Chapter 4

# Successes: Impacts 2003–2008

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# 4.1

# Introduction

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

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

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

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

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

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

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

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

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

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

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

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

# 4.2

# Advancing Knowledge

# 4.2.1

# Subatomic Physics

# 4.2.1.1

# Rare-Isotope Beam Experiments

# 4.2.1.1.1

# Introduction

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

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

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

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

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

# 4.2.1.1.2.1

# The Structure of Halo Nuclei

## Introduction

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

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

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

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

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

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

# Results and Progress

## Correlation of Halo Neutrons in $^{11}$Li

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

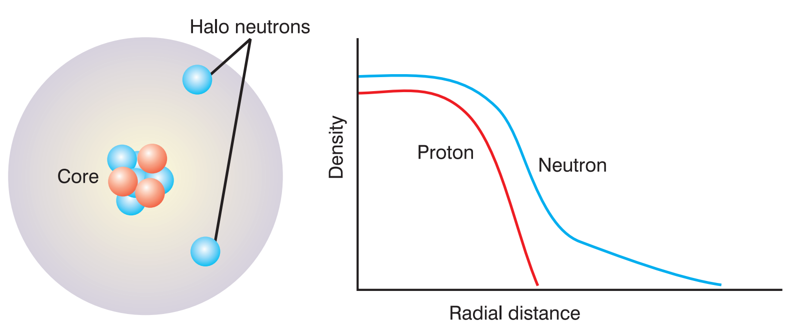


**Figure 1:** Schematic view of a two-neutron halo.

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

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

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

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

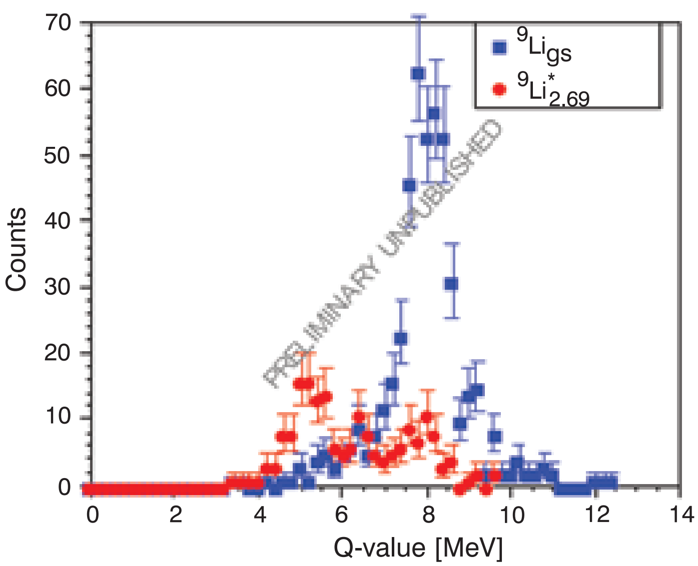


**Figure 2a:** Q-value spectrum for $^{11}$Li($p,t$)$^{9}$Li reaction. The squares (blue) show $^{9}$Li ground state while the circles (red) show the $^{9}$Li excited state.

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

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

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

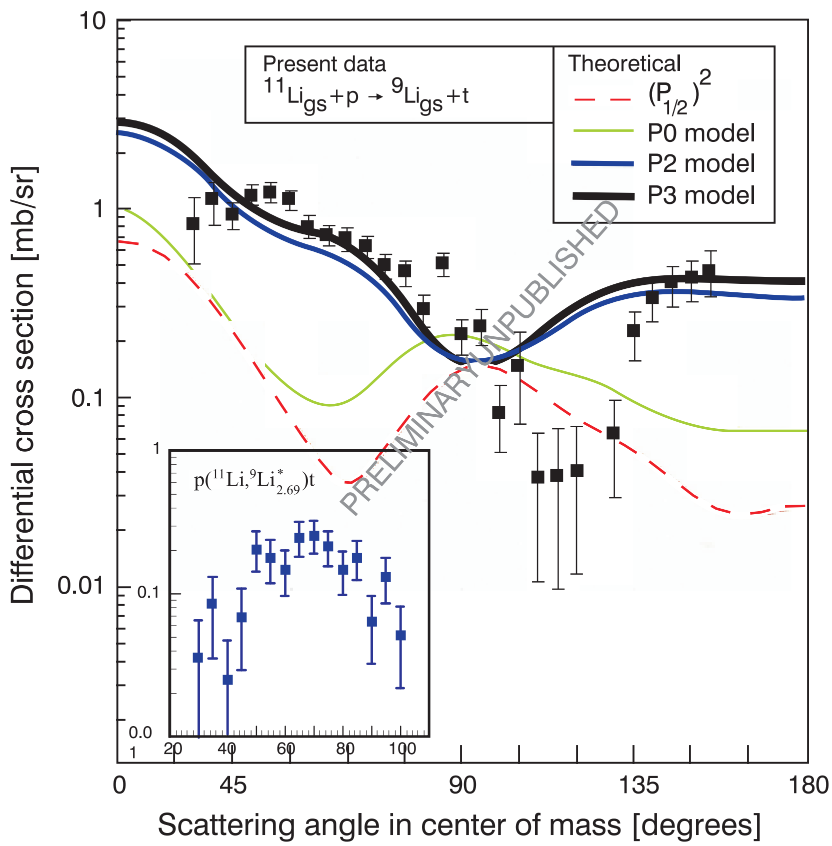


**Figure 2b:** The angular distribution data for $^{11}$Li(*p,t*)$^9$Li (squares). The curves are coupled channel calculations using different model wave functions as explained in the text.

### Charge Radius of $^{11}$Li

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

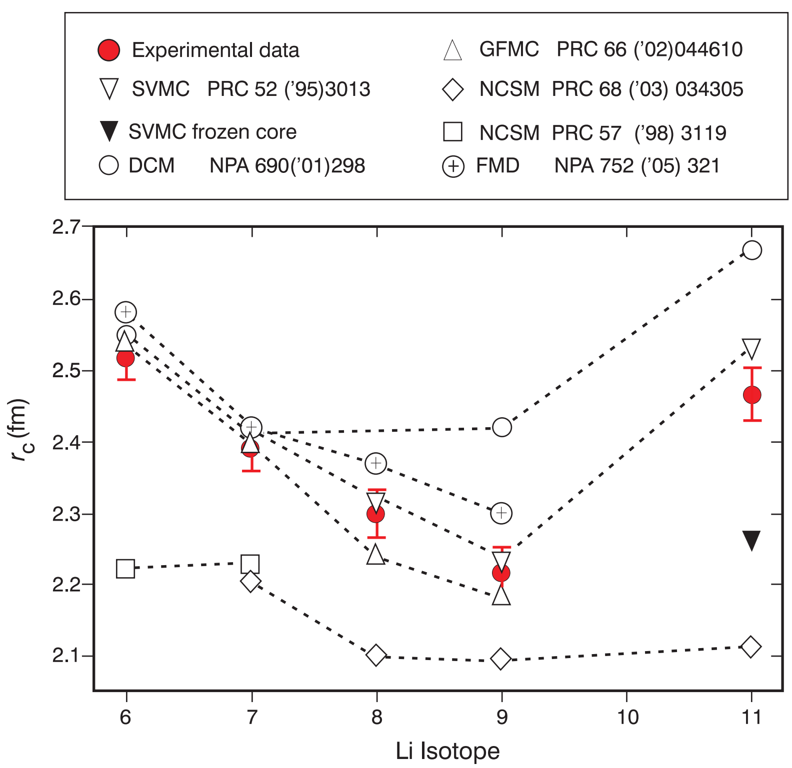


**Figure 3:** Charge radii for $^{6\text{-}11}$Li. (Figure adopted from Phys. Rev. Lett. 96 (2006) 033002.) The red filled circle shows the experimental data. The other symbols are the different theoretical calculations. SVMC= Stochastic Variational Monte Carlo, DCM = Dynamic Correlation Model, GFMC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

## Masses of Halo Nuclei

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

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

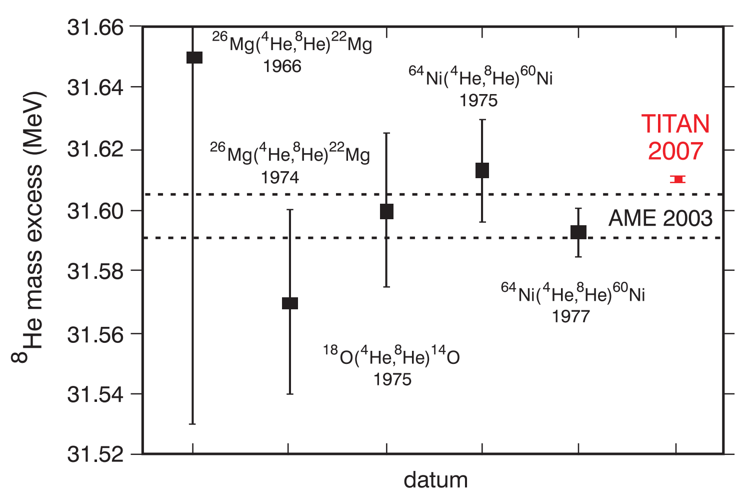


**Figure 4a:** Comparison of mass excess of $^8$He measured using different methods as labeled in the figure.

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

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

## Beta Decay of $^{11}Li$

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

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

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

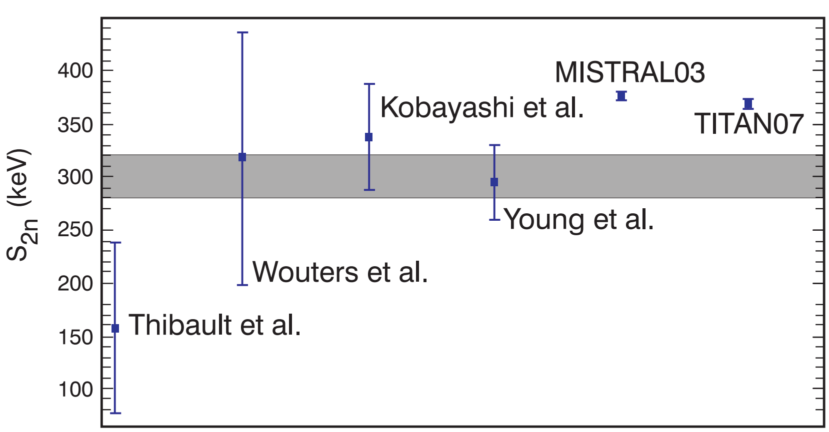


**Figure 4b:** Comparison of two-neutron separation energy for $^{11}$Li from different mass measurements as labeled in the figure.

