Scientific Activities Report 2010 - 2012

TRIUMF

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2010 - 2012

TRIUMF

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TRIUMF's Mission

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

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

TRIUMF's Vision

TRIUMF will:

Lead in Science: The world sees TRIUMF as Canada's leader in probing the structure and origins of matter and in advancing isotopes for science and medicine.
Leverage University Research: The Canadian university research community views TRIUMF as a way to strengthen and expand their research programs.
Connect Canada to the World: International subatomic physics laboratories look to TRIUMF when partnering with Canada and its research community.
Create Social and Economic Growth: The global scientific community sees TRIUMF as a bridge between academia and the private sector and as a model for commercialization & social impact.

TRIUMF's Values

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

Excellence and Impact: A commitment to excellence in achieving TRIUMF's mission and vision while making a real difference.
Collaboration and Teamwork: Working together with others (individuals, groups, or institutions) for our mutual benefit.
Honesty and Transparency: Being responsible and accountable for our actions and their consequences; respecting people, their ideas and diversity; working safely and sustainably with openness, authenticity, generosity, and equity.
Innovation and Relevance: Approaching assignments, tasks, and problems in new and efficacious ways; creating novel ideas and techniques.

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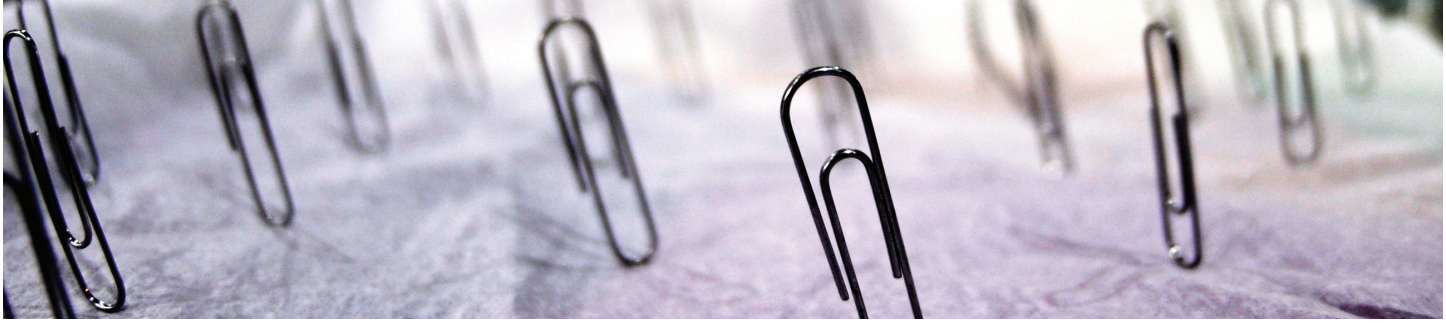

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Preface

All national laboratories prepare a regular science report. This document is the TRIUMF biennial report on science and technical activities. We choose to do this because the impact of the science and technology becomes more apparent every two years, let alone over the 8 -10 year time scale.

A tremendous number of people contribute to this report, and while it is impossible to thank them all, we do want to thank the accredited editors and authors who are acknowledged in the bylines of each article. These people took the time and effort to pool the results of their colleagues, put them in context, and chase down contributions to ensure that TRIUMF's mark on the progress of global science was accurately represented in this report. Thank you to all those dedicated individuals, and thank you to all those people who contributed that we don't know about. The success of TRIUMF, the progress of Canadian science, and the advance of the human condition would not be possible without you doing what you do. Thank you.

Context within TRIUMF's Five-Year Plan

TRIUMF's core operations funding flows from the federal Government of Canada via the National Research Council of Canada. The funding agreements occur in five-year cycles. The present Five-Year Plan started April 1, 2010, and will complete March 31, 2015. This science report outlines the progress that TRIUMF has helped foment across the broader community. Directed by its mission, TRIUMF has made real progress for Canadian science and technology. In particle physics, TRIUMF's contributions to CERN's Large Hadron Collider and the global ATLAS experiment are bearing fruit as the pursuit of the Higgs boson moves within reach. In nuclear physics, TRIUMF's new capability to produce heavy isotopes using proton beams on actinide targets has yielded some early mass measurements that set world records, while high-intensity yields of other isotopes have afforded real breakthroughs in understanding nuclear astrophysics and nuclear structure. In materials science, TRIUMF has been busy building new capacity and capability for muon-spin resonance with the M-20 and M-9 beamlines. Finally, in the realm of nuclear medicine, TRIUMF has established itself as a world leader in the physics and chemistry of medical isotopes, ranging from novel techniques to produce conventional isotopes (e.g., Tc-99m) to significant progress in labeling key neurotransmitters such as norepinephrine with the assistance of visiting scientist Yu-shin Ding.

In terms of the overall five-year ambitions for TRIUMF, the laboratory is on target.

2 Advancing Knowledge

Introduction

The TRIUMF research program builds on its strength in accelerator-based science and the development and exploitation of modern detector systems for experiments in subatomic physics. The local program predominantly makes use of the 500MeV cyclotron for the production of secondary beams of pions, muons, and short-lived isotopes (called rare isotopes or radio-isotopes), which are used for basic research, as well as nuclear medicine. An intensive external program is carried out at offshore facilities, such as CERN (Switzerland) and JPARC (Japan), which contribute to high-impact experimental programs beyond TRIUMF's internal capabilities. Overall, TRIUMF's research is driven by two core themes: (1) Probing the structure and origin of matter and (2) Advancing isotopes for science and medicine.

A primary thrust of TRIUMF's scientific program is aimed at identifying and understanding the nature and origin of the elementary particles—the fundamental building blocks of our world—as well as the forces between those particles. Substantial evidence exists that indicates that the current Standard Model of Particle Physics may be incomplete, that new particles may exist, and that our comprehension of the fundamental forces may be limited. TRIUMF is in an ideal position to make major contributions in this quest through the experiments being performed, internally and externally, by TRIUMF scientists.

The Large Hadron Collider (LHC) at CERN is expected to not only produce the long sought after Higgs particle but also new particles not predicted by the Standard Model. The lightest of these may be a candidate for a dark matter particle, which would confirm the evidence we see in gravitational effects on large scales. Members of the TRIUMF ATLAS group are making substantial contributions in the pursuit for direct particle production of the Higgs. TRIUMF also provides critical support for the Canadian and international particle physics community with the ATLAS Tier-1 data center.

Concurrently, the DEAP experiment currently under construction in SNOLAB will be searching for primordial dark matter particles traversing the earth.

High precision measurements are also an ideal tool to search for deviations from Standard Model predictions. TRIUMF is carrying out, or is involved in, a number of experiments that fall into this category. The T2K experiment in Japan has discovered the first indications that the neutrino mixing angle θ_{13} is non-zero and large, results that were confirmed by several reactor experiments. The EXO experiment, which searches for neutrino-less double-beta decay of Xenon-136, has recently published first observations of the two-neutrino double-

beta decay, demonstrating its impressive sensitivity for the neutrino-less decay mode. At the same time, the TITAN penning trap facility at TRIUMF has started a program to measure nuclear properties, such as masses and electron capture branching ratios, which are important for neutrino measurements. The SNO+ experiment currently under construction at SNOLAB will also study important neutrino properties. The ALPHA experiment at CERN has produced and stored anti-hydrogen for more than 15 minutes and carried out the first microwave spectroscopy of anti-hydrogen.

High precision studies of various electroweak processes at high, medium, and low energies are carried out to probe for new phenomena beyond the standard model of particle physics. Some examples of this are the production of W bosons at the LHC, the measurement of the muon decay parameters with TWIST, the precise measurement of the weak charge of the proton with the Qweak experiment at JLab, the test of lepton universality in pion decays with the PIENU experiment at TRIUMF, as well as measurements of beta decay correlations and transition rates of short-lived isotopes at TRIUMF's ISAC facility.

Understanding the origin of the chemical elements that make up our bodies and the world around us is another major focus of TRIUMF's science program. It is still not fully understood how the elements are produced in the various stages of stellar burning and stellar explosions. It is often the case that rare isotopes that are intermittently produced are involved in these processes and the study of the properties of these nuclei and their contribution to the astrophysical reactions presents a major challenge in modern nuclear physics. Another major focus in this field aims at developing a unified theoretical framework with predictive power for the description of all nuclei and nuclear matter based on nuclear forces that are constructed from first principle. TRIUMF is poised to take a world-leading position in the investigation of rare isotopes. In our world-class experimental facilities—ISAC, and in the future, ARIEL—we offer some of the highest production rates in the world.

With its production facilities for muons and rare isotopes, TRIUMF is also equipped with the unique tools necessary to characterize chemical reactions, molecular binding, and new materials in terms of their magnetic properties. The Center for Molecular and Material Science (CMMS) at TRIUMF serves a wide international user community with several end stations for MuSR and betaNMR experiments. The research topics are relevant to a broad spectrum of applications in other areas of science and industry, including high temperature superconductivity, quantum computing, spintronics, chemical reactions relevant for next generation reactors, and next generation batteries.

TRIUMF applies its core expertise in accelerators and the production and chemical extraction of radioisotopes for contributions in nuclear medicine. On site, we perform eye tumor treatments and produce radioisotopes for research on biochemical and biological mechanisms that contribute to the onset of neurological disease and cancer.
Most of the research at TRIUMF relies on the peak performance of its suite of accelerators, from the 500 MeV cyclotron to the ISAC-II heavy-ion LINAC. Aside from making important improvements to the existing accelerator facilities, TRIUMF's accelerator experts are also advancing fundamental knowledge in accelerator science and technology.

2.2
Direct Particle Production Searches

Isabel Trigger

One of the most straightforward ways to validate a theoretical model in particle physics is to look for direct production of the particles the theory predicts. Their masses, quantum numbers, and couplings to other particles can be measured and compared to theoretical predictions. If the predictions of a theory do not match the properties of the particles observed, the theory may be discarded. If the search for new particles predicted by a theory yields null results, exclusion limits may be calculated and the allowed parameter space of the model gradually reduced.

The Standard Model of particle physics[1] made a number of predictions when it was first proposed over forty years ago. All but one of these have been spectacularly confirmed*; only the elementary scalar known as the Higgs Boson remains elusive. Its allowed mass range was strongly constrained by the LEP experiments[2] in the 1990s, and further limited by the Tevatron experiments[3], but the LHC experiments ATLAS and CMS are rapidly reducing the allowed range (see Figure 1) and have shown preliminary hints[4] of a possible excess of events potentially corresponding to a Higgs Boson mass around 125 GeV, based on a partial analysis of the roughly 5 fb-1 of proton-proton collision data at a centre-of-mass energy of 7 TeV collected by each of the experiments in 2011. The Higgs Boson can decay in many different ways. Members of the TRIUMF group are looking at the cases where it decays to two W bosons, or two Z bosons, and other Canadian groups are considering different channels, including the decay to two photons. Analyses of these three decay channels are combined to give the final result shown in Figure 2.

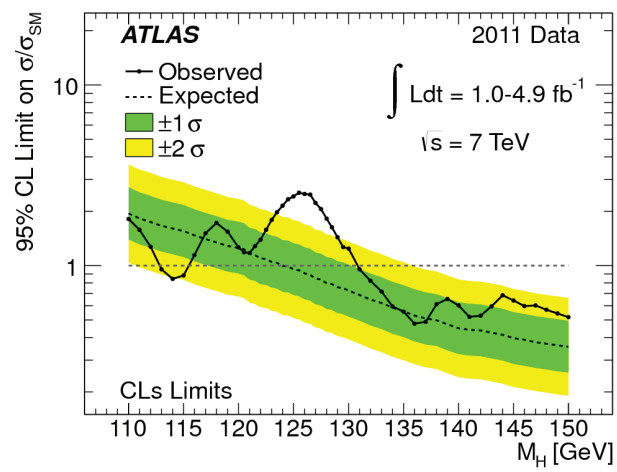

Figure 1. ATLAS data can be used to constrain the Higgs mass. Where above 1, there is still a chance to find the Higgs.

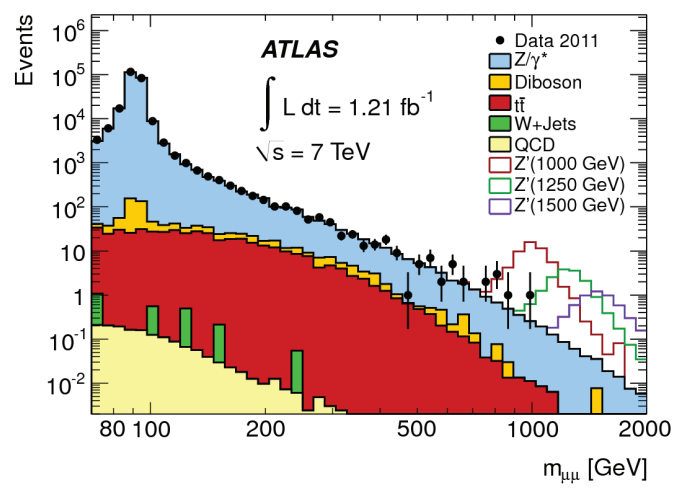

Figure 2. Dimuon masses reconstructed in data compared to simulated production processes.

While the Standard Model requires the existence of one Higgs Boson, virtually all extensions to it require that there be one or more Higgs Bosons, or other scalar particles which perform the same role in electroweak symmetry breaking. It is therefore interesting to search for non-Standard-Model Higgs Bosons, which can be charged or pseudoscalar particles, or may simply have different couplings to the other Standard Model fermions and bosons. One scenario studied at TRIUMF considers supersymmetric extensions to the Standard Model where super-partners can decay to a "Standard-Model-like" Higgs, which decays primarily to pairs of bottom quarks. Because of the enormous multijet backgrounds, this common decay mode for Higgs masses below about 130 GeV cannot be detected at the LHC unless the Higgs is produced in association with another particle which serves as the trigger signature—in this case, through the missing energy carried away by the unseen Lightest Supersymmetric Particle (LSP).

Missing transverse energy is the key to most searches for supersymmetric models where an additional symmetry ("R-parity") is assumed to require that there be at least one supersymmetric decay product in all supersymmetric decays, resulting in the presence of a stable LSP in all final states. Searches for supersymmetry can then be done very generically by looking for missing transverse energy accompanying a variety of other objects. Members of the TRIUMF ATLAS group search for both gauginos (supersymmetric partners of the gauge and Higgs bosons) and sfermions (supersymmetric partners of the quarks and leptons). Current and recent analyses include searches for direct gaugino production with decays to final states including one, two, three, four, or no charged leptons[5], as well as searches for supersymmetric partners of the top quark decaying to top quarks and an LSP. Some of these searches have also been made for variants of supersymmetry with no R-parity conservation[6], where missing transverse energy is not part of the signature.

Most Standard Model extensions predict the existence of additional vector gauge bosons, similar to the W and Z, but more massive. If these exist within the mass range kinematically accessible at the LHC, they produce unique, spectacular signatures (for example, a 1-TeV Z' could decay to two oppositely-charged 500-GeV muons) which are almost background-free. TRIUMF ATLAS-group members are searching for W' and Z' with "Standard Model-like" couplings decaying to electron or muon pairs[7], and also for new gauge bosons that couple preferentially to top-quark pairs[8] which are favoured in many models such as Little Higgs. They also search for excited states of leptons[9], which would be evidence for lepton compositeness. Most of these analyses can be reinterpreted[10] in the context of other models of electroweak symmetry breaking, such as Technicolor, or Randall-Sundrum models with Kaluza-Klein gluons[11].

In 2012, the LHC will run at a higher centre-of-mass energy of 8 TeV, increasing the cross-section for Higgs boson production and allowing it to expand its reach for discovering massive new particles. It is expected to accumulate a dataset several times larger than the 5 fb-1 collected in 2011, which will be sufficient either to exclude the Standard Model Higgs boson over the entire range where it is relevant for electroweak symmetry breaking, or to provide conclusive evidence of its existence.

***** At the time of printing, conclusive evidence for a Higgs-like boson was announced (July 2012).

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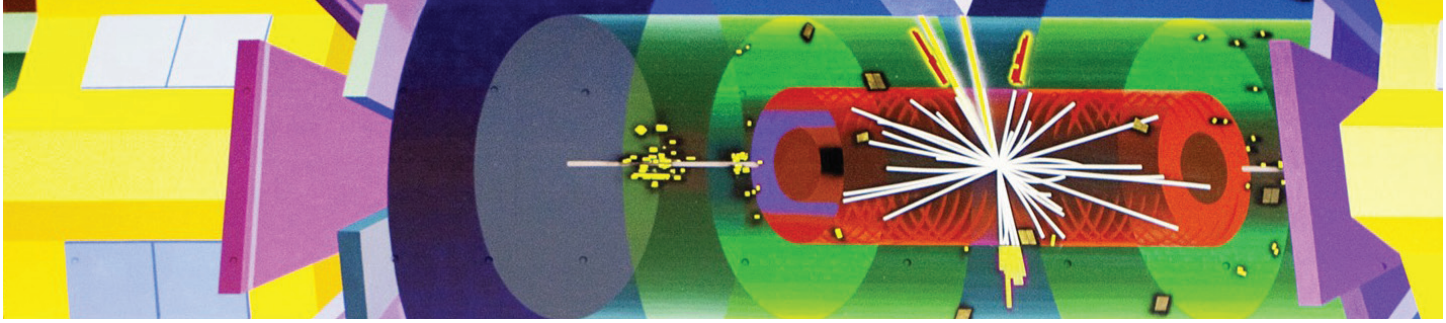

2.3
Neutrino and Dark Matter Physics

Stan Yen and Akira Konaka

Some of the greatest challenges in experimental physics are concerned with detecting the undetectable. Detectors are built to look for two types of "undetectable" particles: neutrinos and dark matter.

Many observations from astronomy and cosmology point to the existence of dark matter, which is matter that exerts a gravitational force but which feels neither the electromagnetic nor the strong nuclear force. The most popular conjecture is that dark matter consists of a vast swarm of Weakly Interacting Massive Particles (WIMPs) surrounding each galaxy. If so, they may be observed via collisions with detectors here on earth (e.g. DEAP in SNOLAB), or dark matter particles may be directly produced in high-energy collisions (e.g. ATLAS at the Large Hadron Collider).

Neutrinos are ghostly particles which feel only the weak nuclear force and can therefore pass through the entire earth with very little probability of a collision. Neutrinos come in three 'flavours' of ν_e, ν_μ, and ν_τ and can change from one flavour to another via 'neutrino oscillations'. TRIUMF scientists play leading roles in past (SNO) and current (T2K) experiments to advance our understanding of neutrinos, as well as in future experiments under construction at SNOLAB (SNO+, HALO).

Theory Group

The TRIUMF Theory Group studies candidates for dark matter based on existing and upcoming data from dark matter searches based on laboratory and collider experiments and astrophysical observations. A specific area of research in 2010 and 2011 were dark matter particles that can also explain the excess of matter over antimatter in the Universe. With collaborators at UBC and Brookhaven, TRIUMF theorists developed a novel theory of dark matter that realizes the dark matter particles as hidden anti-baryons, in which the net baryon charge carried by dark matter is equal and opposite to that carried by visible matter[1]. They also studied ways in which such dark matter particles could be seen in nucleon decay experiments[2]. In the coming years, the theory group will continue its investigation of dark matter by making full use of expected data from the LHC and direct dark matter search experiments.

Indirect Searches for Dark Matter at ATLAS

The ATLAS experiment boasts a broad dark matter program in the context of the search for physics beyond the Standard Model. Supersymmetry (SUSY) is one of the most promising theories of new physics and predicts the existence of a massive, neutral, and weakly interacting particle called the neutralino. Under R-parity conservation, the neutralino is stable and represents an excellent candidate for dark matter. Neutralinos may arise from cascade decays of strongly interacting supersymmetric particles, such as squarks and gluinos, or weakly interacting particles, such as charginos and heavy neutralinos. Since the neutralinos escape detection, the

missing transverse momentum is the key observable for the search. Canadians have contributed to the construction and commissioning of the calorimeter system utilized to measure the missing transverse momentum and to the validation of its reconstruction[3]. Thanks to the excellent performance of the detector, searches for the dominant SUSY production, namely strongly interacting sparticles decaying in a final state with jets and missing transverse momentum, could be carried out in the very early data. Canadians have played a leading role in the analysis, including the interpretation of the results in scenarios other than supersymmetry. Already with a limited amount of data, the limits set by this analysis surpassed the Tevatron limits and excluded the existence of light flavour squarks and gluinos up to 1.5 TeV[4,5,6,7,8]. High sensitivity to dark matter production is also reached in one-lepton events using an innovative fit to data technique developed by the TRIUMF group[9] . TRIUMF scientists have also searched for dark matter in the so-called golden channel of chargino and neutralino production: three leptons and missing transverse momentum, and set model-dependent lower mass limits on the dark matter candidate of ~ 100 GeV[10].

Neutrino Property Measurements at SNO

In 2001, the Sudbury Neutrino Observatory (SNO) experiment solved the long-standing problem of the missing ν_e's from the sun by showing that the solar flux contains a non-ν_e component. Second and third phases incorporated salt and ^{3}He neutron detectors in the heavy water for additional sensitivity to the ν_μ , and ν_τ . A paper presenting a joint analysis of the data from the first two phases of SNO was published during the present reporting period[11]. A significant development for this analysis was the lowering of the analysis threshold to 3.5 MeV, the lowest yet achieved with water Cherenkov detector data. This was accomplished by including scattered and reflected light in the energy estimation, by developing a suite of event-quality cuts based on PMT charge and time information, and by removing known periods of high radon infiltration that occurred during early SNO running.

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

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

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

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

Combining these results with results from all other solar experiments and the KamLAND reactor experiment gave best-fit values of the mixing parameters of

$$\theta_{12} = 34.06^{+1.16}_{-0.84}\,degrees \text{ and } \Delta m^2_{21} = 7.59^{+0.20}_{-0.21}\,x\ 10^{-5}\,eV^2$$

A three-flavour analysis found a best fit value of

$sin^2\theta_{13}$ to be $2.00^{+2.09}_{-1.63}\,x\ 10^{-2}$,

implying an upper bound of $sin^2\theta_{13} < 0.057\ (95\ \%\ C.L.)$

A second publication[12] was based on a search for periodicities in the ^{8}B solar neutrino flux. SNO has previously reported on searches for periods from ten years down to one day. The present work concentrated on periods from one day down to ten minutes. These high-frequency searches were partly motivated by recent expectations for solar helioseismological variations on scales of one hour or less, in particular solar "gravity modes." Three searches were carried out: the first looking for any significant peak in the frequency range 1-144 day^{-h}, the second looking for gravity modes in a more restricted frequency range, and the third looked for any extra power across the entire frequency band. No statistically significant signal was detected in any of these searches.

Neutrino Property Measurements at T2K

The goal of the T2K (Tokai-to-Kamioka) experiment in Japan is to make the first observation of the hitherto unobserved oscillation of ν_μ to ν_e, which is sensitive to the neutrino mixing parameter θ_{13}. The J-PARC accelerator creates the world's most intense beam of muon-type neutrinos at Tokai and shoots them at the 50,000 ton Super-Kamiokande water Cherenkov detector, 279

km away. The start of FY2010 saw T2K taking its first data as operations of the neutrino beamline and near detector began early in 2010. Data taking continued through June 2010, and then resumed in December 2010.The delivered beam power increased continuously over this biennial period, reaching a maximum power of ~150kW in March 2011. Data taking was interrupted by the large earthquake of March 11, 2011. At that point, T2K had collected 1.4×10^{20} protons on target, corresponding to about 1/50th of T2K's planned data set.

In June 2011, T2K released the first oscillation results from the 2010-2011 data[13]. Six candidate ν_e events were found in the data collected before March 2011, with an expected background of 1.5±0.3 for $\theta_{13}=0$. This ~2.5σ excess suggested that θ_{13} may be large, at or just below the existing CHOOZ limit. T2K's suggestion of a large value for θ_{13} was recently confirmed at high significance by reactor neutrino results from the Daya Bay and Reno experiments. In a companion paper[14] submitted in January 2012, T2K analyzed its data for muon neutrino disappearance, clearly confirming neutrino oscillation seen in previous experiments.

The 2011 earthquake resulted in no injuries to T2K members and no significant damage to the beamline or detectors. Recovery efforts continuing throughout the year re-established beam operations in December 2011, and T2K took limited data in January 2012. Neutrino data taking resumed on March 2, 2012 and will continue until summer, with the prospect of doubling T2K's data set. An upgraded oscillation analysis using additional data from T2K's near detectors is in preparation that will further reduce background uncertainties. If electron neutrino events continue to appear in the beam at the rate they did for previous T2K data, T2K may expect to achieve 3σ significance evidence for non-zero θ_{13} this year. Further data taking is expected between fall 2012 and summer 2013, at which point J-PARC will shut down for a LINAC energy upgrade.

The two main near detector components constructed at TRIUMF, the fine grained detector (FGD) and the time projection chamber, were successfully commissioned and operated throughout the physics data taking period. FGD and TPC detects momentum and type of neutrinos before oscillation. TRIUMF hosts the collaboration web page and T2K Tier-1 center. It has played a significant role in T2K's data analysis, and hosts the largest analysis group in the collaboration. T2K members ran a dedicated experiment (DUET) in the M11 beamline at TRIUMF to measure pion scattering parameters relevant for neutrino interaction physics, and are doing optical calibration measurements at TRIUMF for T2K's far detector Super-Kamiokande.

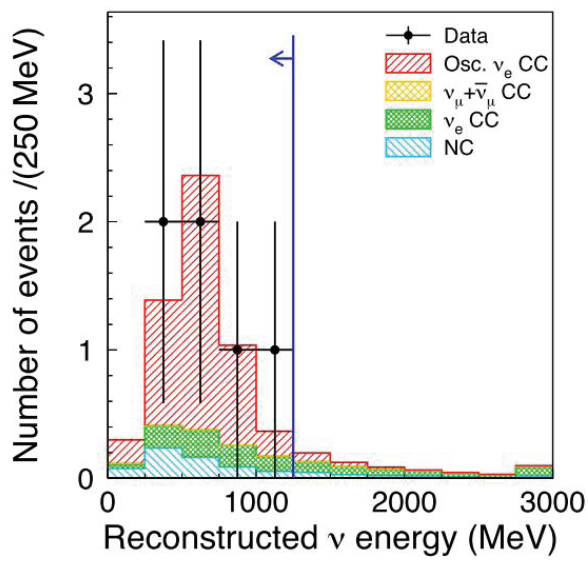

Figure 1. Energy spectrum of candidate electron neutrino events in T2K's far detector.

Neutrino Property Measurements at EXO

The discovery that neutrinos oscillate among the flavour states shows that neutrinos possess mass. This does not fit into the normal standard model of particle physics because the normal mechanisms by which fermions acquire mass requires both right and left handed partners, while the neutrino appears to exist in only one chiral state. There is a natural explanation for small neutrino masses if the neutrino is its own antiparticle. The observation of neutrino-less double beta (ββ) decay would verify this conjecture, as well as demonstrate for the first time a violation of total lepton number, and would thus help in our understanding of the creation of matter in the Big Bang.

The EXO experiment is a search for neutrino-less ββ decay in xenon. The work is in two parts: a 200 kg liquid xenon TPC is taking data in the WIPP

facility in New Mexico while R&D into a tonne scale detector is progressing largely in Canada.

In 2011, EXO published the first observation of the two-neutrino decay mode of ^{136}Xe[15], which is significant for two reasons. First, it indicates that there is nothing anomalous about the nuclear structure of the decay (as might have been inferred from an earlier limit). Second, it shows the care in reducing the backgrounds has been successful as the signal to background through most of the spectrum is better than 10:1. In contrast, the Heidelberg-Moscow group has a signal to background of 1:2 for the equivalent measurement in germanium. The detector is now taking data as one of the world's most sensitive detectors for double beta decay.

Measurements at TITAN to Support international Neutrino Measurements

The TITAN facility in ISAC at TRIUMF is capable of measurements of nuclear parameters relevant to neutrino interactions and double beta (ββ) decay.

The SAGE[16] and GALLEX[17] experiments in Russia and Italy detect the low-energy neutrinos produced by the pp reaction in the sun, via the reaction ^{71}Ga(v,e)^{71}Ge. The Q-value (the mass difference between initial and final states) determines the available phase space for the reaction. The TITAN collaboration recently carried out the first direct precision Q-value measurement of this reaction, using on-line produced mother and daughter nuclei and separation by threshold charge breeding in the TITAN EBIT[18]. The Q-value was determined by preparing clean samples of neon-like $^{71}Ga_{21}$+ and $^{71}Ge_{22}$+ in the Penning trap. In addition, isoionic samples of Ge and Ga in charge state 21+ were stored quasi-simultaneously in the Penning trap. Both independent measurements agree within error and the Q-value was determined to be 234 +/-2 keV. This agrees with previous indirect internal bremsstrahlung measurements, but provides an important independent check at the required accuracy and precision. Together with a recent measurement of the b-response from the excited states in ^{71}Ge, we eliminated the potential uncertainties in the nuclear structure previously blamed for the discrepancy between the SAGE and GALLEX calibration measurements performed with neutrinos from reactor-produced ^{51}Cr and ^{37}Ar sources.

The TITAN-EC program measures electron capture branching ratios (ECBRs) using X-rays and beta-particle tagging in a spectroscopy Penning trap, for a set of nuclei relevant to Nuclear Matrix Element calculations for double beta decay. The proof-of-principle method has been demonstrated with ^{107}In, 1^{24,126}Cs beams, and the X-ray detection array has been tested with ^{112,114}In beams. The ultimate goal is to measure the weak ECBR of ^{110}Tc and elucidate the discrepancy between the predicted value and the value implied by charge exchange measurements.

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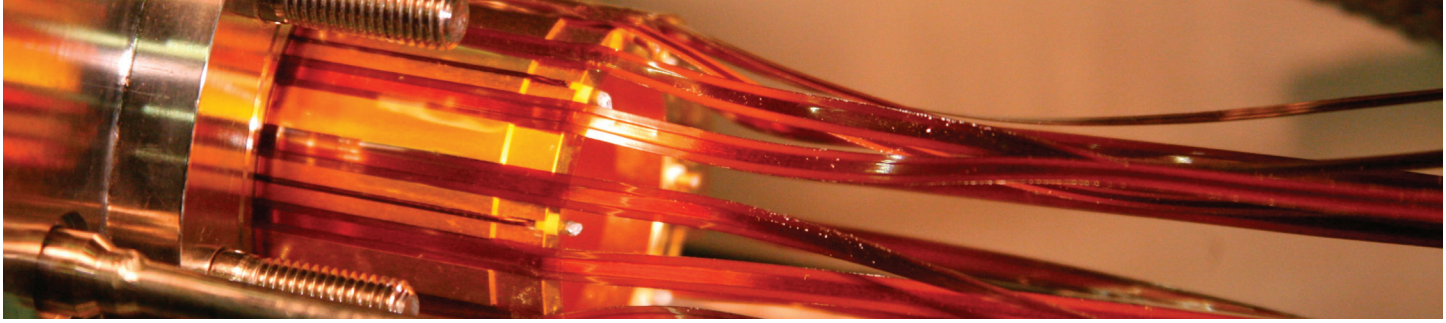

2.4
Test of Discrete Symmetries (CP, CPT)

Jeff Martin, Gerald Gwinner, and Akira Konaka

Precise studies of symmetries and their violations provide a powerful way to probe the fundamental forces of nature at "low energy," (i.e. an energy scale well below that of collider physics). This work is often described as the precision frontier, in distinction to the energy frontier explored at the LHC. TRIUMF has been very active in this field, launching several new efforts in recent years.

Small breakdowns of symmetries lead us to hints of 'new physics' beyond the Standard Model. The FrPNC facility at TRIUMF aims to make precise measurements of atomic parity violation (i.e. mirror symmetry violation) in the francium atom. Three groups are trying to find the first evidence for permanent electric dipole moments (EDMs); their existence would imply a breakdown of time-reversal symmetry. The Radon EDM experiment is sensitive to quark color EDMs, the neutron EDM search can reach both quark chromo-EDMs and quark EDMs, and FrEDM is sensitive to a potential EDM of the electron. Finally, the ALPHA experiment at CERN will test the combined symmetry of charge, parity, and time (CPT) by performing microwave and laser spectroscopy on anti-hydrogen.

FrPNC: Towards Parity Violation Measurements in Laser - trapped Francium

In atoms, extremely weak electric dipole transitions between states of the same parity are induced by the parity-violating exchange of Z-bosons between the orbital electrons and the quarks in the nucleus, an effect known as atomic parity violation (APV). By measuring the nuclear-spin independent part of this amplitude, one can study neutral-current weak interactions with atomic physics methods and search for 'new' physics such as extra gauge bosons and leptoquarks. Some 'little Higgs' models predict new Z bosons with larger couplings to the first generation, so the present APV measurement in Cs constrains those Z's to have mass greater than 1.4 TeV[1]. The nuclear-spin dependent component in heavy atoms is predominantly due to the nuclear anapole moment, caused by parity-violating nucleon-nucleon interactions; measurements in a chain of isotopes could constrain the weak nucleon-nucleon couplings. APV is strongly enhanced in heavy atoms, growing roughly as the nuclear charge cubed, but the atomic structure calculations necessary to extract the weak physics are only feasible to the required precision in alkali atoms. This makes francium, the heaviest alkali, an interesting choice for a new APV experiment[2]. As francium possesses no stable isotope, it has to be produced on-line at a radioactive beam facility, such as ISAC.

Starting in December 2010, ISAC has been delivering francium beams from UC_x and UO_2 targets to users. An international collaboration, FrPNC, has been formed with the goal of carrying out atomic parity violation experiments with cold, laser-trapped francium isotopes. In fall 2011, a dedicated beam line was established in the ISAC-I area under the TITAN platform, and an electromagnetically shielded clean room has been built, to house the magneto-optic laser trap and the numerous lasers required to carry out the planned experiments.

Laser trapping of rubidium was demonstrated and the first trapping of francium is planned for 2012. A first run will commission the trap setup, and the science program will commence, measuring hyperfine anomalies (also known as the Bohr-Weisskopf effect) to study the distribution of magnetism inside the nucleus.

Francium EDM

A prototype laser-cooled cesium atom-fountain electron EDM experiment was recently demonstrated by the LBNL-SLAC group[3]. It established a way of controlling systematic effects by reducing static magnetic fields to the lowest possible level and quantizing the atom in the electric field through its tensor polarizability. Compared to cesium, francium is nine times more sensitive to an electron EDM, and francium isotopes, made in large numbers at ISAC ($^{213, 211, 209}$Fr), with their large tensor polarizabilities because of their large hyperfine interactions[4], are far less sensitive to these systematic effects. An LBNL, SLAC, TRIUMF collaboration has submitted a Letter of Intent (S1324 LOI), which has been endorsed by the EEC.

Radon EDM

The Radon EDM experiment will search for an EDM in radon isotopes which have enhanced sensitivity to CP-odd interactions due to octupole deformation of the atomic nuclei. The most precise EDM measurement to date is in ^{199}Hg at the University of Washington with an upper limit of 3.1×10^{-29} e·cm at the 95% C.L. The isotopes ^{221}Rn or ^{223}Rn could be up to 600 times more sensitive than ^{199}Hg to fundamental CP-violating interactions. Our program consists of development of techniques essential to making an EDM measurement on-line at ISAC, in parallel with nuclear structure studies essential to establishing the size of the enhancements.

The Radon EDM development apparatus has been installed on a dedicated beam line in the ISAC-I hall. A set of measurements with rare-isotope xenon beams (^{120}Xe and ^{121}Xe) established several of the techniques necessary to collect and transfer the gas to a measurement cell[5]. The 5 keV beam is implanted in a foil, which, releases the gas when heated. Studies of diffusion of xenon in several different metals and measurement of diffusion constants[6] led us to select zirconium. The gas is transferred several metres in a few seconds to a LN2 cold finger near the measurement station and then pushed into a measurement cell with a plug of gaseous nitrogen. After the transfer, the cell is valved off. The transfer efficiency from the cold finger to the cell has been refined to be approximately 80%, compared to the 40% efficiency reported in[5]. The principle of the Radon EDM experiment provides for polarization of the radon isotopes by spin exchange with laser-polarized rubidium. The apparatus has been used to study polarization in the measurement cell using stable xenon, both natural abundance and istopically-enriched ^{129}Xe. The natural abundance xenon contains both ^{129}Xe (I=1/2) and ^{131}Xe (I=3/2). Adiabatic-fast-passage NMR is used to monitor the time constants of the xenon polarization. The spin-3/2 ^{131}Xe isotope is useful for studies of wall relaxation due to interactions of the nuclear electric quadrupole moment. Studies of ^{209}Rn polarization at Stony Brook using gamma-ray anisotropy polarimetry included the temperature dependence of the polarization, from which an estimate of the spin-polarization-relaxation times was possible[7]. An attempt to observe ^{121}Xe polarization using gamma-ray anisotropy polarimetry at ISAC was not successful due, in part, to poor Rb polarization. Improvements to the optical pumping set up were implemented using electron-spin-resonance as a diagnostic of the Rb polarization.

The studies of the nuclear structure of the neutron-rich radon isotopes are planned to take place at ISAC, using the 8π apparatus with supporting studies planned at MSU-NSCL and ISOLDE. The ISAC measurement requires astatine isotopes be produced and extracted with sufficient suppression of francium background. The nuclear structure information and accurate estimates of the octupole enhancements are essential prerequisites to developing a full-scale apparatus for the Radon EDM experiment.

UCN: Neutron Electric Dipole Moment Search with a Spallation Ultracold Neutron Source at TRIUMF

A new search for the neutron electric dipole moment is planned for TRIUMF. The basic design of the experiment calls for a room-temperature EDM experiment to be connected to our cryogenic ultra cold neutron (UCN) source. The UCN source is based on the design successfully deployed by the Japanese part of our collaboration, led by Y. Masuda[8]. Neutrons will be moderated and converted into ultra cold neutrons via down-scattering in superfluid He. A second generation source is nearing completion (cold tests are ongoing as of early 2012). The new source features improvements to the geometry, production volume, storage lifetime, transport efficiency, and higher-energy transported UCN, which are anticipated to result in higher UCN density.
The EDM experimental apparatus has a few features which are unique compared to other experiments elsewhere. We intend to use a spherical coil within a cylindrical magnetic shield to generate the DC magnetic field. We also intend to use a ^{129}Xe comagnetometer, which will act as its own buffer gas to address false EDM's due to a geometric phase effect (GPE). Furthermore, we will develop a room-temperature experiment based on our existing prototype. Anticipating higher UCN density, we will keep the measurement cell size considerably smaller than the previous ILL apparatus. While having a negative impact on statistics, the reduced cell size limits systematic effects, particularly from the GPE. Also, the reduced cell size will enable the use of modern magnetic shielding at reduced cost.

The source and EDM experiment will be operated at the Research Center for Nuclear Physics (RCNP, Osaka) at low luminosity until 2014 and then moved to TRIUMF in 2015 for installation. Our precision goal for our first experiment at TRIUMF is $d_n < 1\times10^{-27}$ e-cm, to be completed by 2017. In 2018 and beyond, we would attempt further improvements to the apparatus, and some improvements to the UCN source itself, with the eventual goal of achieving $d_n < 1\times10^{-28}$ e-cm. Further experiments on the neutron lifetime in a magnetic trap, and on quantized energy-levels of neutrons confined above a mirror by Earth's gravitational field, and others, are considered as candidates for the long-term physics program.

ALPHA: Anti-hydrogen Spectroscopy

A comparison of the hydrogen atom spectrum with that of its antimatter counterpart, anti-hydrogen, tests the validity of CPT (charge conjugation, parity, and time reversal) symmetry, an essential element of relativistic quantum field theories. The goal of the ALPHA experiment, first approved at CERN in 2006, was to develop methods to confine anti-hydrogen in a magnetic minimum trap and study the spectroscopy of these antiatoms with increasing precision, aiming at the extreme precision with which hydrogen has been measured.

Magnetic minimum traps are very shallow: the ALPHA trap (Figure 1) can confine only antiatoms with energies equivalent to 0.5 K. By 2010, the techniques[9] enabling synthesis of these very cold anti-hydrogen atoms were sufficiently developed enough that the search for trapped atoms could begin. The properties of these plasmas were studied by exploiting our sensitive particle detector systems, developed by the scientific and technical staff of the Liverpool and TRIUMF laboratories. About 1/3 of the collaboration is from Canadian institutions.

