hardware and to revise documentation and system displays has begun. The conceptual design of the Proton Hall e-linac safety system that will replace this equipment is slowly taking shape as exclusion area boundaries, shielding thickness, and operational requirements become better defined.

Jim Hanlon is the manager of Human Resources and Administration at TRIUMF; he is president-elect of the Society for Research Administrators, International.



External Relations

In 2008 – 2009, a number of changes took place in terms of External Relations. This section will go over these changes in the areas of governance, administration, collaborations, insurance, security, and human resources.

Governance

Effective March 31, 2008, the TRIUMF Joint Venture member universities signed a revised Joint Venture agreement and reaffirmed their long term commitment to TRIUMF by also agreeing to the establishment of a decommissioning fund, in compliance with the Canadian Nuclear Safety and Control Act.

The following agreements were formally put in place in support of the revised Joint Venture agreement with the most significant being the signing of a 99-year lease between the Joint Venture members and UBC. This is the first lease that TRIUMF has had with UBC and is indicative of the strong relationship with its major stakeholder.

Following is a complete list of the formal agreements that were put in place in 2008 in support of the revised Joint Venture agreement:

- Amended and Restated TRIUMF Joint Venture Agreement dated March 31, 2008
- UBC lease dated March 31, 2008
- Management Agreement between TRIUMF Accelerators Inc., and TRIUMF dated March 31, 2008
- NRC Contribution Agreement dated March 31, 2008
- Amendment No. 1 to the Contribution Agreement dated March 31, 2008
- CNSC Financial Security and Access Agreement dated January 7, 2008

- Fund Contribution Gap Agreement dated January 7, 2008
- Escrow Agreement dated January 7, 2008

In 2008, University of Manitoba, Queen's University, and the University of Guelph became full members. In the same year, York University became an associate member, and later a full member, and the University of Calgary joined as an associate member. The new members were voted in unanimously by the TRIUMF Board of Management.

In 2008, Dr. Feridun Hamdullahpur, Academic and Provost, Carleton University, stepped down as Chair to be replaced by Dr. Howard Brunt, VP Research, University of Victoria. The Board also approved the establishment of a Private Sector Advisory Committee and approved a revised committee structure for the Senior Promotions Committee

Administrative Reorganization

A number of reorganization changes were made over the reporting period as follows:

The Federal Government has awarded, through TRIUMF a \$14.95M grant for the establishment of a Centre of Excellence for Commercialization and Research (CECR). As the host institution, TRIUMF has established AAPS (Advanced Applied Physics Solutions), a not-for-profit corporation that will be responsible for commercializing accelerator based technologies. As a result of the formation of AAPS, the Technology Transfer Division will no longer exist, and will be regrouped and reorganized when the next Five-Year-Plan is in place. In the interim, a Technology Transfer Panel has been created to oversee technology transfer activities at TRIUMF.

In order to streamline reporting functions, the Administration Division was eliminated and those employees previously in this division will now be part of the Director's Office. For more information, see the Administrative Structure section of this report.

In order to recognize the growing importance of nuclear medicine at TRIUMF and across Canada, the Life Sciences Group has been elevated to a Division status.

Collaborations

TRIUMF signed collaboration agreements with the following institutions:

- CERN – upgrade of accelerators
- JLAB – technical exchange
- MDS Nordion – research collaboration
- IUAC, Delhi – scientific collaboration
- RIKEN – scientific collaboration
- BC Cancer Agency – F18 supply agreement

Insurance

TRIUMF acquired a \$50M Nuclear Energy Liability policy from the Nuclear Insurance Association of Canada (NIAC). This is the first time that TRIUMF has been able to secure this coverage from NIAC. This complements other Commercial General Liability coverage of \$50M and coverage for Directors and Officers to \$10M from \$5M.

Security

TRIUMF received a number of visits from both federal and local police agencies to review security coverage in anticipation of the 2010 winter Olympics. All security preparations were deemed adequate. CNSC also audited TRIUMF's security plan and found it to be in compliance.

Human Resources

A number of initiatives were taken on by the Human Resources team. These were; succession planning, mentorship, improvements to the Performance Review system, and the establishment of new Job Families and salary scales for the TRIUMF technical staff.

A new in-house Human Resource Information system was also introduced as a Web based application. In terms of benefits, improvements in the wellness program included on-site personal coaching, reimbursement for audiology tests, travel vaccines, and smoking cessation drugs, among other things. Vacation policies were also updated. There are now improved vacations for technicians, and streamlined vacations for technical and professional staff. A new paid leave policy was also instituted.

Byron Jennings is the Deputy Head of the Science Division and chair of the Project Management Oversight Group at TRIUMF.



Project Management

TRIUMF is moving into a new era, driven both by the complexity of the science and technology required to pursue its mission and by the increasing emphasis on public accountability and predictable performance. Plans for 2010-2015 are ambitious and will provide TRIUMF with a bright future. Success will require distribution of TRIUMF resources to projects and operations in a fair and transparent manner, and projects must be managed in a manner to make optimal use of their resource allocation. Over the past two years, TRIUMF has established a Project Oriented Management System to advance these goals. The system assists project leaders and personnel in managing their work and it provides portfolio management tools to TRIUMF's senior management.

In January 2009, the TRIUMF director formed a Project Management Working Group (PMWG) that seconded leaders from across the enterprise including science, engineering, human resources, communications, finance, and scheduling. The mandate was to define and then launch implementation of the most appropriate project and resource management system for TRIUMF. The project management system was substantively implemented by the end of 2009 with tools of choice; standard procedures and protocols for identifying, managing, and monitoring projects; and a framework for generating information about the overall portfolio of TRIUMF's activities and commitments. The working group was disbanded and a standing oversight group was convened to oversee the remaining implementation issues and the maintenance of the project management system.

Key Elements

The project management framework has several key elements:

Standardized Project Life Cycles: All projects at TRIUMF are now described in a standard framework that moves from initiation and planning through execution, commissioning and release, operations, and eventual decommissioning. Transition between these general project stages is requested by the project proponents and subject to so-called "gate reviews" that advise TRIUMF senior management on readiness, scope creep, and effectiveness of resource utilization. The level of scrutiny applied to a project is binned into three categories taking into account the overall size of the project, the degree of TRIUMF's involvement, and other types of risks.

Project Charter Sheets: All projects are initiated with a Project Charter Sheet that notifies TRIUMF about the potential development of a project involving TRIUMF resources. The Project Charter Sheets provide a nominal estimate of future resource requests and allow TRIUMF to develop loose projections.

Commitments List: This document identifies all activities and obligations (both in terms of operations and maintenance and new projects and initiatives) "on the books" which involve TRIUMF resources. Every activity on the Commitments List has a Project Charter Sheet and has passed through Gate Review 1. The Commitments List also includes a binned priority rating for each activity (reviewed and approved by oversight bodies such as the Policy and Priorities Advisory Committee) according to "importance" and "constraints" such as schedule and readiness.