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

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

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

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

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

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

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

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

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

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

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

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

## Disappearance of Shell closure in *N*=20 region

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

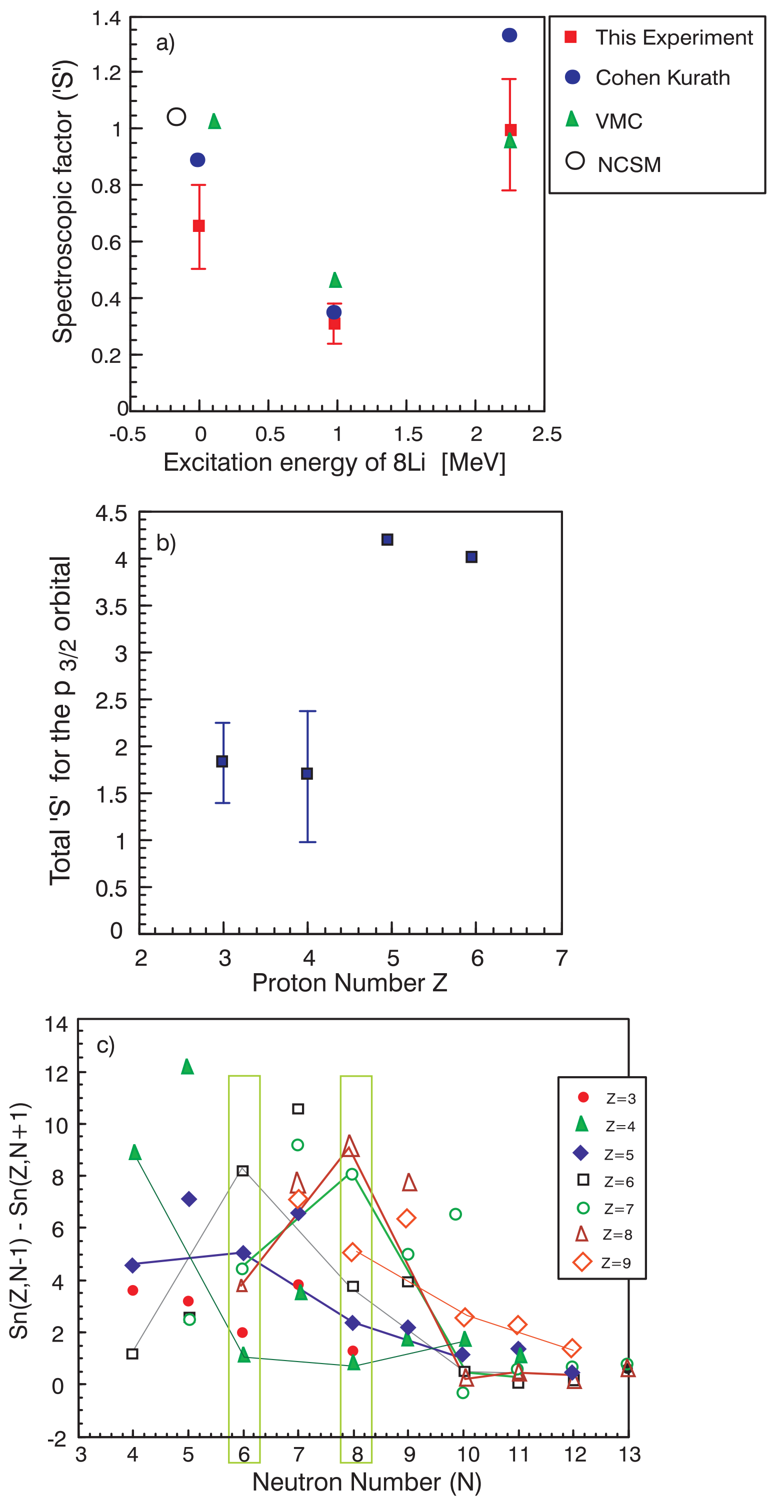


**Figure 5:** (a) Spectroscopic factors for ($^{9}$Li,$^{8}$Li) overlaps compared to various theoretical predictions. VMC = Variational Monte Carlo, NCSM = No core shell model. (b) Total spectroscopic factors for $p_{3/2}$ orbital in the *N*=6 isotones from Li to C. (c) A measure of shell gap at *N*=6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

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

# Partners

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

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

# TRIUMF's Role

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

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

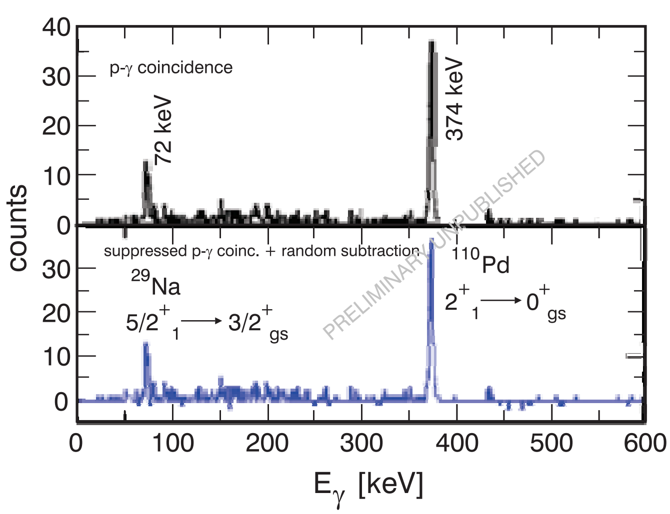


**Figure 6:** Gamma rays observed in the Coulomb excitation of $^{29}$Na.

# 4.2.1.1.2.2

# The Structure of Heavy Nuclei

## Introduction

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

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

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

# Results and Progress

## Evolution of Shell Structure

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

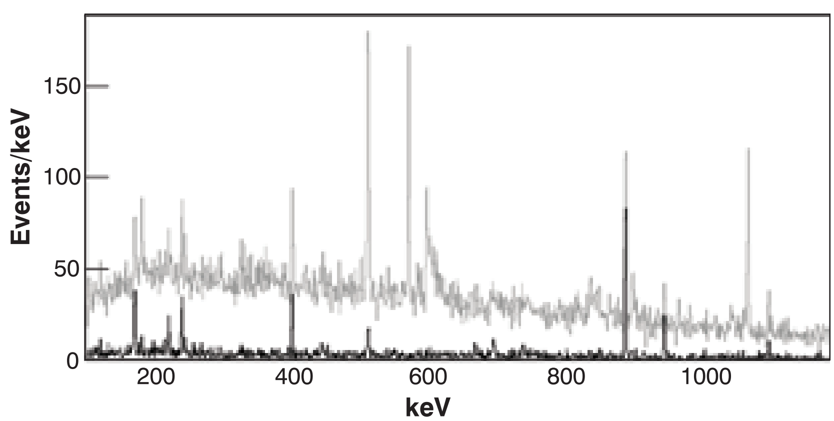


**Figure 1:** Projections of the γγ coincidence matrix (light spectrum) and βγγ coincidence matrix (dark spectrum) resulting from $^{32}$Na β-decay. The use of the β-particle coincidence removes the uncorrelated background allowing for the transitions to be identified and placed in the $^{32}$Mg level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

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

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

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

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

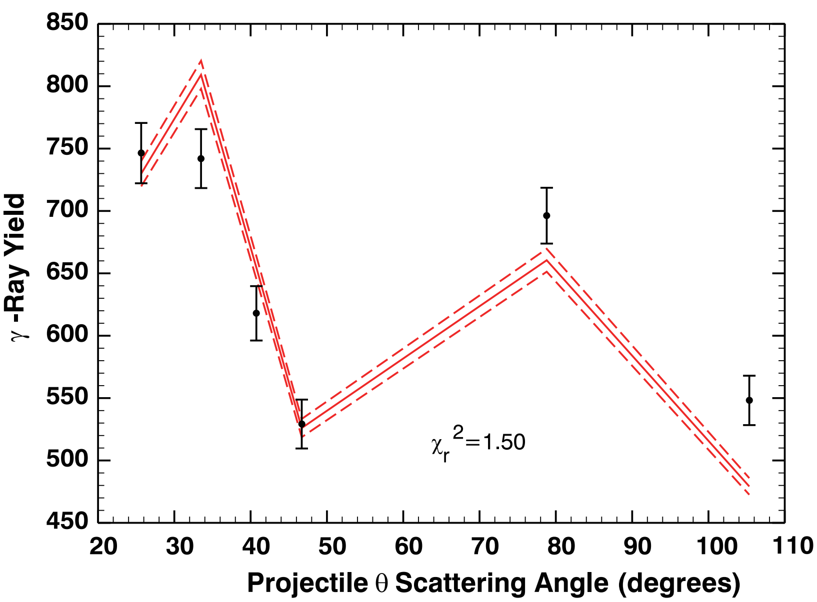


**Figure 2:** Yields of the $^{21}$Na 332-keV $5/2^+ \rightarrow 3/2^+$ transition as a scattering angle. The curves represent calculated yields using the GOSIA code.

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

## Investigation of Collective Excitations

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

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

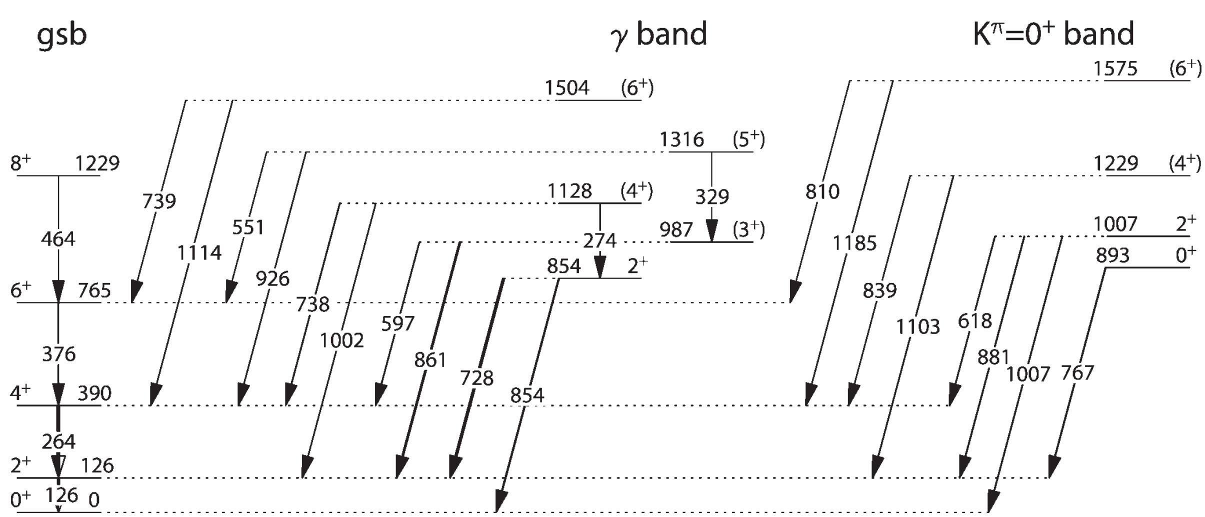


**Figure 3:** Partial level scheme for $^{160}Er$ established from $^{160}Tm$ decay observed with the 8π spectrometer. From P.E. Garrett et al., Acta Physica Polonica B 38, 1169 (2007).

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

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

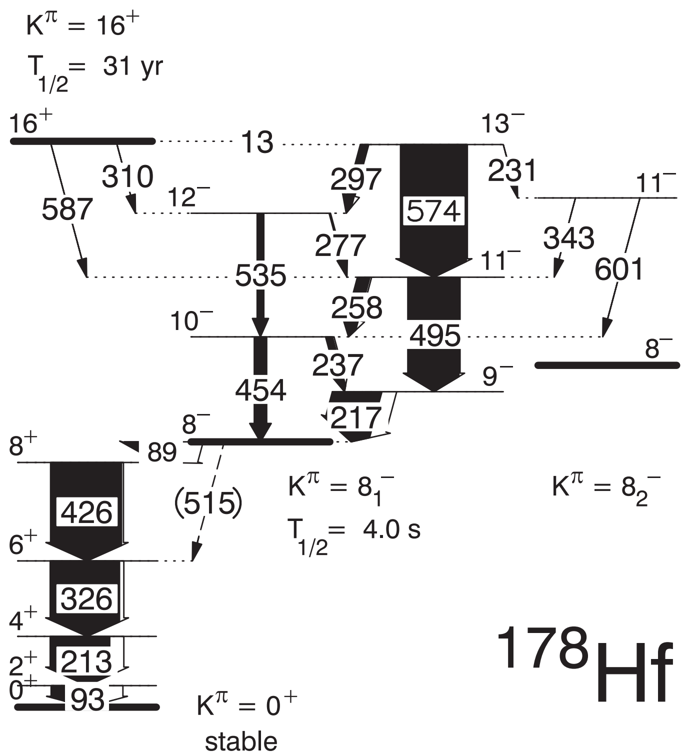


**Figure 4:** Level scheme following the decay of the $t_{1/2}$ = 31 y $K^{\pi}$=16$^{+}$ isomer in $^{178}$Hf observed with the 8π spectrometer. The 310 keV M4 and 587 keV E5 transitions are newly placed. From M.B. Smith et al., Phys. Rev. C 68, 031302(R) (2003).