The first definitive evidence of 38 anti-hydrogen atoms confined in the trap and producing identifiable annihilation signals when released[10] was quickly followed by a more detailed study of the dynamics of a sample of 309 antiatoms, where we established confinement times as long as 1000s[11]. It was immediately clear that such long times opened up the opportunity to perform spectroscopic measurements on ground state anti-hydrogen even with very small numbers of antiatoms.

While the ALPHA trap design did not allow laser access, a Canadian-led initiative was able develop a method to inject significant microwave power into the plasmas. We have recently had success in inducing resonant quantum transitions in the trapped anti-hydrogen—a proof-of-principle that the spectroscopy of anti-hydrogen can be studied with very few atoms[12]. We are currently

constructing a new antiatom trap incorporating features required for precision spectroscopy. The trap cryostat is being designed by a TRIUMF engineer and will be fabricated at the University of Calgary and TRIUMF.

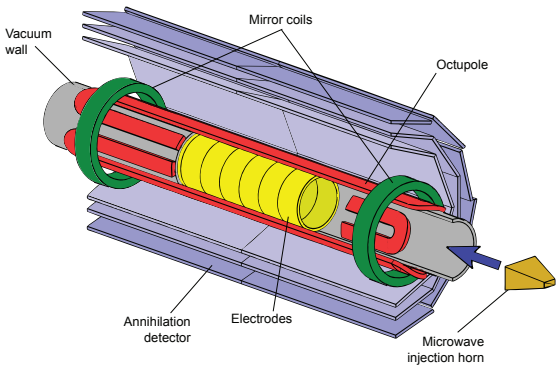

Figure 2. Cut-away, schematic drawing of the antihydrogen synthesis and trapping region of the ALPHA apparatus. The superconducting atom-trap magnets, the annihilation detector, and some of the Penning trap electrodes are shown. An external solenoid (not shown) provides a 1 T magnetic field for the Penning trap. The drawing is not to scale. The inner diameter of the Penning trap electrodes is 44.5 mm and the minimum-B trap has an effective length of 274 mm. Microwaves are injected along the axis of the trapping volume using a horn antenna, which is located about 130 cm from the trap axial midpoint.

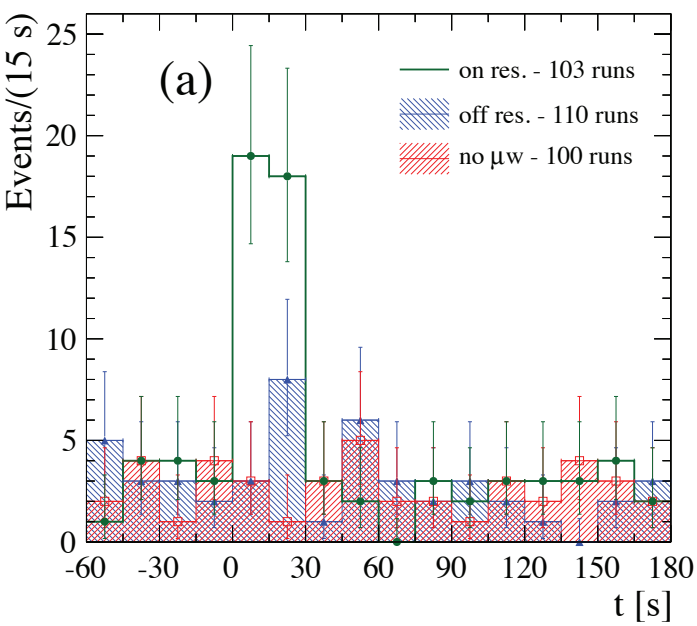

Figure 3. Observation of resonant microwave transitions which cause antihydrogen to be ejected from the magnetic trap, producing annihilation signals from the trap walls. Microwave power is first applied at time t = 0 and is swept over the two hydrogen hyperfine resonance frequencies alternatively every 15 seconds. Background studies using microwave frequencies 100Mhz below the resonance, and also without microwaves are also shown.

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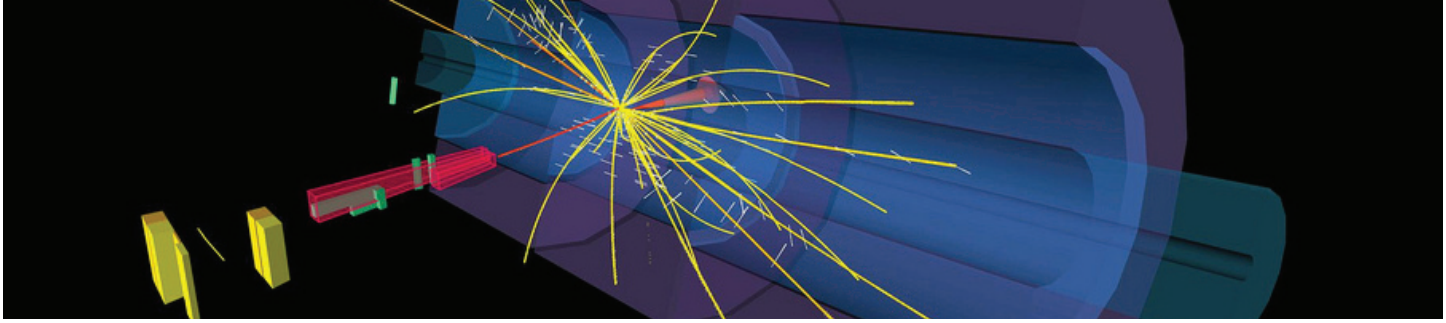

2.5
Weak Interaction Studies

David Morrissey and Dan Malconian

Weak interactions are significantly different from the other fundamental forces. They are thought to be mediated by the W and Z vector bosons, and are known to violate the would-be discrete symmetries of parity (P) and charge-conjugation (C). In fact, unlike the other forces, the weak interaction maximally violates parity, and even violates the combined symmetry CP. Investigations of various aspects of the weak force via high, medium, and low-energy experiments aim to further our understanding of the underlying theory of massive vectors to a very high degree of accuracy, and also offer the exciting possibility of discovering new physical phenomena.

ATLAS

The ATLAS experiment at the CERN Large Hadron Collider is able to directly probe the structure of the massive vector W and Z bosons that mediate the weak force. The main mechanisms for producing W bosons with small transverse momentum at the LHC are the leading order electroweak processes uD→W and dU→W. Since the LHC is a proton collider, the quarks usually carry more momentum than the anti-quarks, so the W bosons produced at large rapidity tend to be boosted in the direction of the (left-handed) quarks, and are almost entirely left-handed, while the more centrally produced W bosons are the ones where the antiquark carries a larger share of the momentum, and their helicity state is a mixture of left- and right-handed states. However, for W bosons with large transverse momentum, three main processes contribute which are not pure electroweak anymore: ug→Wd, uD→Wg, gD→WU, and conjugates, and the production of W bosons in longitudinal states is also possible because of the vector nature of the gluon. The longitudinally polarized fraction is expected to vanish for $p_T^W \to 0$ and $p_T^W \to \infty$, with a maximum around $p_T^W = 45$ GeV. Precise measurements[1] of the W bosons created in W+jet final states test their couplings to quarks.

Theory

The theory group studies weak interactions among elementary particles and composite nuclei.
The weak force plays a key role in astrophysical systems, like supernova explosions and neutron stars. Neutrino interactions with neutron matter are an example, which were recently investigated for density and temperature conditions reached in simulations of core-collapse supernovae. In[2], earlier work was extended to address the non-degenerate regime. Spin relaxation rates based on chiral effective field theory interactions were calculated and found to be typically a factor of two smaller than those obtained using the standard one-pion-exchange interaction alone.

The coefficient of the time reversal odd correlation function in nuclear beta decays has long been known to be a sensitive probe of CP violation sources beyond the standard model. In an effective field theory approach it was shown in[3] that it contributes directly to the neutron electric dipole moment (EDM) at the one-loop level. Although this coefficient is less sensitive than the neutron EDM, it does not suffer from as much model

dependence as the EDM. New constraints on leptoquark models are also given from both types of experiments.

Qweak

The Qweak experiment seeks to measure the parity-violating asymmetry, related to the coupling of the Z boson to the proton, by scattering longitudinally polarized electrons from liquid hydrogen and measuring the change in scattering probability when the electron helicity is reversed. Theoretical estimates using existing standard model parameters predict a measured asymmetry of approximately -250 ppb. New physics at up to the few TeV scale 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 a combined systematic plus statistical uncertainty of 6 ppb. This accuracy will also determine the weak mixing angle at low momentum transfer to 0.3% of $\sin^2\theta_W$, an important measurement in its own right. Phase I data taking took place from January to May 2011, with the objective of measuring the proton's weak charge to better than 25%. Although unblinding of this data set has not yet taken place, all indications point to reaching this goal with the Phase I data.

S1249 and J-PARC Muon (g-2) Project

In collaboration with groups from KEK and RIKEN in Japan, a TRIUMF/University of Victoria group has performed experiments to measure and characterize the emission of muonium (μ^+e^-) into vacuum following muon thermalization in silica aerogel. It is part of a much larger project proposed at J-PARC, which is also in Japan, to measure the anomalous spin precession of the muon, or g-2. As demonstrated by Brookhaven E821, the muon anomalous magnetic moment can be determined very precisely, and the current result[4] shows a difference of more than three standard deviations from increasingly sophisticated theoretical standard model estimates[5]. The J-PARC experiment uses a much different approach, with different systematic uncertainties. It requires acceleration of muons following laser ionization of muonium in vacuum. Following an initial SR experiment at M20 to identify promising materials, silica aerogel derived from a unique process[6] was studied further via imaging of muon decay positrons from vacuum near the aerogel surface. Two experimental periods at M15 allowed the characterization of muonium emission from several types of aerogel. This input was crucial to the J-PARC evaluation process that resulted in the g-2 project receiving Phase 1 approval in early 2012.

π→ev (or PIENU)

The branching ratio of pion decays $R_{e/\mu}\frac{\Gamma(\pi\to e\nu+\pi\to e\nu\gamma}{\Gamma(\pi\to\mu\nu+\pi\to\mu\nu\gamma'}$ predicted to be $1.2352(1)\times10^{-4}$ in the standard model, has provided the best test of the hypothesis of electron-muon universality in weak interactions and is sensitive to many forms of new physics (pseudoscalar interactions, R-parity violating SUSY, extra dimensions, leptoquarks, compositeness and charged Higgs bosons). The PIENU collaboration at TRIUMF has accumulated more than half of the anticipated 2×10^7 π→ev events during its 2009-2011 running. It has begun study of the most important systematic effects such as the "tail correction" for π→ev events hidden below the π→μ→e spectrum. For this purpose, the detailed shape of the NaI(Tl) crystal spectrometer's resolution function was studied and found to contain additional small bumps at low energy due to photonuclear interactions, effects never seen before in crystal calorimeters[7]. Using refined techniques and the detailed line shape measurements, PIENU succeeded in suppressing π→μ→e events by a factor of $>10^5$ reducing the tail below 55 MeV to <7% of π→ev events.

PIENU will operate throughout 2012. Along with the data collected during the past years, the statistical uncertainty for the branching ratio measurement would be <0.04%, consistent with the goals of PIENU. In addition to data taking runs, we will perform several special runs designed to facilitate evaluation of systematic uncertainties., and once the data collecting is completed at the end of calendar year 2012, we expect one to two years of analysis.

TRINAT

Using atom trap technology, the TRIUMF Neutral Atom Trap collaboration is poised to complete two experimental programs that should reach similar sensitivity to that of radiative π decay and indirect EFT-dependent constraints

from $\pi \rightarrow e\nu$, and begin to allow sensitivity to SUSY left-right sfermion mixing. The near-term goals of the spin correlation program using ^{37}K include a simultaneous measurement of the β and recoil asymmetries, A_β and A_{recoil}, and a measurement of the ν asymmetry, B_ν to 0.3%. Specifically, the A_{recoil} measurement would be sensitive to the tensor couplings C_T+C_T', while the β and ν asymmetry parameters will be used to search for right-handed and 2nd-class currents.

TRINAT has made major revisions to the design of their apparatus in order to optimize it for the polarized program (while maintaining the ability to improve the scalar search with ^{38m}K); currently, they are testing a new atom-trapping technique with their new chamber and detector/acquisition system before they start to take data in 2012. During this development, an attempt to search more directly for massive particles in the decay of nuclear isomers produced a precise measurement of isotope shifts in rubidium atomic frequencies of the sort needed for astrophysical observations of changes in fundamental constants[8].

$0^+ \rightarrow 0^+$ Superallowed Decays

The pure Fermi superallowed decays are a special group of nuclear transitions which are well suited for precision electroweak tests because the decay is predicted to high precision by the theory. The unpolarized program of TRINAT is based on the $0^+ \rightarrow 0^+$ decay of ^{38m}K, for which the best limits on interactions of spin-0 bosons coupling to the first generation of particles have been made via a measurement of its β-ν correlation. Most systematic uncertainties for this experiment are determined from statistics-limited kinematic observables that are independent of the angular correlation, and an upgraded version has a goal to reach 0.1% accuracy. Furthermore, their measurement of the β asymmetry in ^{37}K offers the chance to improve the value of V_{ud} from $T=1/2$ mirror transitions.

The TITAN group has the ability to measure, with extreme precision, the masses of highly charged ions that are very short-lived. In addition, the bunched beam they provide can be coupled to the collinear-laser spectroscopy line at TRIUMF and used to measure the charge radii of nuclei very precisely. This was done for ^{74}Rb[9], which has improved the isospin-symmetry-breaking correction term used to calculate its *Ft* value.

The 8π collaboration's fast-tape transport system is able to measure the lifetimes of radioactive nuclei over many half-lives with minimal contaminants. In 2011 they published a measurement of the superallowed decay of ^{26m}Al[10] that was two and a half times more precise than the previous world average. Their results promoted the Ft value for ^{26m}Al to be the most precisely measured of all $0^+ \rightarrow 0^+$ transitions.

All of these groups will continue to reduce uncertainties in measurements going into the *ft* values of superallowed transitions as well as test the theoretical corrections that are applied for determination of V_{ud} and testing CKM unitarity.

TWIST

The TRIUMF Weak Interaction Symmetry Test (TWIST) collaboration has completed a simultaneous measurement of the muon decay parameters ρ,δ, and Pμε through the analysis of the momentum and angle distributions of positrons from polarized positive muon decay. The values obtained represent an improvement in precision of approximately one order of magnitude compared to prior experiments, testing the validity of the Standard Model (SM) in a system dominated by leptonic interactions. The results are compatible with SM predictions, setting more stringent limits on possible deviations from maximal parity violation. TWIST scientists from Canada, the USA, and Russia exploited a considerable allocation of time on the intense high-quality muon beams available at TRIUMF, a high-precision positron tracking spectrometer designed specifically for these measurements, and extensive computational resources from WestGrid. The summary of results from a blind analysis of billions of muon decays was published[11] in early 2011. As is true for most precision experiments, the uncertainties depended largely on systematic effects whose magnitudes had to be assessed and verified carefully. Detailed explanations of these uncertainties were presented in two subsequent publications in 2011 and early 2012[12,13].

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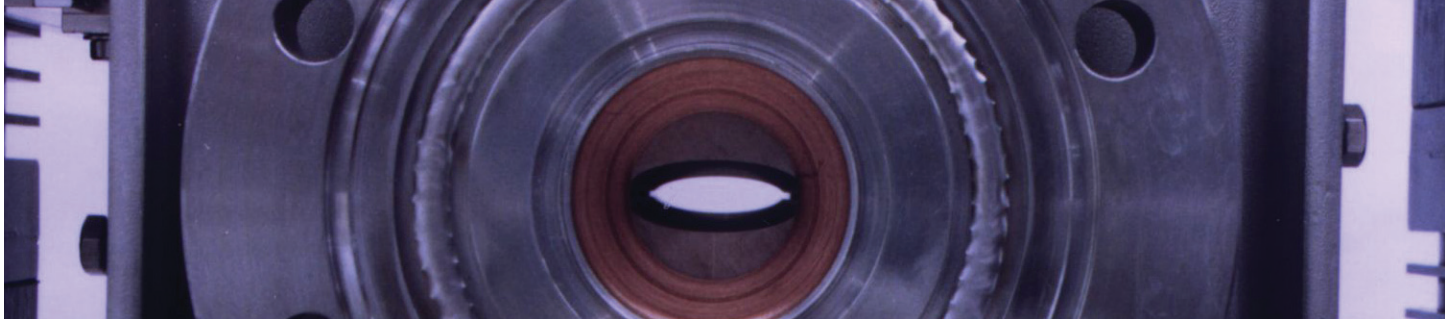

2.6
QCD and Hadron Structure

Richard Woloshyn

Quantum Chromodynamics (QCD) is part of the standard model of particle physics and provides a fundamental microscopic description of strongly interacting particles (hadrons) in terms of quarks and gluons. This theory is relevant to a large part of the TRIUMF subatomic-physics research program from the lowest energy nuclear physics experiments done at ISAC, to the highest energy collider studies at the LHC. QCD, through a low-energy effective theory, is the basis for understanding the interactions that bind nuclei, and thus, forms the theoretical foundation for nuclear physics studies described elsewhere in this report. It is used to explain the spectrum and structure of hadrons. This is the subject of experimental and theoretical studies carried out by TRIUMF personnel and also plays a large role in the experiments carried out at the LHC. Some research highlights are discussed in this section.

The primary collisions are governed by strong interactions and, though the focus of many measurements is electro-weak physics and searches for physics beyond the standard model, the microscopic QCD processes have to be understood very well in order to calculate production rates, backgrounds, etc. Therefore, it is useful to collaborate with large collider groups, such as ATLAS, to carry out the many studies[1,2] needed to validate the description of the hard parton (quark and gluon) level interactions given by perturbative QCD, and of the more phenomenological quantities, e.g., parton distribution functions, which are required to achieve a complete description of the high-energy collision processes.

The high-energy collider experiments can also search for new hadronic states. For example, the ATLAS collaboration recently announced the discovery of the previously unobserved bottomonium $\chi b(3P)$ states[3]. This complements the theoretical study of bottomonium carried out in the TRIUMF Theory Group.

A Canadian group led by TRIUMF, working in the HERMES collaboration, has been studying the relationship between the orientations of the spin of the proton and those of its constituent quarks. This is done by deep inelastic scattering (DIS) of spin-polarized electrons on spin-polarized atomic hydrogen gas in a high-energy electron storage ring at DESY in Germany. Because the motion of quarks in the proton is highly relativistic, this correlation between proton and quark spins can differ when the spin polarizations are longitudinal or transverse to the direction of the beam. Previous measurements[4] with longitudinal polarization had already revealed much about the longitudinal spin structure function g1, which is a combination of helicity distributions of the quarks in the proton. In contrast, the transversity PDF was unknown until HERMES produced the first DIS data with transverse beam and target polarizations[5]. This measurement is much more challenging because the naive-T-odd property of transversity excludes it from having any effect on measurements, detecting only the scattered electron. Only by also detecting an energetic hadron produced by the struck quark can a signal of transversity be seen through a T-odd kinematic correlation, the so-called "Collins effect"[6]. This correlation is expected to be

particularly strong when the proton and produced hadron have a quark flavour in common so that the struck quark can be "contained" in the hadron in a statistical sense.

Those first HERMES results, from the detection of charged pions, attracted much attention for two reasons: the signals are large, and those for negative pions are significantly larger than for positive pions. The latter was unexpected, because negative pions are statistically less likely to "contain" the struck quark, thereby supposedly being less influenced by the target spin structure. It was postulated and later confirmed by electron-positron collider measurements of the Collins correlations by the Belle collaboration, that energetic hadrons not containing a quark of the same flavour as that struck, have nevertheless a strong negative kinematic correlation with the polarization of the struck quark[7]. The new HERMES data set[8] for both detected pions and charged kaons confirms with higher precision the previously observed pion signal, and reveals a significant signal for positive kaons even larger than that for positive pions. Such a difference would be contrary to expectations based on similar large probabilities for both positive pions and kaons to "contain" the struck quark, suggesting a possibly significant role for strange-flavoured sea (virtual) quarks in the proton. These new data will substantially improve global fits that extract values for the transversity distributions from all such DIS data available in conjunction with those from Belle. The G0 experiment carried out at Jefferson Lab (with participation from TRIUMF and Canadian academic partners University of Manitoba and University of Winnipeg) developed techniques to make precision measurements of asymmetries in polarized electron scattering. The focus of the G0 experiment was the study of a small parity-violating asymmetry in the scattering of longitudinally polarized electrons. However, the same techniques could also be used to measure the parity-conserving asymmetry B_n of transversely polarized electrons[9]. This small asymmetry ($\sim 10^{-5}$) arises due to the interference of the imaginary part of the two-photon exchange amplitude with the leading one-photon exchange term.

As the precision of electron scattering experiments and the extraction of nucleon electromagnetic form factors has improved, it has been found that two-photon exchange contributions to the scattering amplitudes must be included in the interpretation of the data. The two-photon exchange amplitude can receive contributions from a variety of intermediate hadronic states, and the single spin asymmetry is sensitive to how these intermediate states are treated. Figure 1 shows results[9] from the G0 collaboration for measurements of B_n made at 362 MeV and 687 MeV. The results are in good agreement with a calculation which includes pion-nucleon states as well as nucleons in the intermediate state[10].

Energy (MEV)		Cross section μb/sr	$B_n^{n,p}$ (ppm)	$B_{n\ theory}^{n,p}$
362	n	8	86.6±41	72
	p	23	-176.5±9.4	-158
687	n	1.1	-138±268	20
	p	2.6	-21.0±24	-35

Figure 1. Estimate of the proton and neutron cross sections and asymmetries at the energies of the G0 experiment[2]. The theory prediction is from[3].

On the theory side, QCD research projects at TRIUMF focus on heavy-quark systems, that is, hadron systems that involve charm or bottom quarks. The spectroscopy of D and Ds mesons was studied using lattice QCD. In this method, the theory is formulated on a discrete space-time and a numerical evaluation of the resulting path integral, capturing in a nonperturbative way the effects of quark and gluon interactions. The recent calculation[11] improves on previous work by including the effects of so-called sea quarks, that is, quark-antiquark vacuum fluctuations which couple to gluons and influence hadron properties. Also, this calculation was done using up and down quarks with masses that were near the small values that appear in nature[12]. In contrast, earlier work was done utilizing larger values of up and down quark masses, which necessitates a large extrapolation to the physical region.

The calculated spectrum of S- and P-wave D and D_s mesons is shown in Figure 2. Overall, the pattern of the experimental values is reproduced. However, the P-wave states that are observed to have large widths are still not very well described. Physically, these states are expected to be influenced strongly by nearby two-meson thresholds. It is an ongoing project to try to incorporate these effects explicitly into the lattice QCD calculation.

Lattice QCD was also used to study bottomonium, that is, the hadron made from a $b - \bar{b}$ pair. The first bottomonium Y was discovered in 1977[13], but it was only recently that its pseudoscalar partner, the η_b, was observed[14,15]. The discovery channel was the radiative decay of excited Y—this motivated a theoretical study of this process[16]. Nonrelativistic QCD was used to describe the heavy b quarks. A major challenge was to isolate the excited state contribution from the dominant ground-state pieces. This was done by multiexponential fitting to sets of correlation functions, constructed using operators designed to enhance the excited state terms. Robust signals for the decay of Y (2S) and Y (3S) to η_b were obtained. At this stage, only the leading nonrelativistic piece of the M1 transition operator was included, and with this approximation, the calculated decay amplitudes were found to be considerably larger than the values inferred from the experimentally measured decay widths[11]. Further work is underway to include higher-order relativistic corrections and there are indications that this will improve agreement of the calculation with experimental values.

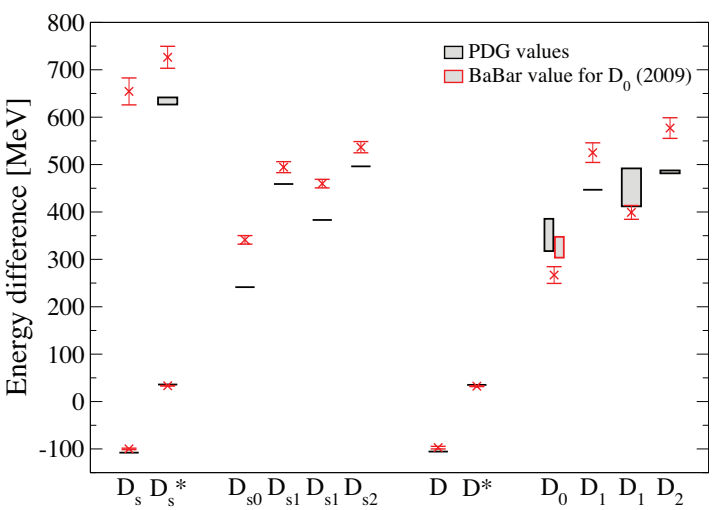

Figure 2. Mass differences in MeV for D and D_s meson states compared to experimental values.

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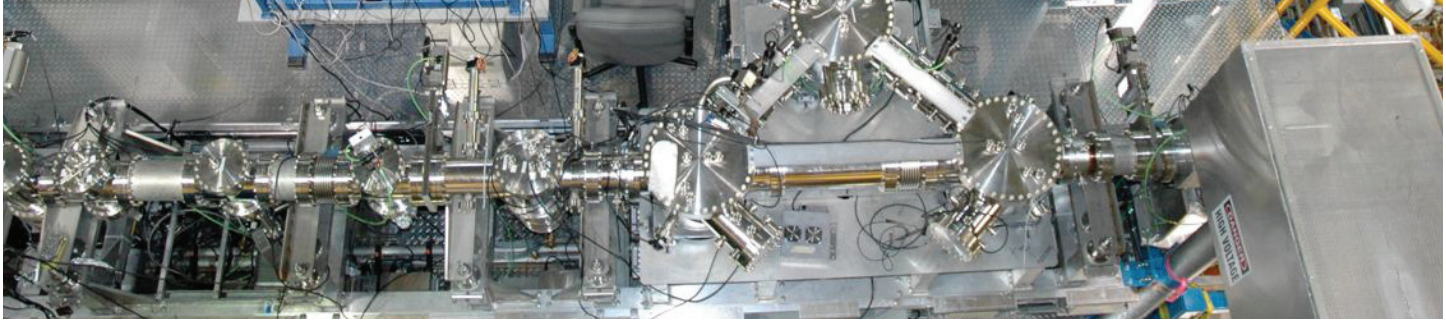

2.7
Nuclear Structure at the Extremes of Isospin

Jens Dilling and Reiner Kruecken

In recent years, major theoretical advances were made in describing the structure of light nuclei using ab-initio methods and bare nuclear forces. In particular, the use of models based on chiral effective field theory (ChEFT) promises to provide the long-thought connection between low-energy QCD and nuclear interactions. Ab-initio calculations using various methods, such as Green-function Monte Carlo (GFMC)[1] and No-Core Shell Model (NCSM)[2] have demonstrated the importance of three-body and tensor components in the bare nuclear force to correctly describe light nuclei.

Further developments of the interactions rely on precise experimental tests based on ground and excited state energies and include the expansion to transition matrix elements and reaction rates. An area of particular focus has been the structure of halo nuclei, with their weak binding, extended wave functions, and intricate correlations involving bound and continuum states. ISAC is particularly suited for such studies , as it is currently the facility with the highest intensities of such beams, including ^{6,8}He, ^{11}Li, ^{11}Be. One of the first ISAC experiments on halo nuclei was the measurement of the charge radius of ^{11}Li, which was determined using isotope-shift laser spectroscopy[3] in combination with precision atomic theory. For the latter, the knowledge of the mass-shift contribution to the isotope shift is essential, and for this, the mass of the nuclei has to be determined with comparable precision. A program of high-precision mass measurements on halo nuclei was set up, taking advantage of the TITAN Penning trap facility[4]. The program included measurements of ^{11}Li, which is the isotope with the shortest half-life ($t_{1/2}$= 8.75 ms) ever measured in a Penning trap[5].

Mass measurements of the 2-and 4-neutron halo, ^{6}He and ^{8}He, were used to determine the neutron separation energies as well as aid in the determination of the charge radius. Both properties are used to test and refine ab-initio calculations[6], indicating the importance of the 3-body force in accurately describing properties. Figure 1 shows the derived radius as a function of separation energy, both for the experiment, as well as for various theoretical approaches.

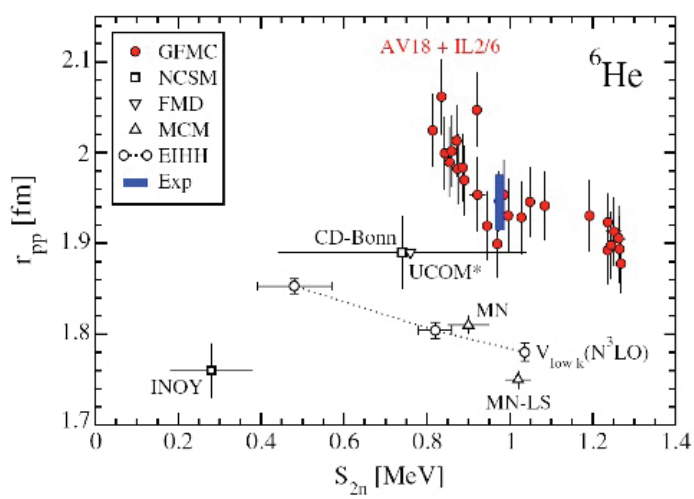

Figure 1: Charge radius as a function of two-neutron separation energy for ^{6}He, for the TITAN experiment, as well as for different theoretical approaches[21].

The halo-studies using the MAYA active target from GANIL were pioneering experiments studying the p(^{11}Li,t)^{9}Li reaction with 33 MeV[7] and 44 MeV[8]

^{11}Li ions accelerated with the ISAC-II superconducting post accelerator. Further reaction studies on the structure of halo nuclei were carried out using the ISAC-II re-accelerated beams, the d(^{11}Be,p)^{12}Be transfer reaction[9], and a study of the E1 transition matrix element from the first excites 1^+ state in ^{11}Be with the TIGRESS gamma-ray spectrometer.

In heavier nuclei, not accessible to ab-initio theory yet, effective nuclear interactions are combined with many-body models (such as shell model calculations or density functional theory) and are used to describe their structure. The shell structure in nuclei is a benchmark in the study of heavier nuclei. Investigations in recent years have revealed that the magic numbers may change locally in exotic nuclei via the disappearance of classic shell gaps and the appearance of new magic numbers[10,11]. The first region in which modifications of shell structure were observed is the so-called Island of Inversion around ^{32}Mg, which has been investigated extensively over the years. In 2009, the transition matrix elements in ^{29}Ne were obtained from a Coulomb excitation experiment[12] with the TIGRESS gamma-ray spectrometer. This experiment established it to be on the transition line between normal and inverted shell structure. Today, it appears that these local changes to the shell structure are driven by the monopole components of the residual interaction between the valence nucleons and, in particular, the tensor interaction[13,14] and three-body forces[15,16] play an important role. Further studies of this region include direct separation energy measurements from TITAN mass determinations[17], which showed evidence for a very small shell gap. The shell strength of nuclides near the valley of stability is typically 4-5 MeV. For doubly-magic nuclides, this value increases and reaches up to 9 MeV for cases where N = Z. The N = 20 shell was initially shown to be quenched to about 2 MeV. The value obtained in this work appears even smaller than that. Moreover, new magic shell closures for 24O, which has been confirmed experimentally, and ^{54}Ca, have been associated with these effects. With the TITAN Penning trap facility, it has recently been possible to extend precision mass measurements from ^{50}Ca[18] to ^{52}Ca[19]. The extracted neutron separation energies seem to indicate that experimental trends can be best described by using effective interactions derived from realistic nuclear forces including three-body components.

Aside from investigating the evolution of shell structure directly, collective motion in nuclei provides important clues on the working of the underlying nucleonic dynamics. These dynamics are responsible for the emergence of collective degrees of freedom, degenerate states with different competing shapes, as well as rotational and vibrational motion. Topics of recent interest include the question of how collectivity evolves with neutron or proton number, how shape changes can occur in almost phase transitional manner, and how different shapes can coexist at almost equal excitation energy. With high beam intensities or rare isotopes and modern spectroscopic tools, it is possible today to perform precision spectroscopic studies identifying the different degrees of freedoms at low energies and to test how good the concept of collective motion is realized in real nuclei.

The study of low-spin excitations in nuclei can be carried out in almost ideal fashion by decay spectroscopy studies. The 8π gamma-ray spectrometer, in conjunction with its suite of ancillary detectors for the detection of beta-particles and conversion electrons, is ideally suited for such studies. Excited states at low spin and a range of excitation energies are populated in the beta decay of the short-lived isotopes extracted from the ISAC target and implanted into a tape positioned in the center of the 8π vacuum chamber. The detection of conversion electrons enables the determination of the multipolarity of transitions and, in the case of excited 0^+ states, their identification via the detection of E0 transitions.

Recently, a precision decay study of states in ^{112}Cd[20] revealed evidence that the structure in this poster-child nucleus for vibrational motion shows some substantial deviations from the vibrational model. Using an intense beam of 5×10^5 pps of ^{112}Ag from the ISAC target, 108 events of gamma-gamma coincidences were collected with the 8π gamma ray spectrometer. Extensive spectroscopic information was extracted on the decay pattern of excited 0^+ and 2^+ states up to 3 MeV excitation energy. Using the measured decay branching ratios of these excited states and known level lifetimes reveals that in ^{112}Cd there are no suitable candidates for 0^+ and 2^+ members of the three-

phonon multiplett and that the expected electromagnetic transition strength is absent in the expected energy range. These findings indicate that the vibrational picture in this nucleus is much less robust than previously assumed.

Using the new availability at ISAC of neutron-rich fission fragment beams produced in a UCx target, the 8pi was used for the spectroscopy of neutron-rich Sr isotopes following the beta decay of ^{96,98,100,102}Rb, a region of rapid transition from spherical to deformed ground states in the Sr and Zr isotopes around neutron number 60. The gamma-ray and conversion electron data collected will enable the measurement of the E0 transition strength from shape coexistent excited 0^+ states in the even-even Sr isotopes in this mass region. ogether, with known half-lives of these states, it will be possible for the first time to extend our knowledge of absolute E0 transition probabilities between 0^+ states, and in some cases, even 2^+ states.

state was known before the recent 8pi study of this nucleus. In this study, about ten particles per second of ^{102}Rb could be delivered to the mother nucleus and, for the first time, it was possible to observe the first excited 4^+ state and several other excited states.

Another study of shape coexistence was carried out in the semi-magic nucleus ^{116}Sn, also using the 8π spectrometer. High statistics coincidence data for gamma-rays, and conversion electrons was obtained allowing for detailed spectroscopy and the identification and characterization of very weak transitions. The major aim of the experiment was to identify weak decay branches to excited 0^+ states which could represent deformed intruder configurations in this singly magic nucleus. Figure 2 shows the total projection and a coincidence gamma-ray spectrum gated on a transition in ^{116}Sn, clearly showing the high quality of the data set and the richness of levels populated in this decay study.

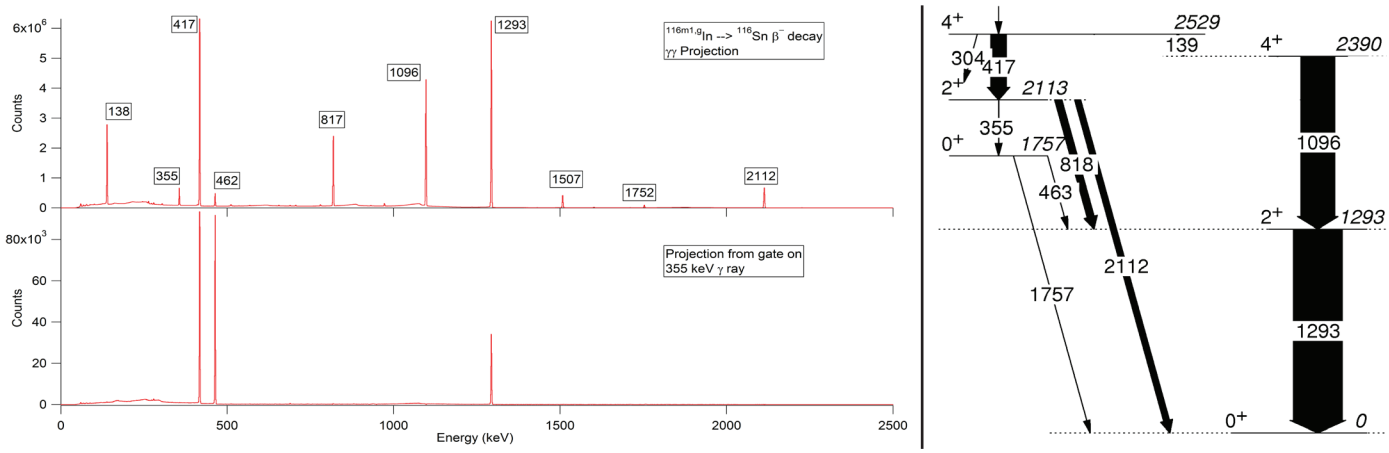

Figure 2: (Top left:) Total projection of gamma-gamma-coincidence matrix measured with the 8π spectrometer in the decay of ^{16}In to ^{116}Sn. (Bottom left:) Coincidence gamma-ray spectrum gated on the 355 keV transition in ^{16}Sn. (Right:) Partial level scheme of ^{116}Sn[22].

This information will be used to quantify the degree of mixing between the two coexisting shapes. Modern beyond-mean field calculations have made great progress in recent years in being able to describe these shape-transitional and shape-coexisting situations not only qualitatively. The new results on the neutron-rich Sr isotopes will be confronted with state-of-the-art calculations and help improve our understanding of correlations beyond the mean field in the structural evolution of collectivity. In ^{102}Sr, only the first excited 2^+

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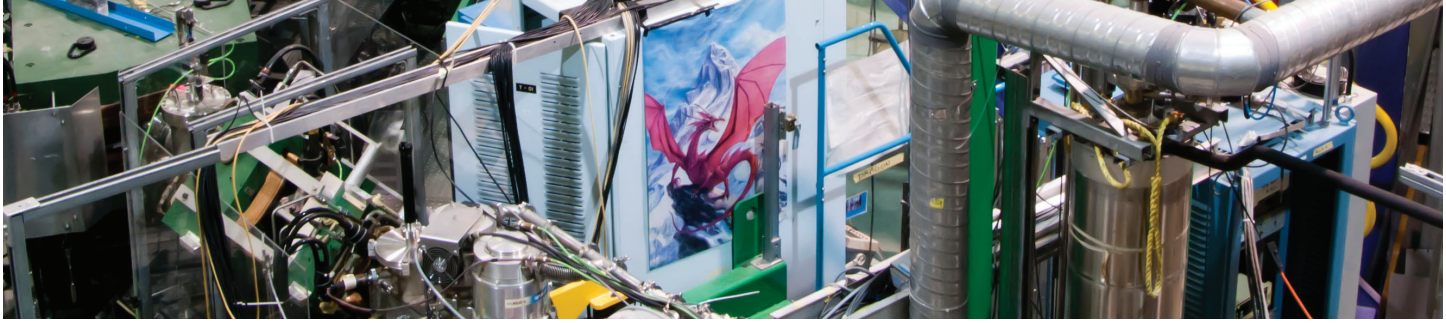

2.8
Nuclear Astrophysics

Chris Ruiz and Barry Davids

In the 2010-2012 period, the TRIUMF Nuclear Astrophysics Group and collaborators performed both experimental and theoretical work towards problems relating to explosive hydrogen burning and the stellar sites of classical novae and core-collapse supernovae. In addition, experimental work was performed relating to quiescent stellar helium burning, production of solar neutrinos and Big Bang Nucleosynthesis (BBN). The experimental work was performed using the DRAGON Recoil Separator facility, the TRIUMF-UK Detector Array (TUDA) facility, and the ISAC Implantation Station (IIS).

Explosive Hydrogen Burning in Classical Novae

This burning process occurs in sites with large hydrogen abundances, and the elevated temperatures seen in thermonuclear runaways during stellar explosions. Here, proton-captures on both stable and radioactive nuclei with emission of either EM radiation (radiative capture) or charged particles in the exit channel are involved. Explosive hydrogen burning has a large influence on energy generation and nucleosynthesis in various stellar scenarios, but commonly occurs in *classical novae* – the thermonuclear explosions resulting from accretion from a less evolved companion star onto the surface of a white dwarf in a binary system – which are important targets for γ ray astronomy and the understanding of stellar physics in general.