Skills Inventory: Commensurate with an enterprise-wide framework for planning and

managing projects using work breakdown structures and resource-loaded schedules, is the need for a detailed inventory of TRIUMF's human-capital resources. The skills inventory identifies the knowledge, skills, and abilities of each employee in a general framework that optimizes the flexible movement of staff in a responsible, respectful fashion between projects.

Project Approval Process

Before TRIUMF allocates resources to the project, it must undergo Gate Review 1 to achieve "approval in principle and preliminary resource allocation." This approval only commits TRIUMF to supplying those resources necessary for a proper conceptual design and a detailed project plan. The Project Charter Sheet is used to decide the nature of Gate Review 1. The nature of the review will depend on the scale of the project and its risks or hazards. As the project progresses, there will be Gate Reviews, Status Reviews, and Safety Reviews as needed. In particular, Gate Review 2 will determine if the project proceeds to the construction stage and will be the major decision point for most projects.

The priority of a project depends on two things: the importance and the constraints. The importance rating of a project measures its alignment with and contribution to the TRIUMF program. It reflects not only the scientific motivation of a project, but also how the project addresses TRIUMF's mission and priorities. The importance rating is used in conjunction with urgency, need, and other constraints, to determine the allocation of TRIUMF resources. There are four categories of importance: crucial, high, medium, and low. Projects crucial to TRIUMF are those whose failure would have a significant impact on TRIUMF's viability or Canada's standing in the community. A project with high importance makes a substantial contribution to TRIUMF, but is not, by itself, crucial. Medium importance projects provide key additions to TRIUMF or upgrades to existing facilities. Low importance projects, while perhaps important or significant on their own, do not align well with TRIUMF's mission or would only make a small contribution to it. The importance rating is assigned by the Director in consultation with the Priorities Committee with a number of annual overights. This rating does not replace scientific peer review but rather is based, in part, on the result of peer review processes.

Project Approval Criteria

TRIUMF's project approval criteria include:

Scientific merit: Projects are judged first and foremost by the quality of the science they produce or facilitate. This includes the accelerator systems and infrastructure needed to perform the science program.

Alignment with TRIUMF's global priorities:

TRIUMF's priorities are given, in the first instance, by the current NRC-TRIUMF funding agreement and the current Five-Year Plan. The Director, with advice from PPAC and the Priorities Committee, upgrades the priorities on a regular basis.

Canada and TRIUMF impact and visibility:

Projects supported by TRIUMF are expected to increase TRIUMF's visibility in the community. Projects in support of experiments at foreign facilities are expected to give Canada an enhanced visibility.

Alignment with community priorities: Projects will be rated on how well they match the priorities of the Canadian research community as given by IPP, CINP, the Sub-Atomic Physics Community Five-Year Plan developed in conjunction with NSERC, and other appropriate statements of the Research Community. In general, TRIUMF will only support detectors and experiments at foreign laboratories if there is strong participation and intellectual input from the Canadian research community.

Benefit to society: This includes training highly qualified personnel, transfer of technology to industry, and medical applications.

External funding: Scientific projects will only be supported if they have independent peer review funding. However, such funding does not guarantee TRIUMF support since support may be precluded by other demands on TRIUMF's finite resources.

Leveraging/sharing: Projects that leverage resources from other sources will be considered more favourably than those that don't.

Technical feasibility and proponents' technical capability: Projects will only be approved if there is a high likelihood that the project will perform as proposed. This will include assessment of both the technical difficulty of the project and technical strength of the group making the proposal.

Safety: Projects with the potential for environment, health, or safety concerns will only be accepted after safety clearance by TRIUMF.

Government priorities: TRIUMF and the projects it supports should align with the priorities of the governments that fund it.

Rolf Keitel is head of TRIUMF's Engineering Division and leader of the quality management efforts at TRIUMF. He is an expert in control systems.



Assuring Quality and Results

Over the 40+ years of its life, TRIUMF has always put a strong emphasis on safe working practices to protect the health of its workers, its neighbours, and the environment.

TRIUMF has implemented a formal Quality Management System (QMS), the design of which is guided by international standards such as ISO 9000. The goal was to create and implement a system that works for a unique environment like TRIUMF and that allows us to objectively demonstrate to ourselves, our users, and our regulator — the Canadian Nuclear Safety Commission — that we have a safe, efficient, and productive research environment. This system is still evolving and will continue to improve our ability to deliver reliable value to the larger community.

Quality assurance is a vital component of daily activities at TRIUMF and critically important to our success.

The process is steered by the Quality Management System Implementation Panel. The panel is chaired by the Head of the Engineering Division with strong guidance from the QA Manager. The panel members are senior staff with the broadest and deepest knowledge of TRIUMF activities. All divisions at TRIUMF are represented. This panel is charged with ensuring that documentation is up-to-date and that staff are properly trained and following TRIUMF Standard Operating Procedures (TSOPs). The resources required for both the implementation and sustainability of the QA program are reviewed at the Quarterly Safety Management Meeting.

The QA Manager, Phil Jones, is responsible for the day-to-day operation of the Quality Management System. He reports on nonconformities, training,

and internal assessments to the Director of TRIUMF through the weekly Senior Management Meeting and the quarterly Safety Management Committee. The QA Manager sets the schedule of internal assessments and selects assessment teams with the appropriate independence to perform the assigned assessments.

The TRIUMF Quality Management System is defined by the TRIUMF Quality Manual, 14 TRIUMF Standard Operating Procedures (TSOPs), the TRIUMF Document Manual, and a collection of Group Manuals. In total, these documents define the operating processes of TRIUMF covering everything from access to the TRIUMF restricted site up to project management.

Information about the QMS is conveyed to staff through the Quality Management web page and via the Quality Times newsletter.

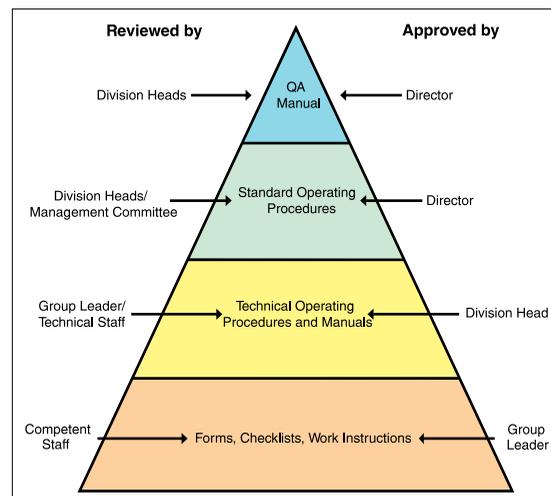


Figure 1: Documentation hierarchy.