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

# Partners

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

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

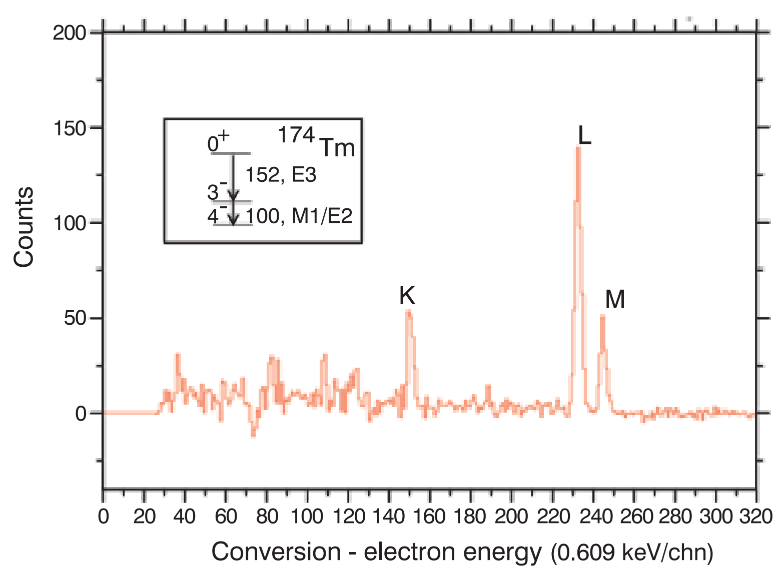


**Figure 5:** Conversion electron spectrum in coincidence with the 100 keV γ-ray in $^{174}$Tm. The use of PACES was critical in establishing the isomer decay scheme (inset). From R.S. Chakrawarthy et al., Phys. Rev. C 73, 024306 (2006).

# TRIUMF's Role

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

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

# 4.2.1.1.3

# Nuclear Astrophysics

## Introduction

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

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

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

# Results and Progress

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

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

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

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

## Explosive Hydrogen Burning and Characteristic Gamma Emitters

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

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

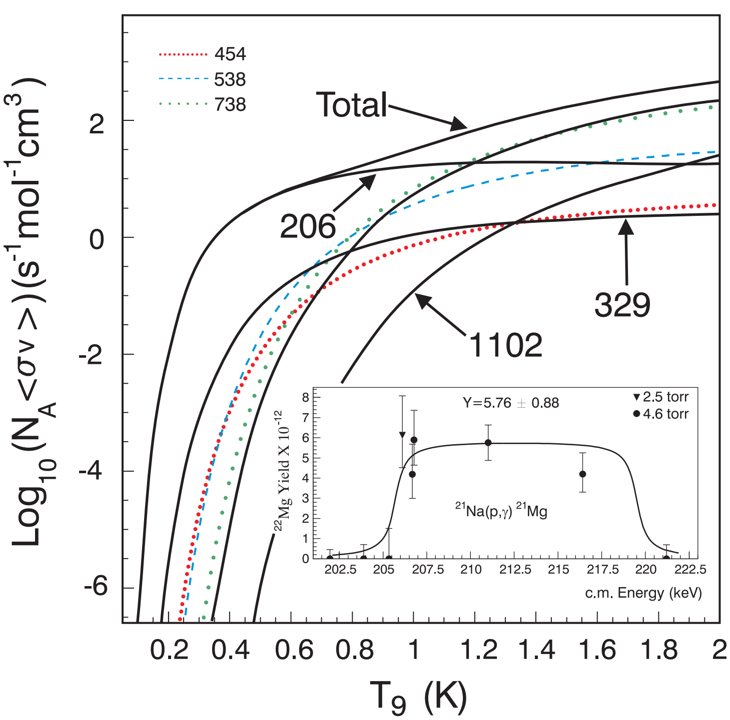


**Figure 1:** Temperature-dependent reaction rates for the $^{21}$Na($p$,γ)$^{22}$Mg reaction, showing contributions from some of the resonances measured at DRAGON. **Inset:** Thick-target scan over the narrow, dominant 206 keV resonance.

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

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

### Measurement of the $^{21}Na(p,\gamma)^{22}Mg$ Reaction

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

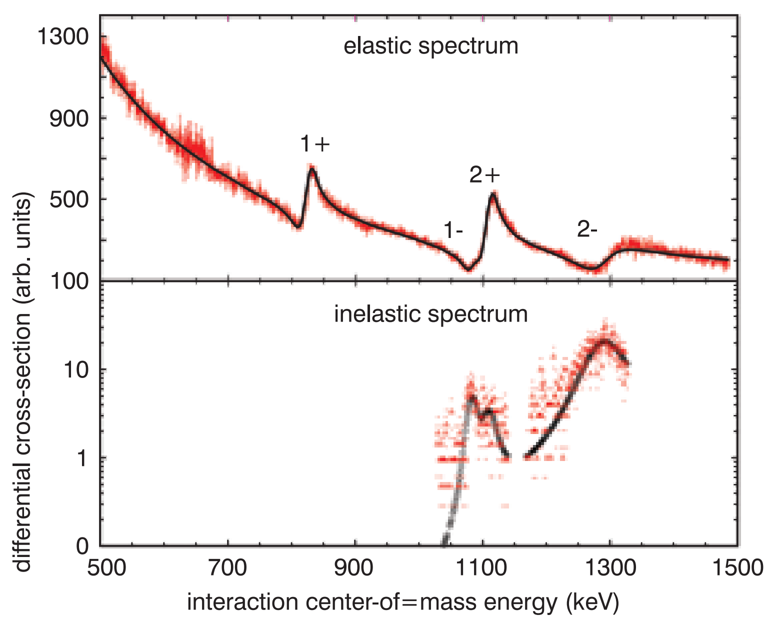


**Figure 2:** TUDA excitation function from $^{21}Na(p,p)$ and $^{21}Na(p,p')$ scattering, fitted with a multichannel R-matrix.

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

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

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

## Measurement of the $^{26g}Al(p,\gamma)^{27}Si$ Reaction

Also of significant importance to explosive hydrogen burning scenarios is the synthesis of the radioisotope $^{26}Al$. This isotope, with its characteristic γ-ray at 1809 keV, has long been a target for γ-ray astronomers. Because of its relatively long half-life [$t_{1/2}=(7.2\pm0.2)\times10^5$ yr], it provides insufficient flux given the ejected yields from stellar objects to enable detection from an individual source. However, the bulk of the $^{26}Al$ produced in our galaxy from all sources does provide enough γ-ray flux to be measured (see Figure 3).

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

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

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

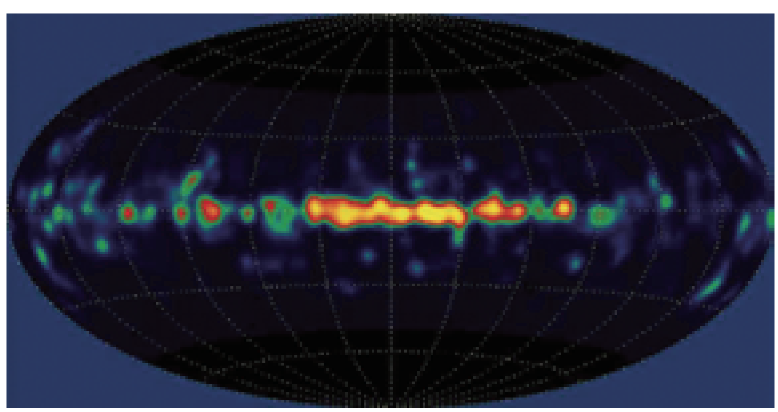

**Figure 3:** COMPTEL All-Sky map of the Galactic distribution of $^{26}$Al, as determined by the flux of the characteristic 1809 keV gamma ray.

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

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

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

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

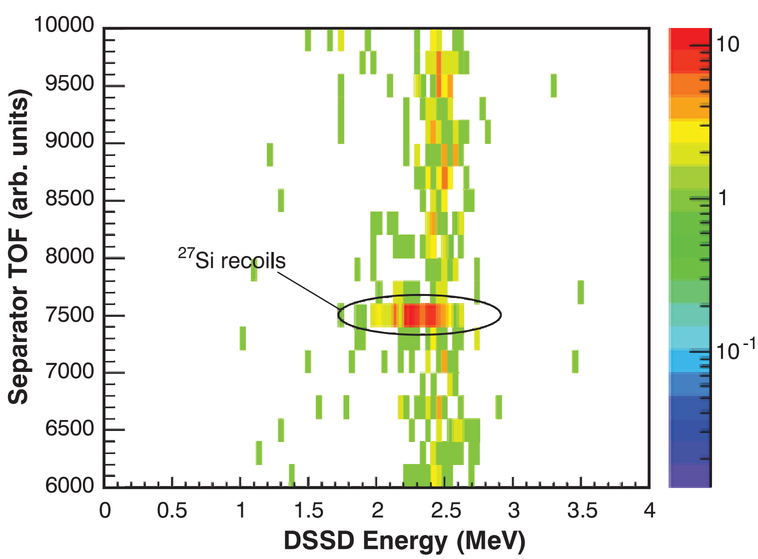


**Figure 4:** Detected Energy vs Time-of-flight plot showing gamma-coincident $^{27}$Si recoils from the extremely weak $^{26}$Al(p,γ)$^{27}$Si reaction against a random background.

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

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

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

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

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

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

## Stellar Evolution and Helium Burning in Massive Stars

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

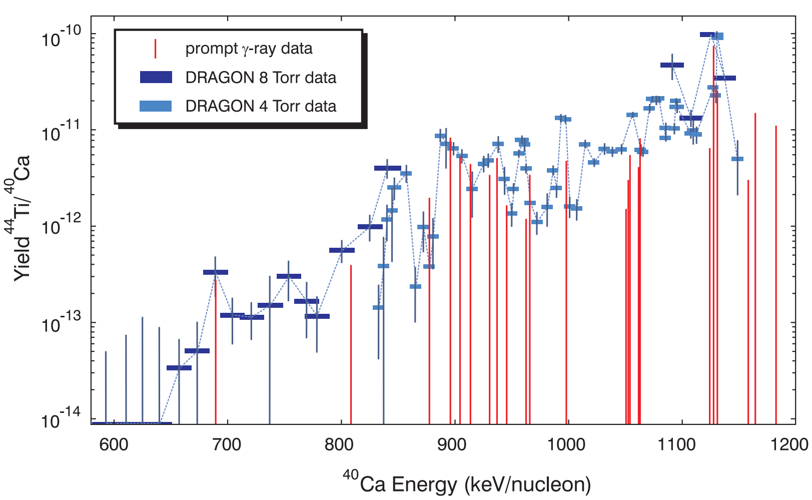


**Figure 5:** Excitation function of the $^{40}$Ca(α,γ)$^{44}$Ti reaction in the astrophysical energy range as measured by DRAGON, shown against previous experimental data.