^{33}S(p,γ)^{34}Cl (S1122): Sulfur isotopic ratios in meteoric pre-solar grains are a clear indicator of classical nova nucleosynthesis, where large overabundances of 33S relative to the other stable sulfur isotopes are found. Such grains have been discovered with other nova-like isotopic ratios, but sulfur ratios would be the definitive test of whether these grains formed in novae. However, the uncertainty in the rate of the ^{33}S(p,γ)^{34}Cl reaction must be reduced before this can be achieved. The DRAGON facility has measured the strengths of several contributing resonances in the ^{33}S(p,γ)^{34}Cl reaction, in inverse kinematics, reducing the uncertainty of the rate to below the levels needed to solve the sulfur abundance problem. The intense ^{33}S accelerated beam produced using enriched sulfur samples and a multi-charge ECR source made this experiment possible with DRAGON, which does not suffer some of the problems encountered in measurements made in normal kinematics. The experimental data have been analyzed and a publication is under preparation.

^{18}F(p,γ)^{19}Ne (S1123): This reaction has a strong influence on the ejected ^{18}F, and thus on the resulting 511 keV annihilation (a target for space-based telescopes) in O-Ne novae of the hottest variety. For the first time, a contributing resonance to this reaction has been measured. This was done at the DRAGON facility in inverse kinematics using a radioactive ^{18}F beam, produced using a high-power silicon-carbide ISAC target and FEBIAD ion source. This experiment was made possible due to the high ^{18}F intensities produced at ISAC. Data are under analysis and preliminary results show that the resonance in question, whose strength

was previously based on an uncertain analogue state assignment, is substantially weaker than expected. If confirmed after detailed analysis, this will reduce the uncertainty of the 665 keV resonance contribution to the $^{18}F(p,\gamma)^{19}Ne$ rate at the relevant temperatures for the first time based on experimental information, and warrant a measurement of the lower, dominant resonance strength, possible at DRAGON with projected ^{18}F intensity increases. This work is closely related to the $^{18}F(p,\alpha)^{15}O$ studies performed at TRIUMF that were recently published[1].

$^{17}O(p,\gamma)^{18}F$ (S1281): This reaction, also an important contributor to the ejected ^{18}F abundance and hence the 511 keV γ ray emission from novae, was studied in inverse kinematics at the DRAGON facility using very high intensity accelerated ^{17}O beams. This was achieved by using enriched ^{17}O gas in the multi-charge ECR offline ion source. A peak intensity of 1.3×10^{12} s^{-1} was achieved. The astrophysical S-factor in the energy region $E_{c.m.}$=250-500 keV was extracted from these data and compared to previous work. It was found that the S-factor in this region, which is dominated by direct capture, derived from the DRAGON work is larger in magnitude than all previous work, but follows a similar energy dependence to the most recent work. The result is that these experiments have motivated a careful re-measurement of higher lying resonances in order to obtain a sufficiently accurate determination of the astrophysical reaction rate. The work has been accepted for publication[2].

The Nova Project: As part of a new initiative to bring stellar modeling and nucleosynthesis activities to TRIUMF, we have engaged in a collaborative effort with the University of Victoria and the Joint Institute for Nuclear Astrophysics (JINA) to make a new generation of Classical Nova models using the state-of-the-art codes, MESA and NuGrid. So far, a series of carbon-oxygen nova models based on differing white dwarf masses have been generated. For an example of generated abundances from one of the models, see Figure 1. The resulting models have been submitted for publication in the Astrophysical Journal[3]. The TRIUMF Nuclear Astrophysics Group obtained a multi-core high-performance computer for dedicated calculations. The next step is to generate a series of O-Ne Nova models before embarking on nucleosynthesis sensitivity studies that will determine which nuclear reactions are of importance in novae and warrant experimental measurement.

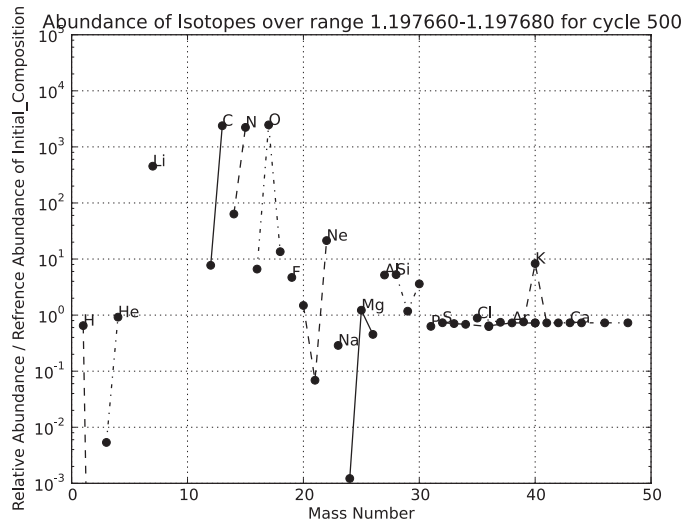

Figure 1. Ratios of final to initial (solar) abundances of stable isotopes in the expanding envelope of our 1.2 solar mass CO nova model. The model was obtained for a white dwarf with the central temperature 30 MK accreting at the rate of 10^{-10} solar masses per year. Convective boundary mixing was taken into account, which resulted in the 30% enrichment of the nova envelope in C and O at the beginning of its thermonuclear runaway (compare this plot with Figure. 1 from J. José & M. Hernanz, Astrophysical Journal, 494, (1998) 680).

Core-Collapse Supernovae

^{26}Al Implantation (S1200): The long-lived radioisotope ^{26}Al ($t_{1/2}$=717,000 yr) is an important indicator of galactic nucleosynthesis, having been mapped by orbiting γ ray telescopes. Massive stars resulting in core collapse supernovae are important contributors to the galactic ^{26}Al distribution. The overall ^{26}Al production in these sites, involving explosive and quiescent hydrogen burning, is uncertain due to many nuclear reaction rates, amongst them the destruction of ^{26}Al via neutron capture through (n,p) and (n,α) reactions. The Nuclear Astrophysics Group plans to measure these reaction rates using a special detector called NEURAL[4], designed at TRIUMF. A ^{26}Al target created at TRIUMF will be bombarded with neutrons at the LANSCE facility at the Los Alamos National Laboratory, and protons and alpha particles will be detected using both silicon and gas detection media. In 2011, we made a large step towards this project by the demonstration of a proof-of-principle implantation of a ^{26}Al target in a thin carbon matrix, using the newly

constructed ISAC Implantation Station. Here, ultra-high vacuum conditions and raster capabilities made it possible to implant the pure, radioactive ^{26}Al at a shallow depth in the thin matrix without destroying the fragile carbon foil, and successfully contain and transport the target for use in the experiment. The next step in this project is to construct the detector, before implantation of a much more intense ^{26}Al target for the final experiment takes place.

Quiescent Helium Burning

^{16}O(α,γ)^{20}Ne (S1282): The carbon-to-oxygen ratio as a result of core helium burning in stars is one of the most important quantities in stellar evolution. Highly critical to this is the much sought-after ^{12}C(α,γ)^{16}O rate, but also involved is the ^{16}O(α,γ)^{20}Ne reaction. A more precise determination of the ^{16}O(α,γ)^{20}Ne cross section over the relevant energy regime is required, and a measurement in inverse kinematics was made possible at DRAGON due to the availability of very high intensity ^{16}O beam from the multi-charge ECR offline ion source. This was the first measurement of the total S-factor, and its components, at the low energy of Ec.m.=1.69 MeV, following an earlier DRAGON measurement at a higher energy. The most recent work is under preparation for publication, while the earlier work has been published[5].

^{18}F(α,p)^{21}Ne (S1287): This reaction is a significant determinant to the ejected stable fluorine abundance from asymptotic giant branch (AGB) stars. Though most fluorine is made in supernovae by the neutrino process, the contributions of novae and AGB stars are still quite uncertain. The group have made progress towards the measurement of this rate via the time-reversed approach, namely performing the ^{21}Ne(p,α)^{18}F reaction at the TUDA facility. This was a proof-of-principle experiment using a technique of filling the entire TUDA vacuum chamber with hydrogen as an extended target volume, and detecting the alpha particle ejectiles and ^{18}F recoils in coincidence. The data from the experiment are currently under analysis to see if the relevant cross sections can be extracted to partially determine the stellar ^{18}F(α,p)^{21}Ne reaction rate.

Solar Neutrinos and Big Bang Nucleosynthesis

^{3}He(α,γ)^{7}Be (S1227): The DRAGON collaboration has measured the rate of the ^{3}He(α,γ)^{7}Be radiative capture reaction at three different relative energies (1.5 MeV, 2.2 MeV and 2.8 MeV) using a ^{3}He recirculating gas target. The ^{7}Li observed in ancient stars was created via the radioactive decay of ^{7}Be nuclei predominantly formed in the ^{3}He(α,γ)^{7}Be reaction just minutes after the Big Bang. For this reason, measurements of this reaction rate are an important step in resolving the stark discrepancy between the Big Bang Nucleosynthesis prediction of ^{7}Li abundances and astronomical observations. In addition, the radiative capture of protons by ^{7}Be and the radioactive decay of ^{7}Be produce the best-measured solar neutrino fluxes. Over 300,000 ^{7}Be fusion product nuclei were detected at DRAGON's focal plane in total (see Figure 2). The completion of this DRAGON measurement adds another reaction rate determination in an energy range where previously only two discrepant measurements existed. The experimental data are currently under analysis.

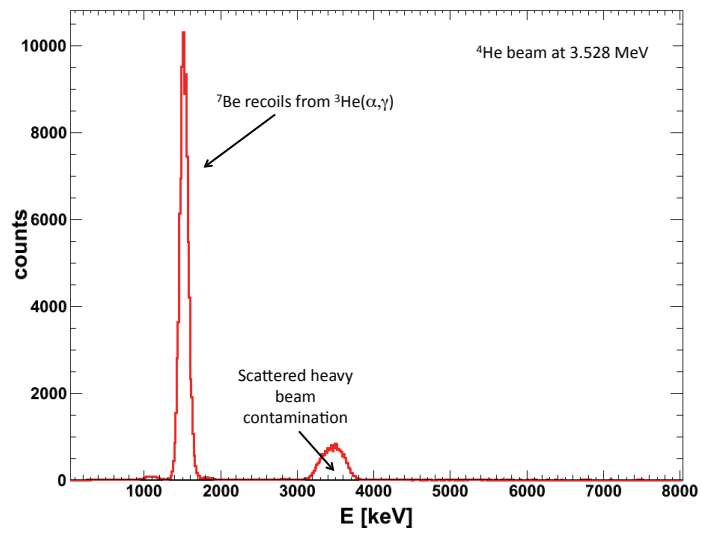

Figure 2. Detected energy spectrum of particles at the focal plane of the DRAGON recoil separator during the ^{3}He(α,γ)^{7}Be experiment, showing the ^{7}Be fusion products, as well as some contamination from scattered ^{12}C and ^{16}O present with the ^{4}He beam.

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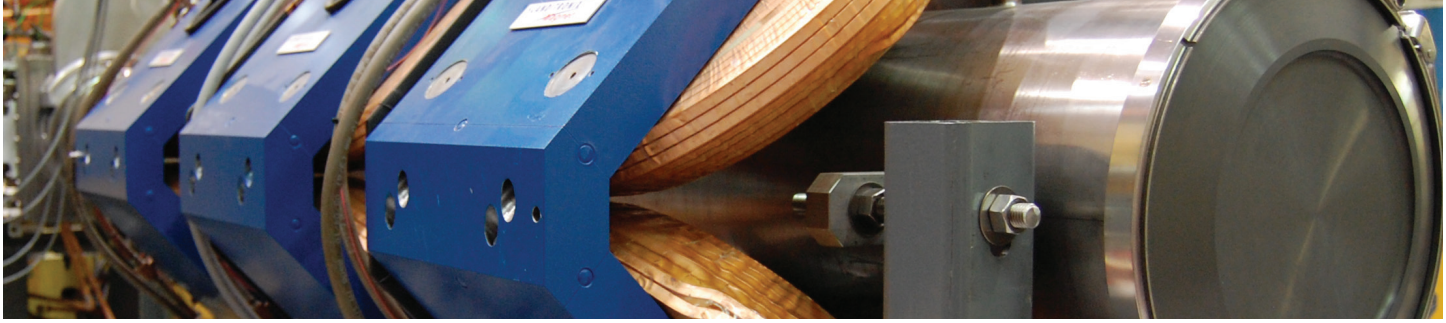

2.9
Molecular and Materials Science

Iain McKenzie

Introduction to μSR and β-NMR

The positive muon and the ^{8}Li nucleus are exceptionally powerful microscopic probes of materials. These radioactive particles are implanted into materials where they reside in the inter-atomic volume and interact with the internal magnetic fields generated by the constituent electrons and nuclei. In some materials the muon can acquire an electron and form an isotope of hydrogen called muonium (Mu), thereby opening up and expanding the field of H-atom chemistry into a range of compounds that would otherwise be unavailable for study.

The information about the local environment of the muon or ^{8}Li comes from the temporal and spatial evolution of the probe's ensemble spin polarization, which is transmitted to the outside world by measuring the angular distribution of the products of the radioactive decay. Implanted muons are studied with magnetic resonance techniques known as muon spin resonance/rotation/relaxation, or μSR, while implanted ^{8}Li nuclei are studied with a technique called beta-detected nuclear magnetic resonance (β-NMR). Muons and ^{8}Li can be implanted into any material, so μSR and β-NMR do not suffer the restrictions present in neutron scattering or Mössbauer spectroscopy. The initial polarization of implanted muons (~100%) and ^{8}Li (~70%) is several orders of magnitude larger than in traditional magnetic resonance experiments, and this leads to enhanced sensitivity. The positive muon has a lifetime of 2.2×10^{-6} seconds, which is rather long compared with motion at the atomic and molecular level. Combined with the ability to detect the particles on a sub-nanosecond timescale, which allows μSR experiments to routinely extract information within the five orders of magnitude time range from 10^{-9}–10^{-5} seconds. μSR can be used to measure a broad range of reaction and/or fluctuation rates in either chemical or condensed matter systems. ^{8}Li has a lifetime of 1.2 seconds, which means that it can probe in the 10^{-3}–10^{2} second range and can be implanted at specific depths from a surface, which has opened up the possibility of studying the magnetic and electronic properties of surfaces, layered structure, and buried interfaces.

The Centre for Molecular and Materials Science (CMMS) at 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 time-resolution pulsed muon beams, and the other two (PSI in Switzerland and TRIUMF) deliver high time-resolution continuous wave (CW) beams. These two complementary methods of muon delivery serve distinct sets of experiments. The CMMS β-NMR facility is the only one in the world to focus on materials science and capable of performing depth-resolved measurements. Fifty-five μSR and β-NMR experiments were performed at CMMS in 2010 and 2011, covering a broad range of scientific topics in condensed matter physics and chemistry. It is not possible to describe them all in this report, so we have restricted ourselves to providing examples of experiments that have had a significant impact on the larger scientific community.

Characterization of Magnetic and Superconducting Materials

Studies of magnetic and superconducting materials are at the forefront of research due to the numerous uses of these materials in modern technology. Muons implanted in these materials can be used as a "microscopic magnetometer" because the frequency of the spin precession of the implanted muon—as measured by the time dependence of the spatial asymmetry in the decay positron emission—is directly related to the magnetic field at the muon site. Researchers use μSR to study magnetic ordering and spin fluctuations, even in materials that show no long-range order.

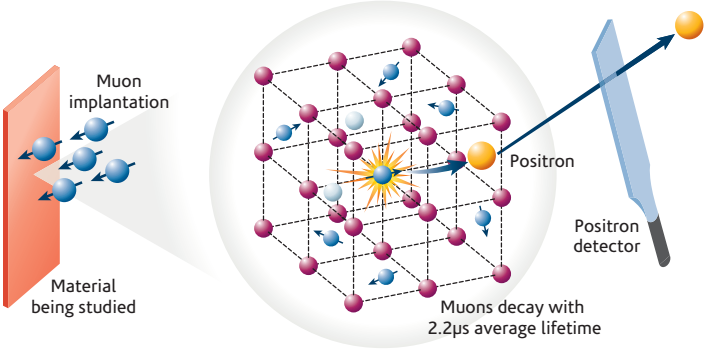

Figure 1. Schematic of a μSR experiment.

Novel Magnetic Materials

Novel magnetic materials can be rationally designed by combining molecular building blocks (i.e., spin carriers and bridging elements) in different patterns. For example, the Leznoff/Sonier (SFU) collaboration has produced a series of coordination polymers based on the dicyanoaurate(I) and tetracyanoaurate(III) building blocks and used μSR to determine how the magnetic properties depend on the transition-metal magnetic moment. They found that $Cu(H_2O)_4[Au(CN)_4]_2$ magnetically orders at 0.6 K, while in $Mn(H_2O)_4[Au(CN)_4]_2{\cdot}4H_2O$ and $Ni(H_2O)_4[Au(CN)_4]_2{\cdot}4H_2O$ there was a gradual slowing down of spin fluctuations at low temperatures, but no spin freezing above 0.02 K. The insights provided by the μSR measurements will allow chemists to design new materials with more interesting magnetic properties[1].

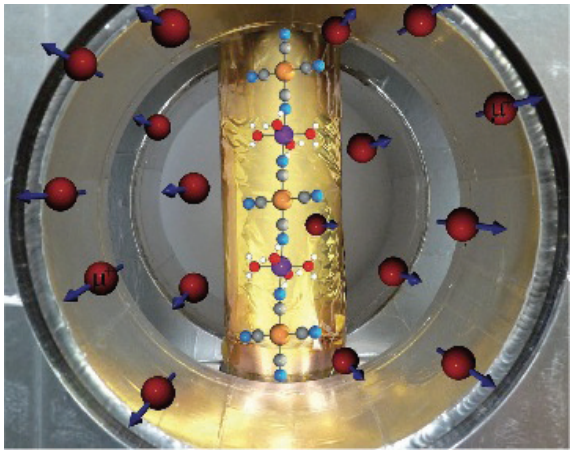

Figure 2. Muons as microscopic magnetic probes of isostructural $M(H_2O)_4[Au(CN)_4]_2$-based coordination polymers (M = Mn, Co, Ni, Cu, Zn)

Studying the Interplay Between Magnetism and Superconductivity

Superconducting systems continue to challenge and intrigue scientists, especially because of the myriad of potential applications. μSR can provide a wide range of information on both the static and the dynamic magnetic behavior in superconducting systems, even in the absence of external magnetic fields. μSR is used to determine the phase diagram of superconducting compounds, which represents a starting point for further investigation and is therefore one of the first goals for experimentalists. Most of the newly discovered superconductors have 'parent' compounds - the undoped and non-superconducting versions of the materials - that order magnetically. Understanding the details of how the transition from the magnetically ordered state to the superconducting state occurs with increasing doping concentration can provide essential information about the mechanisms of electron pairing and condensation, which lie at the origin of superconductivity.

The phase diagram of $Ca_{2-x}Sr_xRuO_4$ exhibits a rich variety of physical phenomena going from Sr_2RuO_4, which is an unconventional superconductor that exhibits spin-triplet p-wave pairing associated with time-reversal symmetry breaking, to Ca_2RuO_4, which is an antiferromagnetic Mott–Hubbard insulator. The phase diagram for $Ca_{2-x}Sr_xRuO_4$ was determined using μSR by a collaboration led by Graeme Luke (McMaster)

and Yasutomo Uemura (Columbia), and corrected a previous phase diagram determined using electrical conductivity, specific heat and magnetic susceptibility measurements. They found that $Ca_{2-x}Sr_xRuO_4$ has a ground state with static magnetic order for $0.5 \leq x \leq 1.5$ and that there is close proximity of superconductivity in Sr_2RuO_4 to competing static magnetic order.

High-temperature superconductivity arises from the doping of charge carriers into the CuO_2 planes of copper oxide Mott insulators. Doping beyond an optimal concentration causes the superconductivity to disappear. If the disappearance of the superconducting state is due to ferromagnetic fluctuations, then a ferromagnetic phase is predicted to exist at very low temperatures. Jeff Sonier (SFU) and Douglas MacLaughlin (U. C. Riverside) investigated this scenario in overdoped $La_{2-x}Sr_xCuO_4$ using muon spin relaxation and detected the onset of static magnetic moments of electronic origin at low temperature. The magnetism does not exist in a long-range ordered state, but as a dilute concentration of static magnetic moments. These results lend support to models that predict weak localized ferromagnetism at high doping[2,3].

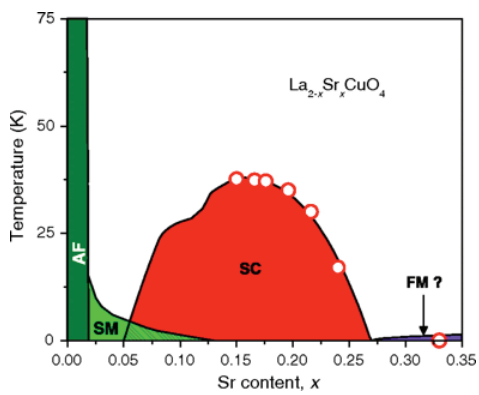

Figure 3. Schematic phase diagram of $La_{2-x}Sr_xCuO_4$. The dark-green area represents the region in which static long-range AF order is observed, the light-green area represents the region with inhomogeneous static magnetism (SM) and the red region represents the superconducting (SC) phase. The red open circles are the T_c values of single crystals measured by μSR. The purple area beyond the SC dome represents the long-range static FM phase.

Exotic Magnetic Phenomena

A major area of research is the study of frustrated magnets, which are materials in which localized magnetic moments, or spins, interact through competing exchange interactions that cannot be simultaneously satisfied, giving rise to a large degeneracy of the system ground state and exotic magnetic properties. There has been a recent high profile report of μSR experiments on the highly frustrated magnetic system Dy_2Ti_2O, where the results were interpreted in terms of the formation of deconfined magnetic monopoles [Bramwell et al. Nature 461, 956 (2009)]. This controversial conclusion prompted a team of researchers led by Sarah Dunsiger (T. U. München) to perform further μSR experiments on this system where they demonstrated that magnetic monopoles are not observable in a μSR experiment due to spin fluctuations that become temperature independent at low temperatures[4].

Magnetic Polarons

For half a century, physicists studying magnetism in solids have been searching for "magnetic polarons" (MP) - tiny ferromagnetic "droplets" mediated by strong exchange interactions of neighbouring spins with a single electron, which in turn is localized by those same interactions. Indirect evidence has been found for MP in various highly correlated systems, but until now direct observation of MP has remained elusive, and their size has been unknown. Using positive muons as local magnetic probes, Vyacheslav Storchak (Kurchatov Institute) and Jess Brewer (UBC) have detected MP in magnetic semiconductors, magnetically frustrated metals and other exotic metals like MnSi, and confirmed that the hypersensitivity of the electrical resistance of some materials to applied magnetic fields ("colossal magnetoresistance") can be explained in terms of MP as small as a single unit cell[5].

Characterizing Reaction Intermediates

Organosilicon and organogermanium compounds are employed in the manufacture of polymers (e.g. silicones), thin-film devices (by chemical vapour deposition), and catalysts. Optimizing industrial processes and developing improved materials requires detailed knowledge of chemistry. For example, which parts of the molecule are reactive, how fast does this happen, and are the reaction products stable? Muonium is an excellent, unbiased probe

of reactivity, having no charge or dipole moment. Paul Percival (SFU) and Bob West (U. Wisconsin-Madison) used μSR to identify the sites of Mu addition in quite complicated molecules. For example, two distinct free radicals were detected as a result of muonium addition to a silylene-carbene complex. The same two Mu sites were identified for the silylene in the absence of carbene, but the different properties of the muoniated free radicals demonstrates the effect of complexation[6].

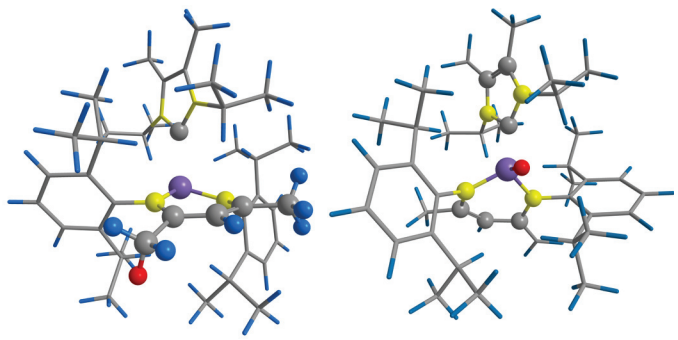

Figure 4. The molecular structures of the two radicals formed by Mu addition to a silylene-carbene complex (Si violet, N yellow, C gray, H blue, Mu red).

Chemical Reactions in Green Solvents

Supercritical water and CO_2 can be used as solvents instead of toxic organic compounds, which has a considerable benefit to the environment. Little is known about how the water or CO_2 molecules interact with solutes and what effect they have on chemical reactions. The high temperatures and pressures make it difficult to study these systems with traditional techniques, but high-energy muons and the decay positrons can penetrate the pressure vessels. Khashayar Ghandi (Mt. Allison) studied the reaction of Mu with vinylidene fluoride in supercritical CO_2 and found that reaction rate constants can change significantly near the critical point with small changes in the pressure, temperature, and density, so the chemistry can be tuned very easily with minimal consumption of energy.

Lithium Ion Diffusion in Battery Materials

Lithium-ion batteries are rechargeable batteries that are commonly used in consumer electronics. The performance of batteries could be improved through a better understanding of the underlying physical processes, such as the diffusion of the lithium ions. Many materials used as positive electrodes contain magnetic ions, so the diffusion coefficient of Li^+ ions (D_{Li}) cannot be determined using traditional techniques like ^{7}Li-NMR. Muons are ideal probes as they are not sensitive to the fluctuating magnetic moments at high temperature, but instead react to the change in nuclear dipolar field due to Li^+ diffusion. Jun Sugiyama (Toyota Central R&D Labs) and coworkers have used μSR to measure D_{Li} and magnetic properties in several cathode materials including $LiFePO_4$ and $LiNO_2$[7].

β-NMR Studies of Thin Films and Interfaces

β-NMR is a unique tool for performing depth-resolved magnetic resonance experiments in the vicinity of surfaces and interfaces. The development of a broad user program has been limited by the small amount of beamtime, but this will improve substantially with the development of ARIEL. Increased beamtime will make it possible to expand the exciting work already performed on magnetic semiconductors and the magnetic properties at interfaces and to open up new areas for investigation, such as topological insulators and polymer dynamics.

Figure 5. Rob Kiefl (UBC) with the high-field β-NMR spectrometer.

Magnetic Semiconductors

β-NMR can be used to study materials that can only be produced in the form of thin films. $Ga_{1-x}Mn_xAs$ is a magnetic semiconductor that can only be produced in thin films due to the limited equilibrium solubility of Mn.

Magnetic semiconductors are materials that exhibit ferromagnetism and semiconducting properties and have potential use in spintronic applications. Although $Ga_{1-x}Mn_xAs$ has been extensively studied it was unknown whether the ferromagnetism is mediated by valence holes or by the Mn-derived impurity band, and if it is magnetically phase separated. Andrew MacFarlane (UBC) and collaborators found that the hole contribution to the magnetization scales with the macroscopic magnetization through T_c, but deviates below 40 K, and that the hyperfine coupling constant of $^8Li^+$ in $Ga_{1-x}Mn_xAs$ is negative. This may indicate the Fermi level falls into a Mn derived impurity band, and that there is no magnetic phase separation below T_c.

Magnetic Properties of Interfaces

In general, the physical properties of an interface between two materials are different from the bulk properties of both. A dramatic example is the interface between two insulating perovskite oxides, TiO_2-terminated $SrTiO_3$ (STO) and $LaAlO_3$ (LAO), where there is the formation of a high mobility two-dimensional electron gas. There is evidence that this interface can be both magnetic and even superconducting below 300 mK but most reports of magnetism at the STO/LAO interface were based on indirect measurements, such as transport properties at high applied magnetic field. Zaher Salman (PSI) and coworkers used β-NMR to directly observe the internal magnetic fields generated from electronic moments in superlattices (SLs) of LAO/STO. Depending on the thickness of the LAO layers, the spin-lattice relaxation rate of polarized ^8Li measured in some SLs exhibits a strong temperature dependence with a maximum at $T^* \sim 30$ K. This behaviour is attributed to a slowly fluctuating internal magnetic field near a magnetic transition at T^*, and provides direct evidence of magnetism at the interface between insulating and nonmagnetic LAO and STO.

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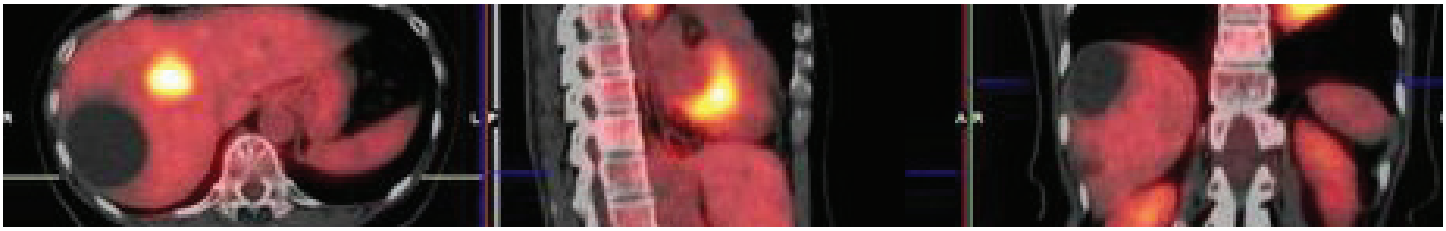

2.10
Nuclear Medicine

Paul Schaffer

Accelerator science is the backbone of TRIUMF's nuclear medicine program, a program that maintains a strong isotope and radiopharmaceutical production capability enabled by four on-site cyclotrons. These cyclotrons drive the spectrum of research encompassed by the division, which starts with the physics of particle acceleration and target bombardment, followed by a deep radiochemistry capability in radiopharmaceutical production, which is ultimately used for biological and imaging studies with our collaborators. Molecular imaging with the tracers produced at TRIUMF is used to gain an understanding of disease at the molecular level.

Core Competencies

To focus our efforts, the division has articulated its core competencies into three key areas:

- Accelerator target design
- Medical isotope production/isolation
- Radiopharmaceutical synthesis

The division has been structured, our roles within our collaborations are defined, and our future efforts are guided with these competencies in mind. The three core competencies described do not preclude the possibility that, as the division grows, additional competencies may become evident.

Collaborations

TRIUMF's Nuclear Medicine division is built upon a long-standing collaboration with the Pacific Parkinson's Research Centre, for which we routinely provide various tracers for human pre-clinical imaging studies. These studies aim to establish the relationship between dysfunction in the dopamine neurotransmitter system and the progression of Parkinson's disease, but also include studies into other neurodegenerative diseases, such as Alzheimer's. The tracers produced are often literature-established, small-molecule pre-clinical and/or clinical imaging agents with a heavy focus on safety and Good Manufacturing Processes (GMP). The purpose of producing these radiopharmaceuticals is to enable our collaborators to perform cutting-edge imaging research in order to gain a better understanding of disease initiation, progression, patient stratification, and treatment response – a crucial expertise to maintain in light of the growing acceptance of molecular imaging in the clinic. This effort defines the core of TRIUMF's Nuclear Medicine Program.

Commitment to Discoveries

In addition to its core efforts, TRIUMF strives to make new discoveries in nuclear medicine and the related fields of research. By formally recognizing TRIUMF's considerable expertise in each of the three core areas—target design, isotope production/isolation, and pharmaceutical synthesis—the Nuclear Medicine group and its partners have mobilized and secured over

Name	Target	2010	2011	Variance (2010 - 2011)
Raclopride	D2, D3	62	64	2
Dihydrotetrabenzine	VMAT	4	11	7
(+) Dihydrotetrabenzine	VMAT	53	54	1
Methylphenidate	DAT	43	20	-23
PMP	Ach substrate	23	18	-5
PIB	Amyloid b	11	18	7
MDL100907	5-HT2A	0	8	8
SCH23390	D1	0	4	4
MRB	NET	0	4	4
Yohimbine	Numerous	0	4	4
FDOPA	Dopaminergic function	26	89	63
EF5	Hypoxia	1	4	3
FMT	Dopaminergic function	1	0	-1
	Total	**224**	**298**	**74**

Figure 1. The number of tracer deliveries from TRIUMF to UBC and BCCA during 2010 and 2011.

$8.5 M in grant and contribution funding since 2009. Several of these funding opportunities also provided a means to establish or enhance existing collaborations with other radiopharmaceutical centres across the country. The focus of these funds ranged from improving TRIUMF's aging chemistry facilities for radiopharmaceutical production under GMP guidelines, to leveraging TRIUMF's expertise in accelerator-based isotope production to address the recent medical isotope crisis.

Moving forward, the division will continue to focus on research within the framework of our core competencies and will be either in i.,) the development of platform technology to advance the field of accelerator-based medical isotope production and to better enable radiopharmaceutical development, or ii.,) the development of novel isotope production and isolation methods for the design and synthesis of novel large molecular weight radiotracers which includes labeling peptides, proteins, oligonucleotides, and peptide nucleic acids with radiometals.

Radiochemistry

Core Program: GMP production of tracers for the Pacific Parkinson's Research Centre

The Radiopharmaceutical Production Group at TRIUMF has worked in conjunction with the Pacific Parkinson's Research Centre at UBC to study neurodegenerative diseases for more than twenty years. Currently, seven compounds are produced on a routine basis using TRIUMF-designed automated synthesis equipment. Also, part of the radiopharmaceutical production lab was upgraded in 2010 with a contribution from Western Economic Diversification of Canada, allowing the group to purchase new equipment and to better conform to GMP standards.

Recently, three new tracers have been developed and established for production in the new GMP lab. The core group has established the synthesis of [11C] MRB (methyl reboxetine), a selective norepinephrine

transporter (NET) blocker, for a collaborative study with Dr. Yu-Shin Ding. [11C]Yohimbine was developed for Dr. Doris Doudet to image adrenergic receptors in the brain followed by [11C]DASB in early 2012, which will be used to assess the serotonin function in the brain. [18F]EF5 was also resurrected for shipment to BC Cancer Agency for a clinical trial on the use of PET in prostate cancer imaging. All tracers are in the process of being transferred to the new facility.

Radiopharmaceutical Synthesis

Aqueous F-18 chemistry: Sulfonyl fluorides

Due to its high sensitivity and spatial resolution, positron emission tomography (PET) has emerged as the premier molecular imaging technique for the in vivo detection and quantification of a variety of human physiological and pathophysiological processes[1]. In the context of disease, the goal of PET imaging is to improve a patient's outcome through better diagnosis, progression analysis, clinical staging and evaluation of response to treatment. To this end, PET chemistry has evolved alongside the imaging modality, with continual efforts to improve the efficiency and cost of the radiopharmaceutical production process and develop superior functional probes.

The radioisotope ^{18}F is often considered the ideal radionuclide in terms of imaging resolution. However, its half-life of 109.7 minutes makes multi-step synthesis, often necessary for the production of radiopharmaceuticals, a challenge. Before making the final tracer suitable for injection, the ^{18}F has to be selectively isolated from the target material on a column, scrupulously dried at high temperatures, radiopharmaceutical synthesis completed and all residual chemistry components removed before injection. Each of these steps leaves less ^{18}F for the final pharmaceutical. In response, chemists at TRUMF have developed a faster and easier method of producing ^{18}F-containing radiopharmaceuticals by using bifunctional arylsulfonyl [^{18}F]fluorides – which can be produced in under 15 minutes at room temperature, greatly improving the amount of usable ^{18}F. This new method should be able to replace the time-consuming multi-step processes otherwise necessary.

Aqueous F-18 Chemistry: Aryltrifluoroborates

The Perrin lab has proposed the use of arylboronic acid bioconjugates as shelf-stable, stockable precursors for one-step aqueous ^{18}F labelling. The feasibility of this approach was disclosed several years ago by examining the in vivo fate of ^{18}F-labelled biotin-ArBF35 and more recently with ^{18}F-labelled marimastat-ArBF3, a potent inhibitor of matrix metalloproteinases, which provided some of the first in vivo PET images of tumour-associated protease activity[2]. The synthetic advantages of this method, which include a one-step aqueous fluorination to provide radiochemically pure, labelled ligands was detailed in a recent publication[3]: conserving time and therefore the amount of ^{18}F, radiochemical purity and higher specific activity. Unfortunately, there are also some disadvantages: low specific activity in order to afford high radiochemical yields, a need to work with very small volumes and low pH, and a need to work with large amounts of activity in order to gain specific activity.

In order to improve on past efforts, TRIUMF's chemist have expanded the investigation. For example, a new discovery made it possible to shorten the fluorination to ~25 minutes with higher yields at lower fluoride concentration, therefore improving the specific activity.

In a second effort, TRIUMF's chemists have successfully extended this labelling technique to "click" chemistry, a labelling procedure via two steps in only one pot, resulting in a very quick and reliable generation of radiopharmaceuticals with high- yield.

Applications: Preparation of targeted radiolabelled peptide nucleic acid (PNA) and oligonucleotide (ODN) chimeras for PET

There are approximately 200 different types of cancer, with some analyses suggesting that greater than five genes mutate in each tumour[4]. With genetic heterogeneity across any given patient population, symptomatic diagnosis of cancer and/or classification of tumours are increasingly becoming an insufficient means of dictating treatment and/or determining patient outcomes. Genetic profiling techniques have enabled the identification of specific

genes that are over-expressed in various cancer types and with that, the identity of unique gene clusters acting together in a specific subset of transformed cells, driving disease forward. This knowledge offers a potentially powerful indicator of tumor function at the genetic level. Since individual gene alterations likely occur at too low a level to detect with existing imaging methods, mRNA over-expression resulting from gene modification could potentially serve as one of the earliest diagnostic indicators for the development of cancer in humans.

Genome BC has funded an effort through TRIUMF to advance the field of antisense positron emission tomography. The effort involves conjugating peptide nucleic acids (PNAs) to cell penetrating peptides for enhanced access to the cellular interior. Specifically, the TRIUMF group will work progressively toward the proposed chimeras, first building complementary PNA constructs to known target sequences of two genes (GFP and HER2). These sequences will be modified with a terminal azide to allow for 'click' modification with a fluorescent dye or radiolabelling precursor followed by in vitro analysis. Once the selected PNA sequences have been validated, full construct synthesis will then be afforded by producing the CPP portion of the chimera on solid support. The conjugates will then be labelled using the radiolabelling methods discussed above. Once the in vitro work has been completed, the goal is to analyze the chimeras in vivo.

Accelerator Target Design

Tc-99m production on Canada's existing cyclotron network

Since 2007, several sudden and prolonged outages of the major Tc-99m production centres have highlighted the fragile state of the reactor-based isotope supply chain. With the capacity to produce over 80% of the world's Tc-99m demand, the Canadian NRU nuclear reactor has played a pivotal role in the production of this isotope. However, due to its age, unexpected shutdowns have become more frequent and are affecting the supply and availability of technetium-99m. Used in over 85% of the 20-40 million nuclear imaging procedures performed worldwide every year, alternative production methods of Tc-99m are desperately needed.

Since 2011, TRIUMF has led an effort that could potentially address the global isotope crisis by decentralizing the production of Tc-99m by using existing medical cyclotrons installed in major urban hospitals. This project started as a proof-of-feasibility effort jointly funded by NSERC and CIHR and has since evolved into two parallel efforts, with the second proof of concept effort being funded by Natural Resources Canada (NRCan).

While this project was underway, the Non-Reactor Based Isotope Supply Contribution Program (NISP) was launched by NRCan, offering $30 M in support of demonstrating the production of Tc-99m on medical cyclotrons from proof-of-feasibility to proof-of-concept. The consortium of institutions (TRIUMF, the BCCA, Lawson, and the CPDC) led by TRIUMF has now established that scale-up production of Tc-99m on existing (16.5 – 19 MeV) medical cyclotrons is possible.