Introduction

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

In March 2010, the Government of Canada awarded TRIUMF five years of core operating funds at the level of \$222.3 million. Through these funds, the following program will be supported 2010-2015:

- Exploitation of the existing cyclotron-based science programs including ISAC and CMMS;
- Targeted cyclotron refurbishment;
- Expansion of the nuclear medicine program; and
- Full support for the ATLAS Tier-1 Data Centre.

In addition, the laboratory will work with the Canadian community to support a limited number of supplemental projects funded through mechanisms such as the Canada Foundation for Innovation (CFI). The flagship initiative will be the Advanced Rare Isotope Laboratory (ARIEL) and its e-linac. With support from CFI, a university consortium of 13 partners, the Government of British Columbia, and TRIUMF (including National Research Council and Industry Canada), this program will launch in mid-2010.

For a full description of TRIUMF's plans, please see *Five-Year Plan 2010-2015: Building a Vision for the Future*.

Illustration:
Artist's conception of the
ARIEL facility to be constructed at TRIUMF.



Looking Forward

ARIEL
Goals



Chris Oram is the incoming Division Head of Engineering and is co-leader of the ARIEL project at TRIUMF.

The Advanced Rare IsotopE Laboratory

The Advanced Rare IsotopE Laboratory (ARIEL) project has the long-term aim to triple the beam delivery to ISAC experiments and showcase the next-generation superconducting radio-frequency accelerator technology. To achieve this, the following items will be constructed (see Figure 1) over a 10-year time scale:

A 50 MeV 10 mA electron linear accelerator (e-linac) will be built and subsequently housed in the existing proton hall.

There will be a new ARIEL isotope production hall housing built for two targets, a 500 kW electron target and a 100 kW proton/electron target; a possible RF separator to allow simultaneous electron beams on both targets; two front-end systems to deliver two RIB beams to ISAC experimental halls; and the associated infrastructure.

A tunnel will be built to connect the main cyclotron building to the new ARIEL isotope production hall. The tunnel will house new beam lines to transport beams to the two new targets: a 50 MeV 10 mA electron beam from the new e-linac, and a 480 MeV 100 μ A proton beam from the TRIUMF cyclotron.

The e-linac is designed to allow an upgrade path for an energy recovery ring in the existing proton hall, that would drive a free-electron laser.

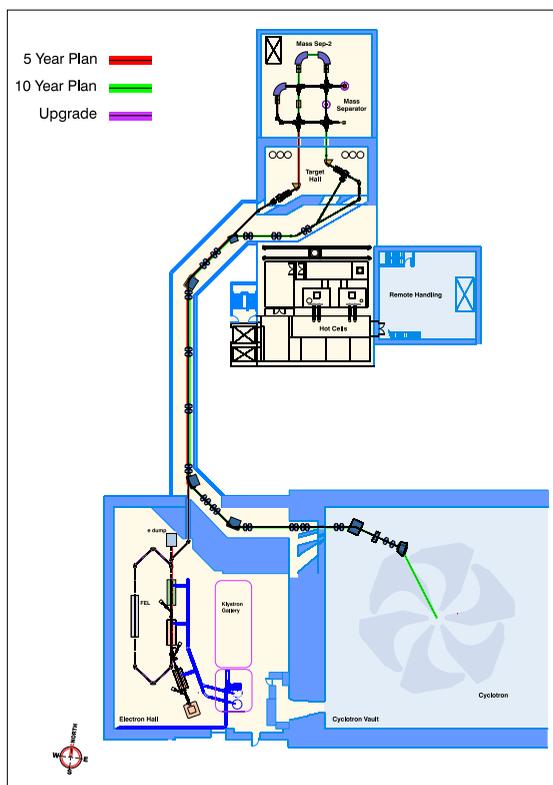


Figure 1: The layout of ARIEL showing the locations of the e-linac, tunnel, and new building.

Overview of Progress in 2008 - 2010

The ARIEL era started with the writing of the TRIUMF Five-Year Plan, which was completed in June 2008. This defined the project in two stages. The initial stage (the first 5 years) provided a proton and an electron beam onto a single target, along with a single front-end. The second stage (the second five years) provided an additional electron target, along with a second front-end. During the preparation of the Five-Year Plan document, the project also received its name, Advanced Rare IsotopE Laboratory (ARIEL).

The project then quickly moved forward with a successful request to the Canada Foundation for Innovation (CFI) for the e-linac with an electron beam line to a target. The target and front-end were not included in the CFI request; funding was

planned to be available from the NRC Contribution Agreement. The CFI request was submitted in October 2008 by Prof. Dean Karlen (U. Victoria) as Principal Investigator of a national consortium of 13 Canadian institutions. The University of Victoria received notification of a positive response from CFI in July 2009. The preparations for this request required an independent cost analysis of the ARIEL civil construction, including the relocation for the Stores and Remote Handling office buildings, and a detailed cost outline and schedule for the e-linac. To release the CFI funds and start work on the e-linac two further hurdles had to be crossed: TRIUMF had to obtain matching funds from the Government of British Columbia and had to successfully renew its five-year core operating funds awarded by the Government of Canada. These steps could not be concluded prior to the announcement of the Federal budget in spring 2010. While awaiting this Federal and Provincial government funding, ARIEL moved forward in two thrusts:

A project to jointly develop the ion source and capture cavities with the VECC Laboratory (based in Kolkata, India), which had begun with discussions in January 2008, was formally started with the signing of an MoU agreement. This allowed work to start on the ARIEL e-linac injector along with an injector for the VECC Laboratory.

An ARIEL team was set up to make the final decisions and move forward on engineering designs so that the project could move ahead quickly when the CFI funds were released. The critical path for the project was identified to be the civil construction. AECOM, an international engineering and construction management company, was retained to develop the civil construction concepts to full readiness. These steps allowed construction plans to progress as far as possible while awaiting full project approval and funding.

An organization structure was set up with one sub-team for each major component (see Figure 2) and a Project Management Office (see Figure 3). The ARIEL work breakdown structure (WBS) was defined and a manpower loaded schedule produced. Milestones were established, an open questions list made, and a risk analysis undertaken for the project. A start on an initiative for an equipment naming convention was made. The project was reviewed by TRIUMF's external Accelerator Advisory Committee (AAC) in December 2009. Their insightful recommendations

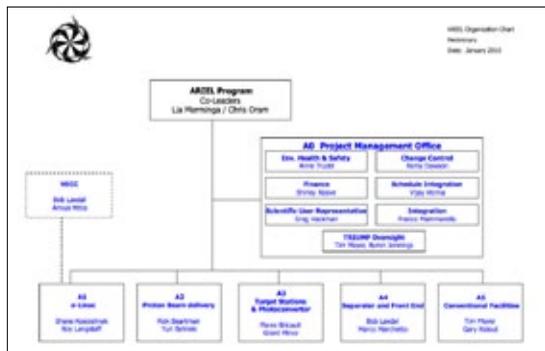


Figure 2: The top level organizational structure for ARIEL.