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

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

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

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

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

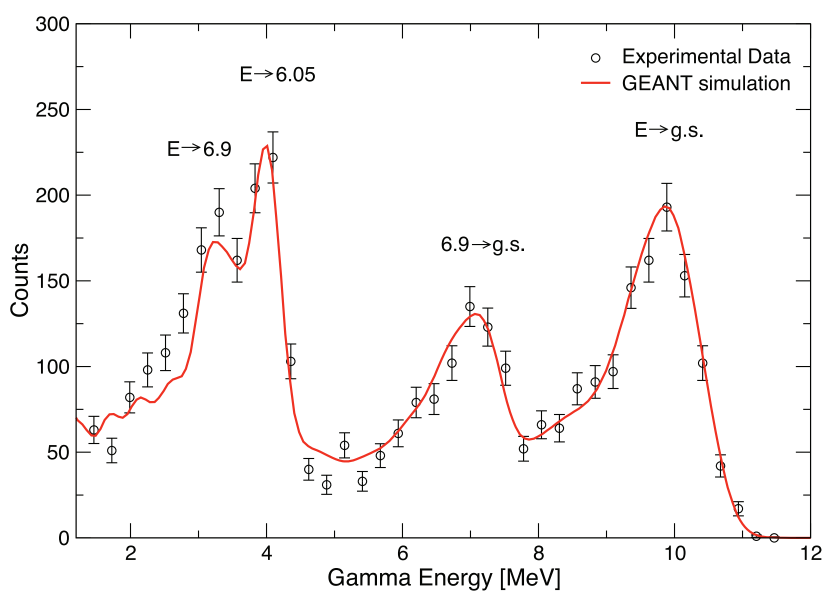


**Figure 6:** DRAGON gamma-ray spectrum for the $^{12}C(\alpha,\gamma)^{16}O$ reaction, shown with GEANT simulation results which include pair-decay from the 1st excited state of $^{16}O$.

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

Using R-Matrix fits, including both the E1 and E2 contributions to this cascade, an extrapolation was made (see Figure 7) that takes into account the interference between higher lying resonances, direct capture, and the sub-threshold resonances. A value of the *S*-factor of $S_{6\overline{H}_0}(300) = 25^{+16}_{-15}$ keVb was determined from this data [C. Matei *et al.*, Physical Review Letters 97 (2006)]. Given the value of $S_{total}(300)$ = 170 keVb for static helium burning argued from stellar nucleosynthesis models, and the fact that this *S*-factor is required to less than 10%, the cascade through the first excited state of $^{16}O$ can no longer be ignored and makes up a significant proportion (15%) of the total reaction strength. This conclusion is only made possible due to the unique capabilities of the DRAGON facility.

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

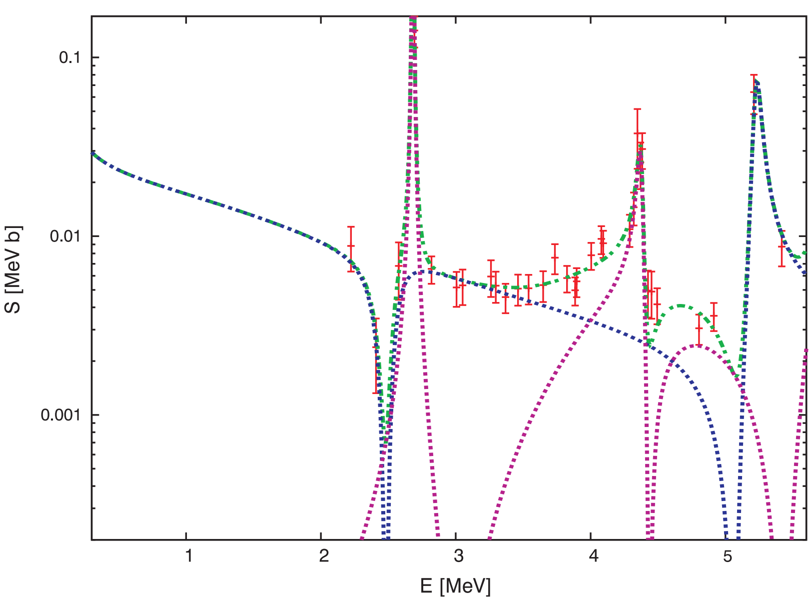


**Figure 7:** S-factor for cascades through the 6.0 MeV state in $^{16}O$ in the $^{12}C(\alpha,\gamma)^{16}O$ reaction, fitted with R-Matrix and including both the E1 (short-dashed), E2 (dotted) and total (long-dashed) components.

## The Nuclear Trigger for X-ray Bursts

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

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

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

where $B_\alpha$ is the alpha-branching ratio and τ is the mean lifetime of the state.

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

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

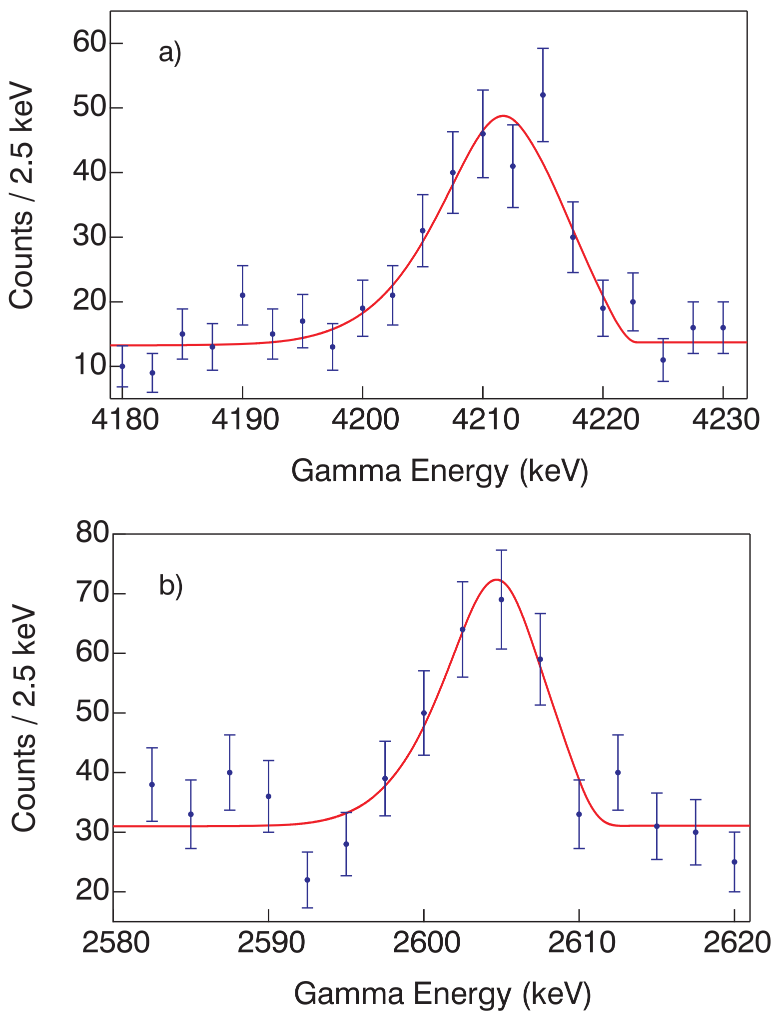


**Figure 8:** Doppler-shifted line shapes due to two transitions of the 4035 keV level in $^{19}Ne$, populated in the TRIUMF $^{3}He(^{20}Ne,^{4}He)^{19}Ne$ experiment, from which the state lifetime was extracted.

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

## Additional Studies and Future Directions

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

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

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

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

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

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

# Partners

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

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

# TRIUMF's Role

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

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

# 4.2.1.1.4.1

# Superallowed β-Decay Studies

## Introduction

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

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

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

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

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

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

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

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

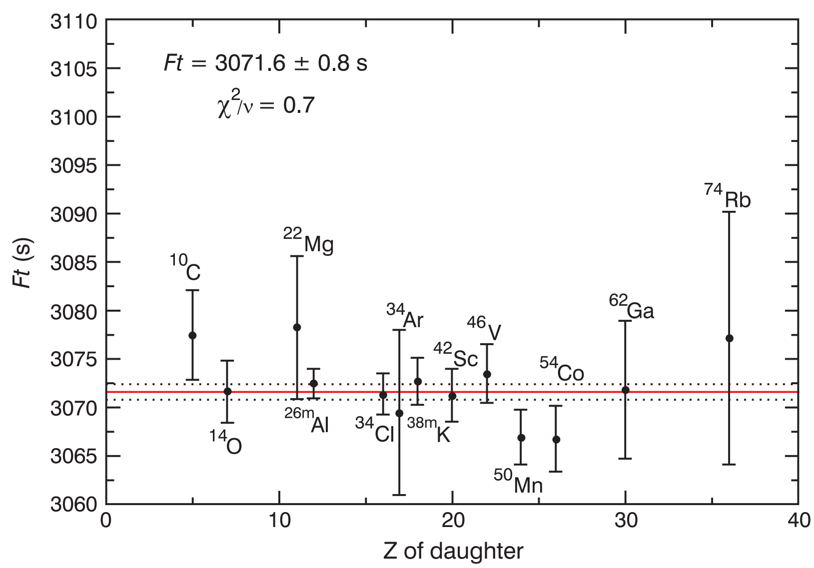


**Figure 1:** Present status of the *Ft* values for the 13 most precisely determined superallowed decays and the overall weighted average *Ft* with corresponding statistical uncertainty and reduced $\chi^2$ value. The data are taken from I.S. Towner and J. C. Hardy, arXiv:0710.3181vi [nucl-th] Oct 2007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