The team has successfully demonstrated the feasibility of producing Tc-99m and Tc-94m using medical cyclotrons. Our research established the parameters for optimal irradiation of Mo-100 targets in order to obtain high quality Tc-99m for clinical translation. New targets and target preparation methods were developed for routine production of Tc-99m. High production yields were shown to be achievable on a practical basis which, when coupled to newly developed purification methods to extract and purify Tc-99m from irradiated targets, as well as molybdenum recycling processes, serve to make this a realistic solution.

Work has been done to establish the human dosimetry of cyclotron-produced Tc-99m has been calculated based on theoretical yields, and experiments have shown that cyclotron-produced Tc-99m could reconstitute commercial technetium kits without problems.

The remaining work in this project will focus on improving the yields of the separation of Tc-99m (currently sitting between 75 and 90%) and the recovery efficiency of 100-Mo for recycling. So far, NISP has been completed with the proof-of-principle that commercial quantities can be produced. In an extension of this project, studies continue

toward the actual production of Tc-99m production across Canada and the evaluation of its suitability for use in clinical settings. In response, the federal government, through Natural Resources Canada has announced a second initiative called the Isotope Technology Acceleration Program (ITAP) which is designed to push the technology developed during NISP into the commercial arena.

The final objective through ITAP is to enable routine, large-scale Tc-99m production in seven centres across the country located in British Columbia, Saskatchewan, Ontario and Nova Scotia. Production will be sufficient to meet regional market demand for those centres by 2016. This made-in-Canada technology will be commercialized through engaged private sector partners who have global distribution capabilities in established and emerging markets, thereby providing an opportunity to export Canadian technologies and services and show a return on Federal R&D investment.

Target Research – Improved ^{11}C Production and Radiometal Production in Solution

TRIUMF's PET target group works on the design, development, and implementation of PET targets suitable for medical cyclotrons. In 2010 - 2011, several improvements and new targets were worked on. For example, a new niobium-bodied target to produce [^{11}C] CO2 was successfully tested and characterized and is now in production for several tracers. In addition, two efforts were undertaken to improve the yield of [^{11}C]CH4 produced in target. In the first effort, a new target design was developed and a prototype bench tested[5]. This design incorporates a fan inside the target to introduce turbulences and mixing of the target gas and potentially increasing the yield of the [^{11}C]CH4 produced. The design is now being tested at the TR13 cyclotron. The second effort included the use of a metal-foil liner in a target, which did change the yield of the produced [^{11}C]CH4 by up to 32%. Other liner materials will be tested as well.

In a separate effort, Tc-94m was produced in a liquid target loaded with a Mo-salt solution[6]. This unique technique allows irradiating materials dissolved in a liquid solution, which are normally available in metal powder or foil form. Therefore, the existing liquid targets and infrastructure of many PET cyclotrons can be used and the expenses and complications of a solid target station for quick testing of new isotopes can be avoided. Different concentrations of Mo solution and their effect on the target performance were tested, see Figure 2. Quantities large enough for pre-clinical studies were able to be produced.

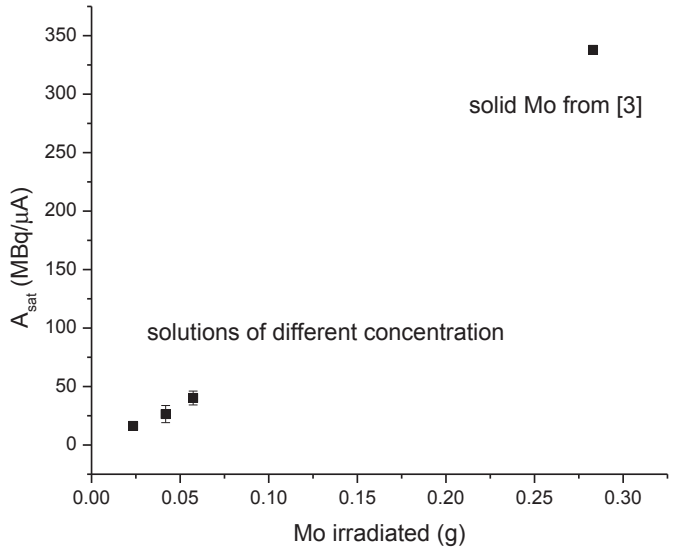

Figure 2. Saturation yield A_{sat} with solutions of different Mo concentrations. The data point on the far right is for a target of solid Mo from the literature.

Proton Therapy Program

Along with our production and research programs in nuclear medicine and molecular imaging, TRIUMF, also provides radiotherapy in collaboration with the BC Cancer Agency and the UBC Eye Care Centre by operating Canada's only Proton Therapy facility. Since 1995, patients with ocular melanomas have come to TRIUMF to receive treatment, achieving a local tumour control of 91%[7]. Between January 1, 2010 and December 31, 2011, 16 patients were treated with protons during five scheduled treatment sessions each year. This brings the total number of patients treated with protons at TRIUMF to 161, with an average per year of 9.5. Treatment is carried out at the main cyclotron, using a modulated beam of 74 MeV protons with the dose delivered over four once-daily fractions of about 90 seconds each.

In 2011, the computer program FLUKA, a particle physics Monte Carlo simulation package for simulating

the interaction of particles with matter, was used to model the proton therapy beam line. Figure 3 shows how the proton beam (in green) passes through the different elements in the beam line and the subsequent creation of secondary particles (in red and black). The simulation was verified against several sets of experiments. This computer model can now be used as a means to quickly and economically study changes to the beam line while avoiding significant disruptions in beam line operations. Modifications intended to improve beam characteristics can be tested experimentally with the goal of reducing patient dose from secondary particle emissions. Work will continue on this effort.

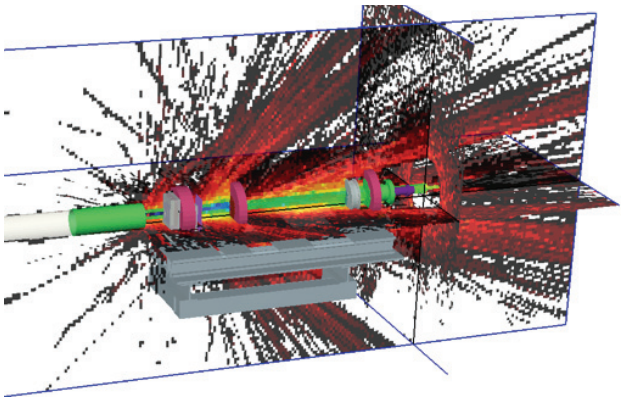

Figure 3. Simulation of the proton therapy beam line in 3D.

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2.11
Accelerator Science

Yu-Chiu Chao

The period of 2010-2012 saw progress on multiple fronts in accelerator science and technology at TRIUMF. We continued to support the upgrading, commissioning, and operation of the main cyclotron, ISAC, and VECC facilities. Most notably cyclotron Beam Lines 1A and 2A were retuned for 480 MeV operation, leading to experimentally confirmed reduction in beam loss. Substantial work was done to advance the ARIEL/e-linac project, leading to the finalization of designs for the gun, the beam transport from gun to targets, and the beam separation schemes in anticipation of future multiple pass operation in energy doubling and energy recovery modes. Ground was also gained in advancing knowledge and developing performance-enhancing techniques in accelerator science and technology.

Design and Commission of the TRIUMF 300 keV H- Vertical Injection Line

The optics for the new 12 m long vertical injection line was designed entirely using the code TRANSOPTR. This is first order and fully 6-dimensional; it can track all 21 second moments and space charge is included by solving, at every integration step, the three elliptic integrals and rotating the forces to the lab frame. This is essential due to the 3D fully coupled nature of the fields in this line and in the inflector. TRANSOPTR was extended to include: varying axial magnetic fields, electrostatic spiral inflector, and motion through the first few turns of the cyclotron including acceleration effects. Commissioning began in April 2011 and was very successful. Using entirely theoretical settings at startup, followed by less than an hour of fine-tuning the steering correctors, the beamline reproduced the nominal 60% transmission, a record that took six years to achieve with the previous vertical line. The transmission reached 70% after a few more hours of tuning.

Suppression of Cyclotron v=3/2 Resonance

A new technique was proposed and borne out by simulation to use two independent sets of harmonic coils to suppress the v=3/2 resonance driven by field imperfection in the cyclotron, which was responsible for fluctuation in current density after resonance crossing (Figure 1).

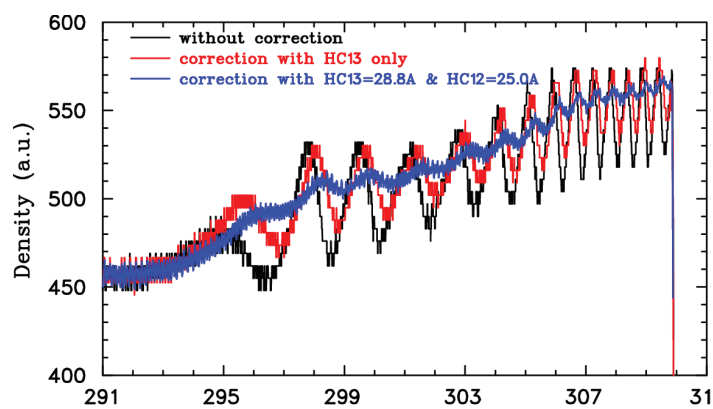


Figure 1. Suppression of the vr= 3/2 resonance: Current density around extraction with 0, 1 and 2 correction coils. Top: simulation; Bottom: experimental results .

The implementation of this technique resulted in greatly stabilized extracted beam current. In addition, one of the harmonic coils was used in Br mode to

correct the vertical position at extraction. These techniques are expected to significantly improve the cyclotron performance during the 2012 run.

Advances in Simulation of Beam-Material Interaction

A prototype G4Beamline model of Beam Line 2A was developed and helped quantify losses due to scattering in the cyclotron extraction foil. G4Beamline was modified to provide spin tracking of muons, enabling study of beam line M9B by the μSR group, which provided insight into muon collection and transport processes, as well as how to improve efficiency in this unique facility. We are further developing models for ARIEL/e-linac, initially on momentum tail collimation. As a contributing member of the Geant4 collaboration, we have extended its 3D visualization toolbox with a number of new features, such as rapid navigation, bookmarked viewpoints, view rotations, and a fly-through feature. Various data converters have also been created, allowing interoperability with existing codes COMA, REVMOC, ACCSIM, and ASTRA. A graphical analysis and plotting facility was built via MATLAB for G4Beamline tracking data.

Poincare Analyticity and the Complete Variational Equations

Work was done to generalize to all orders the usual first-order variational equations associated with any specific solution of any given (ordinary) differential equation. In doing so, it provides an explicit procedure for computing the Taylor series that describes how the final conditions of a solution depend on the initial conditions and, if present, arbitrary parameters. Such Taylor maps are commonly used in accelerator design. They are expected to be of general utility for many other applications of ordinary differential equations including control theory. For example, it is illustrated that an eighth-order polynomial approximation (including parameter dependence) well reproduces the behavior of the exact stroboscopic Duffing map, including infinite period doubling cascades and strange attractors. This work was submitted to *Physica D.*

Optimal Design of Short Quadrupoles

Theoretical study was undertaken to arrive at optimal pole shape for short quadrupoles whose length is comparable to or shorter than the aperture. Conventional 2D treatment and fabrication practice assuming sufficiently large pole length break down in such cases, leading to far-from-optimal aberrations. We have derived, analytically, a new 3D shape, and demonstrated that this shape yields smaller aberrations. Though the exact shape is impractical, for short quads it can be approximated with a simple spherical pole, provided the sphere's radius is correctly chosen: it must be 1.65 times the quadrupole's aperture radius. This work was submitted to *Physical Review Letters Special Topics Accelerators and Beams.*

Generalized Global Optimization Platform

Building on the framework developed to optimize e-linac beam dynamics, a program was launched under partial NSERC funding to develop an integrated, general purpose optimization platform built to rigorous software standards, enabling the global optimization of a wide range of beam delivery systems as a unique accelerator design tool. Infrastructure development started in 2011 and has been tested in the context of e-linac design through the programs ASTRA and TRANSOPTR. Current work involves optimization of bending section design using CSRTRACK and other programs.

Low-β Empirical Model for Online Modeling and High-Level Applications

An efficient but accurate beam dynamics model suitable for high-level applications at low-energy (< 10 MeV for electrons), despite its importance, has not been developed for machine control anywhere. We attempt to bridge this gap with an online empirical model through capturing tracking results into interpolatable and polynomial-expandable data as input to an online empirical model. This is more efficient than on-demand tracking, but more accurate than analytical models over considerable range of beam and hardware parameters. Optimal physical data format and software structure have been worked

out to take advantage of the mature XAL framework developed at SNS. On this basis, quite a few demo high-level applications have been created and beta tested against data taken from the VECC test facility.

3 Facilities

Introduction

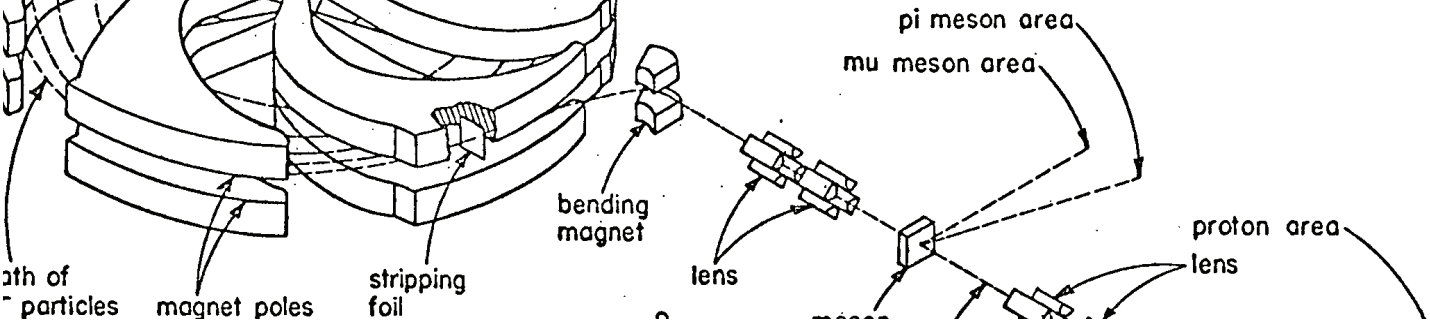
As a laboratory, TRIUMF represents a set of knowledge, skills, and abilities for science, technology, and innovation in Canada. However, just as important as the talented staff, is the physical infrastructure that provides Canada with a competitive advantage for discovery science. The origins of TRIUMF are in particle and nuclear physics and thus the lab's key physical resources involve accelerators, beam lines, and detectors.

Science never stands still. This chapter discusses the advances and performance of TRIUMF's facilities and experiments in service of the greater mission.

During the 2010 – 2012 period, key elements of TRIUMF's engine for discovery and innovation, the main cyclotron, were upgraded. The vertical section of the cyclotron injection beam line was replaced. Downstream, new beam lines for materials science are being expanded and upgraded. On the rare-isotope science side, advances in isotope-production technology were installed, enabling improved delivery of isotopes to the suite of nuclear-physics experiments in ISAC-I and ISAC-II. TRIUMF achieved several new milestones with the introduction of actinide targets and improvements to the charge-state booster to enable heavier-mass isotopes to be delivered. New experiments and detectors have been built and are being commissioned.

New laboratories, complete with hot cells and chemistry suites, have been developed for nuclear-medicine research. Underground pneumatic pipeline connections between the TRIUMF production labs and laboratories at UBC were upgraded and designs for an expansion were completed. In the area of scientific computing, TRIUMF's stewardship of the Canadian ATLAS Tier-1 Data Centre expanded simultaneously with an upgrade of the lab's core network fabric.

These enhancements were not without challenges or tradeoffs. Elements of TRIUMF's infrastructure date from the original installations dating back to the 1970s. Talent and resources to maintain, repair, and expand TRIUMF's capabilities are in high demand and the lab is identifying, assessing, and developing options to deal with aging infrastructure that underpins many of the lab's core capabilities.



3.2 Cyclotron and Primary Beam Lines

Jamie Cessford, Roman Ruegg, and Rick Baartman

3.2.1 500 MeV Cyclotron Performance

Jamie Cessford

The Accelerator Operations Department operates the three major beam delivery facilities at TRIUMF: TR13 PET Isotope Cyclotron, the 520 MeV Cyclotron, and the ISAC Rare-Isotope Beams Facility.

The 520 MeV Cyclotron has four independent extraction probes with various sizes of foils to provide protons to up to four beam lines simultaneously. Beam line 1A (BL1A) routinely delivers protons at 480 MeV to two target systems. The beam power ranges from 50 to 75 kilowatts. The first target, T1, services three experimental channels, one of which is used for the T2K project. The second target, T2, services two μSR experimental channels. Downstream of T2 is the 500 MeV Facility used to produce strontium, which is used in medical imaging generators and the Thermal Neutron Facility. Beam line 1B separates off 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 tumors) 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 480 MeV proton beams at up to 50 kilowatts to the on-line ISAC target that produces exotic radioactive ion beams for a host of experiments.

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

520 MeV Facility Operation - 2010 Totals

2010 saw a switch in maximum energy to 480 MeV for routine beam production in BL1A and BL2A. This change was rewarded with a 30% reduction in the residual radiation fields within the machine for shutdown and maintenance day activities.

The cyclotron ran for 5,407 hours, or 90.8% of the 5,957 hours scheduled. Our annual fall mini-shutdown ended in early September and our winter shutdown began on December 21. The major downtime for 2010 was related to vacuum, accounting for 53% of the total 494 hours. Most of the 200 hours of vacuum downtime was due to a leak inside the LINDE 1630 Helium refrigerator.

Beam line 1A ran for 4,219 hours, or 87% of the 4846 hours scheduled and received a charge of 486 mAh, or 93% of the 525 mAh scheduled. The final week of BL1A running was lost when a vacuum leak opened up between 1AT2 and M9. 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 eight weeks of Proton Irradiation

Facility operation. BL2C4 ran for 3,517 hours, or 88% of the scheduled 3,993 hours and also received 92% of the scheduled charge (251 mAh of the scheduled 274 mAh).

BL2A delivered 4,061 hours of beam to East or West Target Stations, or 76% of the scheduled 5372 hours. BL2A received a record 215 mAh, or 75% of the scheduled 285 mAh.

The total extracted beam was a record 951 mAh. This was 144 mAh more than was delivered in 2009 (the previous record year).

520 MeV Facility Operation - 2011 Totals

In 2011, the new Vertical ISIS Beam line (VIB) was installed. Testing and commissioning went very well and the VIB performed well all year.

The cyclotron ran for 5,159 hours or 94.0% of the 5,485 hours scheduled. The major downtime for the running period was RF, accounting for 22% of the total 299 hours. Services accounted for another 17%. The 299 hours of downtime was the least in at least six years.

Beam Line 1A ran for 1,549 hours or 93.7% of the 1,654 hours scheduled and received a charge of 149 mAh or 89% of the 168 mAh scheduled. These numbers are only about 40% of a normal year due to the length of the Meson Hall shutdown and a re-opening of the vacuum leak between 1AT2 and M9. This leak resulted in the operation of BL1A with 1AT2 out after the September shutdown. Beam Line 1B delivered beam to the Proton Irradiation Facility for three weeks.

The 2C1 line was used for Proton Therapy (five sessions of ten patients) as well as for eight weeks of Proton Irradiation Facility operation. BL2C4 ran for 2002 hours or 91.3% of the scheduled 2,194 hours and also received 93.8% of the scheduled charge (138 mAh of the scheduled 147 mAh). These numbers are also well below normal due to the loss of the product market because of a regulatory situation with the downstream vendor.

BL2A delivered 4,020 hours of beam to East or West Target Stations, or 94.5% of the scheduled 4,254 hours. BL2A received 175 mAh or 95% of the scheduled 184 mAh.

The total extracted beam, 462 mAhrs, was less than half of last year's record 951 mAhrs.

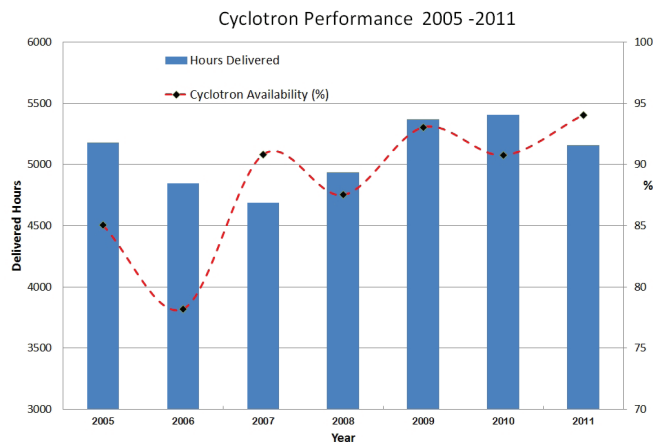


Figure 1. Cyclotron performance for 2005-2011 in terms of hours delivered and cyclotron availability.

3.2.2 Injection Line Vertical Section

Roman Ruegg and Rick Baartman

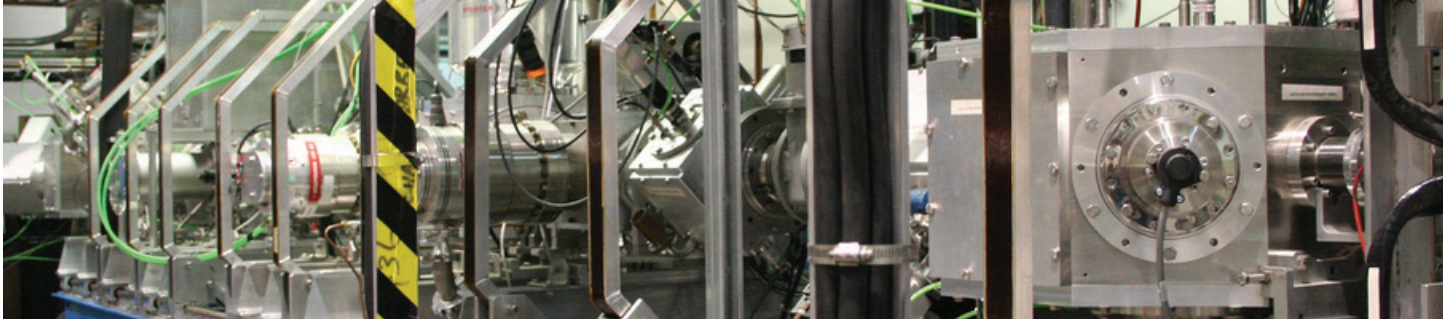
After 36 years of continuous service, the original vertical section of the beam line that transports beam directly into to the TRIUMF 500MeV cyclotron has been decommissioned and replaced with a new one. This line is 12 m in length, and consists of 26 electrostatic quadrupoles, 14 steering correctors. The old line has transported as much as 0.6 mA H-, and with bunching, this represents a peak current of 5 mA. The line's function is to transport the beam to and then match into the electrostatic inflector.

The new line optics were designed entirely using the code TRANSOPTR. Details are in the Beam Dynamics section of this report. The first 19 quadrupoles are in a periodic arrangement similar to the old line, but the final seven quads are used for the complex matching task between the bunching beam and the inflector. The positions and strengths of these final seven

quads were found by an optimization that minimized the emittance of the beam in the cyclotron according to optimization calculations that included 3D space charge, the axial cyclotron field, the strong coupling of the inflector, and the optics on the first few turns of the cyclotron including the RF focusing at the dee gaps.

Commissioning began in April 2011 and was very successful. Using entirely theoretical settings at startup, the beam line reproduced the historical best transmission between the buncher and the cyclotron. It circulated beam (60%) after less than an hour of fine-tuning the steering correctors. 12% unbunched, produced at 90 kV dee voltage is an historically good measure. Somewhat later, we achieved 70% transmission bunched, which is good based on historic amounts. Wire scanners were used to verify the beam sizes at various locations. The injection line has operated trouble-free up to the winter shutdown in spite of the fact that some capacitive beam-position monitors (BPM) and bunch shape monitors have yet to be fully commissioned.

Figure 1. The installation of the vertical section of TRIUMF's new main injection line. The line is used to transport hydrogen ions from the ion source to the centre of the cyclotron.



3.3
ISAC Targets and Ion Sources

Colin Morton, Jens Lassen, Friedhelm Ames, and Peter Kunz

3.3.1
ISAC Performance

Colin Morton

The overall performance of ISAC, TRIUMF's rare isotope beam (RIB) facility, was challeneged by a series of equipment failures in 2010. Consequences of those failures continued to have an impact on ISAC operations in 2011, but the performance of the facility was significantly improved over the previous year. The energy range of the facility was extended with the completion of the ISAC-II Phase Two upgrade, while a task force was formed to solve challenges associated with the delivery of high-mass (A ≥ 30) accelerated RIB.

Continued improvements in reliability and the successful delivery of high-mass beams to an experimental location are expected in 2012.

ISAC is an isotope separation on-line, or ISOL, facility. Rare isotopes are produced in thick production targets in reactions driven by 480–500 MeV protons from TRIUMF's main cyclotron. These isotopes are extracted as heavy-ion beams at modest energies (a few tens of keV) for transport to low-energy experiments or for post-acceleration to higher energies (several MeV/nucleon) for reaction studies. A full description of the facility can be found on TRIUMF's website (http://www.triumf.ca/research/research-facilities/isac-facilities-for-rare-isotope-beams). The final element of the ISAC accelerator chain, the ISAC-II superconducting linear accelerator, was designed to accelerate beams to energies above the Coulomb barrier over a broad range of masses. This goal was achieved with the completion of its Phase Two upgrade. This upgrade comprised the installation of twenty new, locally fabricated high-beta superconducting RF cavities, doubling the accelerating potential and allowing the acceleration of RIB (and stable ion beams from OLIS, the ISAC Off-Line Ion Source) to upwards of 10 MeV/u, depending on the mass-to-charge ratio of the beam. The upgraded ISAC-II linear accelerator has been used for experiments and development on a routine basis since early 2010.

The delivery of beams with masses greater than thirty is still in development. The first accelerator in the ISAC chain, a room-temperature RFQ, is limited to beams with mass-to-charge ratios less than thirty; with most RIB being singly charged from the online target ion source, this has imposed a de facto limit on the mass of beams that can be accelerated. Beams with masses greater than thirty require charge breeding with the ISAC charge-state booster (CSB) to have mass-to-charge ratios low enough to be accelerated. A first attempt to deliver charge-bred RIB to an experimental location at ISAC-II was made in August 2010; a task force was struck shortly thereafter to determine how to deliver these beams on a routine basis. Beam development has continued through 2010 and 2011. A number of improvements to the CSB have been made to reduce isobaric contaminants in the charge-bred beam (Section 3.3.3). Additional upgrades to the beamline infrastructure, including the installation of new dipole and

quadrupole power supplies and the fabrication of a Bragg detector for beam characterization, have also been carried out. A workshop on the topic, with invited experts from other facilities, was held in late 2011, with the results of that workshop directing development during the 2012 winter shutdown. The first delivery of high-mass accelerated RIB to an experimental location is planned for the summer of 2012, with a first experiment to follow later in the year.

From an operations and beam delivery standpoint, 2010 was a difficult year. Eight to ten RIB production targets are typically used at ISAC in a year; in 2010, failures of targets, ion sources, or the target modules in which the target and source are housed, cut short four target runs. Cyclotron vacuum problems compromised an additional target run through the month of May, while problems with the ISAC-II cryogenics systems limited the delivery of high-energy RIB for much of the summer running schedule. 2010 saw approximately 2,800 hours of RIB available for experiments and beam development but over 2,000 hours of downtime (cyclotron and ISAC).

The 2011 running period was shorter than usual to accommodate the installation of a new injection beamline for the cyclotron during the 2011 winter shutdown. Delays in returning one target module to service following a failure late in 2010 forced changes in the order and type of production targets used; however, no target runs were cut short due to failures. Despite the late start-up due to the extended shutdown, roughly 3000 hours of RIB were delivered with fewer than 800 hours lost due to downtime.

As in 2011, the 2012 running period is expected to start later than usual. The causes of downtime in 2010 have largely been addressed, as reflected in the improved facility reliability in 2011. Further improvements in facility performance are expected with the availability of multiple target modules from the start of the beam schedule, the continued routine use of the full ISAC-II linear accelerator, and the ongoing effort to increase the mass range of accelerated beams available.

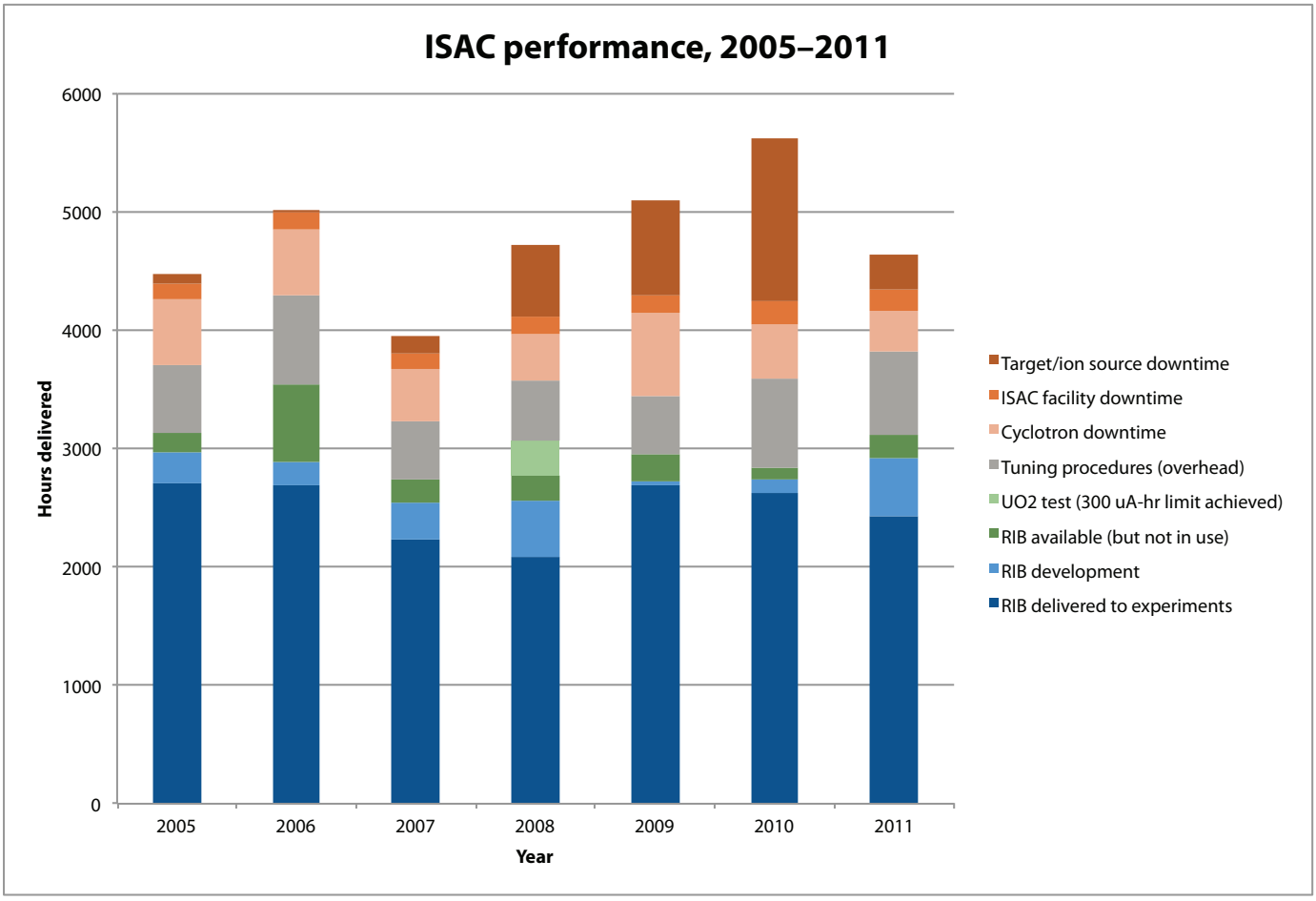


Figure 1. ISAC Performance from 2005-2011

3.3.2 Target and Ion Source Development

Jens Lassen

Laser resonance ionization spectroscopy with high-repetition-rate pulsed laser systems provides element selective ionization from the multitude of isotopes produced in the ISAC target ion sources. This allows TRILIS (the TRIUMF Resonant Ionization Laser Ion Source) to extract and deliver intense, pure beams of radioactive isotopes, which are requested as beams for the ISAC facility science users, who conduct experiments at the forefront of nuclear and particle physics.

In-Source Laser Spectroscopy (S1237)

An NSERC-funded research program on "in-source laser resonance ionization spectroscopy" was launched. The laser spectroscopy of astatine (experiment S1237), which is the rarest element on earth, resulted in confirming the only known two optical transitions (McLaughlin 1964) and the discovery of 41 new atomic energy levels and 55 new optical transitions, as well as the development of an efficient laser ionization scheme for Astatine that can be used to provide Astatine isotopes for EDM experiments. Even laser spectroscopy on the much more well-known Actinium allowed us to identify twenty high-lying Actinium atomic energy levels.

Progress in 2010-2012

In 2010, TRILIS was available for the first time also to the east target station – so that full scheduling flexibility for laser ion source operation was achieved. This resulted in more than 50% of all radioactive ion beam shifts on the 24/7 beam schedule required laser ion source operation. The TRILIS group was met this demand with reliable and consistent TRILIS operation, whilst developing new laser excitation schemes for Titanium-Sapphire laser (TiSa) based resonance ionization and conducting experiments in parallel. By the beginning of 2012, isotopes from a total of 13 elements had been delivered from the all solid-state laser based TRILIS. On-line delivered NEW beams were Tc, Ge, Ac, and Ra. Off-line development work, guided by user requests and the beam strategy group, began on elements Sc, Y and Sb. Laser development on our TiSa laser systems for laser spectroscopy and resonance ionization resulted in a continuously tunable, narrow bandwidth laser system that was key to achieving the laser spectroscopy results, which were key to development. One spectroscopy laser is under construction and a set of three TiSa lasers were completed and delivered to work at the GANIL SPIRAL2 RILIS. In terms of beam development, the capabilities for TiSa based RILIS operation are extended with two new elements annually for on-line beam delivery, with a new focus on providing isobar free(er) beams in the heavy mass region, through a radiofrequency ion guide assisted laser ion source.

3.3.3 Charge State Breeder

Friedhelm Ames

Accelerating ions with a mass greater than 30 at ISAC requires the injection at higher charge states to match the acceptance of the accelerators. If those ions are to be accelerated to an energy above 150 keV/u, the mass to charge ratio that can be accepted by the DTL and superconducting LINAC is below 7 amu/e. Thus, for heavy ions, which are usually extracted singly charged from the ISAC target ion source system, the charge state has to be increased accordingly. Already during the preceding years, a charge state breeder has been developed and setup. It is based on an electron cyclotron resonance ion source (ECR) (14.5 GHz PHOENIX from Pantechnik), which has been installed after the mass separator in the B2 level at ISAC. During 2010 and 2011, commissioning of the system continued with injecting several stable and radioactive ions into the ECR source and determining the efficiency and charge state distributions. Table 1 shows a summary of efficiencies obtained for the charge breeding of radioactive ions during those first experiments. Soon after the first beams of highly charged radioactive ions were injected into the accelerator it became obvious that, in most cases, the background of stable ions accompanying the desired isotopes is too high, both for a proper setup and optimization of the accelerators and for the experiments.

Those ions originate from residual gas atoms and molecules inside the ECR plasma and from material sputtered from the walls of the plasma chamber. The original plasma chamber of the source was made from stainless steel. Isotopes of its constituents like Fe, Cr, Ni, Mo, etc. could be clearly identified. They are extracted as highly charged ions with a broad charge state distribution. In many cases the intensity of those ions with a mass-to-charge ratio close to the desired one can be orders of magnitude higher than the one from the radioactive isotope, which has been injected into the source. Therefore, during the shut down in 2011, the plasma chamber has been exchanged for a new one made from aluminum. The amount of constituents and impurities is much less, especially in the range of heavy masses, which can interfere with the desired masses for the acceleration of radioactive ions. During a first test of this chamber with the charge breeding of Rb and Cs isotopes, the efficiency in both cases could be increased by a factor of about two, which can be attributed to a higher electron release probability of the wall material. However, the amount of background ions did not change substantially. The conclusion is that many of those ions originate from material of the electrodes surrounding the plasma chamber at the injection and extraction of the source. Those will be exchanged during the shut down in 2012.

Beside the upgrades to the source, additional upgrades to the beam line and accelerator infrastructure are being carried out, which will allow better beam characterization and partial separation of impurities after acceleration.

Isotope	q	A/q	Efficiency [%]	I (in) [1/s]	Background [pA]
46K	9	5.11	0.5	4.0E4	340
64Ga	13	4.92	0.7	8.4E4	150
64Ga	14	4.57	0.75	8.4E4	210
74Br	14	5.28	3.1	3.2E7	10000
74Br	15	4.93	2.1	3.2E7	25
78Br	14	5.57	4.5	2.8E7 AlBr	20
74Kr	15	4.93	6.2	2.1E6	25
76Rb	15	5.07	1.68	3.8E6	15
80Rb	13	6.15	1.17	5.7E7	35
80Rb	14	5.71	1.1	5.7E7	70000
122Cs	19	6.42	1.1	3.1E5	6
124Cs	20	6.2	1.37	2.75E7	50

Figure 1. Charge state breeding efficiency and background for radioactive ions from ISAC, with a stainless steel plasma chamber.

3.3.4
Actinide Target Development
Peter Kunz

Radioactive isotopes of heavy elements such as Ra, Fr, At and Rn as well as neutron-rich isotopes are essential for the ISAC scientific program. Actinide targets are absolutely necessary for the production of those ion beams from spallation and fission reactions. They have been in use at facilities such as CERN-ISOLDE for more than 30 years[1].

The ISAC facility at TRIUMF obtained the operating license to run uranium targets up to a maximum proton beam current of 2 µA at 500 MeV and started out with two test runs in 2008 and 2009 using uranium dioxide (UO_2) as a target material[2]. The main goal of those test runs was to establish operational procedures and safety protocols. However, UO_2 is not an ideal material for high-power targets due to its relatively low thermal conductivity and high vapor pressure. Uranium dicarbide (UC_2) has much better properties in this regard, but is more problematic to handle and difficult to obtain commercially.

Procedures to manufacture UC_2 by carbothermal reduction ($UO_2 + 4C \rightarrow UC_2 + 2CO(g)$) were developed in the Actinide Target Laboratory in 2010. A high vacuum furnace was used to bake a mixture of UO_2, graphite at temperatures of up to 1750 °C until the reduction process was completed. Methods developed for non-radioactive composite ceramic targets[3] were modified for UC_2. Its radioactivity and reactivity on air require that all production steps have to be performed in an inert gas atmosphere in a glove box. Non-oxidizing solvents and binder material for the grinding and slip casting procedures[3] had to be tested. The final product is a D-shaped target disk with approximately 50 mg UC_2/cm^2 with the same molar ratio of graphite per foil, slip-cast on a graphite backing. SEM pictures show a very fine granularity and high porosity of the end product, see Figure 1. These properties accommodate a fast release of short-lived isotopes. That UC_2 is the main component could be confirmed with XRD measurements. Up to 400 target disks can be stacked into to a standard low-power target container. Until December 2011, three UC_2 targets were fabricated this way and employed online. After obtaining a license amendment from the CNSC, the latest target was irradiated with a maximum proton beam current of 10 µA. Previously at TRIUMF, inaccessible ion beams like Ac, Ra, Fr, At, and neutron-rich Sr, Rb, K, Al, Mg isotopes could be produced with great success.