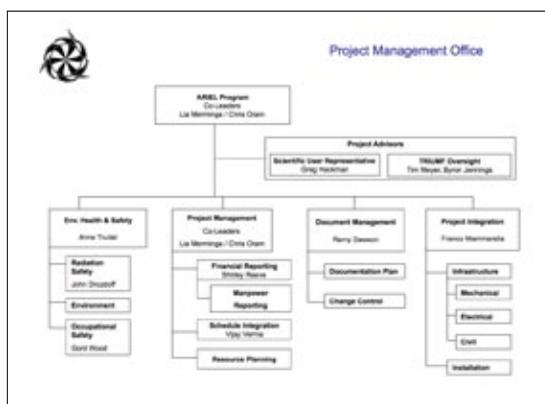


Figure 3: The ARIEL Project Management Office for ARIEL.

were useful in guiding discussions during which the ARIEL group reached a consensus to move items from the open questions list to the decisions list.

The e-linac design entered the detailed conceptual design stage, resolving a number of challenging and correlated design issues. This era started by defining the parameters required for the upgrade path for a free electron laser. Beam dynamics calculations for the e-linac were undertaken comparing the single 2-cell versus a pair of 1-cell SC capture cavities. From these studies it was decided to use a pair of 1-cell SC capture cavities. In March 2009, Y.C. Chao introduced a generic algorithm for global optimization of the injector from the gun exit to the ICM exit, allowing studies to proceed to narrow the choices for layout. By October, this effort had concluded with a baseline layout for the injector with adequate space for diagnostics, and was adopted as a basis for the engineering design. This design had a 650 MHz buncher; SC capture cells $\beta=0.7$, second cell $\beta=1.0$; and solenoid focusing. Meanwhile design work on magnets at DPACE (a Richmond, B.C. company)

produced preliminary magnet designs for the Low Energy Beam Transport (LEBT) solenoids and dipole, and Medium Energy Beam Transport (MEBT) dipole. Beam optics studies concluded with a preliminary concept for electron beam line from e-linac to the east target with electrons and protons sharing final focus optics elements. This was then followed by a study to decide on a layout of the electron and proton beam lines in the tunnel. For access reasons, this resulted in the lines being moved to the east side of the tunnel, with the proton beam above the electron beam. To allow room for the electron beam, the tunnel floor was lowered by 1 foot. Late fall 2009 studies included a detailed review of the Personnel Radiation Safety System proposal and Machine Protection System proposal with Kelly Mahoney (JLab), as well as presentations from Toshiba and CPI on klystrons. The klystron presentations were necessary because the supplier of the klystron specified in the CFI proposal had announced they were no longer manufacturing scientific klystrons. In December, the AAC visited TRIUMF and recommended a second separate injector for light source, noting that this would give complete independence of beam properties for fission and light source. They also recommended a NC graded-beta capture section to avoid mechanical complexity of SC single cells and to speed the schedule. These and other recommendations aided design decisions in early 2010.

Initial discussions with CNSC regarding the licensing were successful in establishing that the e-linac should be licensed as a "Class 2" 49.9 MeV 500 kW electron accelerator facility.

The target design during this era was advanced to a detailed conceptual design suitable for engineering design. To aid the optimization of the target for both protons and electrons, a decision was made to have the proton beam and electron beam be orthogonal at the target in order to separate the electron beam transport system from the proton beam line. This arrangement also simplifies the installation and usage of the 100 kW converter for the electron beam. An extensive design of the target hall and hot cell complex was

undertaken, with full consideration of personnel access to the building being undertaken for the first time. In the target hall, a design was adopted where the RIB beam line elements are installed and maintained from above using the overhead crane. This allows a close packed shielding design to be adopted, thus reducing the neutron fields in the RIB building (an issue that has created considerable difficulty at the existing ISAC target). The new design simplifies the servicing and maintenance of the key components and access to the mass separator.

A detailed layout of the front end systems was developed and space allocated for future upgrades, power supplies, and services.

The goal in this phase was to be ready with the concept, design, and specifications for the design consultants who would provide final construction drawings. AECOM's extensive expertise with previous science projects at TRIUMF, as well as other research infrastructure around the world, drove the construction-design planning and advanced the detailed schematic design.

Design of the main ARIEL facility was sub-divided into teams for the e-linac vault, tunnel, target hall, and RIB section.

Extensive studies of radiation shielding requirements were made for all the above areas, with detailed studies of neutron and gamma ray backgrounds. Requirements for services were detailed, and preliminary room data sheets were developed. Studies were undertaken to specify the shoring requirements so that adjacent buildings would not be compromised by the ARIEL civil construction. Egress requirements were considered in detail and a plan of suitably located entrances and exits designed.

In addition, studies were undertaken for relocation of the Stores building, a new personnel entrance through the TRIUMF radiation fence under the MOB auditorium, and the re-organization of the site plan with new fire and traffic routes.

Finally, a revised cost estimate was undertaken in early 2010, replacing the earlier 2008 estimate for the initial CFI submission.

Nigel Lockyer, Director of TRIUMF, joined the laboratory in May 2007. He is a particle physicist with broad interests in medicine, technology, and business.



Next Steps

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

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A brief description of TRIUMF's plans are in the ARIEL section of this report. For a full description, please see *Five-Year Plan 2010-2015: Building a Vision for the Future*.

During the next two years, TRIUMF will focus on achieving the initial phases of the Five-Year Plan. Some of these activities will include:

- Delivering high-value, high-impact scientific results
- Construction and completion of the M-9A and M-20 beam lines to expand μ SR capabilities for TRIUMF's Centre for Molecular and Materials Science
- Exploiting data from the ATLAS experiment at the Large Hadron Collider for Canadian leadership on key physics analyses
- Producing world-leading results with the T2K neutrino experiment in Japan
- Expanded development of rare-isotope beams for ISAC, including beams from actinide targets for science experiments

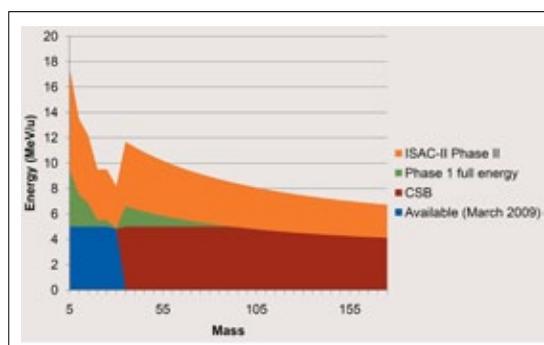


Figure 1: Overview of TRIUMF's capabilities to provide accelerated beams of rare-isotopes. It is the combination of tools that provides broad coverage.