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

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

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

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

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

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

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

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

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

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

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

# Description of Dedicated Apparatus: GPS Experimental Station

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

## Results and Progress

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

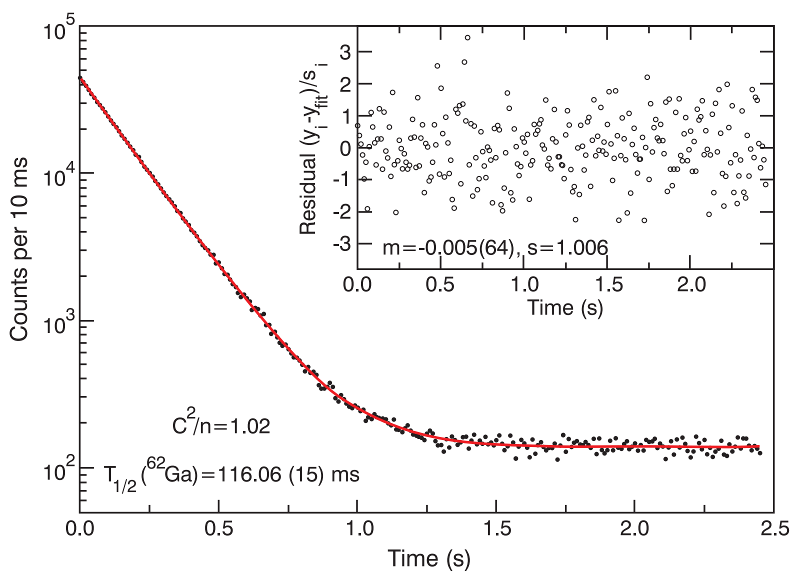


**Figure 2:** Dead time corrected decay curve from a single $^{62}$Ga run summed over 1668 cycles.

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

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

# Description of Dedicated Apparatus: 8π Spectrometer

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

## Results and Progress

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

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

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

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

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

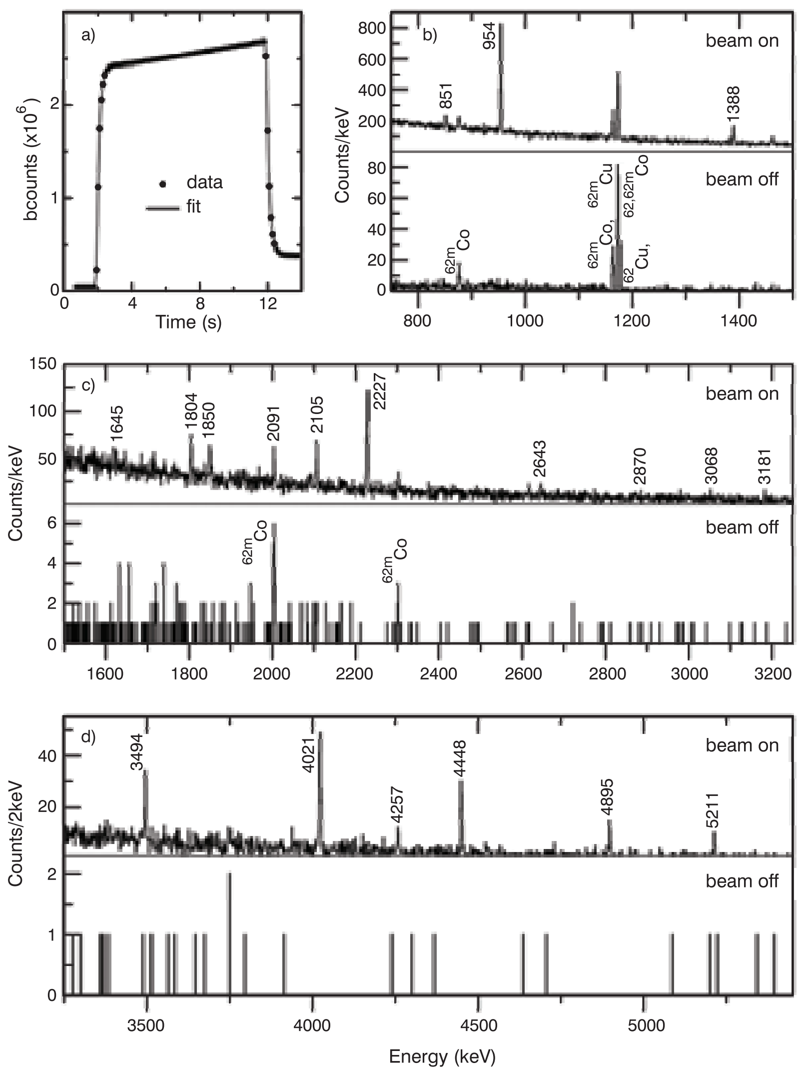


**Figure 3:** The γ-ray spectra obtained with the 8π spectrometer for the β-decay of $^{62}$Ga: (a) β activity observed in SCEPTAR and (b)-(d) Compton and bremsstrahlung suppressed coincident γ-ray spectra for the “beam-on” (upper panels), and “beam-off” (lower panels) periods.

## Results and Progress

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

## Other Recent Measurements, and Future Plans

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

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

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

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

# Partners

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

# TRIUMF's Role

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

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

# 4.2.1.1.4.2

# Fundamental Symmetries: Exotic Physics Searches

## Introduction

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

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

# Results and Progress

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

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

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

$$a = \frac{(|C_v|^2 + |C'_v|^2) - (|C_s|^2 + |C'_s|^2)}{|C_v|^2 + |C'_v|^2 + |C_s|^2 + |C'_s|^2}$$

$$b = \frac{-2\sqrt{(1 - (\alpha Z)^2)}\ \mathrm{Re}(C_s + C'_s)}{|C_v|^2 + |C'_v|^2 + |C_s|^2 + |C'_s|^2}$$

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

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

The result from the first experiment is:

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

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

## Right-Handed Currents

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

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

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

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

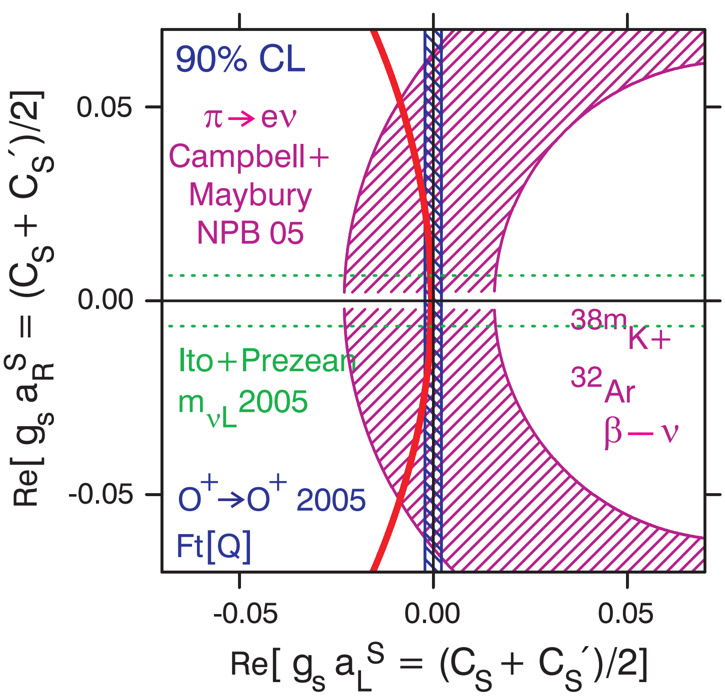


**Figure 1:** Constraints on first generation scalar couplings.

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

## Tensor Interactions

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

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

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

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

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

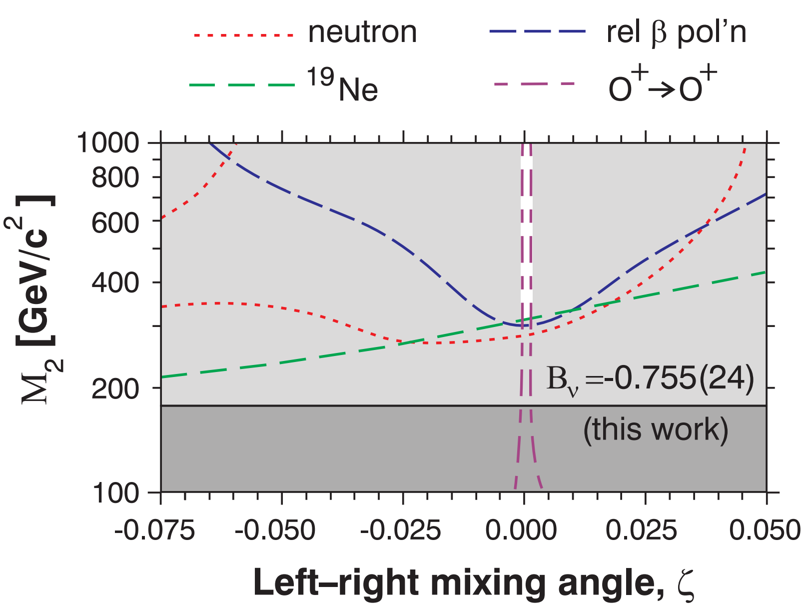


Figure 2: Exclusion plot for right-handed currents including current limits from TRINAT.

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

## Exotic Massive Particles

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

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

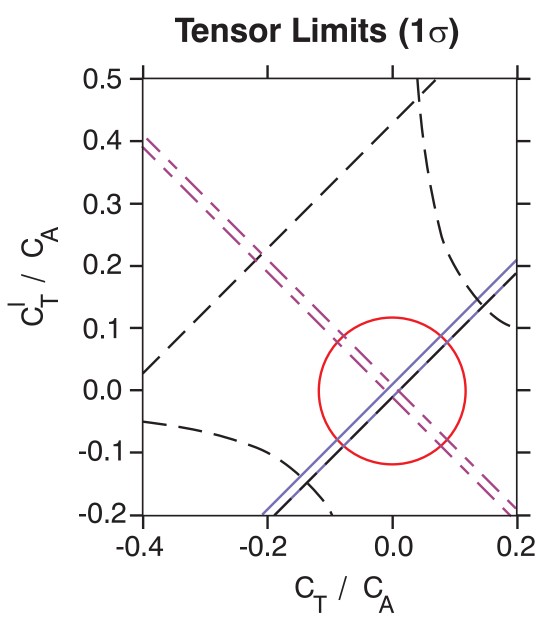


**Figure 3:** Exclusion plot showing complementarity of the present $^{80}$Rb constraints to other measurements. Allowed regions are consistent with the standard model inside: red circle, $^6$He β-neutrino at ORNL, blue solid lines, β+ polarization in $^{14}$O, $^{10}$C at Louvain, magenta dash-dot lines,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

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

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

## Permanent Atomic Electric Dipole Moments

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

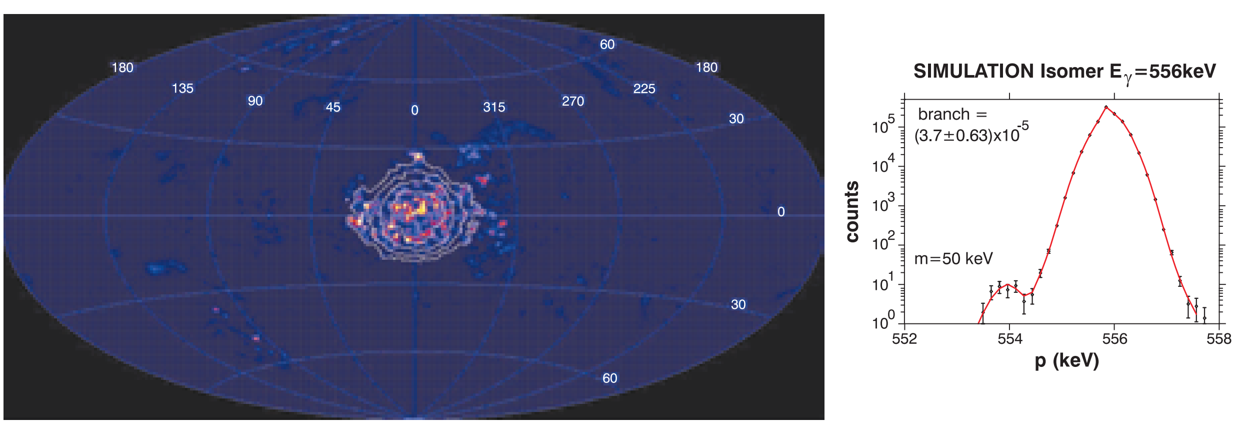


**Figure 4:** Left is the galaxy imaged by the INTEGRAL satellite in 511 keV γ-rays, yet unexplained. Right is the result of a simulation showing the expected distortion for a 50 keV/c2 massive particle.