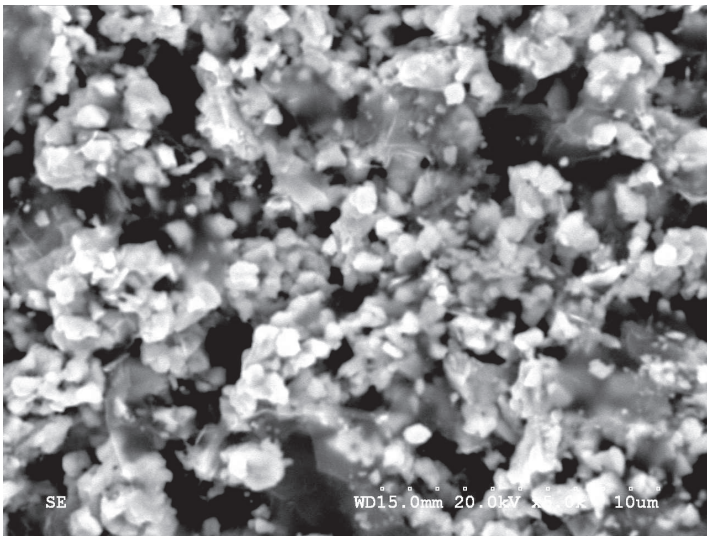


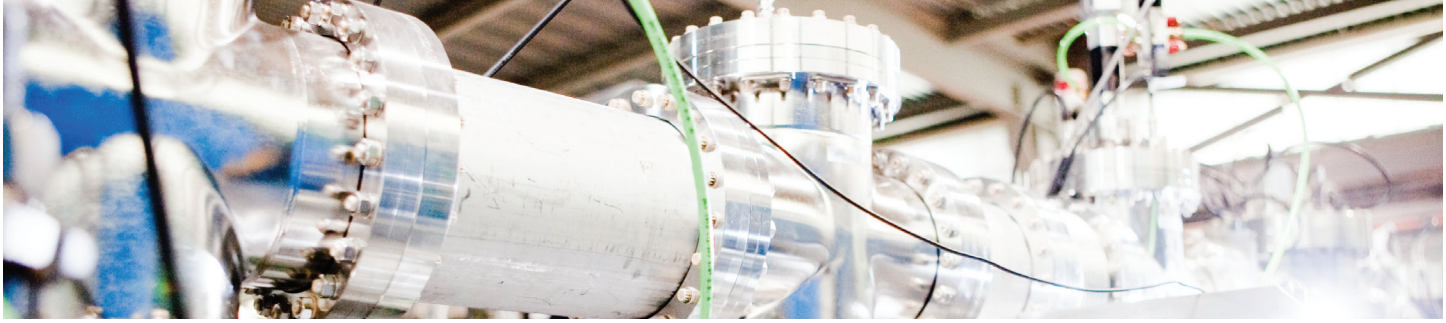
Figure 1. SEM picture of UC_2/C after slip casting, binder burnout, and sintering at 1750 °C (magnification 5000x)

References

[1] A.M. Evensen et. al., The ISOLDE Collaboration, Nucl. Instrum. Meth. B 126, 160-165 (1997)

[2] TRIUMF Scientific Activities Report (2008-2010) p. 127

[3] V. Hanemaayer et al., Nucl. Instr. and Meth. in Phys. Res. B 266 (2008) 4334–4337



3.4
Meson Beam Line Development

Syd Kreitzman and Roman Ruegg

CMMS Muon Beamlines

During the 2010 and 2011 years, much progress toward completing the new M20C/D and M9A beamlines was made. Both of these beam lines operate from the T2 target (see below) and will deliver 100% polarized surface muons to their respective experiments. Also, both beam lines incorporate ultra-fast (200ns on/off time) electrostatic kickers, which allows for a doubling of the time window in which data can be effectively recovered. This capability creates new scientific research possibilities at TRIUMF for the investigation of advanced materials, inclusive of semiconductors, superconductors and, compounds being developed for the next generation of car batteries, which exhibit slower relaxation characteristics than that normally accessible to standard MuSR studies. All of the major M9A devices/ components are on-site and have passed their factory acceptance tests with the exception of the M20 Kicker. The FAT for this device is scheduled in the spring of 2012.

T2 Target Challenges

As is clear from the diagram, both M20 and M9 derive their source of muons from protons which impact a Be target located in the T2 target monument. This monument has been undergoing slight shifts in position and orientation over the past 25 years, making it increasingly challenging to couple, with long term reliability in what is an environment with very high radiation, the respective vacuum spaces. In addition to this challenge, the radiation hard front-end quadrupole magnets for both of these beam lines are approaching the end of their lifetimes. TRIUMF recognizes these realities and, in its upcoming Five-Year Plan, seeks to incorporate the required front-end upgrades that will ensure the longevity of the T2 muon source.

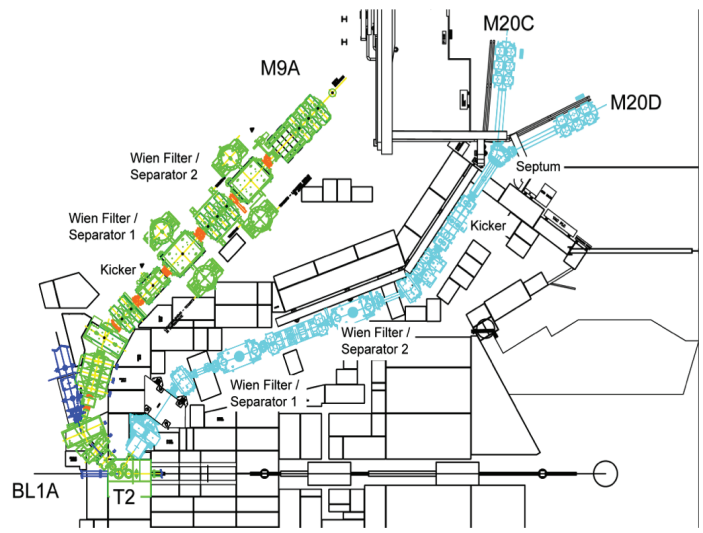
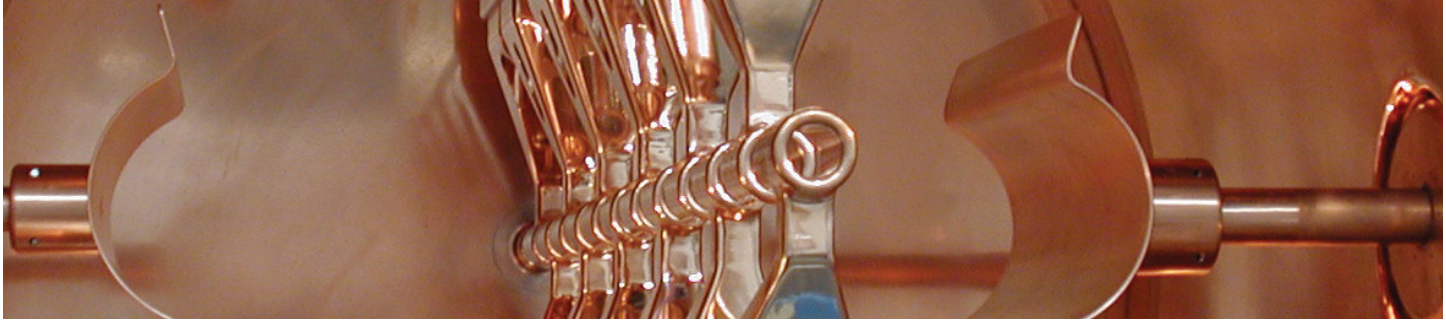


Figure 1. With the completion of these beam lines in 2013, the CMMS will not only recover its full complement of beam lines, but with the state-of-the-art second legs in both M20 and M9 operational, it will lay the foundations of growing its traditional user base into one that encompasses a broad array of non-expert users who will utilize MuSR as one of many techniques with which to characterize their research materials.



3.5 Experimental Facility Development

Andy Miller, Robert McPherson, Paul Garrett, Barry Davids, Adam Garnsworthy, Greg Hackman, Jens Dilling, Matt Pearson, Rich Helmer, and Stan Yen

3.5.1 Detector Development and Support

Andy Miller

All particle physics, nuclear physics, and condensed-matter experiments require instruments to detect energetic subatomic particles. These detectors measure various kinematic properties of each particle, such as its energy, momentum, the spatial location of its track, and its time of arrival at the detector. Scientific progress often emerges from advances in detector technology. Such advances include: enhanced precision in measurement of kinematic properties; the rate at which particles may be detected, leading to improved statistical precision; and in reduced costs, resulting in larger systems with greater sensitivity to rare processes.

Over the last several decades, TRIUMF's Detector Group has established an international reputation for developing, designing, and constructing state-of-the-art detectors, as well as developing new detector technologies. New instruments have been successfully deployed in measurements at TRIUMF and in collaborative projects elsewhere in Canada and abroad.

Responding to the needs of the TRIUMF community, the main focus of the Detector Group has shifted over the last two years from large systems for particle physics to a larger number of smaller instruments for the ISAC program at TRIUMF. An example that has consumed much effort over the entire two years is the CFI-funded IRIS charged particle spectroscopy station that studies transfer nuclear reactions on unstable nuclei (see section 3.5.6). The Group developed the concept for the vacuum chamber that will contain both the target and various detector elements that can be conveniently deployed at the appropriate positions in the chamber for each measurement. This work continued with the detailed design of the associated detector-related mechanics, and then the supervision of the construction and assembly of the system. Also, the Group designed and fabricated a low-pressure multi-sampling ion chamber through which the beam will pass just before the target. This chamber has the ambitious goal of resolving the charge states of beam particles in order to suppress impurities in the beam. All of this equipment is scheduled for installation in early 2012.

Other examples of work done for the ISAC program include the design of a system of vacuum and gas vessels and a low-pressure wire chamber for the focal plane of the EMMA radioactive-ion mass analyzer (see section 3.5.4), and detailed design of the vacuum chamber, target ladder, intricate plunger assembly, diode detector wall and multi-segmented CsI mini-ball for the TIGRESS Integrated Plunger (TIP – see section 3.5.3) for measuring very short nuclear lifetimes. The Group also has considerable expertise in the design and construction of systems for the provision of gas mixtures for relevant detectors, at high purity and precise pressure. Such systems were developed for IRIS, EMMA, and other ISAC projects. Finally, the Detector Electronics subgroup

designed and built preamplifiers/discriminators for Qweak diamond detectors (see section 2.5), and amplifier/shapers for the silicon detectors of TIGRESS/SHARK (see section 3.5.3) and TRINAT (see section 2.5).

Work for the particle physics community includes the testing of the radiation tolerance of new diamond sensors that are candidates for a major upgrade of the ATLAS detector at LHC (see section 3.5.2), as well as high-luminosity test measurements, simulations and signal processing development for a liquid argon detector being considered for this upgrade. The Group designed and constructed a model portion for performance evaluation of the Fine-Grained Detector that was previously built for the T2K long-baseline neutrino experiment at J-PARC in Japan. Also for T2K, the team designed a mechanism for the detailed study of the underwater optical properties of the large photomultiplier tubes used in the super-Kamiokande water Cherenkov detector. The Group also has expertise in the development and application of the GEANT4 tool for detailed Monte Carlo simulation of particle interaction and transport. A number of TRIUMF experiments have benefitted from the Group's application development and tutoring.

The Group has also contributed to practical applications of detector technology. This includes the design and supervision of assembly work for a system of scintillator arrays to be used underground in mines to map ore deposits by means of their signature effect on cosmic ray muons reaching the detectors via a wide range of trajectories through the overburden. Furthermore, the Group worked to develop new detector concepts for medical imaging with some combination of higher resolution, higher sensitivity and/or lower cost. This effort exploits the new pixelated avalanche photodiode technology, examples of which are being characterized in close collaboration with the manufacturers, Hamamatsu and Excelitas, to develop next-generation devices with enhanced photo-detection efficiency, faster pulses and suppressed secondary avalanches. Finally, the Group contributed its expertise and manpower to crucial projects of the TRIUMF Accelerator Division, such as the control system for the upgraded cyclotron injection beam line, the rebuilding of ISAC isotope production targets, the beam-loss detectors for the ARIEL e-linac, and the assembly of elements of the low-energy test beam facility for ARIEL.

3.5.2 ATLAS Detector Development at TRIUMF

Robert McPherson

ATLAS Detector Upgrades

The initial ATLAS detector at the CERN Large Hadron Collider (LHC) has been running with proton-proton and lead-ion collisions since the autumn of 2009. In 2011, about 5 fb^{-1} of data was recorded with $\sqrt{s}$=7 TeV, enough to provide the sensitivity to discover or exclude the Standard Model Higgs Boson and also many realizations of Supersymmetry and other models of physics beyond the Standard Model (for most of mass range currently accessible by the LHC). Using the 2011 ATLAS data, $\sqrt{s}$ = 7 TeV, with a similar amount of data recorded at $\sqrt{s}$=8 TeV in 2012, ATLAS has established the existence of a new scalar particle at a mass of about 125 GeV which is consistent with the Standard Model Higgs boson (ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", arXiv:1207.7214, submitted to Physics Letters B).

A sketch of the LHC schedule for the coming two decades is shown in Figure 1. It is expected to continue $\sqrt{s}$=8 TeV proton collisions until the end of 2012, and then shut off for a period of 18 months, called "long- shutdown 1," or LS1, to consolidate the machine safety systems to allow for operation at, or near, the full LHC energy of $\sqrt{s}$=14 TeV. After about three years of operation, a 12-month shutdown, LS2, will be used to integrate further accelerator and detector upgrades, which will allow the LHC design luminosity to be increased by about a factor of two. The final planned long shutdown, LS3, is anticipated to take about two years starting in 2022.

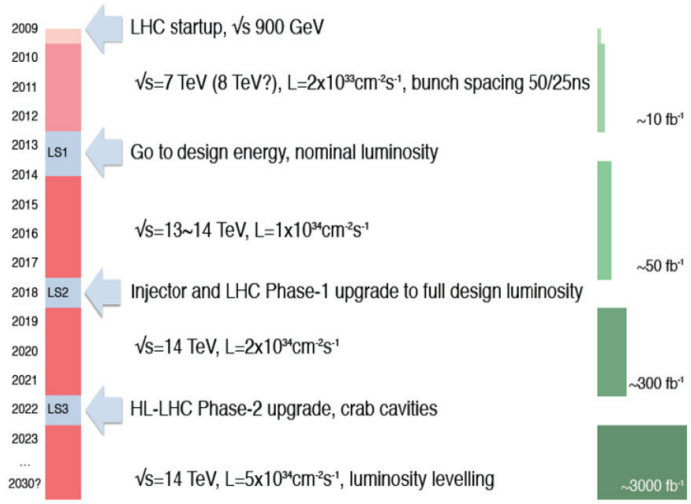


Figure 1. LHC schedule and plans for the coming two decades.

The anticipated collision rates in ATLAS after LS2 in 2018 will require upgrades to the ATLAS readout electronics and trigger systems in order to allow current physics performance to be maintained. Higher rates and enormous radiation damage after LS3 in 2022 will present even more of a challenge.

Extensive upgrades will be necessary to continue ATLAS operations in the SLHC era. The entire tracking system near the beam intersection point will need to be replaced, including both the detector particle sensors and their readout electronics. This is particularly challenging because the new systems will need approximately an order of magnitude more active elements in order to cope with the extremely high occupancies expected at the SLHC. However, the services (cooling, front-end readout electronics, cables) will have to fit into the same space. In addition to the tracking upgrades, the energy-measuring calorimeter systems nearest to the beam axis may see rates beyond their maximum operational values, and new detector systems and readout electronics may be required. The outermost ATLAS muon system will be difficult to operate due to large numbers of interactions from the increased numbers of low-energy neutrons created at the SLHC, and technologies for either reducing the number of neutrons or coping with the high rates will be required. It took about five years of research and development (R&D) to develop technologies for the initial ATLAS detector, and another ten years to construct and install the full system. Taking advantage of our expertise from building ATLAS, we plan to compress that timeframe to about three years of R&D and five years of construction and installation for ATLAS upgrades in order to be ready for ATLAS operation in the SLHC era.

Canadian groups made leading contributions to the design, construction, installation, and commissioning of the ATLAS liquid argon (LAr) calorimeter system, with critical leadership from the TRIUMF laboratory and the support of TRIUMF infrastructure for the contributions made from Canadian university groups. For ATLAS upgrades for the SLHC, several Canadian contributions are being considered, all of which require strong support from TRIUMF. NSERC has provided three years of R&D funding leading towards ATLAS upgrades, supporting, in particular, R&D for new technologies for high-rate calorimetry and high-rate pixel tracking detectors.

TRIUMF personnel and facilities have been critical to several ATLAS upgrade R&D projects over the past two years, centred primarily on the LAr systems. ATLAS is planning several upgrades to our calorimeter systems, including electronics upgrades allowing the use of finer detector granularity in the first level trigger and detector upgrades that will maintain high performance forward calorimetry at the highest rates expected by the LHC. ATLAS is exploring two options for the forward calorimeter, likely either the complete replacement of the current system with a “super Forward Calorimeter” (sFCal) or the less expensive option of installing a smaller, high-rate calorimeter (MiniFCal), which would shield and protect the existing detectors while maintaining precise energy measurements.

Tooling for End-cap Calorimeter

TRIUMF engineers and designers were critical to the overall design of the current ATLAS LAr end-cap calorimeters, and supervised the assembly and installation of the detectors at CERN. If the FCal is replaced with an sFCal, significant tooling will need to be installed in the ATLAS pit to handle the highly activated, massive detectors. The installation of the MiniFCal would be simpler and less risky than the full replacement option, but still involves working in a challenging environment

with radiation shielding issues. TRIUMF engineers and designers have led the effort to design the full set of tooling needed for handling the forward calorimeters for ATLAS upgrade options. They have also completed designs of tooling required to remove the hadronic endcap calorimeters (HEC) for replacement of the electronics mounted on the detectors should that be required. A sketch of the MiniFCal option is shown in Figure 2, developed by Roy Langstaff and Mark Lenckowski.

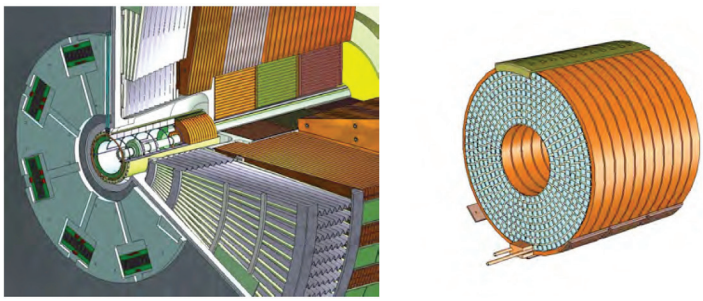


Figure 2: On left is a SolidWorks design by Roy Langstaff showing the installation of a MiniFCal, shown on the right, in ATLAS. Langstaff and Lenckowski have developed complete installation scenarios for both the MiniFCal, and complete FCal replacement, options, as well as designed tooling for handling the HEC calorimeter required for replacement of electronics mounted on the edges of the detector.

Radiation Hardness of Polycrystalline Chemical Vapour Deposit (pCVD) Diamond Detectors

Developing an active detector able to handle the high rates and radiation fluences near the ATLAS beam pipe is essential for the MiniFCal. Diamond technology promises very fast response from radiation hard detectors, but pCVD diamonds had only been tested to fluences of 10^{16} particles/cm^2, about an order of magnitude less than that expected in the ATLAS FCal region over ten years of running at the upgraded LHC. In a set of continuing irradiation tests at TRIUMF different grades and thicknesses of pCVD diamond detectors have been tested above 2×10^{17} particles/cm^2, the level required for use in ATLAS forward calorimetry. Tests have been performed in both the "NBIF" facility in the TRIUMF cyclotron vault and using TRIUMF Beam Line 1A. The highest fluence results, from tests in TRIUMF Beam Line 1A, were published in D.Axen et al., "Diamond detector irradiation tests at TRIUMF", JINST vol 6 no. 05, P05011, 2011. The normalized detector response

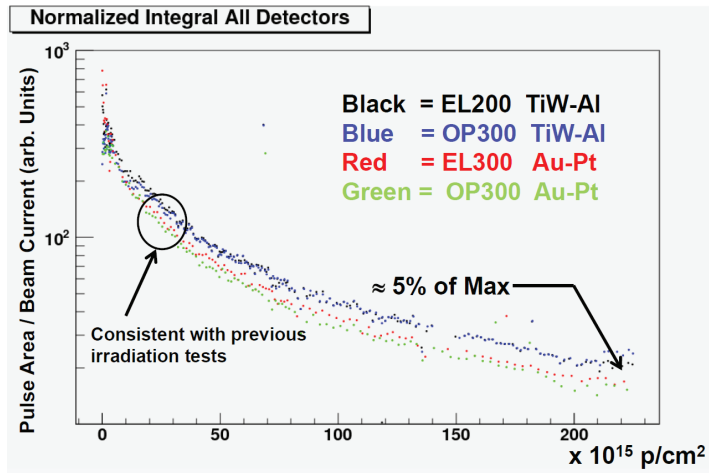


Figure 3: Normalized response of four different detectors irradiated in TRIUMF Beam Line 1A. These tests extend the levels of previous measurements by about an order of magnitude. "EL" and "OP" refer to the grades of the pCVD diamonds (high quality electronics grade and medium quality optical grade), "200" and "300" refer to the detector thicknesses in microns, while the chemical symbols refer to the composition of the electrodes coating the pCVD diamond surfaces.

Spatial Uniformity of pCVD Diamond Detectors

For use in a calorimeter, the active detector elements must also be uniform since their signals are summed prior to digitization. Using muons in TRIUMF beam line M11, we studied the response uniformity of pCVD diamond detectors to single particles. The analysis from those studies is completed, and the paper submitted to JINST (preprint number JINST_002P_0712). Figure 4 shows the spatial uniformity results from the detector tested in M11.

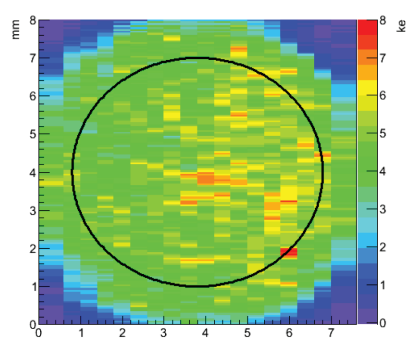


Figure 4. Response uniformity of a diamond detector tested in Beam Line M11 at TRIUMF. The plot shows the results for negative bias voltages on the pCVD diamond detectors.

The ATLAS upgrade program is moving into the construction era. The R&D completed at TRIUMF has been critical to understanding the performance of the Canadian end-cap calorimeter systems at the LHC, and for

developing alternative technologies that are better able to cope with the higher luminosities anticipated in the coming years. Both construction for near-term upgrades and R&D for longer-term upgrades will proceed in the coming years.

3.5.3 TIGRESS Auxiliary Detectors

Paul Garrett

The TIGRESS spectrometer performs experiments looking for γ rays from excited nuclei. These γ rays contain information about the structure of the nucleus, or the rate at which a reaction takes place. Since the research uses the exotic beams from the ISAC-II accelerator, the rate at which these γ rays strike the TIGRESS detectors can be very low – well below the rate at which γ rays from radioactive decay present all around us or cosmic rays enter the detectors. To distinguish the background from the beam-induced signals, auxiliary detectors are used for all experiments with TIGRESS.

During the 2010-2012 period, four main auxiliary detectors for TIGRESS were in operation or for which substantial development occurred: Bambino, SHARC, the TIGRESS integrated plunger (TIP), and DESCANT. The first two, Bambino and SHARC, are designed to detect charged particles and have been used in experiments. TIP, for lifetime measurements, was fabricated and commissioned; while DESCANT, for neutron detection, had its design finalized and its components manufactured. Each device will be described below.

Bambino

Bambino consists of a pair of segmented, annular silicon detectors that are placed 3.0 cm away from the target in both the forward and backward hemisphere. Bambino has a solid-angle coverage of 26.6% of 4π with 24 rings in θ and 32 sections in ϕ. It was designed to detect the scattered or recoiling charged particles in coincidence with the γ rays detected by TIGRESS. It has been employed successfully to study various nuclear structure issues in ^{20,21,29}Na and ^{10,11}Be using the Coulomb excitation technique, and to explore the halo structure of ^{12}Be using the inverse (d,p) reaction with ^{11}Be beam. It also has the flexibility to form a ΔE-E detector array by placing them in a back-to-back geometry for light charged-particle identification. With this geometry, one experiment was fielded to study the resonances beyond the α threshold in ^{2}Mg using the inverse (p,p') reaction with the ^{21}Na beam.

Shown in Figure 1 are the most recent results for the ^{11}Be beam on ^{196}Pt target, where the background-subtracted, Doppler-shift corrected γ-ray spectrum in red is superimposed on the uncorrected one in black. Energy resolution of ~ 1.4% is achieved after Doppler-shift correction, and time resolution of ~ 27 ns is obtained.

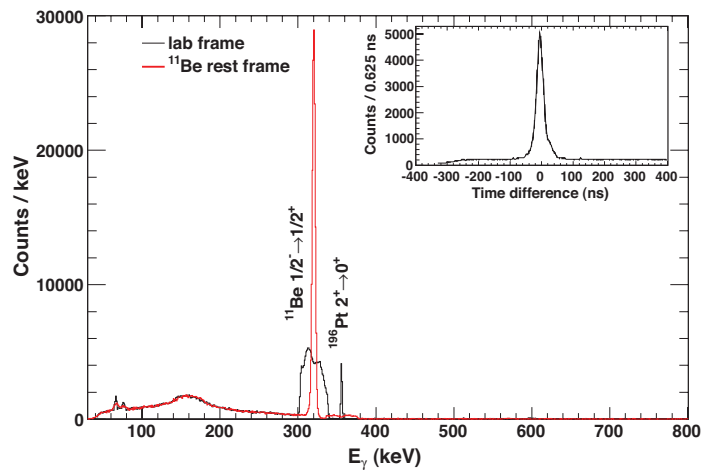


Figure 1. Spectrum from the Coulomb excitation of ^{11}Be beam on a ^{196}Pt target measured with TIGRESS and Bambino. The red curve shows the spectrum Doppler corrected for the ^{11}Be recoils, whereas the black is the uncorrected spectrum. The inset shows the time resolution between the events detected in Bambino and TIGRESS.

SHARC

The combination of γ-ray spectroscopy and charged-particle spectroscopy is a powerful tool for the study of nuclear reactions with beams of nuclei far from stability. SHARC, the Silicon Highly-segmented Array for Reactions and Coulex, is a new silicon-detector array designed for use in reactions with radioactive ion beams in conjunction with the TIGRESS γ-ray spectrometer. SHARC is built from custom Si-strip detectors, utilising the fully digital TIGRESS readout (TIG-64 modules). SHARC has more than 50% overall efficiency, and approximately 1000-strip segmentation yielding angular resolutions of Δθ ≈ 1.3 deg. and Δϕ ≈ 3.5 deg. Furthermore, 25-

30 keV energy resolution, and thresholds of 200 keV for up to 25 MeV particles have been achieved, and flexible gain settings cover energies up to approximately 600 MeV, used for detection of beam-like reaction products. Figure 2 shows SHARC retracted from the target chamber as installed in the TIGRESS array. SHARC is now complete, including integration of the very successful 0-degree Trifoil detector as well as the first upgrade, in which additional detectors were added for improved particle identification. Furthermore, details of the array performance and scientific programme been published [C.Aa. Diget, et al., J. Inst., 6(02):P02005, 2011.] For the near future, the SHARC chamber and electronics will be combined with a sophisticated ΔE-E setup with extremely thin, segmented silicon detectors (20μm and 40μm), for ^{11}Be particle identification.

The SHARC science program has included experiments in nuclear astrophysics and nuclear structure. The primary experiments that have been run with SHARC so far are: S1107 ^{25}Na(d,p)^{26}Na and ^{26}Mg(d,p), S1212 deep-inelastic scattering of ^{24,26}Mg on ^{208}Pb, S1201 ^{6}He two-neutron transfer onto ^{12}C, and S1213 ^{20}Na(^{6}Li,X), α-particle and deuteron transfer.

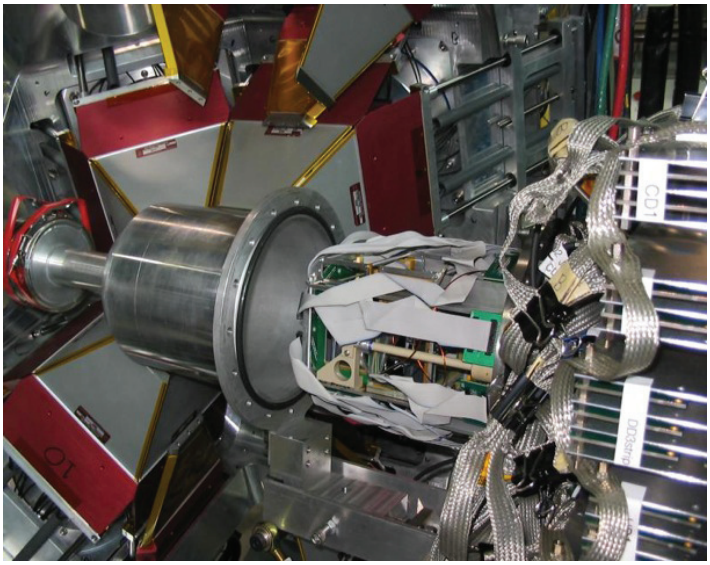


Figure 2. The SHARC chamber and the associated electronics mounted on the TIGRESS beamline. Several TIGRESS detectors are shown surrounding the chamber, which houses the Si detectors.

The TIGRESS Integrated Plunger (TIP)

Electromagnetic transition rate measurements provide fundamental probes of the behaviour of atomic nuclei and stringent tests for theoretical models. Therefore, precise lifetime measurements with the TIP are an integral addition to nuclear structure studies at TRIUMF, as they use intense re-accelerated beams from ISAC-II. TIP was developed by collaboration between Simon Fraser University and TRIUMF for recoil distance method (RDM) lifetime measurements of short-lived exotic isotopes using TIGRESS. It was designed to provide precise (sub-micron) control of distance shifts between thin target and stopper foils while maintaining parallel alignment between the two to achieve picosecond-order lifetime sensitivity.

TIP offers a high degree of versatility for lifetime measurements, employing a variety of reaction mechanisms and several particle-tagging techniques. It can run in stand-alone mode with TIGRESS, or in tandem with an extensive suite of auxiliary charged-particle detector systems. For Coulomb excitation reactions, a highly-segmented annular silicon detector and modular PIN diode array have been implemented for precise kinematic reconstruction of inelastic scattering events in coincidence with gamma-ray detection in TIGRESS. A compact 3π CsI(Tl) scintillator ball is being developed for lifetime measurements of exotic nuclei along the N=Z line produced by fusion-evaporation reactions. The identification of evaporated charged particles via digital pulse-shape analysis will enhance the experimental sensitivity through reaction channel discrimination. TIP is also designed to be coupled with the forthcoming deuterated neutron detector array, DESCANT and the electromagnetic spectrometer EMMA. A photograph of TIP is shown in Figure 3.

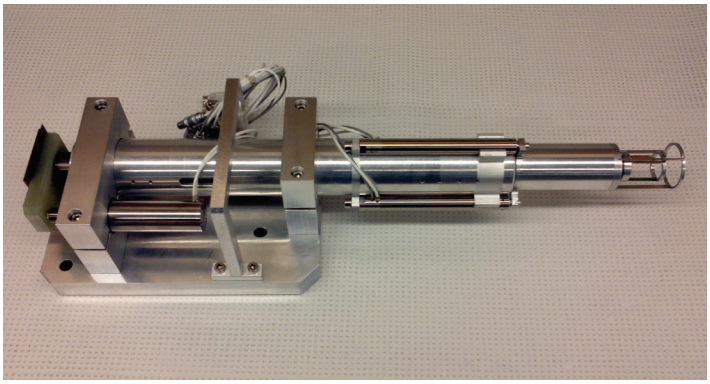


Figure 3. TIGRESS integrated plunger, or TIP, to be used with the TIGRESS array and its auxiliary detector systems for measurements of nuclear level lifetimes.

SPICE

SPICE (SPectrometer for Internal Conversion Electrons) is a project currently underway at TRIUMF to design and build an in-beam electron spectrometer ancillary detector for the TIGRESS array. SPICE will have a particular sensitivity to higher energy electrons in the energy range 100 keV to 4000 keV. In-beam electron spectrometers operating today are limited to below about 500keV electron energies.

Electrons emitted from the reaction target of TIGRESS following a nuclear reaction will be collected by a rare-earth permanent magnetic lens and directed around a photon shield into an array of electron detectors. Coincident gamma rays will be detected in the TIGRESS clover detectors. The TIGRESS+SPICE setup will allow scientists at TRIUMF to study electric monopole transition strengths which provide insight into the phenomenon of shape coexistence in nuclei. In nuclei displaying shape coexistence one observes separate nuclear states of distinct shapes such as spherical (soccer ball), prolate (like an american football) or oblate (like a squashed basketball). The interaction between these shapes is very complex and electric monopole transition strengths can help interpret the underlying physics. The results of these experiments will help understand how different shapes exist together in the same nucleus and how shell structure changes as the ratio of neutrons to protons increases.

Since 2010, a full GEANT4 simulation of SPICE has been developed and used to optimize the detailed design of the components of the spectrometer. This will improve the signal-to-noise ratio which makes in-beam electron spectroscopy quite challenging. Fabrication of the spectrometer is underway in the later part of 2012 and the first operation of SPICE will be seen in 2013.

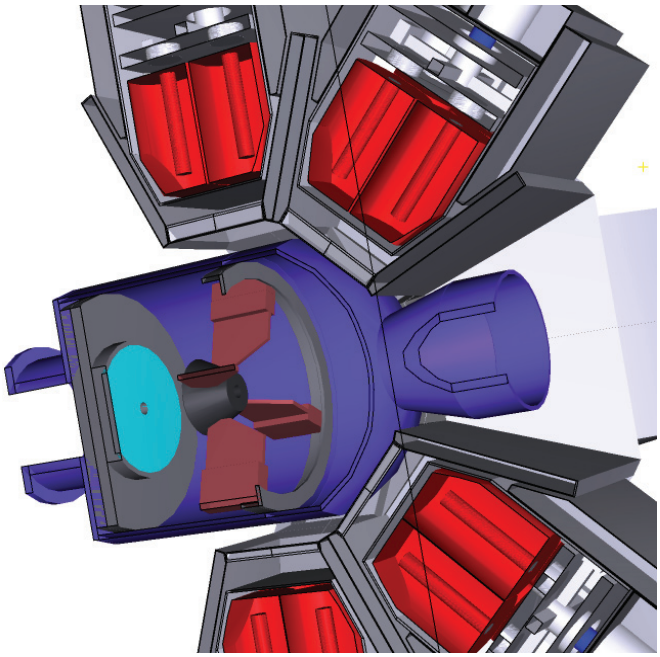


Figure 4. SPICE inside of TIGRESS.

DESCANT

The DESCANT spectrometer is designed to be coupled with both the TIGRESS, (Figure 4), and the future GRIFFIN spectrometer. It will replace the forward "lampshade" of four clover-type HPGe detectors (with their BGO suppression shields), and will occupy a solid angle of 1.08π sr with the maximum angle of 65.5 degrees with respect to the initial beam direction. The target-to-detector distance is 50 cm, and the individual detector cans are 15 cm thick. When fully loaded, DESCANT contains 70 individual neutron detectors. DESCANT is designed so that the inner and adjacent ring of detectors surrounding the beam line can be removed to facilitate larger forward detector systems that may be placed downstream of the target. The detector units contain liquid deuterated scintillator, BC537, and were fabricated by the Bicron division of Saint-Gobain. The geometry of DESCANT is based on three basic shapes of detectors, labeled red, white, and blue. However, in order to maximize the solid angle coverage, the outer ring of detectors, which normally

would be based on the white shape, were modified to have a truncated shape, resulting in the green and yellow detectors, which are mirror images of each other. Signals from the DESCANT detectors will be digitized by custom-built 1GHz waveform digitizers manufactured by Instrumentation Services of the University of Montreal. Onboard digital signal processing will integrate the pulse to yield the total charge, determine the event time via a constant-fraction algorithm, and perform neutron-γ discrimination.

During the 2010-2012 period, the DESCANT detectors were delivered and tested, the support structure was designed and built, and the first protptype of the electronics was tested. The components are on track for commissioning in late 2012/early 2013.

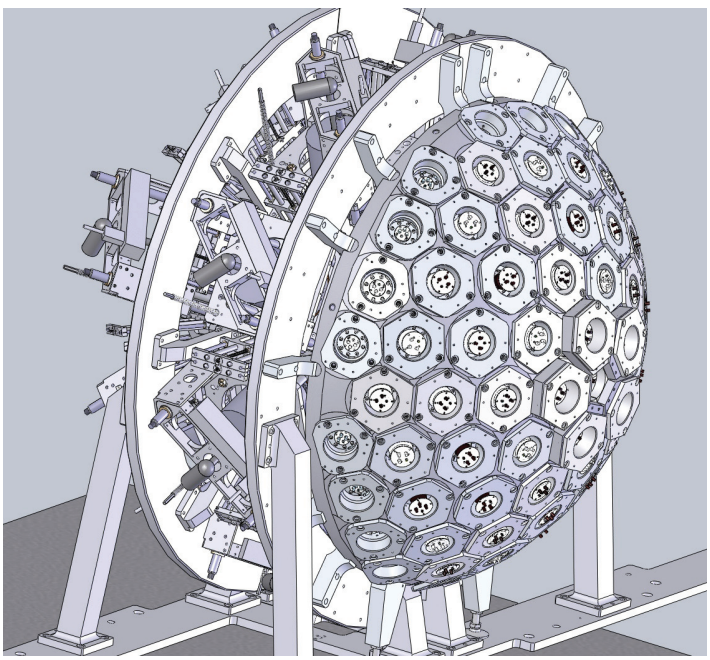


Figure 5. Drawing of the DESCANT detector coupled to the TIGRESS spectrometer. The 70 DESCANT detector units are mounted in a shell that is connected to the large corona rings of the TIGRESS frame, and replaces the four downstream TIGRESS detectors with their BGO shields.

3.5.4 EMMA
Barry Davids

We are constructing an electromagnetic mass analyzer, EMMA, for use with the radioactive heavy-ion beams available from ISAC-II at TRIUMF. EMMA is a recoil mass spectrometer designed to separate the recoils of nuclear reactions from the beam and to disperse them in a focal plane according to their mass-to-charge ratio (m/q). Measurements of position, energy loss, residual energy, and time-of-flight will suffice to uniquely identify the transmitted recoils. In addition to having a large solid angle of 16 msr, the spectrometer will accept recoils within a large range of m/q (±4%) and energies (±20%) about the central values. These large acceptances result in high detection efficiencies. The trajectories of monoenergetic ions of a single mass within the spectrometer are isochronous within 0.1%, allowing high resolution time-of-flight measurements and good background suppression in coincidence experiments. Separation of reaction products from the primary beam at 0° allows the detection of recoils from fusion-evaporation reactions as well as transfer reactions induced by radioactive heavy ions, which emerge from the target in narrow cones centred about the beam direction. The capacity to disperse ions according to m/q combined with multiwire gas detectors in the focal plane will allow high resolution determinations of the atomic masses and atomic numbers of recoil

After completing the ion optical design of EMMA[1], we won an NSERC grant, providing partial funding with the understanding that TRIUMF would furnish the additional capital required to complete the spectrometer. The contract to build the two electric dipoles, the dipole magnet, and four quadrupole magnets was awarded to Bruker BioSpin GmbH of Germany.

Two of the most critical parts are the electric dipoles. The electrodes, field clamps, insulating supports, and vacuum vessels have been produced by Bruker according to our specifications, while we have designed and built the high voltage power supplies at TRIUMF. The anode and cathode were fabricated from solid titanium and are shown in Figure 1 during a measurement of the separation between the electrodes, required to be 125.0 ± 0.1 mm. Fabrication of the magnets is complete and magnetic measurements have been completed on the dipole and two of the quadrupole magnets.

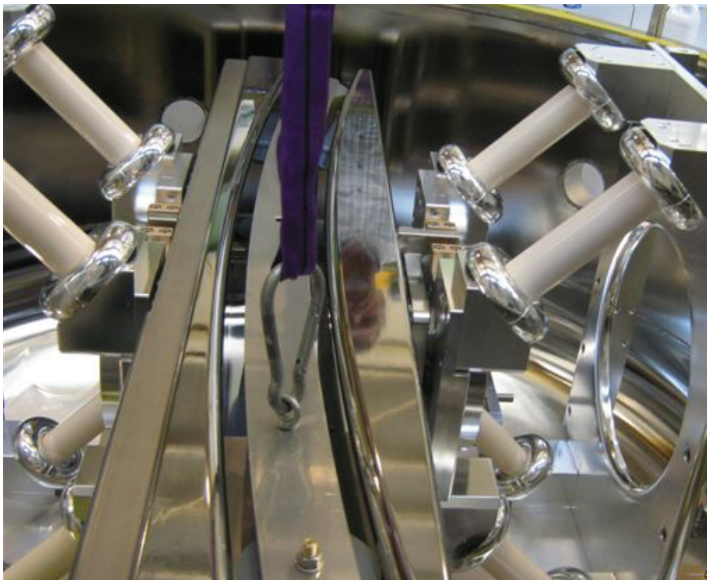


Figure 1. Titanium electrodes and ceramic insulating supports for an EMMA electric dipole shown during a measurement of the separation between the anode and cathode.