- Designing, constructing, and commissioning SRF components within the framework of the collaboration agreement with the Variable Energy Cyclotron Centre in India
- Launching construction of the ARIEL facility and the e-linac machine
- Upgrading elements of the nuclear medicine laboratory space to comply with cGMP standards
- Targeted upgrades, refurbishing, and preventive maintenance of the main cyclotron to enhance reliable delivery of high beam currents and ensure long-term integrity of core equipment (see Figure 1 for current capabilities)
- Implementing summary status and reporting for projects and resources across TRIUMF
- Securing new partnerships with business, governments, and global research organizations to advance TRIUMF's programs.



On June 22, 2010, the Governments of Canada and British Columbia announced full funding for the ARIEL project at TRIUMF with support from the University of Victoria. Here, TRIUMF director Nigel Lockyer speaks with BC Premier Gordon Campbell and federal President of Treasury Board Stockwell Day.



Photo:
Exterior view of the
ISAC-II facility at TRIUMF.



Appendices

**Making Medical Isotopes
Committees List
Publications List**



Tim Meyer is the head of Strategic Planning and Communications at TRIUMF and part of the senior management team.

Making Medical Isotopes

Final Report of the Task Force on Alternatives for Medical Isotope Production

In late 2007, North America experienced a critical shortage of the medical-isotope molybdenum-99 (Mo-99) over a period of several weeks due to an extended shutdown of AECL's NRU reactor at Chalk River, Ontario. Presently, 80-85% of all nuclear medicine procedures use Mo-99. There are about 40 million procedures worldwide per year, which includes 20 million procedures in North America and about 1.5 million of those procedures in Canada. Canada produces about half the world's supply with the NRU reactor (operating since 1957).

Although historically, the supply from AECL-MDS Nordion has been reliable, the long-term supply of Mo-99 worldwide is at potential risk as it presently relies on two ageing reactors that supply 90% of all production. The risks can be reduced by having a greater number of reliable Mo-99 producers. As Canada's national laboratory for particle and nuclear physics, TRIUMF has identified a technology (photo-fission) that uses accelerators to generate photons to produce Mo-99 from natural uranium as compared to the present-day technique that uses neutrons from a nuclear reactor using highly enriched uranium.

Based on preliminary calculations and numerical simulations, significant quantities of Mo-99 can be produced from natural uranium by photo-fission using accelerators. Several laboratory experiments are needed to establish efficiencies, equivalency of products, reliability of operation, and capacity. The technology exists to build an electron accelerator of suitably high beam power (2-3 MW) to produce a meaningful amount of Mo-99. A single multi-megawatt machine could supply the Canadian market or 5-7% of the North American market.

The radio-chemistry needed to recover and refine the Mo-99 generated through photo-fission (from natural uranium targets) most likely resembles that produced by a reactor using HEU targets. The similarity of the initial Mo-99 recovery step will be sensitive to the volume of the target for photo-fission which depends in detail upon optimization of design and performance parameters.

At present, construction of a photo-fission accelerator would take 3-4 years. Depending on the specific technology chosen for the accelerator, the construction costs, including labour, would be C\$50 million, C\$80 million, or \$C125 million. Power would likely dominate operational costs. The total production cycle for medical isotopes includes the manufacture of targets for irradiation, storage of radioactive waste from target processing, and hot-cell facilities to recover and refine Mo-99. These facilities are needed for any new production source of Mo-99 and would cost at least C\$50 million.

Conclusion

Accelerator-driven photo-fission of U-238 is an attractive approach for generating Mo-99 without security issues and with lower decommissioning costs at end of life. To ensure high reliability of supply, a half-dozen multi-megawatt machines could be built that would meet about 30-50% of North American demand.

Recommendation

The Government of Canada should support a Mo-99 Photo-Fission Accelerator Steering Group of public-private partners who select a project director and provide oversight. The director will be responsible for managing the preparation, coordination, and completion of R&D work

packages funded through government and private sources according to an appropriate competitive process of scientific peer review.

A steering group of public and private partners would bring together the skills, resources, and business sense required to develop the technology, oversee a proof-of-principle demonstration, and then assess and/or pursue commercial viability. Work packages should follow from an R&D program outlined in the full report. The completion of these work packages would lead the steering group to

present a recommendation on the photo-fission accelerator technology within 3-4 years. A low-power test to generate Mo-99 with a photo-fission accelerator on a timescale of a few years is possible at TRIUMF using this device as it will utilize the same basic technology. The activities at TRIUMF could be expedited.

The Task Force on Alternatives for Medical Isotope Production was convened by TRIUMF, the University of British Columbia, and Advanced Applied Physics Solutions, Inc., with support from Natural Resources Canada.

Committees List

Board of Management (BOM)

The Board of Management is responsible for the operation, supervision, and control of TRIUMF. It is made up of appointees from the Joint Venture Universities and two representatives from the private sector.

Full Member Universities	Member	Committee
University of Alberta	Dr. R. Fedorak (Richard)	Finance Executive
University of Alberta	Dr. A. Hallin (Aksel)	Personnel & Admin
University of British Columbia	Dr. D. Brooks (Donald)	Chair, Finance Executive Technology Transfer
University of British Columbia	Dr. J. Young (Jeff)	Personnel & Admin
Carleton University	Dr. J. Armitage (John)	Finance Executive
Carleton University	Dr. P. Kalyniak (Patricia)	Chair, Personnel & Admin
University of Manitoba	Dr. D.S. Jayas (Digvir)	Finance Executive
University of Manitoba	Dr. M. Whitmore (Mark)	Personnel & Admin
University of Guelph	Dr. S.N. Liss (Steven)	Finance Executive
Université de Montréal	Dr. C. Leroy (Claude)	Personnel & Admin
Simon Fraser University	Dr. N. Hauerland (Norbert)	Finance Executive
Simon Fraser University	Dr. M. Plischke (Michael)	Personnel & Admin
University of Toronto	Dr. R.P. Young (Paul)	Finance Executive Technology Transfer
University of Toronto	Dr. R.S. Orr (Bob)	Personnel & Admin
University of Victoria	Dr. H. Brunt (Howard)	Finance Executive Board Chair
University of Victoria	Dr. R. Kowalewski (Robert)	Personnel & Admin
Queen's University	Dr. K. Rowe (Kerry)	Finance Executive
Queen's University	Dr. A. Noble (Tony)	Personnel & Admin
York University	Dr. M.K. Siu (Michael)	Finance Executive
York University	Dr. S. Bhadra (Sampal)	Personnel & Admin
Private Sector Representative	Dr. P. Covitz (Peter)	Technology Transfer
Private Sector Representative	Mr. E. Odishaw (Edward)	Technology Transfer
Associate Member Universities		
McMaster University	Dr. D. Venus (David)	Chair, Environmental Safety & Security
University of Calgary	Dr. R.I. Thompson (Robert)	
University of Regina	Dr. B. Maguire (Brien)	
Saint Mary's University	Dr. M.N. Butler (Malcolm)	
Non-Voting Member		
Director, National Facilities, NRC	Dr. W. Davidson (Walter)	
Director, TRIUMF	Dr. N.S. Lockyer (Nigel)	
Chair, ACOT	Dr. R.V. Janssens (Robert)	
Secretary	Mr. J. Hanlon (Jim)	