### Atomic Physics of Heavy, Radioactive Isotopes

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

## Partners

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

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

## TRIUMF's Role

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

# 4.2.1.2

# Particle Physics Experiments

# 4.2.1.2.1

# A Toroidal LHC ApparatuS: ATLAS

## Introduction

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

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

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

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

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

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

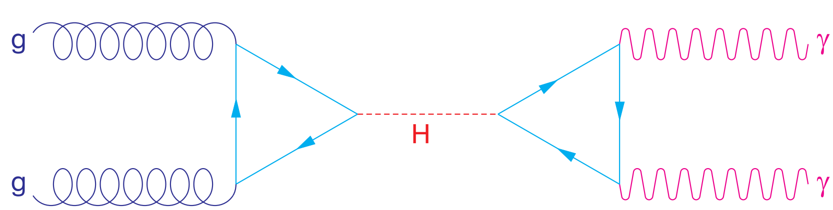


**Figure 1:** Simulation of Higgs produced by gluon fusion decaying to two photons.

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

# Description of Dedicated Apparatus

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

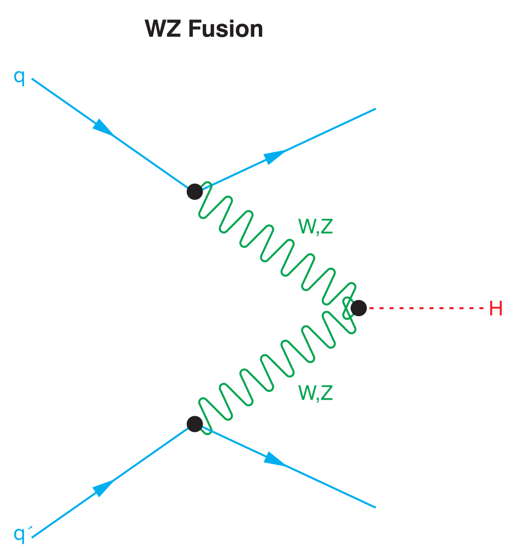


**Figure 2:** Feynman diagram illustrating Higgs production in vector boson fusion.

# Results and Progress

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

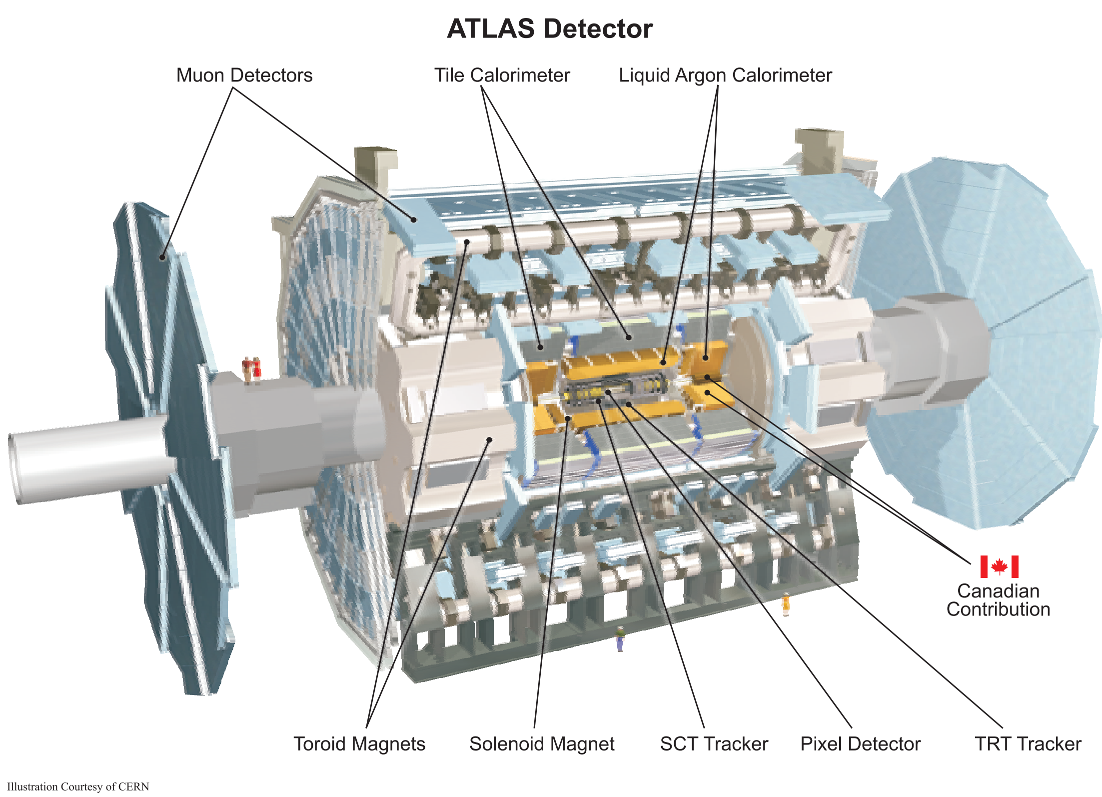


**Figure 3:** The ATLAS detector and its major subsystems. Image courtesy of CERN.

# Partners

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

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

# TRIUMF's Role

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

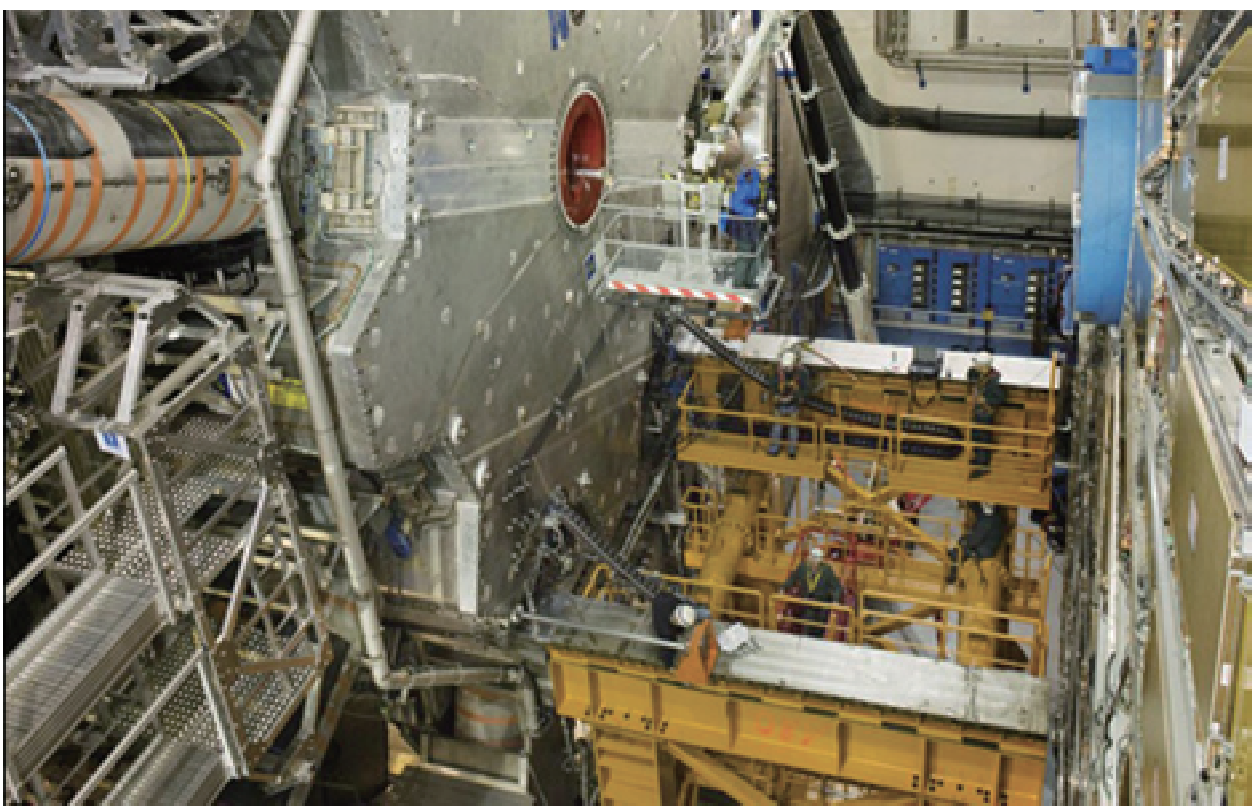

**Figure 4:** A recent view of the ATLAS Detector installed in its experimental cavern. Photo courtesy of CERN.

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

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

# 4.2.1.2.2

# Tokai to Kamioka: T2K

## Introduction

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

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

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


## SCOTT OSER

***Associate Professor, UBC***

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

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

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

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

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

# Description of Dedicated Apparatus

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

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

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

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

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

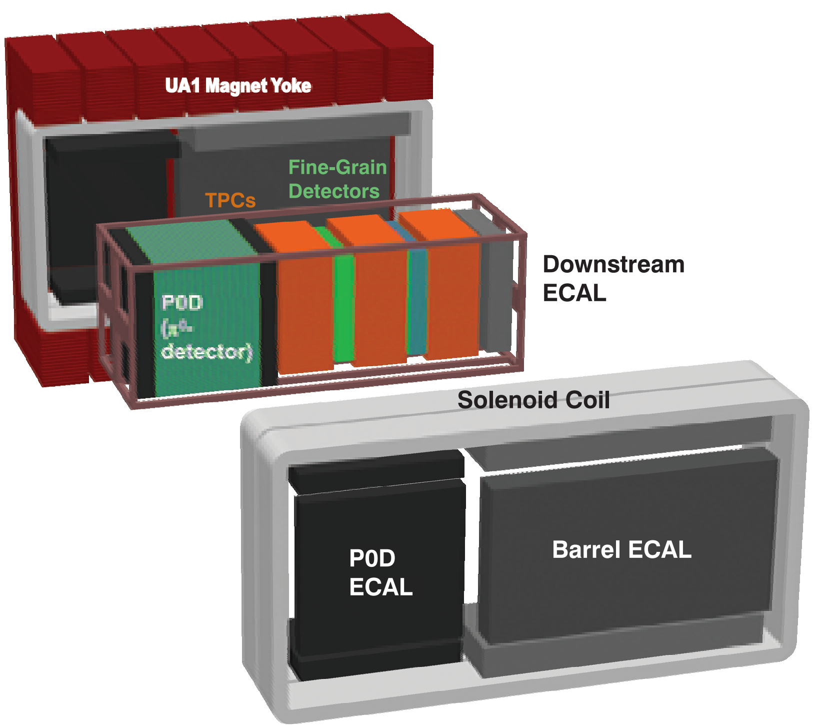


**Figure 1:** Exploded view of the T2K's near detector (ND280).

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

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

# Results and Progress

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

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

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

# Partners

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

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

# TRIUMF's Role

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

# 4.2.1.2.3

# Sudbury Neutrino Observatory: SNO/SNOLAB

## Introduction

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

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

PEOPLE

## DAVID SINCLAIR

*Director, SNOLAB*

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

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

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

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

# Description of Dedicated Apparatus

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

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

# Results and Progress

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

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

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

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

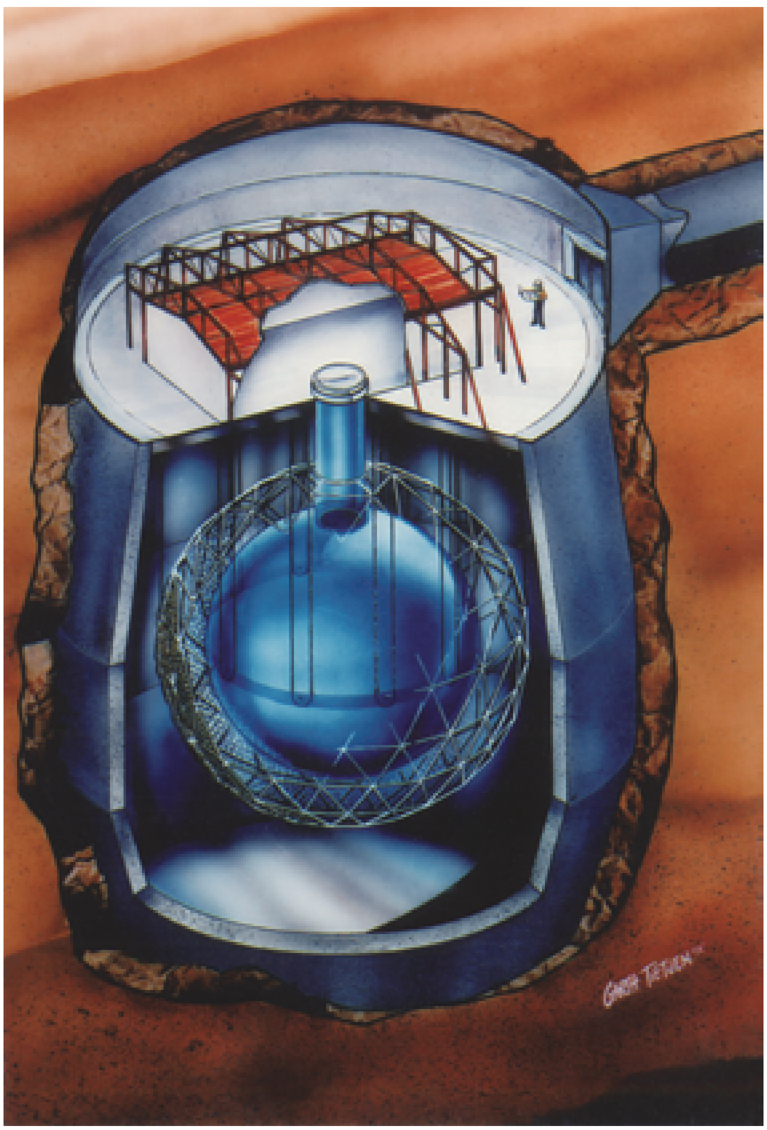

**Figure 1:** The SNO detector.

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

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

## Partners

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

## TRIUMF's Role

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

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

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

# 4.2.1.2.4

# Precision Measurements

# 4.2.1.2.4.1

# TRIUMF Weak Interaction Symmetry Test: TWIST

## Introduction

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

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

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

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

# Description of Dedicated Apparatus

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

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

The detector (see Figure 1) has a symmetric array of 56 low-mass high-precision planar drift chambers, constructed to very high precision while minimizing the amount of material in the tracking region. The chambers provide precise spatial information for event classification, track identification, and track reconstruction. Planes are positioned with relative accuracy of $5\times10^{-5}$ in the beam direction, using specially constructed glass ceramic spacers provided by Russian collaborators. Alignment in the transverse directions is accomplished by fitting straight tracks, but depends also on the wire separation accuracy of 3.3 μm rms for 6,304 sense wires in the chamber modules. Signals are amplified, discriminated, and digitized by multi-hit time-to-digital converters loaned by US collaborators.