References

[1] B. Davids and C.N. Davids, Nucl. Instrum Methods Phys. Res. A **544**, 565 (2005.)

3.5.5 GRIFFIN

Adam Garnsworthy

The Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN) detector is a major new spectrometer that will significantly expand the radioactive decay spectroscopy capabilities at ISAC-I and ARIEL. Radioactive decay spectroscopy using GRIFFIN with the intense radioactive beams produced by ISAC, will allow detailed investigations of the evolution of nuclear structure with unprecedented sensitivity. With the addition of ARIEL, the measurement of nuclear half-lives and the properties of excited states of nuclei at and beyond the astrophysical r-process path will be within our reach.

GRIFFIN will consist of an array of 16 Hyper-Pure Germanium (HPGe) clover detectors (four Ge crystals in a single cryostat resembling a four-leaf clover) coupled to a state-of-the-art digital data acquisition system. Itand will replace these aspects of the present 8π facility that has served ISAC for the past decade. The gamma-gamma coincidence sensitivity for 1 MeV gamma rays with GRIFFIN will be a factor of 300 greater than with the 8π.

The GRIFFIN HPGe detectors will be used to detect gamma rays emitted in the decay of excited nuclear states. The gamma rays carry information on the underlying behavior of the protons and neutrons in the nucleus. GRIFFIN will make use of all the ancillary detection systems that have been developed for use with the 8π. Such combinations of sub-systems enable the investigation of all aspects of radioactive decay. These include the SCEPTAR array of plastic scintillators which detect beta particles, the set of eight lanthanum bromide scintillators for measuring the lifetimes of excited nuclear states in daughter nuclei, the five cryogenically-cooled Lithium-drifted silicon counters (of PACES) to detect Internal Conversion Electrons emitted in an alternative process to gamma-ray emission, and the DESCANT array of neutron detectors to investigate beta-delayed neutron emission of very neutron-rich nuclei.

The project has been awarded $8.7M in funding through the Canada Foundation for Innovation (CFI), TRIUMF and the University of Guelph over FY2011-FY2014. With the first stage of funding received in FY2011, there has already been much progress on the GRIFFIN project. A contract has been awarded to fabricate the 16 HPGe clover detectors, and the first detector will be delivered in May 2012. Members of the TRIUMF Design Office are in the final stages of designing the GRIFFIN support structure, which will be fabricated in the machine shops of TRIUMF, the University of Guelph, and external companies in FY2012 and 2013. The digital data acquisition system, including state-of-the-art new digitizer modules, is being developed in a collaboration of the University of Montréal with the TRIUMF Electronics Development and Data Acquisition groups. Many components of the facility, including the signal cables, high-voltage and low-voltage supply modules, and the liquid nitrogen supply system have already been procured and delivered to TRIUMF.

GRIFFIN will be installed in the low-energy area of ISAC-I during the first part of 2014, with initial experiments to take place in the fall of that year. The facility will reach full capability in 2015, with the

full complement of 16 HPGe clover detectors.

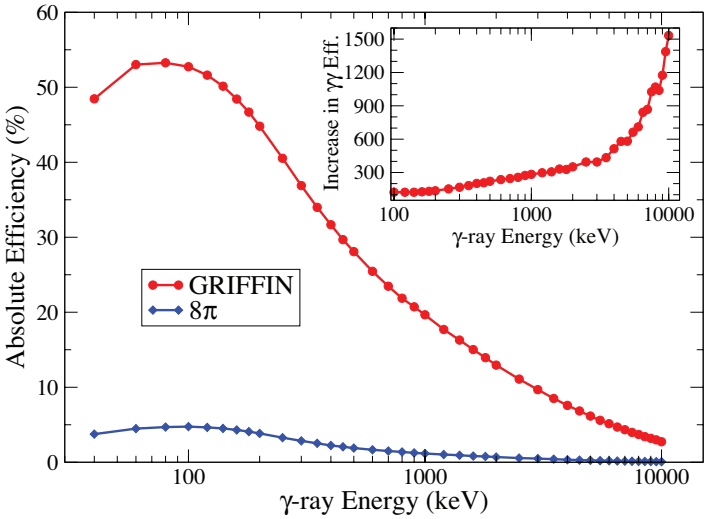


Figure 1. Comparison of the absolute efficiency of the GRIFFIN spectrometer to that of the 8π in both singles (main panel) and coincidence (inset) mode.

3.5.6 IRIS

Greg Hackman

IRIS: ISAC Reaction Spectroscopy (with Charged Particles) Station

The transfer reactions and inelastic scattering of the unstable nuclei need to be performed in inverse kinematics where typically hydrogen isotopes p, d, t are used as targets. The optimum beam energies range from ~ 4-20A MeV, which give reasonably large reaction cross sections. The greatest challenge for these studies is to obtain a measurable reaction yield. An efficient detection system and large number of the target nuclei are necessary to overcome the low beam intensity of the very neutron-rich isotopes.

The IRIS facility plans to utilize a thin solid hydrogen target[1]. The solid hydrogen target cell in Figure 1(a) will be backed by a thin silver foil (3-5 μm).

The solid hydrogen layer of thickness ~ 100 um, is formed on the surface of this backing foil. The orientation of the target will be such that the light target-like ejectiles after the reaction do not pass through the backing foil. This is necessary to avoid a large broadening of the scattering angle due to multiple scattering. The target cell with the backing foil is cooled by a cryocooler with a helium compressor to temperature of around 4K. Hydrogen gas from a diffuser is blown onto the cold foil to form the solid hydrogen target. The target cell assembly is surrounded by a copper cylinder whose temperature will be several tens of Kelvin. This acts as a heat shield and restricts the heating of the target cell. The reaction products from the target are emitted through openings in the heat shield. The facility will also be capable of using foil targets of p, d, and t.

The target-like light reaction products will be detected using a combination of annular silicon strip detectors that act as a ΔE transmission detector (~ 100 μm) and CsI(Tl) (12 mm), which stops the higher energy particles. The heavy beam-like reaction residue will be detected by another silicon detector array placed further downstream, which will cover very forward angles in the laboratory.

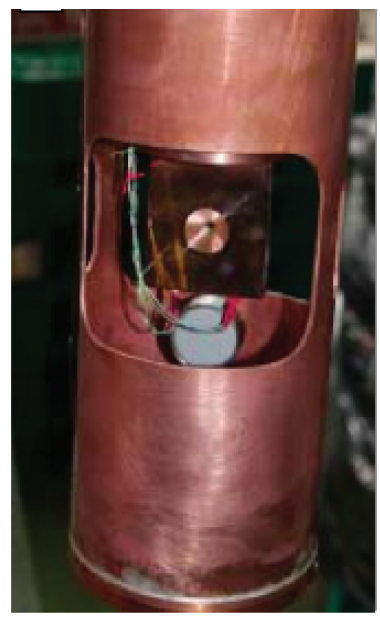


Figure 1(a). The solid hydrogen target cell in the heat shield.

For beams of heavy nuclei, eliminating isobaric contaminants may not be entirely possible. The IRIS facility is, therefore, also developing a low-pressure ionization chamber that will be used as an energy-loss detector, to detect the incoming beam and determine the atomic number of he beam species. The chamber will consist of multiple anodes to best equip it for a higher rate of operation. A

schematic view of the chamber is shown in Figure 1(b), with the scheme of using a co-planar anode design.

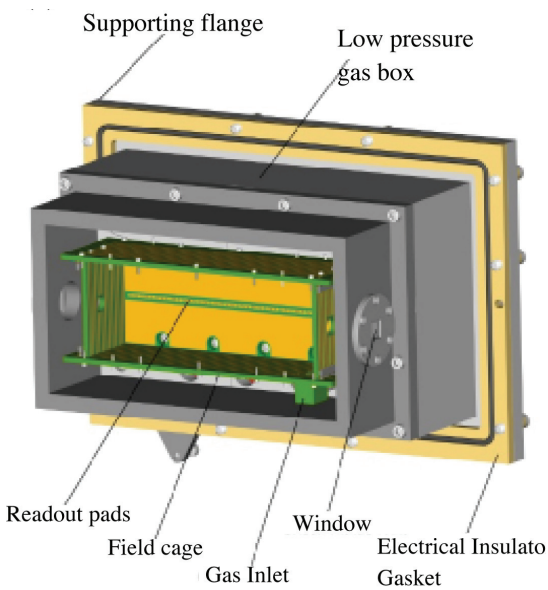


Figure 1(b). Model view of the ionization chamber.

Outlook

In 2012, the major effort will be to commission the IRIS facility, using both a foil target and the solid hydrogen target. The first experiments will be done with stable beams studying two-neutron transfer (p,t) reactions on ^{18}O. The study of resonances in the ^{11,12}Li will be done with higher energy beams using the foil targets. At a later stage, we will take up the challenging study with very weak beam intensity of the two-neutron transfer from ^{12}Be using the solid hydrogen target. We will also plan for developing an implanted tritium target for studying the (t,p) reactions.

References

[1] S. Ishimoto et al., RCNP Progress report 2010.

3.5.7 TITAN Cooler Trap

Jens Dilling

A Cooler PEnning Trap (CPET) is presently being built at TITAN [1] to enhance the mass measurement program of nuclei with short half-lives. The lifetime of radioactive nuclei limits the achievable mass resolution, which is proportional to the measurement time in resonance-based, Penning-trap mass spectrometry. One way to overcome this restriction is by increasing the charge state q of the ion. TITAN (Figure 1) has demonstrated this capability and is presently the only facility with an operational, online charge-breeding electron beam ion trap[2]. However, the charge-breeding process results in an energy spread of the ions of tens of eV/q, which is negatively reflected in the mass measurement in the precision Penning trap.

CPET (Figure 2) has been developed to cool highly charged ions prior to injection into the precision Penning trap [3], which will increase the efficiency and improve the precision of the mass measurement. This is a novel concept, and sympathetic cooling using both electrons and protons will be tested[4,5]. Additionally, CPET will incorporate mass-selective cooling techniques, which provide specific mass-to-charge ratios for the extracted ions.

Simulations characterizing the two cooling techniques and incorporating electron and ion injection have been performed. Designs for the nested trap structure and ion optics were based on the result of these studies. These components and the remainder of the experimental test set up have been fabricated at TRIUMF. The mechanical parts are ready for cleaning, using procedures which will allow a vacuum of 10^{-10} mbar to be achieved, limiting charge exchange between the highly charged ions and background gas. Vacuum requirements facilitated the need for a non-evaporative getter material sputtered on the inside of the vacuum vessel housing the trap structure. The potentials required for trapping and cooling of electrons, protons, and highly charged ions in CPET necessitate the need for complex electronics. Fast-switching power supplies, pulsed programmable generators, and arbitrary waveform generators have been designed at TRIUMF to fulfill these requirements.

Cleaning and assembly of CPET components is ongoing, and assembly of the initial test set up has begun, including the vacuum system. Electronics development and testing is in progress and a full cooling scheme needs to be implemented. First offline experiments will begin in 2012, and the test setup will be incorporated into the existing

TITAN beamline after a full experimental characterization of the two cooling techniques has been completed.

Figure 1. TITAN in ISAC-I at TRIUMF.

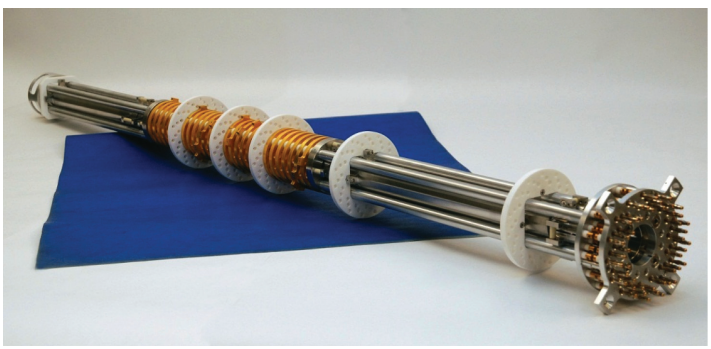


Figure 2. TITAN's Cooler Penning Trap.

References

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[3] V. L. Ryjkov et al., TITAN project status report and a proposal for a new cooling method of highly charged ions, Eur. Phys. J. A 25, 53-56 (2005)

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[5] V. V. Simon et al., Cooling of short-lived, radioactive, highly charged ions with the TITAN cooler Penning trap, Hyperfine Int. 199, 151-159 (2011)

3.5.8 Francium Trapping Facility

Matt Pearson

The Francium Parity Non-Conservation (FrPNC) collaboration has been constructing the Francium Trapping Facility on the floor of the ISAC hall, under the TITAN platform (Figure 1), since September 2011. It consists of a Faraday cage to isolate the interior from electromagnetic interference. The room will have temperature and humidity controls to enable delicate measurements of the weak interaction.

Figure 1. The Francium trapping facility under the TITAN platform within the ISAC hall.

Francium (Fr) is the heaviest alkali and is ideal for studies of the weak interaction in atoms and nuclei. It has many nucleons and the electronic structure is well understood quantitatively. This advantage is counterbalanced by the fact that Fr has the most unstable nuclei of the first 103 elements. To facilitate its study, the FrPNC collaboration is developing laser traps to capture the Fr and to have long interrogation times.

As its name indicates, the weak interaction is very weak. It requires a careful approach to measure it, which usually requires exquisite environmental control. Fortunately, the weak interaction has a unique signature: it does not conserve parity, the symmetry related to the reversal of the system of coordinates from right-handed to left-handed. The weak interaction signal comes from the difference observed under the parity-reversed coordinate systems.

The FrPNC collaboration is working on the interface with TRIUMF to receive Fr ions that after neutralization can be captured in a trap using lasers and magnetic fields (Figure 2). The atoms will undergo interrogation with microwaves and lasers to learn more about how the weak interaction behaves inside the Fr nucleus. We are pursuing three experiments: the first, E1010, will give information on the nuclear structure through hyperfine anomaly measurements; the second, E1065, will measure the nucleon-nucleon weak interaction; the third, E1218, is a full atomic parity non-conservation measurement that will give information of physics beyond the Standard Model.

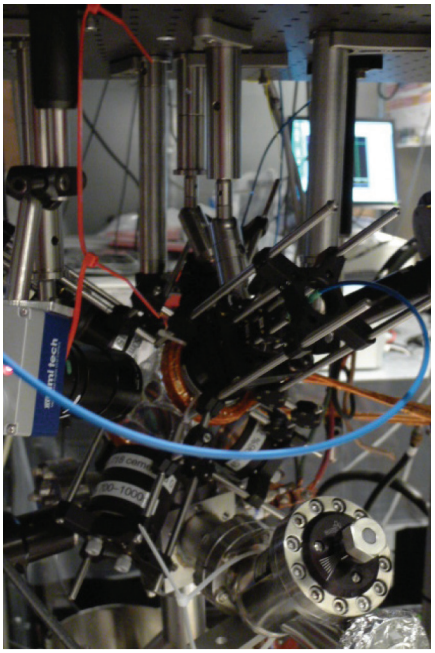


Figure 2. Trap for alkali atoms already tested with stable rubidium inside the Faraday cage.

The collaboration includes TRIUMF, the University of Manitoba (Canada), the College of William and Mary, Texas A&M University, the University of Maryland (USA), Universidad Autonoma de San Luis Potosi (Mexico), The New South Wales University (Australia), and Shanxi University (China). Support for the project comes from NSERC and TRIUMF through NRC from Canada, and the DOE and NSF from the USA.

3.5.9 SNOLAB Activities

Stan Yen and Rich Helmer

SNOLAB, located at a depth of 6800 feet in the active Creighton mine near Sudbury, Ontario, is the world's deepest underground physics laboratory. The large overburden of 6000 metres water equivalent shields the laboratory from cosmic ray muons, enabling experiments to search for the faint signals from neutrino and dark matter interactions and for neutrinoless double beta decay. TRIUMF personnel play significant roles in the design and construction of several experiments at SNOLAB.

SNO+

SNO+ is a successor to the highly successful SNO experiment. The heavy water employed in SNO is being replaced by a liquid scintillator in SNO+, as the higher light yield will permit the detection of lower-energy neutrinos. Specifically, SNO detected only the higher-energy neutrinos from the decay of boron-8 produced by nuclear fusion in the Sun, but SNO+ will be able to detect the more numerous, but lower-energy neutrinos from the "pep" fusion reaction $p+e^-+p \rightarrow d + \nu_e$ and "CNO" neutrinos from fusion reactions involving carbon, nitrogen and oxygen. The pep neutrinos lie in the interesting region between vacuum and matter-enhanced oscillations, which is a good place to look for new physics. While measurement of the CNO flux may help settle recent controversies concerning the Sun's metallicity[1]. At the same time, it will be possible to measure fluxes of antineutrinos from radioactive decay in the Earth and from nuclear reactors. A search for neutrinoless double beta-decay of neodymium-150 will also be performed, by dissolving natural neodymium in the scintillator. This decay mode has never been definitively observed in any isotope, and its observation would confirm that the neutrino is its own antiparticle.

The radioactivity requirements for SNO+ are about one hundred times more stringent in SNO+ than in SNO, and thus a better seal must be provided at the Universal Interface (UI) between the acrylic vessel and the region outside. TRIUMF designed and fabricated the original UI,

so it was natural to take on this responsibility for SNO+ as well. Parts for the UI have been fabricated and are being assembled at TRIUMF before shipment to Sudbury.

DEAP

DEAP is a detector for dark matter. It consists of 3600 kg of liquid Ar, which emits scintillation light if the hypothetical dark matter particles collide with the Ar atoms. Pulse shape discrimination allows for the rejection of background. TRIUMF is contributing to the fabrication of 255 acrylic light guides, and to the design and fabrication of the electronics. The light guide fabrication was successfully prototyped in 2011, paving the way for the full production in 2012. In 2010-2011, the DEAP electronics project has involved the design and test of custom analog electronics boards in collaboration with the University of Alberta, the development of the software and firmware to read out 32 high speed digitizers, and the design of a custom digitizer and trigger module. DEAP is scheduled to start taking physics data in 2013 and will reach discovery potential after six months of continuous operation. It will be the most sensitive dark matter search experiment, until the XENON 1 tonne experiment comes online in 2015,

HALO

HALO is a dedicated detector of neutrinos from galactic supernovae. It is a "detector of opportunity" that consists of 76 metric tons of lead ingots from a decommissioned cosmic ray station, instrumented with the surplus ^{3}He neutron detectors from phase three of the SNO experiment[2]. The large neutron excess of Pb makes HALO primarily sensitive to ν_e, in contrast to other neutrino detectors, which detect primarily anti-ν_e. HALO will not only provide an early warning supernova signal for optical telescopes, but the comparison of data from neutrino detectors of different flavour sensitivities (e.g. HALO and SNO+) will elucidate how the immense electron and neutrino densities in the proto-neutron star cause neutrinos to change from one flavour to another. This has strong implications for our understanding of the neutrino mass hierarchy, as well as supernova dynamics and R-process nucleosynthesis. Starting with the stacking of the Pb blocks in February 2010, the collaboration had, by the end of 2011, assembled almost the entire detector, with the exception of the cabling and water shielding. The detector test stand and cables were fabricated at TRIUMF. HALO went live with a full set of detectors in May 2012, and will join the international SuperNova Early Warning System (SNEWS) after a period of calibration and background studies. There will be a major upgrade of the electronics in 2012-13, following a scheme devised by TRIUMF personnel to build in the redundancy needed to ensure that HALO will be live during the ~20-second-long neutrino burst from the next galactic supernova, which occurs only once every ~30 years.

References

[1] W.C. Haxton and A.M. Serenelli, The Astrophysical Journal 687: 678-691 (2008)

[2] M. Schumacher et al. [HALO collaboration] Data Acquisition for the Helium and Lead Observatory, IEEE Conference Record 2010 Nuclear Science Symposium, paper ID N65-3.

3.6
Nuclear Medicine Infrastructure Development

Paul Schaffer and Cornelia Hoehr

3.6.1
TR13 Status Report

Cornelia Hoehr

The TR13 (Figure 1) is the smallest cyclotron at TRIUMF, accelerating H^- ions to 13 MeV. It is located in the Meson-hall extension and produces isotopes that are primarily used for the production of medical-isotope tracers. The main programs supported are with the Pacific Parkinson Research Centre and the BC Cancer Agency.

Between January 1st 2010 and December 31st 2011, the TR13 Operations Group delivered activity to 17 approved experiments. The different isotopes with their half-lives were ^{13}N (9.97 min), ^{11}C (20.36 min), ^{94m}Tc (52.0 min), ^{18}F (109.77 min), ^{55}Co (17.53h), ^{52}Mn (5.59 d), and ^{56}Co (77.3 d). A total of 1,723 different runs were carried out, adding up to 15,493.76 µA.h of beam delivered. A total of 9.6 % of all runs were development runs to improve existing targets or to investigate new targets.

Figure 2 (following page) shows the number of runs, delivered beam, and performance in comparison to earlier years. In 2010, only 12 runs and in 2011 only 25 runs were lost due to problems at the TR13 cyclotron. In 2011, another ten runs were lost due to problems with the transfer line from TRIUMF to the UBC hospital. Combined for both years, this results in 97.3% reliability of the TR13 and the transfer line.

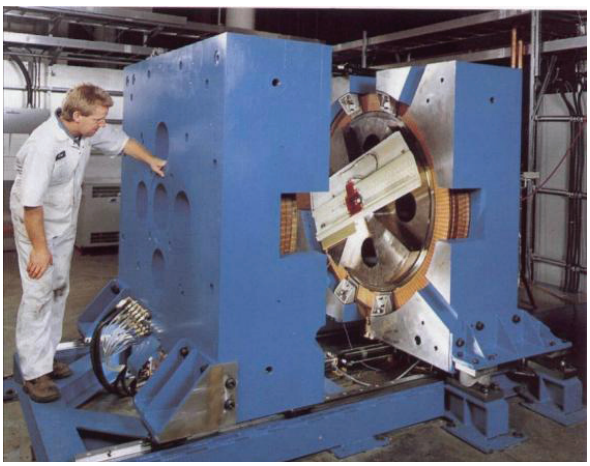


Figure 1. The TR-13 cyclotron was built in a collaboration between TRIUMF and Ebco (now Advanced Cyclotron Systems Inc.). This prototype, installed in the Meson Hall Annex, delivers high-intensity 13-MeV H- ion beams for PET radioisotope production for the UBC Hospital.

Year	Runs Done	Runs Lost	Up Time (%)	Beam Charge µA.min	µA.h
1995	580			1.72	2875
1996	753			2.89	4822
1997	700	13	98.2	3.07	5129
1998	837	7	99.2	4.85	8096
1999	801	1	99.9	4.55	7585
2000	808	42	95.1	9.23	15387
2001	848	8	99.1	6.31	10522
2002	1038	16	98.5	12.58	20972
2003	970	18	98.2	4.30	7177
2004	942	6	99.4	4.54	7573
2005	709	3	99.6	3.70	6180
2006	1099	98	91.8	6.84	11416
2007	1169	156	88.2	7.73	12898
2008	1361	9	99.3	8.49	14151
2009	1445	5	99.7	8.36	13947
2010	784	12	98.5	5.37	8960
2011	939	25	97.4	3.91	6533
		Average =	**97.4**	**Std. dev.=**	**3.6**

Beam delivered in	2010 - 2011
	Delivered
N-13	26
Co-55	21
Mn-52	8
Co-56	5
F-18	738
Tc-94m	1
C-11	758
Development	165

Figure 2. These two charts are representative of TR13's performance since 1995/1997. The numbers of lost runs in 1995 and 1996 are not available.

3.6.2
GMP Laboratory
Paul Schaffer

Recently, a Good Manufacturing Practices Laboratory (GMP) containing three new hot cells for the production of radiopharmaceuticals for human use was completed in the lower level of the Chemistry Annex at TRIUMF. The research focus for this area is in combination with TRIUMF's partners at UBC to produce PET radiopharmaceuticals for use in Parkinson's and Alzheimer's research. This lab is designed with a clean-air room area surrounding the hot cells so that the production of radiopharmaceuticals can be prepared in a controlled air environment. The hot cells also have air filtration that increases the clean-room level inside the cells where the processes are carried out. The laboratory is equipped with surfaces that can easily be cleaned and sterilized. It also has an area outside of the clean room for quality control analysis and shipping. This laboratory also has restricted access. It is expected that all of the current PET radiopharmaceuticals, such as C-11 methyphenidate, Raclopride Dihyrotetrabenzine, DASB, MRB, Yohimbin, and Fallypride as well as F-18 Dopa will all be prepared in this new GMP lab space during this year. These are agents currently being used in the Pacific Parkinson's Research Centre's research program currently funded by a CIHR Team grant.

Figure 1. Some Members of the Nuclear Medicine Division pose in the GMP Laboratory.

3.6.3
MHESA Laboratory
Paul Schaffer

The new joint TRIUMF/Nordion lab in the MHESA basement contains four new hot cells for radiochemistry research and will open during the next year. The lab is equipped with a state-of-the-art ventilation system and control systems to meet current regulatory requirements. As installation and commissioning of the ventilation system must be done in compliance with new codes and standards, this effort has taken additional time. The new lab space will be used primarily for collaborative research projects between Nordion and TRIUMF scientists and students.

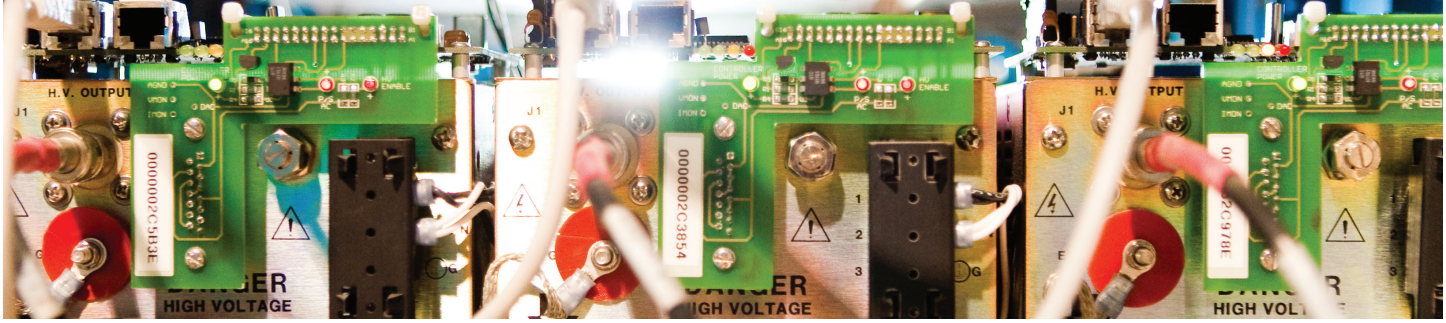
The TRIUMF team will work together with Nordion to add value to their growing line of Nuclear Medicine radiometals. The sales of imaging agents alone have been estimated to be a $5 B market worldwide in 2009, with imaging agents for Positron Emission Tomography (PET) representing the fastest growing class of agents. Much of this advancement is being made possible by the synthetic production of biomolecules (e.g., peptides, lipids, oligosaccharides, oligonucleotides and antibodies) with specific and high affinity for cancer biomarkers. However, the development of these ligands into viable imaging agents has not yet been realized due to the lack of a robust, reproducible, high-yielding and rapid method for introducing the radioisotope of choice into these biomolecules to give chemically stable entities. They intend to expand on the radiochemistry already developed in their labs to prepare coordination chelate derivatives that can be used to label a wide variety of target compounds.

Another focus will be the federally-supported project on the production of Tc-99m using accelerators, detailed in section 2.10 of this report.

For future expansion, there is ample room across the hall that will be renovated to make labs for use in Nuclear Medicine/radiochemistry. In addition, TRIUMF will soon be connected to the nearby UBC Centre for Comparative Medicine by an underground pneumatic radio-tracer

transport line, similar to the existing rabbit line connected to the UBC hospital. The new Centre will have additional lab space and imaging facilities. A CFI funded combination PET/SPECT scanner will be installed within the year.

Figure 1. TRIUMF and Nordion staff inside the MHESA laboratory.



3.7 Scientific Computing

Reda Tafirout and Steve McDonald

The TRIUMF computing and networking environment continues to meet the challenges of the TRIUMF science and engineering programs. In the last two years, TRIUMF has:

1. More than doubled the processor and storage resources of the TRIUMF ATLAS Tier-1 Computing Centre

2. Added 400 TB to the TRIUMF T2K compute cluster.

3. Added a 288 cpu core compute cluster, dedicated to the TRIUMF Theory Group.

4. Expanded its external networking capabilities from 1 GbE to 10 GbE.

5. Made significant contributions to the GEANT4 Simulation toolkit.

Network Upgrade

TRIUMF's external network requirements are constantly challenged. Since the Large Hadron Collider (LHC) has moved into a production phase, and with TRIUMF hosting one of the ten ATLAS Tier-1 centres, TRIUMF has seen a significant increase in the utilization of its network to its external peers. In order to meet this challenge, TRIUMF increased its connectivity to the Research Network from 1Gbps to 10 Gbps. Furthemore, the constraint of 1Gbps between TRIUMF and its dedicated ATLAS Tier-1 and Tier-2 centres has been removed by acquiring dedicated fiber between TRIUMF and the CANARIE ROADM network located at UBC.

T2K and Theory Clusters

TRIUMF is a key contributor to the Detector and Computing resources of the international T2K experiment. Both TRIUMF and the Rutherford Appleton Laboratory (RAL) provide the storage resources outside of Japan for the T2K experiment. In the last two years, TRIUMF has added 400 TB of storage for distribution via grid-enabled services to T2K collaborators from across the world.

A primary goal of the TRIUMF Theory Group is to develop an ab-initio description of bound and scattering properties of nuclei and hadrons. This is achieved via a numerical solution of the quantum many-body problem, which is a time-demanding and memory-intensive task for the CPU. To meet these demands, a modest 288 processor-core cluster was established in the TRIUMF Core Computing and Networking Centre. The cluster is a high-performance computing facility dedicated to the TRIUMF Theory group for developing and debugging new codes and partially running the less demanding jobs for production. The codes are mostly based on large matrix operations and linear algebra applications, which lend themselves to parallel computing. A high-performance interconnect and a large memory/node, characteristics not always satisfied from easily accessible external resources (e.g. WestGrid), are essential. The unlimited wall time configuration is another key feature that makes the Theory Cluster an

indispensable tool in the advancement of our research.

ATLAS Tier-1

Computing resources play a critical role in extracting the science from the ATLAS experiment. As the LHC has been in full operation in 2010 and 2011, an enormous amount of data has been produced, and the ATLAS computing model has matured and evolved in order to adapt to real operating conditions. The data collected is being analyzed on an international network of high-performance computing centres linked together by Grid tools, the Worldwide LHC Computing Grid (WLCG) infrastructure. WLCG has been fully exploited and is a real success. As part of this infrastructure, the Canadian Tier-1 centre at TRIUMF is a key contributer and has been ramped up to full production at nominal capacities for CPU, disk, and tape storage. There are ten Tier-1 centres around the world and they are primarily responsible for storing and processing the raw data, and to produce various derived datasets for distribution to the worldwide ATLAS community, via the Tier-2 centres.

The Tier-1 centre at TRIUMF is a leader in the field by being consistently at the top or near the top in terms of availability, reliability, and efficiency when compared to other sites in the world. The centre runs several Grid monitoring and database services for the entire ATLAS collaboration. TRIUMF also runs a Regional Grid Operation Centre (ROC Canada) to oversee several Grid sites as part of WLCG operations. In terms of connectivity, the Tier-1 centre has dedicated network links to CERN Tier-0, BNL (U.S. Tier-1), SARA (Netherlands Tier-1), and to each of the Canadian Tier-2 centres. The networking infrastructure was put into place with the collaboration and support of CANARIE, BCNet, and HEPNet-Canada. The Tier-1 centre underwent several large expansion phases, and the current capacity that is deployed includes 4,160 CPU cores, 7.1 Petabytes of disk storage and 5.5 Petabytes of tape storage.

GEANT4

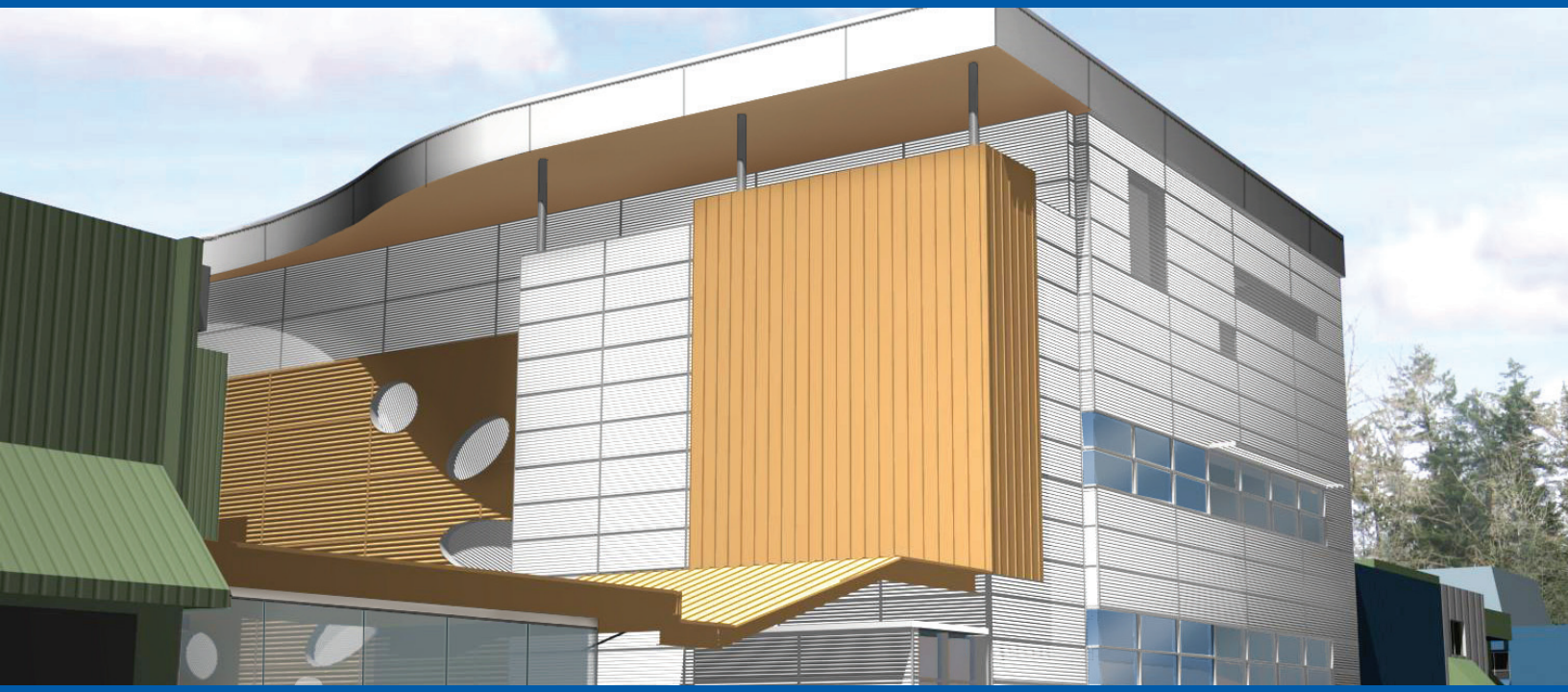
Modern particle and nuclear physics experiments require large-scale, accurate, and comprehensive simulations of the particle detectors. Increasingly, this has also become true for other disciplines, such as space science, nuclear medicine, radiation physics, and accelerator design. In response to this demand, an object-oriented toolkit, GEANT4, has been developed over the last fifteen years by an international collaboration. It builds on the accumulated experience in Monte Carlo simulations of about 100 physicists and software engineers. TRIUMF is a founding member and a lead contributor in the current collaboration, along with CERN, SLAC, Fermilab, ESA/ESTEC, INFN, IN2P3 and KEK. Additional expertise comes from universities and several more national institutes. The TRIUMF group is active in some of the core activities of the collaboration, in the areas of source and example code development, user support, documentation, and testing.

GEANT4 is an ideal framework for modeling the optics of scintillation and Cherenkov detectors and their associated light guides. This is founded in the toolkit's capability of commencing the simulation with the propagation of a charged particle and completing it with the detection of the ensuing optical photons on photosensitive areas, all within the same event loop. TRIUMF's unique and specific contributions are in this simulation domain. The optical physics functionality is particularly useful to neutrino experiments, dark matter searches, double beta decay, and cosmic ray experiments. We regularly respond to inquiries on the GEANT4 User Forum from prominent experiments in all of these areas. We have also continued to improve and correct the simulation. For example, an optical photon's group velocity is derived from a very different physics consideration than that of other particles. This has been resolved and now produces correct optical photon arrival times at the detectors. The details of MIE scattering has also been added to the list of interactions an optical photon may partake in during the simulation. A finite rise time was added to the code, simulating the emergence of scintillating photons. Moreover, the light yield can now be a function of particle type and deposited energy in the case of non-linear light emission in scintillators. We have also added the capability of simulating surface reflections with Look-Up-Tables containing measured optical reflectance for a variety of surface treatments. A surface between two dielectric media may now be specified to have a wavelength

dependent reflectivity <1 and defined transmission probabilities. This allows the simulation of Triple Phase Boundary (TPB) coatings in GEANT4. The interpolation in material property vectors, usually depending on wavelength and so essential to this type of simulation, is now done by spline fitting. A G4OpticalPhysics builder module has been added to the source, allowing users a much easier way to activate this functionality in their application.

We recently added the definition of gravity fields and gravity field tracking to GEANT4, and we now make allowances for the tracking of the magnetic moments of neutral particles in magnetic and electric fields, as well as the force they experience via interaction with a magnetic field gradient. These are essential ingredients for the simulation of TRIUMF's UCN/EDM experiment and for the neutral anti-hydrogen simulation in the ALPHA trap.

4 ARIEL & VECC



Introduction

Construction of the Advanced Rare Isotope Laboratory (ARIEL) at TRIUMF began in 2011 after funding for Phase I was secured in mid-2010. The flagship project is led by the University of Victoria in collaboration with the federal and provincial governments and multiple agencies. The project consists of a civil construction and conventional facilities element (i.e., the buildings and infrastructure) that will be completed in mid-2013; the electron linear accelerator will be subsequently installed and will begin producing isotopes by 2015.

The primary mission of ARIEL is to deliver unprecedented intensities of rare, short-lived exotic isotopes, in particular those with extreme neutron excess, to simultaneous and multiple experiments, at the existing and world-leading ISAC accelerator complex. A secondary mission of ARIEL is to anticipate future uses of e-linac technologies such as free electron lasers, and including commercial uses such as the production of medical isotopes by photo-fission.

When fully installed and commissioned, ARIEL will increase TRIUMF's annual scientific productivity by up to three times its current level: ARIEL will provide two additional beams of rare isotopes to augment the existing single beam line.

The project brings together accelerator technology expertise from British Columbia, as well as India, to develop an electron accelerator capable of saving electricity by roughly a factor of five, as compared to conventional technology. Once complete, the laboratory will have profound impacts on isotopes for science, isotopes for medicine, and next-generation accelerator technologies.

ARIEL construction is now underway. The new target hall is emerging from the large excavation alongside the underground beam line tunnel. In addition, an existing vault adjacent to the main cyclotron is being rehabilitated to house the new electron linear accelerator. Support facilities including the cryogenic compressor building are also being constructed.

In parallel to the construction of the physical buildings, much work has been done 'behind the scenes' in accelerator technology. Designs for the 300 keV thermionic gun, and the 10 MeV injector cryomodule are being completed, and TRIUMF is beginning assembly of these components in 2012. The 25 MeV Accelerator Cryomodule will follow in 2013. The TRIUMF team is also tendering the long-lead procurement items, and has signed contracts for 4 K cryogenic plant, a 290 kW c.w. klystron, and four 1.3 GHz niobium 9-cell cavities from PAVAC Industries, a local Canadian supplier. Moreover, the low energy beam transport is designed and some testing is underway . Procurements are anticipated in mid-2012 for quadrupole magnets for the entire facility, and the klystron's 600 kW HV power supply.