Sub-committees of the Board of Management**Finance**

D. Brooks - Chair
S. Reeve- Secretary

Personnel & Admin

P. Kalyniak - Chair
J. Hanlon - Secretary

Environmental Safety & Security

D. Venus - Chair
J. Hanlon - Secretary

Executive

J. Armitage
N. Haunerland
R. Fedorak
D. Brooks
D. Jayas
H. Brunt (Chair)
S. Liss
K. Rowe
P. Young
M. Siu

Technology Transfer

P. Young - Chair
Secretary - J. Hanlon

Agency Committee on TRIUMF (ACT)

The role of the Agency Committee on TRIUMF is to oversee the Government of Canada's investment in TRIUMF and the economic benefits derived from that investment, with a particular focus on financial and commercialization matters. The Committee provides advice to the Minister of Industry, in conjunction with the reports of the NRC Advisory Committee on TRIUMF which usually meets twice a year.

Member	Notes
Dr. P. Coulombe (Pierre) <i>Chair/Président</i>	President - NRC & Chair, ACT
Mr. R. Dicerni (Richard)	Deputy Minister, Industry Canada
Dr. W. Davidson (Walter)	NRC and ACT Secretary
Dr. S. Fortier (Suzanne)	President, NSERC
Dr. I. Blain (Isabelle)	Vice-President - NSERC

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

Members	Notes
Dr. R.V. Janssens (Robert) <i>President/présidente</i>	
Dr. W. Davidson (Walter) <i>Secretary/secrétaire</i>	
Dr. B.A. Balantekin (Baha)	
Dr. H. Buijs (Henri)	
Prof. J. Dorfan (Jonathan)	
Dr. E. Gallo (Elisabetta)	
Prof. B.D. Gaulin (Bruce)	
Dr. S. Houle (Sylvain)	
Dr. J. A. Lettry (Jacques)	
Dr. M. Wiescher (Michael)	
Dr. S. Boughaba (Samir) <i>Ex-Officio/Membre d'office</i>	Representing NSERC
Dr. H. Brunt (Howard) <i>Ex-Officio/Membre d'office</i>	Representing TRIUMF Board of Management
Dr. M. Lefebvre (Michel) <i>Ex-Officio/Membre d'office</i>	Representing NSERC GSC
Dr. K.S. Sharma (Kumar) <i>Ex-Officio/Membre d'office</i>	Representing Canadian Institute of Nuclear of Physics
Dr. W. Trischuk (William) <i>Ex-Officio/Membre d'office</i>	Representing Institute of Particle Physics
Dr. R. Paul Young <i>Ex-Officio/Membre d'office</i>	Representing TRIUMF Board of Management

contribution to TRIUMF. 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.

Private Sector Advisory Committee (PSAC)

Member

Jack Scott NaiKun - *Wind/ Energy Group Inc.*,
VP Commercial operations
Henri Buijs - ABB
Alan Pelman - former VP Weyerhaeuser
Dan Gelbart - Co-founder and President CREO
Gerry Salembier - ADM WED
Jim Soles - ADM STED
Pierre Coulombe - Former NRC president
Edward Odishaw

Experimental Evaluation Committees

The Experimental Evaluation Committee's review and approve new and ongoing experiments.

- LSPEC (meets annually)
- MMS-EEC (meets bi-annually)
- SAP-EEC (meets bi-annually)

Three Experiments Evaluation Committees (EECs) are in place at TRIUMF: the 'Subatomic Physics EEC' and the 'Molecular & Materials Science EEC' meet biannually at TRIUMF in June/July and December, and the 'Life Sciences Projects EEC' meets once a year in April. The purpose of these committees is to review new research proposals which are presented at the biannual and annual meetings, and advise TRIUMF's management on the feasibility of such research proposals and the allocation of beam time in appropriate priority sequence. They also review the progress of ongoing experiments. The committee members are selected based on their expertise in areas such as nuclear and particle physics, nuclear astrophysics, and application of the muon spin rotation to condensed matter physics and to chemistry and life sciences. The committees are comprised of eight or nine members from both national and international scientific communities, and each member serves for a period of three years.

Two months prior to each scheduled meeting, TRIUMF sends out a call for proposals, with a deadline set for submission, to all TRIUMF users representing national and international scientists in Japan, Germany, Scotland, England, the United States, Switzerland, Italy, France, and Australia. Each applicant must forward a proposal containing a concise summary of the scientific problem under investigation, with appropriate literature references; clear justification for the proposed experiment; the names of collaborators; support required from TRIUMF; a description of the experimental techniques to be used, naming the facility required; an analysis of beam time requirements including, for example, a prioritized list of samples; safety considerations, and an indication of start-up dates for preparation and start of data acquisition. Each proposal is then assigned for a detailed review to two committee members with relevant expertise, and the proposals are evaluated solely on their scientific merit. All accepted proposals and progress reports are distributed to the TRIUMF Library, Publications office and Operations department, as well as to various laboratories and university libraries along with the report that was generated for the specific meeting.

LSPEC: Life Science Projects

Member

Dr. R. Mach (Robert)
Chair / Président

Dr. J.-M. Poutissou (Jean-Michel)
Ex-Officio / Member d'office

Dr. D.A. Hutcheon (Dave)
Secretary / Secrétaire

Dr. N.E. Avril (Norbert)
Dr. Y. Ding (Yu-Shin)
Dr. J. Karp (Joel)
Dr. W. Martin (Wayne)
Dr. J. Soucy (Jean-Paul)
Dr. J.F. Valliant (John)

MMS-EEC: About Molecular & Materials Science

Member

Dr. R. Cywinski (Bob)
Chair / Président

Dr. G. C. Ball (Gordon)
Ex-Officio / Member d'office

Dr. P.W. Percival (Paul)
Secretary / Secrétaire

Dr. L. Balents (Leon)
Dr. M. Gingras (Michel)
Dr. C. Kallin (Catherine)
Dr. K. Kavanagh (Karen)
Dr. S. Nagler (Stephen)
Dr. E. Roduner (Emil)

SAP-EEC: About Subatomic Physics

Member

Dr. R. Tribble (Robert)
Chair / Président

Dr. G.C. Ball (Gordon)
Ex-Officio / Member d'office

Dr. B.J. Jennings (Byron)
Secretary / Secrétaire

Dr. J. Blackmon (Jeff)
Dr. P. Butler (Peter)
Dr. A. Galindo-Uribarri (Alfredo)
Dr. C. Horowitz (Charles)
Dr. W.D. Kulp (David)
Dr. T. Otsuka (Takaharu)
Dr. A. Schwenk (Achim)

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.