At the centre of the array is a thin target in which the muons stop. The detector allows very precise measurement of positron decay tracks symmetrically, in forward and backward directions, while minimizing interactions that would broaden and distort the detector response function. The planar geometry means that the energy loss, which depends on the length of a track in any material in its path, has primarily a simple $1/\cos\theta$ dependence. The detector stack is in a uniform solenoidal field of 2 T, produced by a superconducting solenoid that was originally constructed as a whole body MRI field device. An external steel yoke was fabricated to produce the required field uniformity for the detector tracking volume and to contain the return field. Within the tracking volume, field map measurements determine the variations of the field as a function of position to $5\times10^{-5}$.

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

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

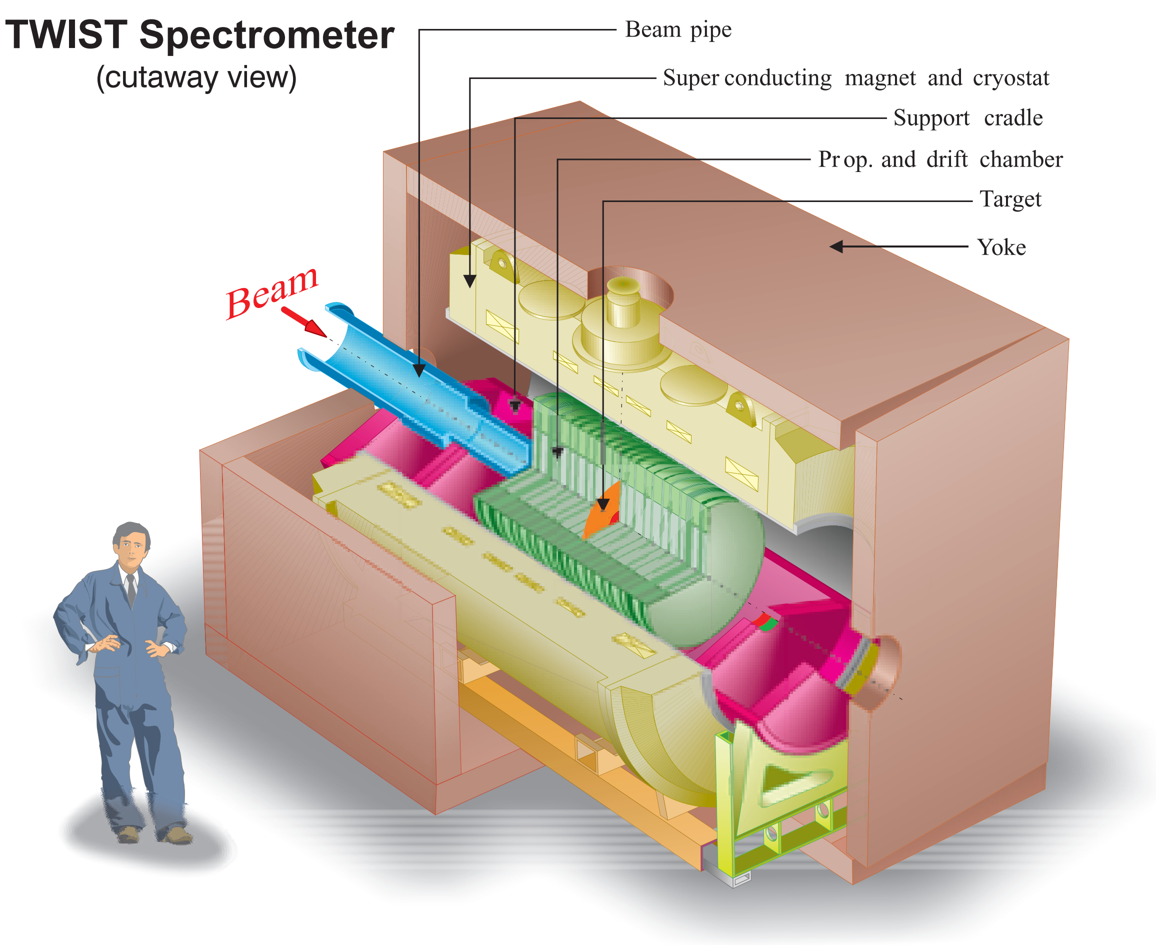


**Figure 1:** The TWIST spectrometer, showing the detector inside the superconducting solenoid.

## Results and Progress

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

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

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

## Partners

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

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

## TRIUMF's Role

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

# 4.2.1.2.4.2

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

## Introduction

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

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

## Description of Dedicated Apparatus

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

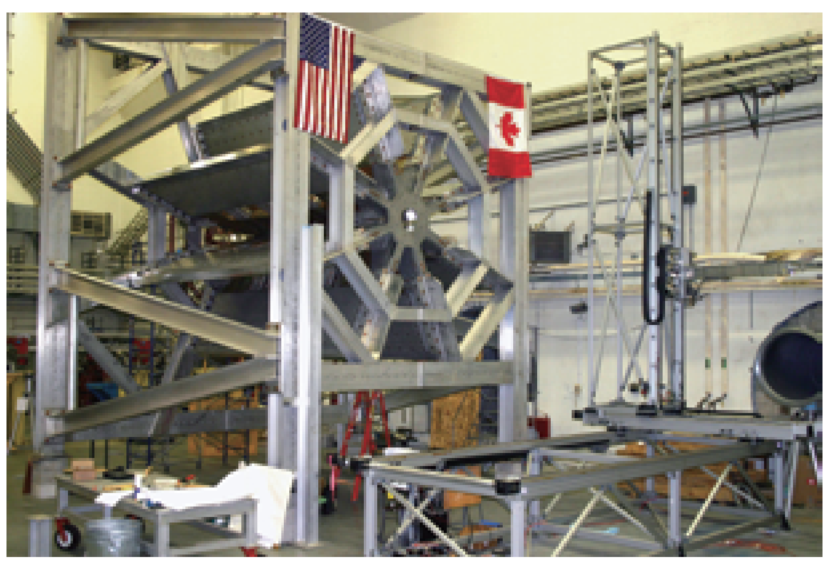

**Figure 1:** $Q_{weak}$ spectrometer magnet and G0/TRIUMF field mapper at MIT-Bates.

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

# Results and Progress

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

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

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

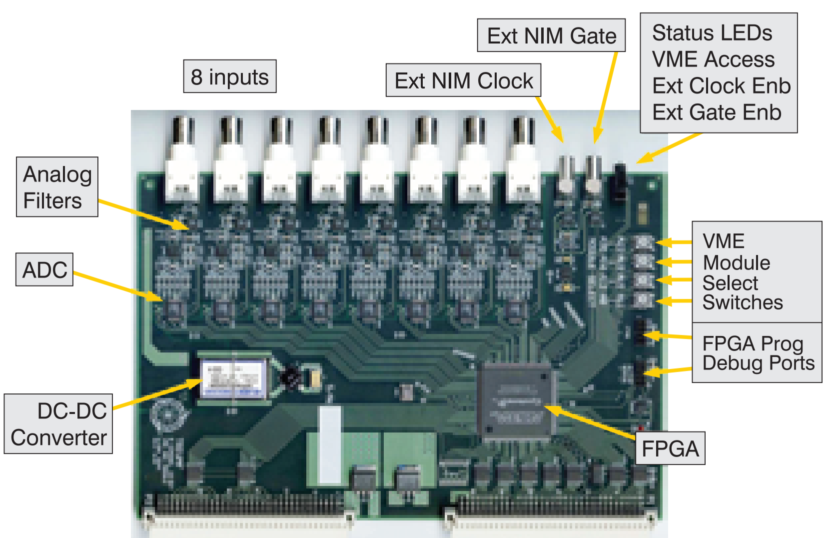


**Figure 2:** Layout of the TRIUMF VME digital integrator.

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

## Partners

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

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

## TRIUMF's Role

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

# 4.2.1.2.4.3

# Experimental Studies of Rare Kaon Decays

## Introduction

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

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

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

# Description of Dedicated Apparatus

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

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

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

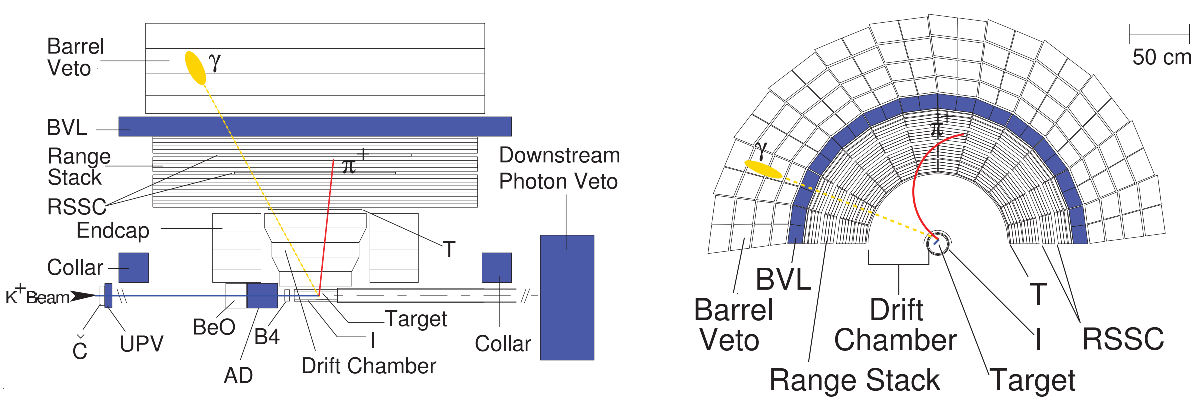


**Figure 1:** Schematic side (a) and end (b) views of the upper half of the E949 detector. Shown are an incoming $K^+$ that traverses all the beam instruments, stops in the target, and undergoes the decay $K^+ \rightarrow \pi^0\pi^+$ and the outgoing $\pi^+$ and one photon from $\pi^0 \rightarrow \gamma\gamma$.