4.2
Civil Construction

Shane Koscielniak and Remy Dawson

In June 2010 the Province of British Columbia provided the University of Victoria with $30.7 M through the British Columbia Knowledge Development Fund for construction of conventional infrastructure for the Advanced Rare IsotopE Laboratory (ARIEL) at TRIUMF. The conventional infrastructure for the ARIEL project consists of four main contracts: the main ARIEL construction, demolition and excavation, the Stores building, and the Badge building. The latter are necessitated by the ARIEL site congestion. The new Compressor Building (CB), for gaseous helium management, forms part of the ARIEL package. In addition, there are major renovations that will transform the former Proton Hall to the Electron Hall (E-Hall).

The Architectural and Engineering design team, Chernoff-Thompson Architects, was selected October 1, 2010 for the design of the buildings. The schematic design report was received March 4, 2011. The design development report was received July 4, 2011.

The first construction contract was awarded on February 16, 2011 to Scott Construction for construction of the replacement Stores and Shipping/Receiving building. To make room for the new Stores building, TRIUMF needed to acquire permission to move the perimeter fence. The Class IB License amendment to allow moving the perimeter fence, removal of the Stores building and relocation of the Badge room for ARIEL site preparation was received August 15th. Construction began after an official groundbreaking ceremony on March 28, 2011. This building was completed September 26, 2011 for move-in, enabling demolition of the old stores building to make way for site construction for ARIEL.

A second construction contract was awarded to Scott Construction on July 30, 2011 for construction of the replacement Badge building. This building is the controlled access portal to the TRIUMF site replacing the function that will be demolished with the old stores building. A temporary badge room was erected until construction of the new building was complete. The new building opened in December 2011.

A third construction contract was awarded to Ellis Don September 14, 2011 for the demolition, excavation, and shoring of the site for the ARIEL building. An official groundbreaking was held on November 1, 2011. Excavation completed at the end of March 2012, making way for the installation of steel and formwork and pouring of the tunnel slab.

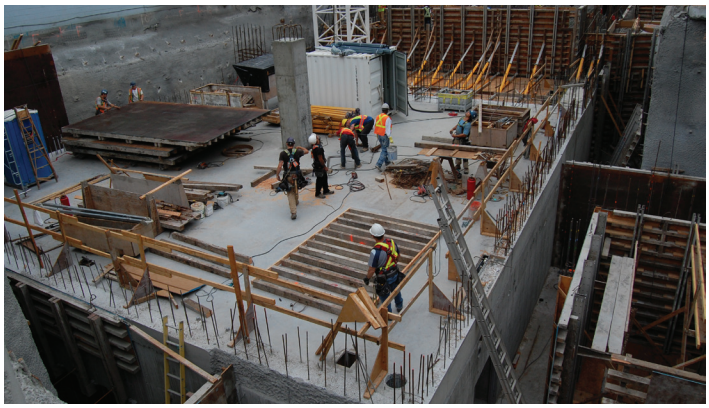


Figure 1. ARIEL construction.

In conjunction with this, the Proton Hall extension in the Meson Hall was cleared out and readied for construction. This area has been renamed the Electron Hall and is being updated to house the electron linear accelerator (e-linac). In the E-Hall, the south wall shielding upgrade is complete, and the north wall shielding (that will protect the E-Hall from the future BL4N proton beam) is near complete. Electrical services and a 10T crane will be installed before the roof beams are sealed and e-hall occupancy taken in October 2012.

The final construction contract was awarded February 10, 2012 to Ellis Don. This contract includes construction of the ARIEL building, the Compressor building, and renovations to the Electron Hall. Work began on the Compressor Building site at the end of March 2012.

The Compressor Building and the Electron Hall are scheduled for completion by October 2012, while the ARIEL building completion is March 2013.

Figure 2. His Excellency the Right Honourable David Johnston, Governor General of Canada examines a model of TRIUMF's cyclotron in the Electron Hall., the future site of the e-linac. Photo: © Ami Sanyal

4.3
Accelerators and Beam Lines

Shane Koscielniak

From funding that was received in June 2010, TRIUMF's accelerator researchers have been designing, testing, and building the components that will be housed in the ARIEL building and Electron Hall. Progress made on the components from 2010 - 2012 are detailed below.

Electron Gun

The thermionic gun[1] provides 300 keV kinetic energy electron bunches with charge up to 16 pC at a repetition frequency of 650 MHz. The main components are a gridded gun in a vessel filled with SF6 at a pressure of 2 bar, in-air HV power supply, and RF modulation feed-through. Unique features of the gun are its inverted cathode/anode geometry to reduce dark current, transmission of RF modulation via a dielectric (ceramic) waveguide, and chokes through the SF6. The latter obviates the need for an HV platform inside the vessel to carry the RF transmitter, which results in a significantly smaller, simpler vessel. The modulation is applied to a CPI Y-845 gridded dispenser cathode via a stepped coaxial line impedance matching section from the RF-collecting choke. The gun bias and heater power are applied through an isolation transformer.

The grid biasing and modulation was tested on a 100 kV prototype source; a conductance angle ±16° at 650 MHz is inferred from the transconductance. The same source confirmed that the beam intensity can be varied by applying a macro pulse structure (over the RF) with a variable duty cycle from 99.9% down to 0.1%. The lowest duty factor is essential for intercepting profile monitors. The RF waveguide was subject to bench testing on scale models and extensive simulation and optimization with HFSS, and has been ordered from Kyocera. The gun electrodes, the vessel internal corona domes and shroud, were subject to extensive 3D electrostatic modeling and optimization. The gun ceramic, anode-tube internal steering coil, gun solenoid, isolation transformer, conditioning resistors, and 350 kV Glassman HV power supply have all been delivered. The SF6 vessel will be fabricated in fall 2012; assembly and integration of components will follow thereafter.

Injector Test Facility

The Injector Test Facility, a collaborative effort between TRIUMF and VECC of Kolkata, India, provides an ideal proving ground for e-linac design and operation strategies. It duplicates the e-linac up to the exit of the injector cryomodule with enhanced diagnostic capability for benchmarking the performance of the gun, various diagnostic devices and procedures, and demonstrating sustained operation under the parameter envelope as designed. Commissioning of this facility at TRIUMF began in November 2011. Stable beam delivery from the gun to various diagnostic devices over the 1.2 m portion of beam line was proven during testing. The following summarizes the outcome of the phase-one test:

- The solenoid and correctors successfully controlled beam trajectory and shape as designed.

▪The beam horizontal emittance was measured directly with an Allison type scanner, and indirectly with scintillator screen and solenoid scan. Both methods confirmed the Gaussian distribution from the gun, and will be used to benchmark the simulation model of the gun.

▪ BPM, Faraday cups, slit scanner, two types of scintillator screens[2] (chromox and YAG), capacitive pickup, PMT-based loss monitor, and Allison scanner were tested[3] and areas for improvement identified. Two additional solenoids and diagnostic boxes have been installed for phase two in the future.

An RF deflecting cavity will be installed for measurement of longitudinal parameters in the phase-three test.

Beam Lines

From the injector linac onward, the most convenient focusing device is the magnetic quadrupole. However, at the lowest envisioned beam energy of 5 MeV, the focal power required is rather small. This forces us to use the shortest possible quadrupoles, otherwise the fields are too low compared with expected remanent field of low-carbon steel. Thus, a theoretical study was undertaken to arrive at optimal pole shape for short quadrupoles whose length is comparable to or shorter than the aperture. Conventional 2D treatment and fabrication practice, assuming sufficiently large pole length, break down in such cases. We have derived[3], analytically, a new 3D shape and demonstrated that this shape yields smaller aberrations. Though the exact shape is impractical, for short quadrupoles it can be approximated with a simple spherical pole, provided the sphere radius is precisely 1.65 times the quadrupole aperture radius.

The beam transport sections are:

▪ The EMBT "Merger" section, so named because in Phase 2B, it will merge the injector beam with the recirculating beam from the ERL

▪ The EHDT section to a low power beam dump

▪ The EHBT which transports to the photofission target

The EHBT consists mainly of a periodic section consisting of six 90° FODO cells, each 4m in length. The EMBT contains a 36° bend section, the EHDT, a 90° bend section, and the EHBT two doglegs and bend sections to the west and east targets. All insertions are achromatic. The beam lines in the E-Hall adopt the weak and medium quadrupoles, with integrated strengths up to 0.2 T and 0.7 T respectively. This is easily achieved with the short quadrupoles of aspect ratio 1 and cylindrical poles with spherical faces. The weak quads are also used for the periodic section in the tunnel. At highest envisioned energy of 75 MeV, the shortest required focal length is 0.24 m in the EHBT dogleg sections. The required integrated gradient is 1.05 T; this will be achieved with a more conventional strong quadrupole design with rectangular cross-section poles and hyperbolic faces. The strong quadrupoless will be water-cooled, the weaker ones air-cooled, and the medium ones indirectly cooled. In total, there will be 77 quadrupoles. All have an aperture diameter equal to 52.0 mm.

Cryomodules and Cavities

Due to heavy beam loading, five 9-cell cavities at 100 kW/cavity are required to reach the 0.5 MW beam power. The injector cryomodule (EINJ) contains a single 9-cell cavity, and has been designed and constructed in collaboration with VECC. The accelerator cryomodules (EACA, B) each house two 9-cell cavities.

The design of the cryomodule is nearly complete and TRIUMF will begin construction on it in 2012. The cyromodule has been designed to utilize a box vessel with a top-loading cold mass. To produce a 2K liquid, a 4 K phase separator, 4K/2K heat exchanger, and Joule-Thomson valve will be installed within each module. The cold mass will be suspended from the lid with mounting posts, struts, and strong back; and it will be surrounded by a LN2-cooled copper box for thermal isolation. A 1 mm warm mu-metal shield will be fastened to the inside of the vacuum vessel. The cold mass will consist of the cavity hermetic unit, a cold mu metal layer, and the tuner. The tuner cold part is the J-lab style scissor type; and will be followed by a long actuator and warm ISAC-II style rotary servo motor mounted on the lid.

The hermetic unit will include the cavity(s), power couplers, rf pick-up(s), the warm-cold transitions with HOM damping material, and warm isolation valves. A carbon fibre reinforced silicon carbide material CESIC was chosen for the damping material with measured conductance at 1.3 GHz and 80 K of 2200 S/m.

Once built, the e-linac cryogenic distribution will be based on a parallel feed of atmospheric LHe from a main trunk to each cryomodule. The LHe will be drawn from a main dewar, which is supplied from the 4 K cold box. An LHe reservoir in each cryomodule will act as a phase separator. In parallel, cold gas will be returned to a common return trunk and then delivered back to the cold box where it will represent a refrigerator load. 2 K liquid will be produced in each cryomodule by passing the 4 K liquid through a heat exchanger in counter flow with the returning exhaust gas from the 2 K phase separator and expanding the gas to 30 mbar through a JT expansion valve. The header pipe above the cavity string will act as a 2 K phase separator, and deliver cold gas back through the 4K/2K heat exchanger to the sub-atmospheric pumping system as a liquid load. A siphon circuit from the 4 K reservoir will be used to cool the 4 K intercepts, with vapour returning back to the reservoir. Initial cool down will be done by delivering 4 K liquid from the 4 K phase separator to the bottom of the cold mass through a dedicated cool down valve.

The nine-cell 1.3 GHz elliptical cavity borrows the TESLA/ILC type inner cell geometry but uses modified end groups to accommodate the large power couplers and to mitigate Higher Order Modes (HOMs). A multi-pass beam break up criterion establishes a limit of Rd/Q*QL < 107 Ohm. End group beam tubes of inner radius 48 mm and 39 are used for the power coupler and RF pick-up end, respectively. The 4K/2K cryo-insert is being built and tested as a separate package. The size of the unit was chosen to be compatible with pre-testing in an existing cryostat, at least in the prototyping phase. The insert includes a 4 K phase separator, 4K/2K heat exchanger, JT expansion valve, 4 K cool down valve plus siphon circuit for intercept cooling. The prototype heat exchanger is from Developpement et Applications des Techniques de L'Energie (DATE) with an estimated capacity of 2.5 gm/sec. All components plus fabricated parts will be assembled for cold test in September 2012. The lid, support posts, strong back and cavity support detailing is complete. Tank and LN2 shield detailing are in progress. The niobium cavity is being fabricated at PAVAC Industries of Richmond Canada. A 7-cell cavity in copper was completed to test all fabrication procedures and manufacturing jigs.

Cryogenic Equipment

Since the project start in June 2010, the e-linac cryogenic system has moved from conceptual design phase to the engineering design and procurement stages. Conceptual design of e-linac cryomodules and cryogenic system went through external design reviews September 2010 and March 2011, respectively. In parallel with SRF cavity and injector cryomodule engineering design, the helium refrigerator-liquefier specification was produced and tendered June 2011. The contract for supplying a He cryoplant consisting of HELIAL 2000 cold-box, main and recovery compressors with oil removal and gas management systems (OR/GMS), and multi-component purity analyzer was awarded to Air Liquide Advanced Technologies (France). This machine is class 700 W cooling power at 4.6 K with maximum liquefaction rate of 288 l/h. The cryoplant final design was recently approved, and will move to production; concluding in delivery the second quarter of 2013. The contract for helium-gas storage was awarded with delivery scheduled January 2013.

The cold-box with 1000 litre liquid-helium storage dewar will be positioned in the immediate vicinity of the e-linac cryomodules in order to minimize losses associated with LHe transfer. The warm part of installation will be located outside the E-Hall in separate compressor building.

Activity is presently focused on designing the liquid helium distribution system, and the tendering of sub-atmospheric helium pumps. Further development is related to helium sub-atmospheric and LN2 system design and manufacturing, installation of services and auxiliaries, instrumentation.

Radio-Frequency Equipment

The e-linac 1.3 GHz high power RF system will be installed in stages: in the first, to be completed in 2014, the injector cryomodule (EINJ) will be fed by a 30 kW c.w. Inductive Output Tube (IOT), and the first accelerator cryomodule (EACA) will be powered by a high power c.w. klystron and power divider. Each cavity is equipped with two 50 kW c.w. couplers.

The IOT with solenoid and trolley has been purchased from CPI, USA, and its HV power supply and drive amplifier from Bruker BioSpin, France. The system has been installed and tested to the maximum rated output power of 30 kW on a water cooled load, and can now be run routinely.

The c.w. klystron is specified with a saturated power of 290 kW and usable linear range (incremental gain of 0.5 dB/dB) up to 270 kW, leaving plenty of margin for transmission loss to the 200 kW nominal rated EACA. After the tendering process, coordinated as a joint venture with Helmholtz Zentrum Berlin (HZB), orders were placed with CPI, USA: one for TRIUMF and three units for HZB. The klystron will be a factory-tuned multi-cavity, high efficiency, high gain, broadband, water cooled tube. The final design review is scheduled for August 2012. The klystron is expected to be factory tested in November 2012 prior to shipment to TRIUMF.

The klystron high voltage power supply, rated at 65 kV 8.65 A, and focus, filament and vacuum ion pump power supplies, and trunk RF distribution system including all control, interlocks and protection and integration of the klystron was tendered March 2012, and a vendor will soon be selected.

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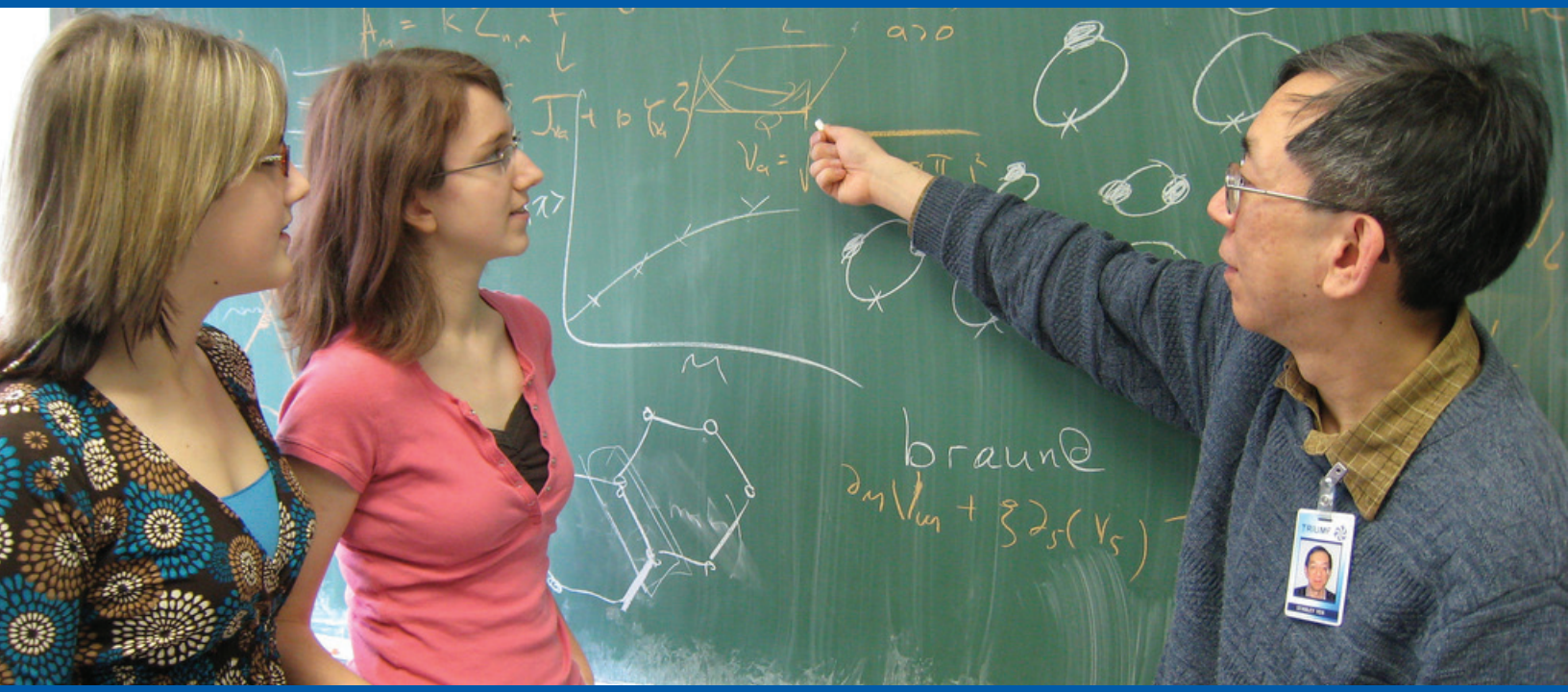
[2] D. Karlen et al: "Beam Diagnostic Systems for the TRIUMF e-linac", MOPPR003, these proceedings.

[3] A. Laxdal et al: "High Power Allison Scanner for Electrons", TUCP04", proc BIW 2012.

5 Creating Social and Economic Impact



Introduction

A key element of TRIUMF's mission is to create social and economic impact:

▪ To transfer knowledge, train highly skilled personnel, and commercialize research for the economic, social, environmental, and health benefit of all Canadians.

This chapter reports on progress in these areas.

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

A core element of TRIUMF's strategy is to generate industrial partnerships that bring the business and market acumen of the real world in order to identify truly innovative science and technology that may be ripe for development. In many instances, TRIUMF's commercialization partner, AAPS, Inc., is the right vehicle to pull together the teams to spin out new companies, license intellectual property, and/or develop products. In other cases, TRIUMF works directly with industrial and research partners to provide solutions and services.

5.2
Training the Next Generation of Leaders

Timothy Meyer

One of the derivative benefits of supporting pioneering research is setting fire to the imaginations of young people. TRIUMF has multiple programs in place that serve to inspire, attract, and train young, talented people that will develop and lead the future.

For each of the past two years, nearly 75 undergraduate and 75 graduate students have gained valuable research opportunities at TRIUMF. The annual summer research-experience program for high-school students provided unique learning opportunities for three to four talented students each year, including Grade 11/12 students from across British Columbia, Shad Valley students, and several first nations students. Students conducted research in particle physics, nuclear physics, and communications and outreach; some of their experiences were captured in blog posts and uploaded to the Quantum Diaries platform and to TRIUMF's Headline News on its website as well as several YouTube videos.

TRIUMF continues to offer drop-in tours of its facility to the public as well as scheduled, private tours for larger groups. During the 2010-2012 biennium, TRIUMF conducted more than 710 tours for 6,200 visitors, including nearly 1,800 students. Working with results from surveys as well as updated best practices from the expert science outreach and engagement community, the laboratory is presently revising its tours program to elevate value and work more closely with local schools and the neighbourhood community.

The annual meeting of the American Association for the Advancement of Science (AAAS) was held in Vancouver during February 2012, marking the first time in 30 years that the meeting was held outside the U.S. TRIUMF was heavily engaged in the local organizing activities as well as an active coordinator of national involvement. Working with the BC Innovation Council and the Government of British Columbia, TRIUMF organized the BC AAAS Student Scholar program that provided scholarships to 200 high-school students from across the province that allowed them to register for the conference and become members of the AAAS. Students attended science sessions, met the Governor General of Canada, pressed speakers with questions about the forefronts of research, and contributed to an overall record-breaking attendance at the AAAS conference.

Figure 1. Two recipients of the BC AAAS Student Scholarship pose with TRIUMF's Director and others at pre-conference event.

In 2011, TRIUMF entered into a five-year cooperation agreement with Science World, the leading science outreach and education agency in British Columbia for kindergarten through ninth grade. The "Partners in Innovation" program now combines TRIUMF's high-school focus with Science World's younger-student focus to provide a systematic and complete opportunity for BC students to engage with and consider science, technology, engineering, and mathematics (STEM) as a potential career path. Examples of new initiatives under this framework include gallery space at the Telus World of Science building for student artwork generated after tours and studio time at TRIUMF, evening lectures for the public featuring speakers such as CERN's Director-General, and summer camps for talented youth as "future science leaders."

Figure 2. A number of the photographers that participated in the Global Particle Physics Photowalk assemble in the TRIUMF lobby before their shoot.

As the practice and inquiry of science becomes more integrated into contemporary culture, TRIUMF's "Artist in Residence" (AIR) program has become more and more relevant. Through an initial partnership with faculty at the Emily Carr University of Art + Design, TRIUMF regularly hosts classes of artists-in-training who learn about black holes and other transformations of energy and then spend studio time at the laboratory generating new artwork. Building on these initial forays, TRIUMF has now developed collaborations with the School of Art and Design in Berlin, Germany (a partnership that successfully obtained funding from the Goethe Institute) as well as advanced programs of study at UBC and SFU. Working with peer institutions around the world and building on the success of a pioneering effort at DESY, TRIUMF led the organization of an amateur photowalk to physics laboratories in five countries that took place in August 2010. The Global Particle-Physics Photowalk attracted more than 200 photographers around the world to behind-the-scenes tours of the participating laboratories. A Vancouver local photographer was awarded international first place by an independent jury of experts for his photograph of the 8pi nuclear physics experiment. Output from the AIR program now graces the walls at TRIUMF as well as several buildings in the community.

5.3
Industrial Partnerships and Innovation

Timothy Meyer

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

Irradiation Services: TRIUMF's accelerators provide beams of particles that can be used to probe materials to reveal their structure or bombard systems to examine their performance in elevated radiation environments. The space industry and segments of the high-performance electronics sector are steady customers.

Isotope Production and Chemistry: TRIUMF's research program in nuclear medicine has developed core competencies in the production of isotopes using a variety of cyclotron and target technologies. TRIUMF also has expertise in the purification, processing, and chemical synthesis that attaches the isotopes to biologically relevant molecules for medical imaging or treatment. These capabilities are regularly in demand by the private sector.

Technical Consulting: TRIUMF's capabilities in physics, engineering, and design are often tapped in the form of short-term technical consulting arrangements. TRIUMF staff might contribute to troubleshooting a private company's product line or provide advice in developing needed high-tech infrastructure. TRIUMF's contributions to the success of AAPS, Inc., projects fall into this category.

Professional Training: Finally, TRIUMF provides training experiences for highly skilled workers ranging from apprentices and journeyman in the technical trades to professional development of scientists and engineers through courses, workshops, and conferences.

TRIUMF is exploring a number of specific opportunities within each of these business lines. In the area of isotope production and chemistry, TRIUMF has developed technologies with industrial partners for producing the medical isotope technetium-99m using cyclotrons, and the radiochemistry for labeling and imaging areas of oxidative stress in the body. The laboratory is also developing industrial partnerships with the aim of transferring technologies for the design, assembly, and quality assurance of high-precision magnets and superconducting cryomodules.

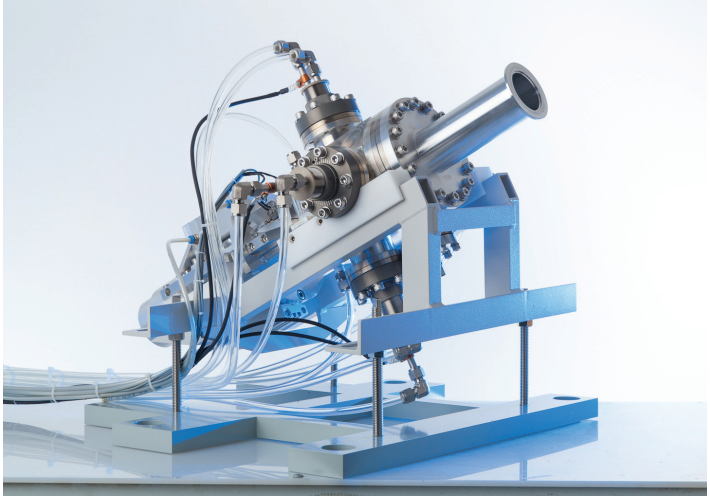
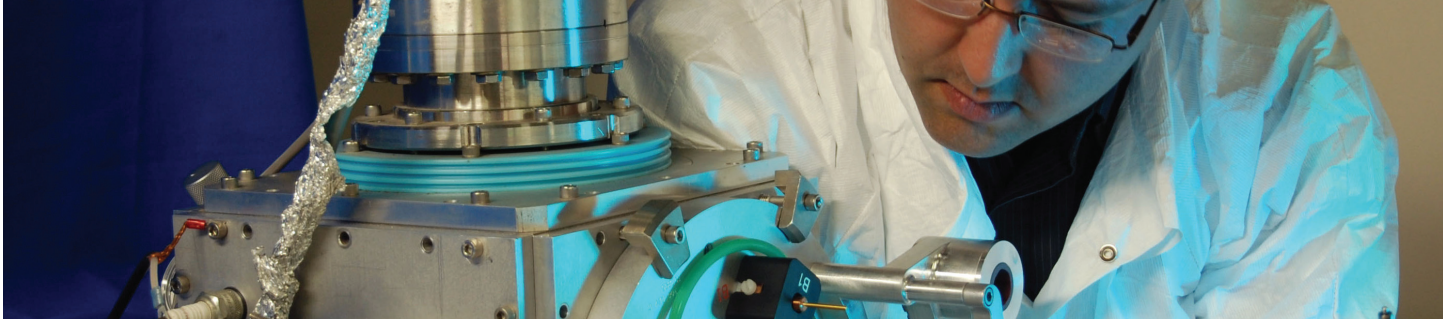


Figure 1. Target transfer system for Mo-100 irradiation in a cyclotron.

Over the past two years, TRIUMF has developed a robust approach to managing these types of opportunities within an explicit business strategy. The Innovation and Industrial Partnerships Panel meets biweekly and considers new opportunities put forward by the TRIUMF community, reviews partnership agreements, balances priorities, and identifies strategic directions for the laboratory. For instance, TRIUMF and its partner, AAPS, Inc., are organizing a national workshop for July 2012 that will bring together the technology licensing offices of all the TRIUMF member universities to develop an effective framework for cooperation among the universities and with common private-sector partners.

With each industrial partnership, TRIUMF develops Canadian business in several ways. TRIUMF might provide direct technical assistance to the company on a product line or a platform for product development. Or, TRIUMF might be involved with a vendor to enhance an existing product to meet an application needed for TRIUMF's research program. Finally, TRIUMF might also collaborate with a company to investigate and develop a new technology, market, or service offering.

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



5.4
Advanced Applied Physics Solutions, Inc.

Timothy Meyer

Advanced Applied Physics Solutions (AAPS) is a nationally designated Centre of Excellence for Commercialization and Research, established at TRIUMF. The non-profit company is focused on bridging the gap between innovation and commercialization in the physical sciences.

AAPS is building on the strong foundation of TRIUMF's internationally recognized expertise in particle accelerators and advanced radiation detection systems to establish an applied research facility that develops and commercializes technologies emerging from worldwide subatomic research. AAPS's ultimate vision is to help position Canada at the forefront of knowledge and application in twenty-first century technologies.

AAPS's strategic plan is designed to enhance Canada's capacity to translate research breakthroughs into products, services, and businesses that drive innovation in key priority areas:

- Health and related life sciences and technologies
- Natural resources and energy
- Environmental science and technologies
- Information and communications technologies

During the past two years, AAPS has advanced technologies in each of these areas, notably muon geotomography for mining applications, and radiation-reducing technologies for standard X-ray fluoroscopy procedures. AAPS also led the formulation of a project that developed a comprehensive survey of the deployment of PET-imaging technology for clinical cancer care across Canada. The report found significant variations from province to province and concluded that Canada is behind in its uptake of this modern imaging tool for diagnosing and staging cancer.

Launched with a five-year strategic plan in 2008, AAPS is presently developing a fresh approach to its next five years in partnership with TRIUMF and the Government of Canada's Networks of Centres of Excellence program.

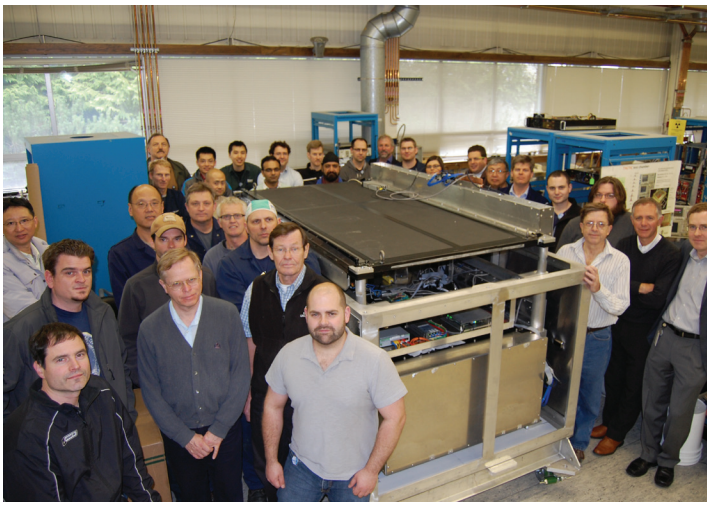


Figure 1. The AAPS team poses with their muon geotomography prototype.

6 Management

Introduction

As Canada's national nuclear and particle physics laboratory, TRIUMF must effectively manage its resources to produce the best results for its public stakeholders. TRIUMF's administrative organization is committed to ensuring that a clear and coherent structure is followed and that TRIUMF remains 100% accountable. Through cutting edge research, developing projects that will help spur economic growth, and by using taxpayer's money responsibly, TRIUMF strives to fulfill its objective: Accelerating Science for Canada.

This chapter highlights TRIUMF's management strategies for 2010 – 2012, while offering perspectives on moving forward in the coming years, in order to ensure that our high standards of excellence can be maintained.

Regulated by the Canadian Nuclear Safety Commission, TRIUMF is committed to operating safely and securely. An application for a new operating license from the Canadian Nuclear Safety Commission (CNSC) was filed in 2012, and an update to the Preliminary Decommissioning Plan (PDP) was prepared.

6.2
Accountability and Management

Jim Hanlon and Henry Chen

Governance

As of March 31, 2012, the TRIUMF Joint Venture is made up of 17 universities from coast-to-coast, 11 full-members and six associate members. The relationship among members of the Joint Venture remains strong, as does the relationship between TRIUMF and UBC, as TRIUMF is located on the UBC campus and considered a major stakeholder in the Joint Venture. The following agreements are in place to support the governance of the laboratory:

1. Amended and Restated TRIUMF Joint Venture Agreement dated March 31, 2008

2. UBC Lease dated March 31, 2008

3. Management Agreement between TRIUMF Accelerators Inc. and TRIUMF dated March 31, 2008

4. NRC Contribution Agreement dated April 1, 2010

5. Amendment No. 1 to the Contribution Agreement dated April 1, 2010

6. CNSC Financial Security and Access Agreement dated January 7, 2008

7. Fund Contribution Gap Agreement dated January 7, 2008

8. Escrow Agreement dated January 7, 2008

Board Chair

Professor R. Paul Young, Vice-President, Research, University of Toronto has served as Board Chair for the current period. With the increase in full-member universities, the need was identified to formally establish an Executive Committee that would deal with important issues that might arise between Board meetings. Under his direction, an Executive Committee was established as well as an Audit Committee.

With the establishment of the Executive Committee there was no longer a need for the TRIUMF Board to meet three times per year. Board meetings are now twice per year, in the spring at TRIUMF in Vancouver, and in the fall at a member university.

Administration: Technology Transfer

With the existence of AAPS (Advanced Applied Physics Solutions), a not-for-profit corporation established by TRIUMF under the Centre of Excellence for Commercialization and Research (CECR) program, innovation and industrial partnership opportunities within TRIUMF are now brought to the Innovations & Industrial Partnerships Panel that meets regularly on a bi-weekly basis. At this time, decisions are made on whether to pursue opportunities and if it is best pursued within TRIUMF or AAPS. Reports from this committee are made to the TRIUMF Board of Management Technology Transfer Committee.

TRIUMF is attempting to standardize its non disclosure agreements with its member universities to facilitate the timely processing of agreements that involve member university faculty.

The agreements have been put in place over the current period with the following entities:

- BCCA on F-18 Backup
- BCPRC
- CAS – IHEP
- CERN – ELENA
- CIAE
- GE (BCCA) UK & US
- Genome BC (UBC and BCCA)
- University of Guelph (GRIFFIN and SPICE)
- IACA
- Korea Institute of Radiological Science
- MEPhI
- Perimeter
- Selkirk College
- Toyota RDL
- UBC on Heat recovery

Insurance

TRIUMF carries a $50 M Nuclear Energy Liability policy from the Nuclear Insurance Association of Canada (NIAC) that complements other Commercial General Liability coverage of $50 M and coverage for Directors and Officers to $10 M from $5 M. In addition TRIUMF is a "named insured" on UBC's Property Insurance policy through the Canadian University Reciprocal Insurance Exchange program (CURIE).

Security

The CNSC performed a compliance inspection of TRIUMF that included a site visit and a formal review of the TRIUMF security plan. TRIUMF was found to be in compliance with all aspects of its security operations.

As a result of the ARIEL construction project, a new badge room was built to allow access to the controlled area. This badge room has optical turnstiles that are designed to eliminate tailgating and improve secure access to the site.

Human Resources

TRIUMF seeks to attract and retain the best talent for its programs. During the past two years, the lab has upgraded its career-recruitment efforts and adopted some of the tools of social media to better attract strong candidates. A recent site-wide employee survey gathered valuable input on programs and services provided to staff. At a more strategic level, the human-resources team also developed a success-planning paradigm for the lab that included all divisions and identified the key functions that need specific management plans for training and maintaining skills.

Financial Office

The Financial Office is responsible for Accounting, Procurement, Logistics, and TRIUMF House, which provides accommodations for the international scientific community. As an ongoing commitment, the Financial Office continually examines TRIUMF's business practices to ensure its services are relevant, to enhance TRIUMF's operational effectiveness and, and to reinforce TRIUMF's status as an effective laboratory. To support this goal, since the start of the current Five-Year Plan, the Finance team has undertaken several initiatives.

Agresso: A New Enterprise Resource Planning System

In September 2009, TRIUMF held an external review of its core computing facilities, including its Management Information System. In its recommendation, the review committee stated that TRIUMF requires a flexible and responsive information system to comply with the changing and increasingly stringent regulatory demands, and to provide reliable management reporting.

Pricewaterhouse Coopers were engaged to propose an acceptable Enterprise Resource Planning System (ERP). Subsequently, the TRIUMF Board of Management approved entering into an agreement with the company Unit4 for the purchase and implementation of their

ERP System called Agresso Business World.

Since the Board approval of this project in November 2010 ($1.1M total cost), a project team was formed in February 2011 and the process of discovery, examination of business requirements, and solution design commenced.

The implementation of the new software is anticipated to be completed by November 2012. As of March 2012, the project team is working on finalizing business requirements, refining customization requirements, completing the solution design for the integration points, and completing scripts for integrated testing.

Preliminary Decommissioning Plan: Financial Guarantee

TRIUMF's operating license, granted to TRIUMF Accelerators Inc. by the Canadian Nuclear Safety Commission (CNSC), expired in March 2012. TRIUMF is currently operating under a license extension until its renewal application has been reviewed. Given its positive safety record, CNSC has encouraged TRIUMF to prepare a renewal application for a ten-year term instead of a five-year term*.

Part of the license renewal process requires TRIUMF to update its Preliminary Decommissioning Plan (PDP). The main objective of the plan is to ensure that the site is brought to a safe state of closure in the event of decommissioning. The Financial Guarantee, a significant component of the plan, demonstrates the funding measures and provides assurance that adequate resources will be available to fund decommissioning activities. TRIUMF has reviewed and updated the PDP and the Financial Guarantee that was last submitted in 2007.

The total cost (expressed in 2011 dollars) to decommission the TRIUMF facility to a greenfield condition is $44.2M (non-greenfield, $38.9M). The cost study was prepared in accordance with generally accepted accounting and quantity-surveying methods and procedures by an independent, quantity surveyor firm.

The lifespan of decommissioning will take 45 years and cost outlays will occur at three distinct phases post shutdown (after three years, at shutdown +20 years, and after 45 years).

Funding for decommissioning activities is derived from two sources: cash funds and proceeds from the sale of assets. TRIUMF's Decommissioning Fund is governed by an escrow agreement. At the end of Fiscal Year March 31, 2012, the balance in the decommissioning fund was $10.2M.

Based on independent estimates and a review conducted by an appraisal firm, the total proceeds from an orderly sale of TRIUMF assets will add $31.4M to the decommissioning fund.

After the initial stage of decommissioning expenditures, significant cash balances derived from the sale of assets will generate interest income. The interest income returns will ensure cash reserves are available to fund decommissioning activities.

* At the time of printing, TRIUMF has been awarded a ten-year operating license (June, 2012)

Supply Chain Management

After exporting the final goods and securing materials for the T2K project in Japan, Procurement began establishing the purchasing requirements for the Advanced Rare Isotope Laboratory (ARIEL) at TRIUMF. This included preparing and managing the tender document for the Architectural and Engineering Services for the ARIEL infrastructure, participating in the tendering processes for the construction of the new Stores building, the Badge room, and the main construction of the ARIEL Infrastructure, including excavation and site preparation.

Now that the main construction has started, Procurement is focused on purchases related to the electron linear accelerator (e-linac), while maintaining a high level of customer service to the other end users.

Logistics relocated in 2011. As part of the ARIEL project, the Stores facility was relocated due to the

demolition required to clear the ARIEL construction site and build the northern annex ("RIB building") of the ARIEL facility. Efforts were made in the design of the new Stores facility, planning the move to the new location, and the execution of the move with minimal impact on service to the TRIUMF site.

The introduction of a "virtual" inventory system enabled the efficient and cost effective distribution of non-stock inventory items like helium dewars and office supplies. This system follows a "Just In Time" concept of inventory management.

TRIUMF House

Ensuring the comfort of visiting scientists staying at TRIUMF House is paramount to its operations. In 2011, TRIUMF House achieved a "perfect score" as reviewed by Tourism BC in their annual assessment visit. This rating reflects the cleanliness and state of repair, two important guest services factors in the accommodation industry.

Several relationships outside of the scientific community were cultivated as a revenue source for those periods not required by visiting scientists.