Member	Notes
Dr. C. Gay (Colin) Chair/président	University of British Columbia
Dr. M. Barbi (Mauricio)	University of Regina
Dr. S. Bhadra (Sampa)	York University
Dr. M. Boulay (Mark)	Queen's University
Dr. S. Godfrey (Stephen)	Carleton University
Dr. A. Hallin (Aksel)	University of Alberta
Dr. M. Hayden (Michael)	Simon Fraser University
Dr. R. Kanungo (Rituparna)	Saint Mary's University
Dr. R.F. Kiefl (Rob)	University of British Columbia
Dr. G.M. Luke (Graeme)	McMaster University
Dr. S.A. Page (Shelley)	University of Manitoba
Dr. M. Pospelov (Maxim)	University of Victoria
Dr. M.J. Roney (Mike)	University of Victoria
Dr. P. Savard (Pierre)	University of Toronto
Dr. V. Sossi (Vesna)	University of British Columbia
Dr. C. Svensson (Carl)	University of Guelph
Dr. B. Vachon (Brigitte)	McGill University
Dr. M.C. Vetterli (Mike)	Simon Fraser University
Dr. M. Wieser (Mike)	University of Calgary
Dr. V. Zacek (Viktor)	Université de Montréal

Safety Committees

Safety Management Committee

The TRIUMF Safety Management Committee supervises matters involving operational and procedural problems that have personal safety implications. It meets quarterly.

Nuclear Medicine Division Safety Committee

This committee is responsible for reviewing the safety reports associated with the proposals submitted to the Life Science Proposal Evaluation

Member	Notes
Dr. N.S. Lockyer (Nigel) Chair/Président	TRIUMF Director
Mrs. Kristina Gildert	Secretary/Secrétaire
Dr. G. Ball (Gordon)	Division Head - Science
Mr. C. Ballard (Curtis)	TAPC Chairman
Mr. C. Campbell (Chris)	AAPS
Mr. J. Cessford (Jamie)	Manager, Accelerator Operations
Mr. J.D. Hanlon (Jim)	Manager, Human Resources & Administration
Mr. P. Jones (Phil)	Manager, QA & Training
Dr. R. Keitel (Rolf)	Division Head - Engineering
Dr. L. Meringa (Lia)	Division Head - Accelerator
Dr. J.-M. Poutissou (Jean-Michel)	Division Head - Nuclear Medicine
Ms. S. Reeve (Shirley)	Chief Financial Officer
Dr. A.J. Trudel (Anne)	Manager, Environment, Health & Safety
Mr. J. Whyte (Jeff)	Nordion
Mr. G. Wood (Gord)	Occupational Health and Safety Officer
Dr. S.K. Zeisler (Stefan)	Head, Applied Technology Group

Committee (LSPEC) and for reviewing the action plans for corrective actions in response to the Non-Conformance Reports (NCR) issued in the division. It will report formally at the Quarterly Safety Management Meeting.

Member	Notes
Dr. J.-M. Poutissou (Jean-Michel) Chair/Président	Nuclear Medicine Division
Dr. M. Adam (Michael)	Nuclear Medicine Division
Dr. K. Buckley (Ken)	Nuclear Medicine Division
Mr. J. Cessford (Jamie)	Accelerator Division
Dr. J. Mildenberger (Joe)	Health & Safety Environment Group

Science Division Safety Committee

This committee will review, on an ad-hoc basis, new experiments and new facilities proposed by experimenters. Members serve a year at a time and are often asked to serve on the committee for continuous years.

Member	Notes
Dr. G.B. Ball Chair/Président	Science Division
Mr. C. Ballard (Curtis)	Engineering Division
Mr. J. Cessford (Jamie)	Accelerator Division
Mr. D. Dale (Don)	Engineering Division
Dr. C. Davis (Charles)	Science Division
Mr. R. Dawson (Remy)	Engineering Division
Dr. J. Dilling (Jens)	Science Division
Mr. F. Mammarella (Franco)	Engineering Division
Mr. C. Marshall (Cam)	Engineering Division
Dr. G. Marshall (Glen)	Science Division
Dr. J. Mildenberger (Joe)	Health & Safety Environment Group
Dr. A. Miller (Andy)	Science Division
Dr. G. Morris (Gerald)	Science Division
Dr. A.C. Morton (Colin)	Accelerator Division
Dr. R. Openshaw (Robert)	Science Division

Employee Liaison Committees

Technicians

This committee exists to assist members of the TRIUMF technicians group with any difficulties that may evolve relating to their workplace environment. Discretion and confidentiality is always assured. This group has been assisting technicians since the inception of TRIUMF. The committee also consults with Human Resources on policies and procedures, salary structure, and other aspects of TRIUMF administration.

Member

Tim Emmens, *Chairman*
Daniel Rowbotham
Bruno Gasbarri
Maico Dalla Valle

Terry Denham
Peter Biglowe
Marco Pecchia

Professional & Supervisory Staff

Member

Stu Austen, *Chairman*
Mike Mouat, *Vice Chairman*
John Drozdoff, *Secretary*
Roman Ruegg, *Ex-Officio*
Brenda Morrey, *Member-at-large*
Nicole Martin, *Member-at-large*
Colin Morton, *Member-at-large*
Curtis Ballard, *Member-at-large*

Library Committee

The Library Committee is responsible for TRIUMF's library located on the second floor of the Main Office Building (MOB).

Member
Dr. L. Buchmann (Lothar) <i>Chair/président</i>
Dr. M. Adam (Michael)
Mr. R. Baartman (Rick)
Dr. M. Comyn (Martin)
Mr. B. Hitti (Bassam)
Dr. B. Jennings (Byron)
Mr. G. Jones (Glenn)
Dr. S. Kreitzman (Syd)
Mr. A. Mitra (Amiya)
Dr. J.-M. Poutissou (Jean-Michel)
Mrs. R. Samasekera (Raso)
Dr. I. Trigger (Isabel)

Publications List

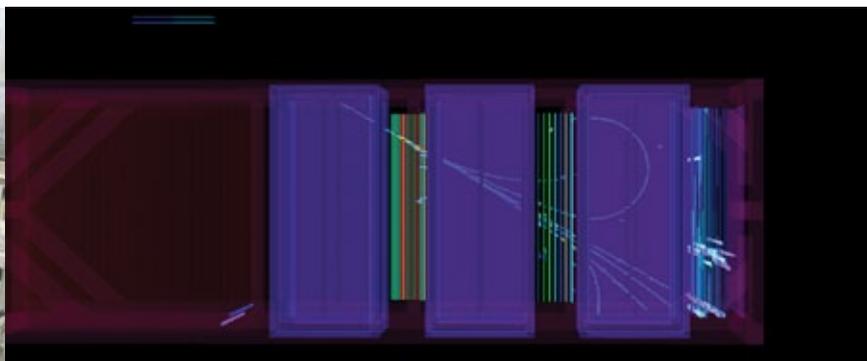
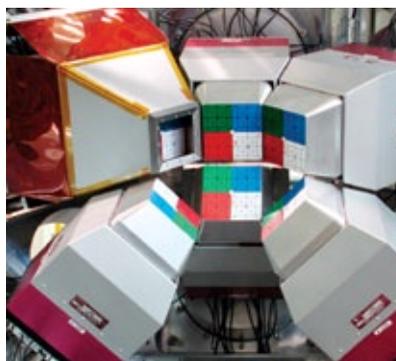
For a complete list of scientific publications in which TRIUMF was involved, please see the web site at <http://www.triumf.ca>. This appendix provides a brief overview of scientific publications activity during the two years 2008-2009.

In calendar year 2008, TRIUMF was involved in 164 scientific publications; this increased to 202 in 2009. By subject area, 80% of publications addressed topics in physics, 43% addressed chemistry (in combination with physics), and 17% materials science in combination with physics or chemistry. About 11% of the articles were published in *Physical Review Letters*, with equal contributions to *Physical Review C* and *Physical Review D*.

Already by early 2010, the most cited article (describing the ATLAS experiment at CERN's Large Hadron Collider) from this time period had 89 citations. The ten articles published in 2008-2009 with the most citations are as follows:

1. Aad, G., et al., ATLAS Collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider," JOURNAL OF INSTRUMENTATION 3 Art No. S08003 2008. Times Cited 89
2. Aharmim, B., et al., SNO Collaboration, "Independent measurement of the total active B-8 solar neutrino flux using an array of He-3 proportional counters at the Sudbury Neutrino Observatory," PHYSICAL REVIEW LETTERS 101 (11): 111301 2008. Times Cited 34
3. Aczel, AA; Baggio-Saitovitch, E; Budko, SL; Canfield, PC; Carlo, JP; Chen, GF; Dai, PC; Goko, T; Hu, WZ; Luke, GM; Luo, JL; Ni, N; Sanchez-Candela, DR; Tafti, FF; Wang, NL; Williams, TJ; Yu, W; Uemura, YJ, "Muon-spin-relaxation studies of magnetic order and superfluid density in antiferromagnetic NdFeAsO, BaFe2As2, and superconducting Ba1-xKxFe2As2," PHYSICAL REVIEW B 78 (21): Art No. 214503 2008. Times Cited 33.
4. Raidal, M; van der Schaaf, A; Bigi, I; Mangano, ML; Semertzidis, Y; Abel, S; Albino, S; Antusch, S; Arganda, E; Bajc, B; Banerjee, S; Biggio, C; Blanke, M; Bonivento, W; Branco, GC; Bryman, D; Buras, AJ; Calibbi, L; Ceccucci, A; Chankowski, PH; Davidson, S; Deandrea, A; DeMille, DP; Deppisch, F; Diaz, MA; Duling, B; Felcini, M; Fetscher, W; Forti, F; Ghosh, DK; Giffels, M; Giorgi, MA; Giudice, G; Goudzovskij, E; Han, T; Harris, PG; Herrero, MJ; Hisano, J; Holt, RJ; Huitu, K; Ibarra, A; Igonkina, O; Ilakovac, A; Imazato, J; Isidori, G; Joaquim, FR; Kadastik, M; Kajiyama, Y; King, SF; Kirch, K; Kozlov, MG; Krawczyk, M; Kress, T; Lebedev, O; Lusiani, A; Ma, E; Marchiori, G; Masiero, A; Masina, I; Moreau, G; Mori, T; Muntel, M; Neri, N; Nesti, F; Onderwater, CJG; Paradisi, P; Petcov, ST; Picariello, M; Porretti, V; Poschenrieder, A; Pospelov, M; Rebane, L; Rebelo, MN; Ritz, A; Roberts, L; Romanino, A; Roney, JM; Rossi, A; Ruckl, R; Senjanovic, G; Serra, N; Shindou, T; Takahashi, Y; Tarantino, C; Teixeira, AM; Torrente-Lujan, E; Turzyski, KJ; Underwood, TEJ; Vempati, SK; Vives, O "Flavor physics of leptons and dipole moments," EUROPEAN PHYSICAL JOURNAL C 57 (1-2):13-182 2008. Times Cited 27.
5. Abazov, V.M., et al., D0 Collaboration, "Evidence for production of single top quarks," PHYSICAL REVIEW D 78 (1): Art No. 012005 2008. Times Cited 23.
6. Bogner, SK; Furnstahl, RJ; Maris, P; Perry, RJ; Schwenk, A; Vary, JP, "Convergence in the no-core shell model with low-momentum two-nucleon interactions," NUCLEAR PHYSICS A 801 (1-2):21-42 2008. Times Cited 21.
7. Park, K., et al., Clas Collaboration, "Cross sections and beam asymmetries for $ep \rightarrow e\pi\pi^+$ in the nucleon resonance region for $1.7 \leq Q(2) \leq 4.5 \text{ GeV}^2$," PHYSICAL REVIEW C 77 (1): Art No. 015208 2008. Times Cited 19.
8. Goko, T; Aczel, AA; Baggio-Saitovitch, E; Bud'ko, SL; Canfield, PC; Carlo, JP; Chen, GF; Dai, PC; Hamann, AC; Hu, WZ; Kageyama, H; Luke, GM; Luo, JL; Nachumi, B; Ni, N; Reznik, D; Sanchez-Candela, DR; Savici, AT; Sikes, KJ; Wang, NL; Wiebe, CR; Williams, TJ; Yamamoto,

- T; Yu, W; Uemura, YJ., "Superconducting state coexisting with a phase-separated static magnetic order in (Ba,K)Fe₂As₂, (Sr,Na)Fe₂As₂, and CaFe₂As₂," PHYSICAL REVIEW B 80 (2): Art No. 024508 2009. Times Cited 17.
9. Aaltonen, T., et al., CDF Collaboration, "Observation of electroweak single top-quark production," PHYSICAL REVIEW LETTERS 103 (9): Art No. 092002 2009. Times Cited 17.
10. Mukherjee, M; Beck, D; Blaum, K; Bollen, G; Dilling, J; George, S; Herfurth, F; Herlert, A; Kellerbauer, A; Kluge, HJ; Schwarz, S; Schweikhard, L; Yazidjian, C., "ISOLTRAP: An on-line Penning trap for mass spectrometry on short-lived nuclides," EUROPEAN PHYSICAL JOURNAL A 35 (1):1-29 2008. Times Cited 17.



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