6.3
QMS, Safety, and Licensing

Phil Jones and Anne Trudel

April 2010 to March 2012 was extremely busy with licensing activities, as both TRIUMF and the Canadian Nuclear Safety Commission (CNSC) staff prepared for the renewal of the Accelerator Operating Licence (PAOL-01/2012), which expires June 30th, 2012. Regulatory programs were inspected, revised and reviewed as part of the licence renewal process. The culmination of these inspections was TRIUMF's application for renewal submitted in November 2011 in time for a CNSC Commission hearing on May 2nd, 2012. A ten year license period was requested by TRIUMF and supported by CNSC staff. The application for renewal was submitted under the new CNSC licence format, organizing the regulatory programs under the new Safety and Control Areas.

Regulatory program activities in this period included six program-specific CNSC inspections for Quality Management Systems, Training, Radiation Protection, Security, and Packaging & Transport, as well as four Compliance Inspection visits. Progress highlights for regulatory programs include:

▪ Implementation of Annual Quality Management System goals and objectives with progress reported quarterly using performance metrics and an annual assessment completed at the Safety Management Committee meeting. Corrective actions are identified for goals that are not met and revised goals for the upcoming year are released.

▪ Additional software tools to facilitate the process of QMS implementation at all levels of the operation. These include a new Corrective Action Database that is linked to the site-wide Fault and Nonconformity Database, an electronic log-book for all operations groups, and a site-wide Work Request System released in early 2012.

▪ Creation of the Training Implementation Panel lead by the head of the Science Divisions and mandated to oversee the work of the training task force and ensure a timely implementation of training requirements for all groups on site. The task force put in place a plan to assess the training requirements for all positions where performance of the tasks can affect operation of beam delivery facilities, or where incorrect performance could result in injury, downtime, expense or unnecessary radiation dose. The task force has identified and prioritized these positions, completed the task analysis for the more critical positions (28 of 38 groups) and expects to complete the process of design, development, and implementation of training for all positions by June 2012.

▪ Fire Protection program documents were revised and approved in October 2010 including procedures for inspection, testing, and maintenance of fire protection systems bringing all of these activities into compliance with the latest versions of regulatory codes and standards.

▪ Upgrades to newer technology microprocessors for the main cyclotron central safety system and the radiation monitoring system. In addition, the January 2012 shutdown saw the culmination of a five-year long project to replace all Access Control System Area

Safety Units microprocessors for the main cyclotron.

▪ The revision of Radioactive Waste Management program documents to comply with the new regulatory clearance levels for defining waste as non-radioactive. In-house upgrades to the instrumentation used for monitoring the waste were also completed to meet the new clearance level criteria.

Several Accelerator Operating Licence amendments were issued since April 2010. Two licence amendments concerned the changes to site access and site perimeter fence to accommodate construction of the new Stores building, and the site preparation activities including excavation for the ARIEL project. The other significant licence amendment was undertaken to increase the operating current for the ISAC actinide target operation. The Safety Analysis Report was revised to include an estimate of emissions in a worst-case scenario based on measurements carried out with the low current irradiations. The safety analysis showed that, with the larger radioactive inventory and under single point and compound failures, engineering controls for the ISAC Target Hall nuclear ventilation needed to be upgraded to ensure that doses to staff, personnel, and members of the public would still remain within the regulatory limits for operation of a nuclear facility. These upgrades were completed and the licence was amended November 2011.

The operating performance for environment health and safety continued to do well in this period. The radiation dose to personnel summarized in the table below indicates excellent ongoing performance for dose management in all areas of operation at TRIUMF, with the total personnel dose continuing to decrease over the previous three-year average of 299 person-mSv.

Environmental releases continue to remain well below the regulatory limit of 0.05mSv/year. TRIUMF annual airborne releases were just below 0.01mSv/yr and sump effluent releases at less than 10^{-6}/yr for this period. Lost-time injuries for TRIUMF in 2010 was 5.9 days/100 person-years and continued to be better than that for BC Universities, the WorkSafe BC equivalent industry group. An incident on the beamline shielding blocks resulted in 21 days/100 person-years for 2011. A full incident investigation was carried out and corrective measures identified, including the implementation of fall-protection equipment for rigging work and procedures and training for all workers working on the shielding blocks. EH&S metrics were used to assess performance with respect to goals for this operating period. Goals were largely met and, in a few areas where performance was not fully met, EH&S identified corrective actions with the aim of continual improvement.

Quality Management System

During much of the reporting period, the QMS Panel was focused on addressing the remaining directives and action notices from the 2006 audit. After a follow-up inspection in 2010, all of the directives and three action notices were closed, leaving two action notices to be addressed: A5 regarding documentation, and A3 regarding nonconformity reporting and resolution.

The documentation focus was to identify all document types and sub-types in use and to ensure that their repositories and workflow were defined and compliant with the required elements in the governing TRIUMF Standard Operating Procedure 01 (TSOP-01).

These document types, repositories, and controls are documented in the TRIUMF Document Type Index, which also serves to identify current compliance with

Annual Dose	Total Site Dose (person-mSv)	Maximum NEW Dose (mSv)	Average NEW Dose (mSv)	Average non-NEW Dose (mSv)
2010	212.4	7.4	1.07	0.0060
2011	196.2	5.6	0.74	0.0081

* Nuclear Energy Worker (NEW)

TSOP-01. Document sub-types are color-coded based on their current state and expected date of compliance and, as document sub-types are brought into compliance, the index is revised and released. It is currently in its fourth release. After their inspection visit in July 2011 the CNSC closed this action notice.

To address the second action notice, the QA Manager began reporting on trends in nonconformities and root cause investigations at each Quarterly Safety Management Committee meeting. Based on this, the CNSC closed the action notice. However, in a follow-up inspection in December 2011, they raised concerns over delays in completing corrective actions. The QMS Panel had also identified this as an issue and a revision to the governing TSOP and TSOP-02 had been drafted. The implementation of revised TSOP-02 requires changes to the NCR application. These changes will be specified and a revised nonconformity resolution procedure will be released by the end of June 2012.

Other major accomplishments include the release of a Work Request System, which provides a single entry point for requesting work to be done by one or more TRIUMF groups and replaces a number of paper forms (REA, RFS, change requests and revisions forms). The QMS Panel completed 33 internal audits focused on ensuring compliance with and verifying the implementation of the various processes defined in the Quality Management System. The QMS panel organizes topical meetings with the QMS leaders to promote and facilitate the communication between panel and leaders. The meetings also offer the opportunity for continuing education.

6.4
Project Management

Byron Jennings

TRIUMF is maturing and moving to a new era in performance management. Driven by the increasing complexity of the required technologies, the need for predictable performance, and the increasing emphasis on public accountability, TRIUMF is developing increased monitoring and planning for projects. TRIUMF's plans are ambitious and require the maximum use of the available resources. This requires that projects and ongoing operations be carefully planned and choreographed to minimize the conflicts due to competing demands for common resources. To this end, TRIUMF maintains a laboratory-wide Level 2 work breakdown structure (WBS) under the rubric of the Commitment List. The Commitment List details all the projects and ongoing commitments that TRIUMF is working on (WBS Level 2) and groups them into programs (WBS Level 1). The financial accounts are approximately a Level 3 WBS. With the implementation of the new enterprise reporting and planning (ERP) software, accounting and the work breakdown structure will be fully integrated to allow seamless reporting of all resources, both monetary and manpower, and to allow reporting at the desired level of the WBS.

An example of the data that can be obtained from the new system is shown in Figure 1 on the following page. The data shows the manpower usage for projects for the year 2012 where the individual projects are rolled up to the program level. It can be seen that half the manpower devoted to projects goes to the TRIUMF flagship program: ARIEL & VECC. As might be expected, the next largest user of resources is projects in nuclear physics. As can be seen, there are projects related to all aspects of the TRIUMF program. For ongoing commitments, the largest shares are taken by running and maintaining the cyclotron and for the running the laboratory.

The laboratory work breakdown structure, at the first and second level, is relevant for managing how the individual commitments interact with each other. However, it is also necessary to manage the individual commitments efficiently. To this end, the commitments are divided into two groups: projects and ongoing commitments. Ongoing commitments are, as the name suggest, the ongoing activities that are necessary as part of running the laboratory. They are managed as a part of the annual budgeting process based on the time of year. Projects are distinguished by having a beginning and an end and are managed based on the phase of the project—initiation, planning, and execution. TRIUMF has instituted a series of gate and status reviews to track projects and maintain an updated list of resource requirements. During the past two-year performance period, TRIUMF has been developing an effective roll-up of all commitments: summarizing the actions and impacts across all activities at TRIUMF. The result is a new realm of performance, where TRIUMF can manage expectations, promises, and results to optimize the delivery of breakthrough science, technology, and innovation.

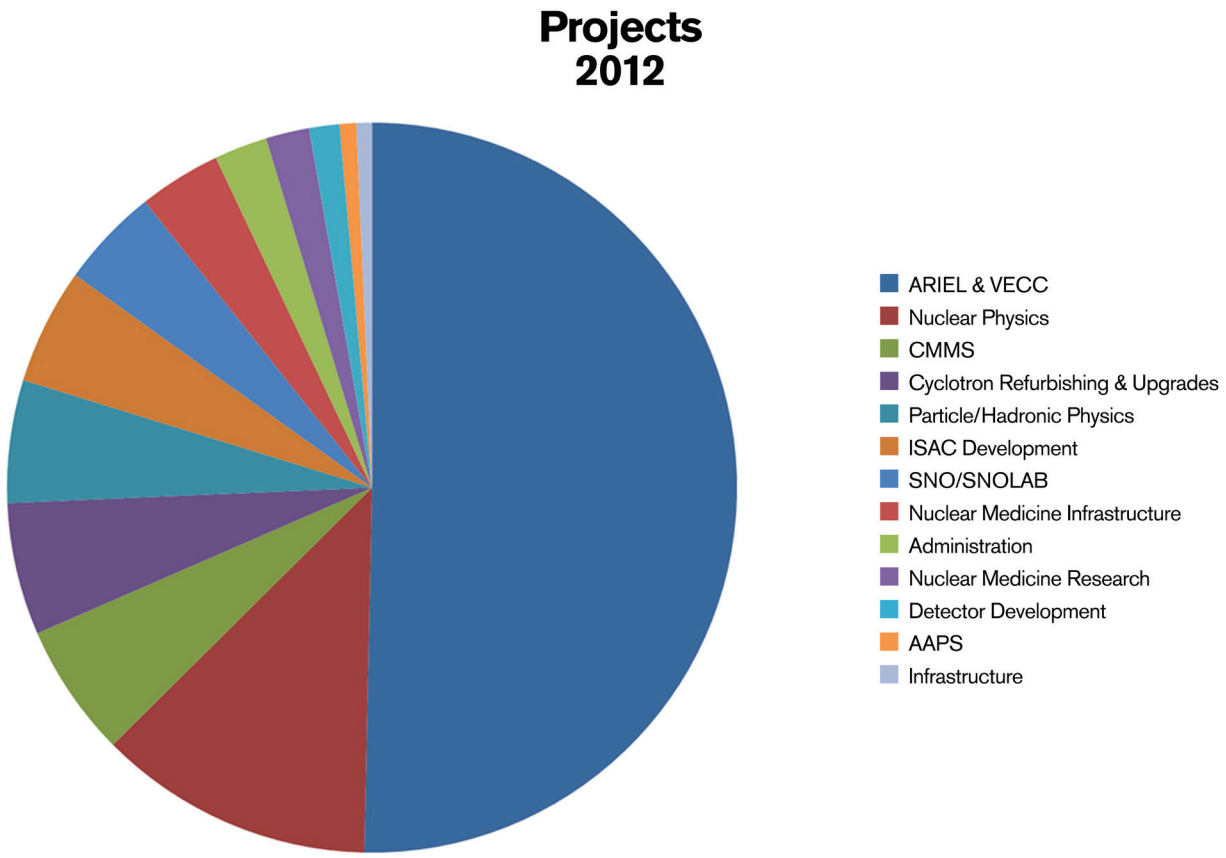


Figure 1. The manpower usage of project, grouped by program.

7 Appendices

7.1 Statistics

Fiscal Year 2010 - 2011

In the 2010–2011 fiscal year, TRIUMF:

Shared the laboratory with **3,339** people for public tours including almost **1,000** students;

Hosted **38** VIP visits including 1 foreign ambassador and **7** Canadian ministers;

Provided educational and /or research work experiences for **6** high-school, **72** undergraduate, and **42** graduate students;

Hosted more than **800** external visiting scientists;

Authored or co-authored **198** scientific peer-reviewed publications;

Supported **22** scientific experiments at ISAC in nuclear physics, **48** experiments at CMMS in molecular and materials science, and **4** experimental programs for life sciences and nuclear medicine;

Operated the main cyclotron for **5,407** hours or almost **91%** of scheduled performance;

Delivered **2,628** hours of radioactive-isotope beams and **1,490** hours of stable-isotope beams to scientific experiments in its ISAC facility;

Achieved **99%** availability for the Canadian ATLAS Tier-1 Data Centre;

Treated **7** cancer patients with proton therapy in cooperation with the BC Cancer Agency (BCCA);

Used its TR13 cyclotron to produce **468** runs of medical isotopes delivered to hospitals for research, **187** runs for medical isotopes to BCCA for the diagnosis of cancer patients, and **101** runs for isotope-production research and development;

Produced up to **1.82** million patient doses (in partnership with Nordion, Inc.) of medical isotopes for commercial sale;

Generated **$2,628,668** of commercial revenue;

Attracted **360,494** visits to its website and was followed by **760** people across social-media platforms (e.g., Twitter, Facebook, etc.); and

Expanded its managing consortium to include **17** Canadian research universities (an increase of **2**), **11** of which are full members.

Fiscal Year 2011 - 2012

In the 2011 - 2012 fiscal year, TRIUMF:

Shared the laboratory with **2,945** people for public tours including nearly **850** students;

Hosted **16** VIP visits including His Excellency the Right Honourable David Johnston, the Governor General of Canada;

Provided educational and /or research work experiences for **6** high-school, **75** undergraduate, and **76** graduate students;

Hosted more than **416** external visiting scientists;

Authored or co-authored **251** scientific peer-reviewed publications including two Nature Physics cover stories;

Supported **30** scientific experiments at ISAC in nuclear physics, **19** experiments at CMMS in molecular and materials science, and **11** experimental programs for life sciences and nuclear medicine;

Operated the main cyclotron for **5,159** hours, or just more than **94%** of scheduled performance;

Delivered **2,432** hours of radioactive isotope beams and **1,883** hours of stable-isotope beams to scientific experiments in its ISAC facility;

Achieved **99%** availability for the Canadian ATLAS Tier-1 Data Centre and increased CPU capacity to **4,160** cores with **7.2** Petabytes of disk storage and **5.5** Petabytes of tape storage to process **14** billion events from the ATLAS detector in **4** million distinct computing-grid jobs;

Treated **9** cancer patients using proton therapy in cooperation with the BC Cancer Agency (BCCA);

Used its TR13 cyclotron to produce **671** runs of medical isotopes delivered to hospitals for research, **72** runs for medical isotopes to BCCA for the diagnosis of cancer patients, and **204** runs for isotope-production research and development;

Produced up to **1,800,000** patient doses (in partnership with Nordion, Inc.) of medical isotopes for commercial sale;

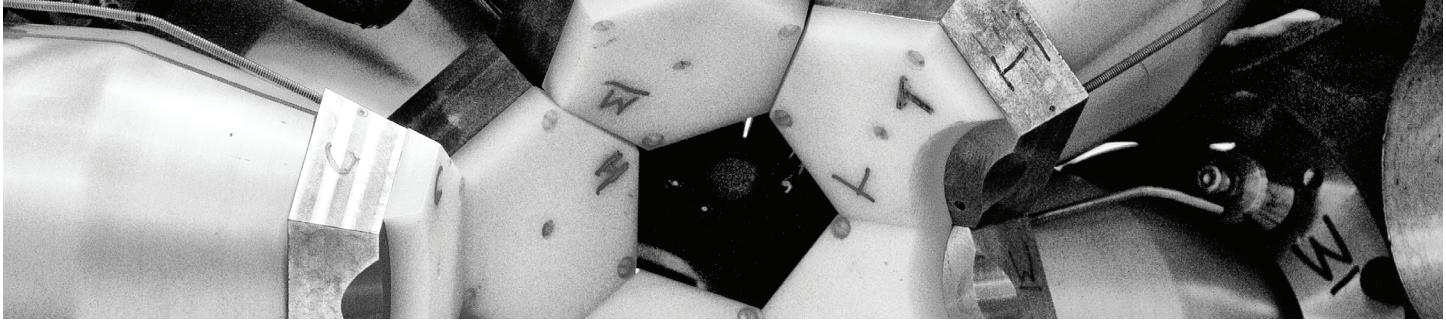
Generated **$1,441,927** of commercial revenue; when averaged over several years, TRIUMF's ratio of generated revenues compare to annual operating budget is about **3%**—equal to the same metric for the Massachusetts Institute of Technology;

Had **406,390** visits to its website and was followed by **1,616** people across social media platforms (Twitter, Facebook, etc.)

Attracted new talent to Canada from **11** different countries;

Received high recognition for its staff:
SNM Michael J. Welch Award for Thomas J. Ruth, APS John Dawson Award for Makoto Fujiwara, Business in Vancouver Top 40 Under 40 for T.I. Meyer, and the CAP-TRIUMF Vogt Medal for David Sinclair;

Assisted in hosting the record-breaking annual meeting of the American Association for the Advancement of Science in Canada for the first time in **30** years, including fostering the participation of **200** B.C. high-school science students.



7.2 Detector Facilities

8π - A "super-microscope" used to examine the behaviour and structure of atomic nuclei, which are collected at the centre of 8pi where they undergo radioactive decay, located in ISAC-I.
Contact: Adam Garnsworthy

ARIEL *(Advanced Rare IsotopE Laboratory)* **-** A project to broaden TRIUMF's capabilities to produce rare isotope beams and to showcase new Canadian accelerator technology using electron beams.
Contact: Lia Merminga and Remy Dawson

β-NMR - β-detected NMR is an exotic form of nuclear magnetic resonance (NMR) in which the nuclear spin-precession signal is detected through the beta decay of a radioactive nucleus, located in ISAC-I.
Contact: Gerald Morris

CFBLS *(Collinear Fast-Beam Laser Spectroscopy)* **-** An experiment designed to exploit the high beam-intensity and radioisotope-production capability of the ISAC-I facility in order to measure the hyperfine energy levels and isotope shifts of short-lived isotopes.
Contact: Matthew Pearson

DESCANT *(DEuterated SCintillator Array for Neutron Tagging)* **-** A neutron detector array to be used at ISAC.
Contact: Paul Garrett

DRAGON *(Detector of Recoils and Gammas of Nuclear Reactions)* **-** A detector designed to measure the rates of nuclear reactions important in astrophysics, located in ISAC-I.
Contact: Chris Ruiz

EDM - The Radon EDM experiment uses contemporary spectroscopy techniques to measure the influence of a parity-violating external field on the angular distribution of gamma rays from polarized odd-spin Rn atoms.
Contact: Matthew Pearson

EMMA *(ElectroMagnetic Mass Analyzer)* **-** A device being constructed to study the products of nuclear reactions involving rare isotopes located in ISAC-II.
Contact: Barry Davids

FTF *(Francium Trapping Facility)* **-** A facility used to measure the anapole moment of francium in a chain of isotopes by observing its parity violating character, induced by the weak interaction.
Contact: Matthew Pearson

GRIFFIN *(Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei)* **-** A detector at ISAC for studying nuclear decays at high resolution.
Contact: Adam Garnsworthy

HERACLES *(HEavy-ion Reaction Array for the Characterization of Light Excited Systems)* **-** A device used for multi-fragmentation studies at intermediate energies, located in ISAC-II.
Contact: Gordon Ball

IRIS *(ISAC Charged Particles Spectroscopy Station)* **-** A detector designed to use nuclear reactions as a microscope to look into the core of nuclear isotopes with large neutron to proton ratios, located in ISAC-II.
Contact: Ritu Kanungo

SHARC *(Silicon Highly-segmented Array for Reactions and Coulex)* **-** Designed for stand-alone use or integration with TIGRESS, SHARC is a device suited for particle detection from reactions, located in ISAC-II.
Contact: Chris Ruiz

SPICE *(The SPectrometer for Internal Conversion Electrons)* **-** An in-beam electron spectrometer that operates in conjunction with TIGRESS, located in ISAC-II.
Contact: Adam Garnsworthy

TACTIC *(TRIUMF Annular Chamber for Tracking and Identification of Charged particles)* **-** A device used in conjunction with TUDA.
Contact: Chris Ruiz

TIGRESS (TRIUMF-ISAC Gamma-Ray Escape-Suppressed Spectrometer) **-** A detector in ISAC-II for studying nuclear decays at high resolution.
Contact: Greg Hackman

TIP *(TIGRESS Integrated Plunger)* **-** A device that uses accelerated radioactive and stable beams from ISAC-II and a variety of reaction mechanisms for electromagnetic transition studies of nuclei far from stability.
Contact: Greg Hackman

TITAN *(TRIUMF's Ion Trap for Atomic and Nuclear science)* **-** An ion trap facility at ISAC-I for high-precision mass measurements of rare isotopes.
Contact: Jens Dilling

TRINAT *(TRIUMF Neutral Atom Trap)* **-** A device to trap and study the radioactive decays of neutral atoms, located in ISAC-I.
Contact: John Behr

TUDA *(TRIUMF U.K. Detector Array)* **-** A detector designed to measure the rates of nuclear reactions important in astrophysics, located in ISAC-I
Contact: Chris Ruiz

UCN *(Ultra-Cold Neutrons)* **-** The UCN source allows experimenters to precisely measure neutron beta decay and quantum levels of neutrons in Earth's gravitational field. It also facilitates the search for the non-zero neutron electric dipole moment (nEDM).
Contact: Akira Konaka

7.3 Committees

Advisory Committee on TRIUMF (ACOT)

The Advisory Committee on TRIUMF advises the National Research Council on all aspects of the TRIUMF program insofar as they relate to the determination and administration of the federal contribution to TRIUMF. The Committee provides scientific program advice to the Director of TRIUMF. The Committee reports to the National Research Council each year on its findings and recommendations, with particular reference to the arrangement entered into by the National Research Council and TRIUMF, under which contribution payments are made, thereby ensuring that TRIUMF utilizes its program in support of its defined role as a national facility and works with all constituencies of the Canadian subatomic physics community to sustain a national program in the field of research, within the context of the funds available.

Members	Affiliation
Dr. D.B. Macfarlane (David) Chair	Associate Laboratory Director, SLAC, Standford University
Ms. D. Delanoe (Deva) Secretary	Planning and Policy Analyst, NRC
Dr. K. Borras (Kerstin)	CMS Group Leader, DESY
Dr. H. Bujis (Henri)	Senior Technical Director, ABB Bomen Inc.
Dr. C. Burgess	Professor, McMaster University
Dr. J.A. Lettry (Jacques)	Senior Physicist, CERN
Prof. P.F. Mantica (Paul)	Professor, Department of Chemistry and National Superconducting Cyclotron Laboratory, Michigan State University
Dr. B. Sherrill (Bradley)	FRIB Chief Scientist, National Superconducting Cyclotron Laboratory, Michigan State University
Prof. J.F. Valliant (John)	Acting Director, McMaster Institute of Applied Radiation Services
Prof. D.A. Weitz (David)	Mallinckrodt Professor of Physics and Applied Physics, Harvard University
Dr. S. Boughaba (Samir) Ex-Officio	Representing NSERC
Dr. R. Lewis (Randy) Ex-Officio	Chair, NSERC Subatomic Physics Evaluation Section
Prof. R.P. Young (Paul) Ex-Officio	Representing TRIUMF Board of Management
Prof. K.S. Sharma (Kumar) Ex-Officio	Representing Canadian Institute of Nuclear Physics
Prof. W. Trischuk (William) Ex-Officio	Representing Institute of Particle Physics

TRIUMF 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
University of Alberta	Dr. A. Hallin (Aksel)	Personnel and Administration
University of British Columbia	Dr. D. Brooks (Donald)	Chair of Finance, Executive, Technology Transfer
University of British Columbia	Dr. J. Hepburn (John)	TBA
Carleton University	Dr. K. Matheson (Kimberly)	Finance Executive
Carleton University	Dr. P. Kalyniak (Patricia)	Chair of Personnel and Administration
University of Manitoba	Dr. D.S. Jayas (Digvir)	Finance, Technology Transfer
University of Manitoba	Dr. M. Whitmore (Mark)	Personnel and Administration
University of Guelph	Dr. K. Hall (Kevin)	Finance
University of Guelph	Dr. A. Vannelli (Anthony)	TBA
Université de Montréal	Dr. L. Lewis (Laurent)	Finance
Université de Montréal	Dr. C. Leroy (Claude)	Personnel and Administration
Simon Fraser University	Dr. N. Haunerland (Norbert)	Finance
Simon Fraser University	Dr. C. Cupples (Claire)	Personnel and Administration
University of Toronto	Dr. R. Orr (Robert)	Personnel and Administration
University of Toronto	Dr. R.P. Young (Paul)	Chair of Board of Management Finance, Executive
University of Victoria	Dr. H. Brunt (Howard)	Finance, Executive
University of Victoria	Dr. R. Kowalewski (Robert)	Personnel and Administration
Queen's University	Dr. S.N. Liss (Steven)	Finance, Executive, Chair of Technology Transfer
Queen's University	Dr. D. Hanes (David)	Personnel and Administration
York University	Dr. R. Hache (Robert)	Finance, Executive
York University	Dr. S. Bhadra (Sampa)	Personnel and Administration
Private Sector Representative	Dr. P. Covitz (Peter)	
Private Sector Representative	Mr. E. Odishaw (Edward)	Technology Transfer
Associate Member Universities		
McMaster University	Dr. F. McNeill (Fiona)	
University of Calgary	Dr. R.I. Thompson (Robert)	Chair of Environmental Safety and Security
University of Northern British Columbia	Dr. G. Fondahl (Gail)	
University of Regina	Dr. D. Fitzpatrick (Dennis)	
Saint Mary's University	Dr. A.J. Sarty (Adam)	
University of Winnipeg	Dr. N. Besner (Neil)	
Non-Voting Member		
Vice President, Physical Sciences, NRC	Dr. D. Wayner (Dan)	
Director, TRIUMF	Dr. N.S. Lockyer (Nigel)	
Chair, ACOT	Dr. D.B. Macfarlane (David)	
Secretary	Mr. J. Hanlon (Jim)	

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 Canadian research communities and member universities.

PPAC includes one member from each of the full member univerisites. 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 dares will be staggered to ensure the Committee has continuity on important issues. Reappointment should only occur in exceptional circumstances and may only be for one year.

Member	University
Dr. C. Gay (Colin) Chair	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

TRIUMF Accelerator Advisory Committee (AAC)

The Accelerator Advisory Committee (AAC) provides advice to the TRIUMF Director and the Head of the Accelerator Division about recent activities and proposed future initiatives. The AAC was convened in 2008 and performed critical work in preparing the Five-Year Plan 2010-2015.

Member	Institution
Mark de Jong Chair	Canadian Light Source
Marco Schippers	Paul Scherrer Institute
Mats Lindroos	CERN
Sergei Nagaitsev	Fermi National Accelerator Laboratory
Hasan Padamsee	Cornell University
Charles Sinclair (Retired)	Thomas Jefferson National Accelerator Facility

Experimental Evaluation Committees (EECs)

The Experimental Evaluation Committees review and approve new and ongoing experiments.

Three EECs are in place at TRIUMF: The Subatomic Physics (SAP) EEC, the Molecular and Materials Science (MMS) EEC, and the Life Science Projects (LSPEC) EEC. SAP and MMS meet biannually at TRIUMF in June/July and December, and LSP meets annually in April. The purpose of these committees is to review new research proposalas, which are presented at the biannual and annual meetings, and advise TRIUMF's management on the feasability of such research proposals and 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 the 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 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.

LSPEC: Life Science Projects

- Dr. R. Mach (Robert) - Chair / Président
- Dr. P. Schaffer (Paul) - Ex-Officio / Membre d'office
- Dr. D.A. Hutcheon (Dave) - Secretary / Secrétaire
- Dr. N.E. Avril (Norbert)
- Dr. J. Karp (Joel)
- Dr. J. McConathy (Jon)
- Dr. R. Menon (Ravi)
- Dr. F. Wuest (Frank)

MMS-EEC: About Molecular and Materials Science

- Dr. R. Cywinski (Bob) - Chair / Président
- Dr. R. Kruecken (Reiner) - Ex-Officio / Membre d'office
- Dr. I. McKenzie - Secretary / Secrétaire
- Dr. L. Balents (Leon)
- Dr. K. Chow (Kim)
- Dr. Y.-B. Kim (Yong-Baek)
- Dr. D. MacLaughlin (Douglas)
- Dr. S. Nagler (Stephen)
- Dr. E. Roduner (Emil)

SAP-EEC: Subatomic Physics

- Dr. A. Galindo-Uribarri (Alfredo) - Chair / Président
- Dr. R. Kruecken (Reiner) - Ex-Officio / Membre d'office
- Dr. P. Navratil (Petr) - Secretary / Secrétaire
- Dr. R. Clark (Rod)
- Dr. A. Garcia (Alejandro)
- Dr. K. Riisager (Karsten)
- Dr. C. Ruiz (Chris)
- Dr. G. Savard (Guy)
- Dr. H. Schatz (Hendrik)
- Dr. A. Schwenk (Achim)

Innovations and Industrial Partnerships Panel

- Josef Orzechowski
- Henry Chen
- Jim Hanlon, *Chair*
- Ewart Blackmore
- Nigel Lockyer
- Yuri Bylinsky
- Mike Trinczek
- Neil McLean
- Tim Meyer

TRIUMF Kitchen Cabinet Advisory Committee

- Jean-Michel Poutissou (Emeritus)
- Ewart Blackmore
- Paul Schmor
- Phil Gardner
- Paul Delheij
- Lothar Buchmann
- Chris Ruiz
- Matt Pearson
- Greg Hackman
- Igor Sekatchev
- Jens Lassen

Continued on the following page

- Shane Koscielniak
- Yuri Bylinsky
- Fred Bach
- Colin Morton
- Rolf Keitel
- Phil Jones
- John Drozdoff
- John Ng
- Achim Schwenk
- Makoto Fujiwara
- Reda Tafirout
- Andy Miller
- Chris Oram
- Mike Adam
- Bassam Hitti
- Stan Yen

TRIUMF User Executive Committee (TUEC)

Chair:

Adam Garnsworthy (TRIUMF)

Chair Elect:

Khashayar Ghandi (Mt. Allison University)

Past Chair:

Andrew MacFarlane (UBC)

Members-at-Large:

Ulrike Hager (Colorado School of Mines)
Kris Starosta (SFU)
Anadi Canepa (TRIUMF)
Catherine Deibel (LSU)

Liaison Officer:

Reiner Kruecken (TRIUMF)

7.4 Collaborations and Groups

Accelerator Research

Group Leader: Lia Merminga (TRIUMF)

TRIUMF Staff: Yuri Bylinski, Robert Laxdal, Rick Baartman, Pierre Bricault, Shane Koscielniak, Amiya Mitra, Yu-Chiu Chao, Yi-Nong Rao, Marik Dombsky, Keerthi Jayamanna, Jens Lassen, Friedhelm Ames, Marco Marchetto, Fred Jones, Dobrin Kaltche, Suresh Saminathan, Ken Fong, Conny Hoehr, Thomas Planche , Victor Verzilov, Peter Kunz

ALPHA

Spokesperson: Jeffrey Hangst, Aarhus University

Canadian Group Leader: Makoto Fujiwara, TRIUMF

TRIUMF Staff: Art Olin, Dave Gill, Simone Stracka, James Storey, Konstantin Olchanski, Leonid Kurchaninov

Canadian Institutions: University of British Columbia, Simon Fraser University, University of Calgary, York University

Other Countries: UK, USA, Denmark, Brazil, Israel, Japan, Sweden

ATLAS

ATLAS Spokesperson: Fabiola Gianotti, CERN

ATLAS-Canada Spokesperson and PI: Robert McPherson, IPP/U.Victoria

TRIUMF Staff signing ATLAS papers, in alphabetical order: Anadi Canepa, Oliver Stelzer-Chilton, Reda Tafirout, Isabel Trigger

TRIUMF Post-docs and Research Associates signing ATLAS papers: Sergey Chekulaev, Dominique Fortin, Alex Koutsmann, Estel Perez-Codina, Doug Schouten, Rolf Seuster

TRIUMF Staff working on ATLAS but not signing ATLAS papers: Valery Akhnazarov, Asoka De Silva, Denice Deatrich, Vitaliy Kondratenko, Leonid Kurchaninov, Roy Langstaff, Simon Liu, Di Qing, Andrew Wong

TRIUMF co-supervised students on ATLAS: Ewan Hill, Arash Khazraie, Sam King, Stephen Swedish, Simon Viel, Rajan Devbhandri, Yun-Ha Shin.

Canadian Institutions: University of Alberta, University of British Columbia, Carleton University, McGill University, Université de Montréal, Simon Fraser University, University of Toronto, TRIUMF, University of Victoria, York University

Other Countries: Argentina, Armenia, Australia,

Azerbaijan, Brazil, Canada, Chile, China, Colombia, Czech Republic, Denmark, France, Georgia, Germany, Greece, Israel, Italy, Japan, Morocco, Netherlands, Norway, Poland, Portugal, Belarus, Romania, Russia, Serbia, Slovak Republic, Slovenia, South Africa, Spain, Sweden, Swizerland, Taiwan, Turkey, UK, USA

CMMS

CMMS is a user facility run by TRIUMF's Iain McKenzie, Syd Kreitzman, Gerald Morris

DEAP

Project Leader: M. Boulay, Queens

TRIUMF Staff: P-A. Amaudruz, D. Bishop, S. Chan, K. Langton, C. Lim, T. Lindner, A. Muir, C. Ohlmann, K. Olchanski, F. Retiere
Temporary TRIUMF staff (paid by CFI): B. Kelly and S. Mead

Canadian Researchers:
Aksel Hallin, University of Alberta
K. Graham, Carleton University
M. Boulay, Queens University,
C. Jillings, Laurentian University
F. Duncan, SNOLAB

Other countries: UK

Laser Spectroscopy

TRIUMF: M.R. Pearson

McGill: F. Buchinger (Lecturer) , J. Crawford (Emeritus Professor), O.T.L. Shelbaya (MSc. Student), S. Gulick (Staff)

University of Manchester, UK: A. Voss (PhD. Student) joint with TRIUMF, J. Billowes (Professor), B. Cheal (Research Council Advanced Fellow)

Michigan State University, USA: P. Mantica (Professor), K. Minamisono (Physicist)

Nuclear Astrophysics

Group Leaders: Lothar Buchmann, Barry Davids Chris Ruiz (rotating)

Other Participating TRIUMF Staff: Petr Navtatil, Sonia Bacca

Canadian Faculty: Falk Herwig (UVic), Alan Chen (McMaster)

Other Countries: USA, UK, Spain, Israel, Switzerland

Nuclear Medicine

Group Leader: P. Schaffer

TRIUMF Staff: M. Adam, K. Buckley, T. Ruth, J. Poutissou, G. Sheffer, M. Dodd, H. Yang, V. Hanaameyer, J. Klug, Q. Miao, S. Zeisler

SNO+

Project Leader: Mark Chen, Queen's University

TRIUMF: Richard Helmer

Canadian Institutions: University of Alberta, Laurentian University, Queen's University, SNOLAB

Other countries: USA, UK, Germany, Portugal

T2K

Canadian Group Leader: Scott Oser (UBC)

Collaboration Spokespeople: Takashi Kobayashi (KEK), Chang Kee Jung (Stonybrook)

TRIUMF: Research Scientists
Richard Helmer, Akira Konaka, Andrew Miller, Jean-Michel Poutissou, Renee Poutissou, Fabrice Retiere, Stanley Yen, Thomas Lindner

TRIUMF: Technical Staff
Pierre-Andre Amaudruz, Wayne Faszer, Peter Gumplinger, Robert Henderson, David Morris, Konstantin Olchanski, Robert Openshaw, Peter Vincent

TRIUMF: Postdocs, etc.
Sujeewa Kumaratunga, Kendall Mahn, Michael Wilking, Simon Claret

Canadian Institutions: University of Victoria, University of British Columbia, TRIUMF, University of Alberta, University of Regina, University of Toronto, York University

Other countries: Poland, Switzerland, USA, France, Korea, Japan, Spain, UK, Italy, Russia, Germany

Theory

Research Scientists: S. Bacca, D. E. Morrissey, P. Navratil, J. N. Ng, R. M. Woloshyn

Postodctoral Research Associates: A. Kumar, D. Mohler, F. Raimondi, C. Romero-Redondo, R. Sharma, A.P. Spray

TIGRESS/8π/GRIFFIN

Group Leader: G. Hackman, TRIUMF

TRIUMF Staff: G.C. Ball, A.B. Garnsworthy, R. Kruecken

Canadian Institutions: Queen's University, Saint Mary's University, Simon Fraser University, University of British Columbia, Université de Montréal, University of Guelph, University of Toronto

Countries: England, France, Germany, India, Italy, Scotland, Spain, USA
Scotland, Spain, USA

TITAN

Group Leader: Jens Dilling, TRIUMF

TRIUMF Staff: Matt Pearson, Mel Good, Ernesto Mané, Martin Simon, Brad Schultz, Ankur Chaudhuri, Anna Kwiatkowski, Alexander Grossheim

Canadian Institutions: McGill University, University of Manitoba, York University, University of Windsor, University of Calgary

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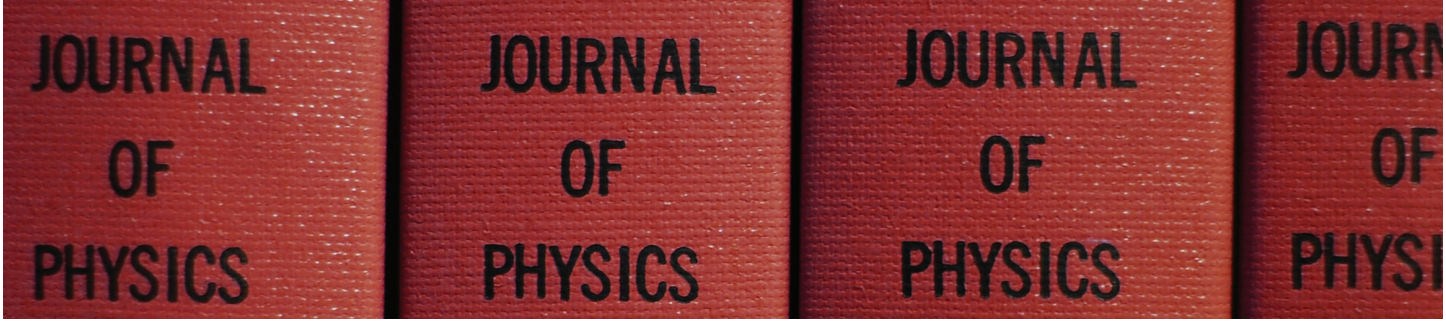

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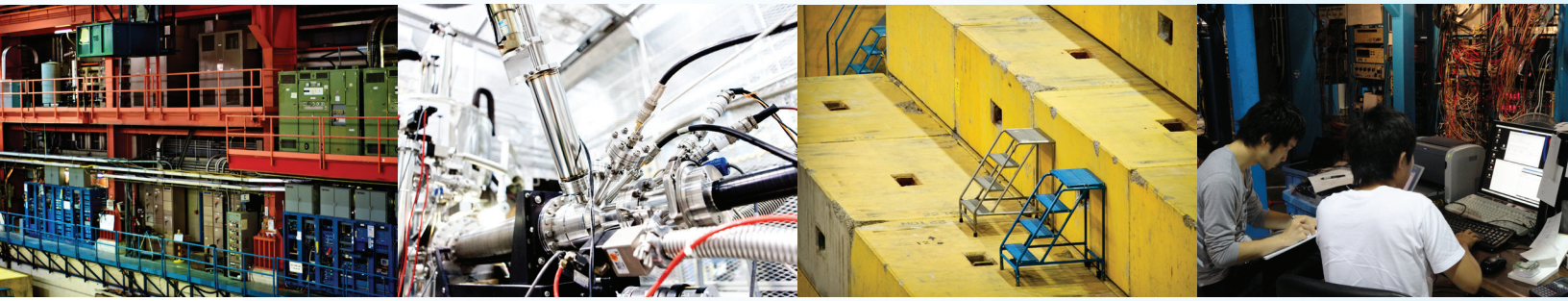

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