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

# Results and Progress

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

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

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

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

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

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

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

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

# Partners

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

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

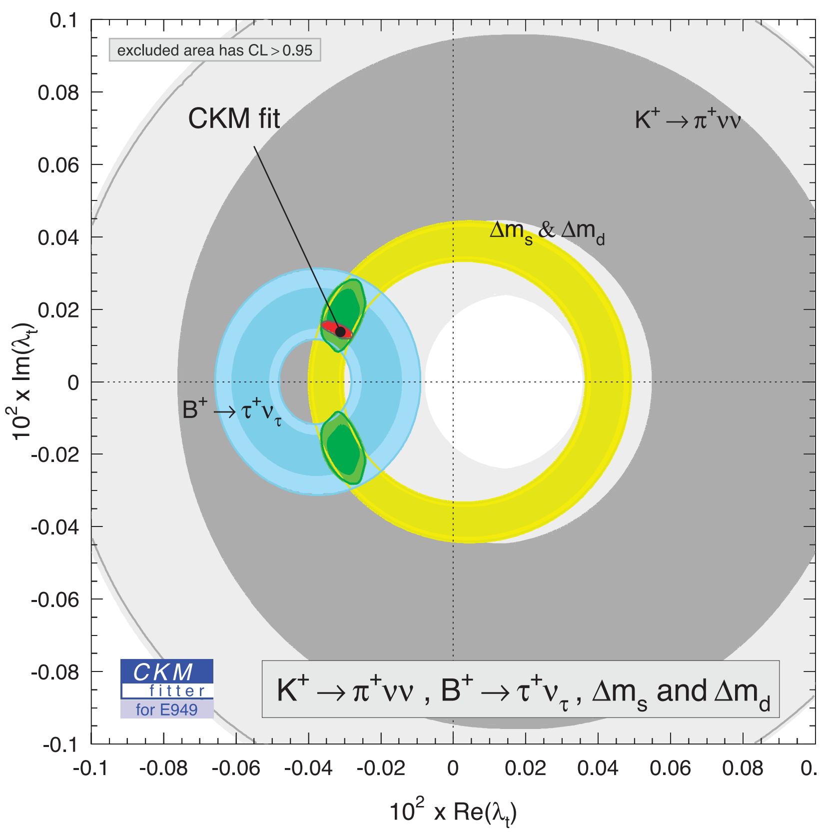


**Figure 2:** The regions in the $\lambda^t$ plane allowed by the combined E787's and E949's determination of the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio (gray), $B^+ \to \tau^+\nu$ (blue) and B-mixing measurements (yellow). The regions outside the lighter (darker) shading have CL>0.95 (0.68). The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

# TRIUMF's Role

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

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

# 4.2.1.2.4.4

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

## Introduction

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

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

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

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

# Description of Dedicated Apparatus

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

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

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

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

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

# Results and Progress

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

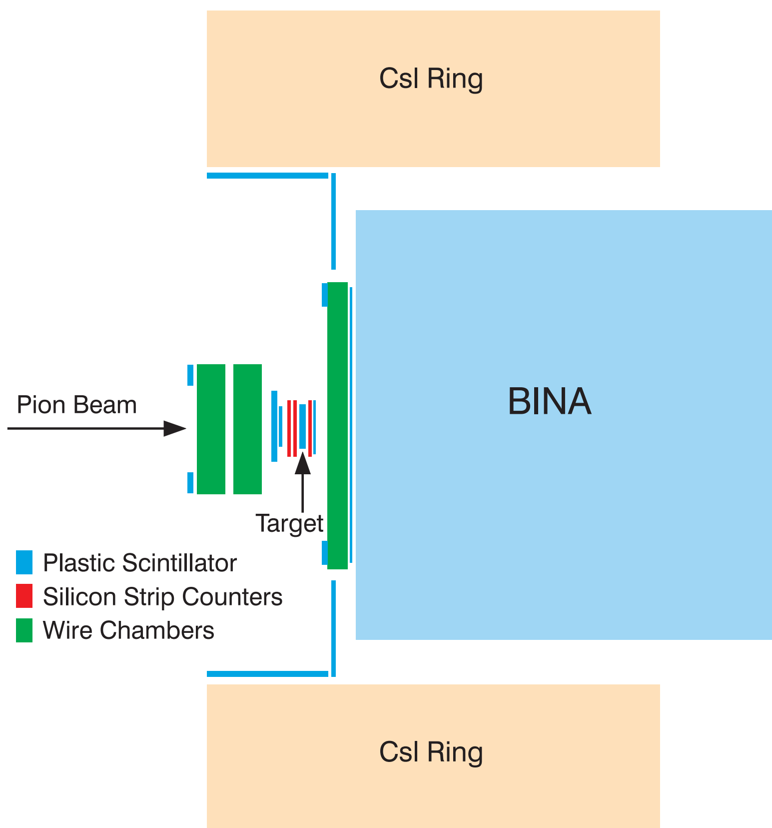


**Figure 1:** Schematics of the PIENU detector. Red lines near the target denote silicon strip pairs; two pairs are located before the target and one pair after. Colour scheme: scintillators are blue; wire chambers are green; NaI crystal is light blue; CsI crystal array is cream.

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

## Partners

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

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

## TRIUMF's Role

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

# 4.2.1.2.4.5

# Antihydrogen Laser Physics Apparatus: ALPHA

## Introduction

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

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

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

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

# Description of Dedicated Apparatus

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

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

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

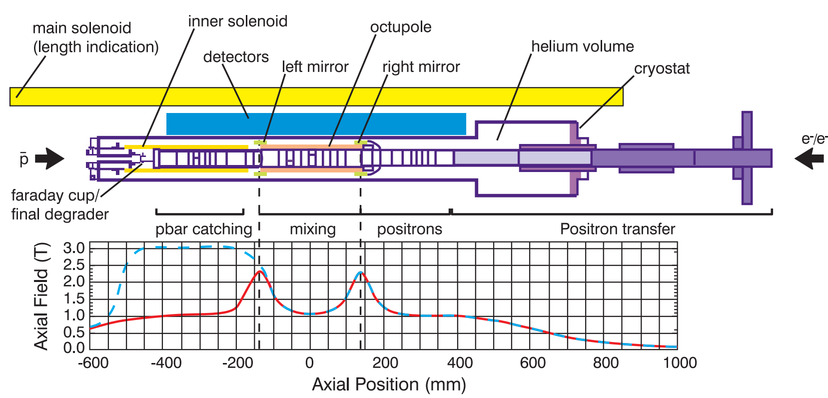


**Figure 1:** The ALPHA combined charged and neutral particle trap.

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

# Results and Progress

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

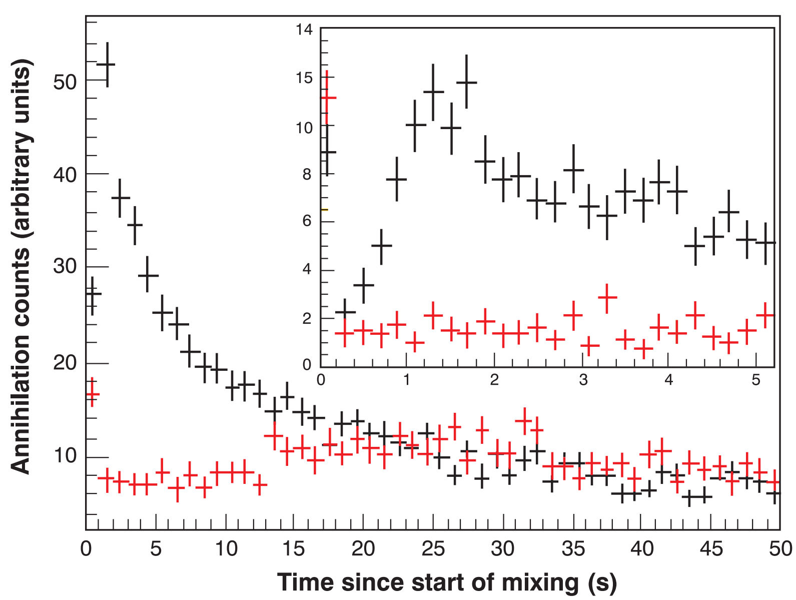


**Figure 2:** Production of $\bar{H}$ in the ALPHA trap. This figure shows the count rate in the TRIUMF-UBC scintillator system surrounding the mixing region. The start time is when the $\bar{p}$ are introduced in the mixing trap overlapping the $e^+$. Black points are data taken with cold $e^+$, while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

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

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

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

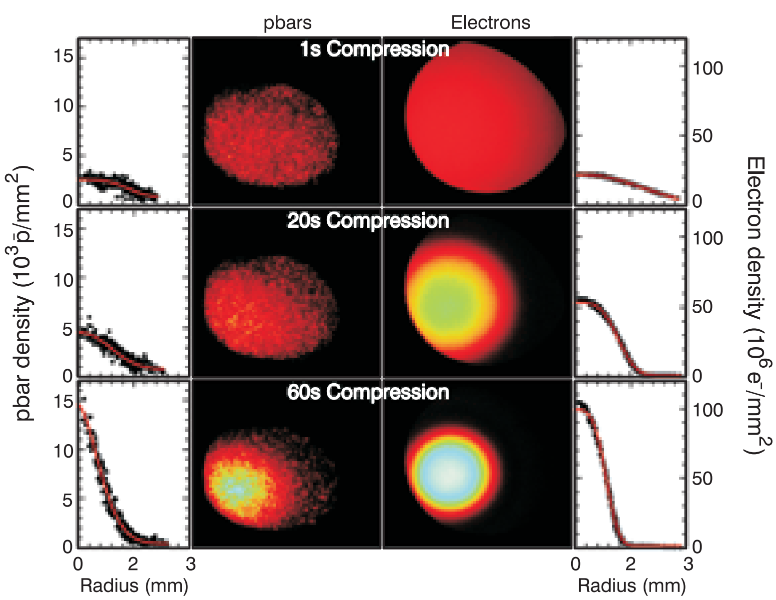


**Figure 3:** Multi-channel plate images of antiprotons and electrons trapped in a Penning trap demonstrate radial compression of antiprotons, an important step towards antihydrogen trapping.

# Partners

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

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

# TRIUMF's Role

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

# 4.2.1.2.5

# Hadron Structure

# 4.2.1.2.5.1

# HERMES Experiment

## Introduction

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

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

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

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

# Description of Dedicated Apparatus

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

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

# Results and Progress

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

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

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

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

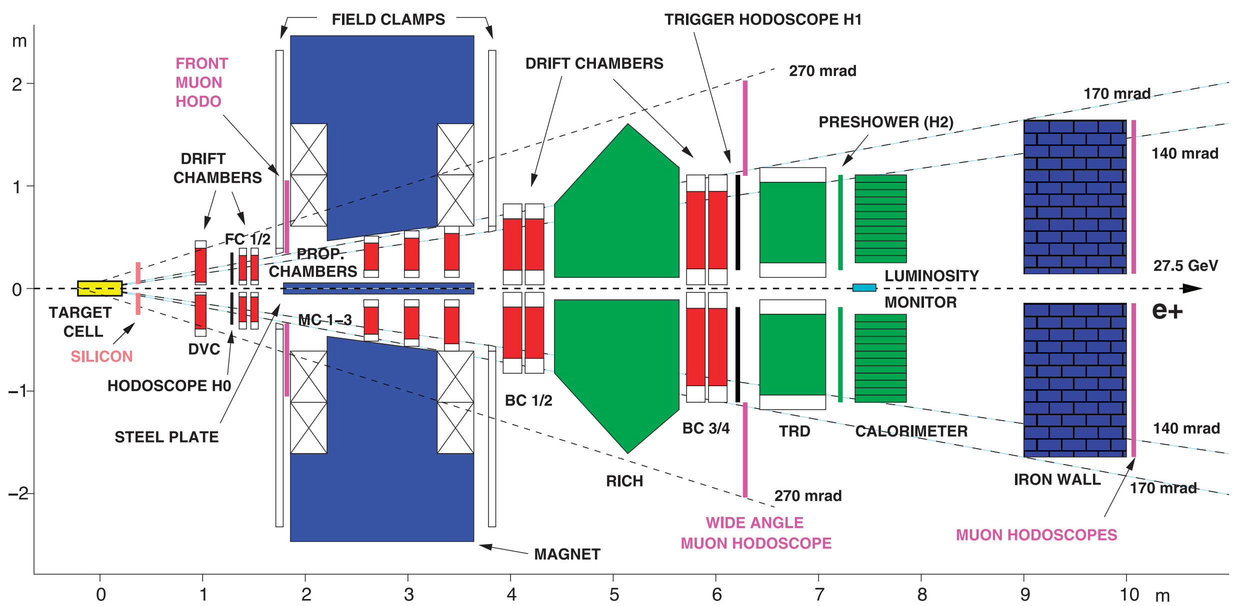


**Figure 1:** The HERMES apparatus.

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

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

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

# Partners

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

# TRIUMF's Role

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

# 4.2.1.2.5.2

# G-Zero (G0) Experiment

## Introduction

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

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

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

## Description of Dedicated Apparatus

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

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

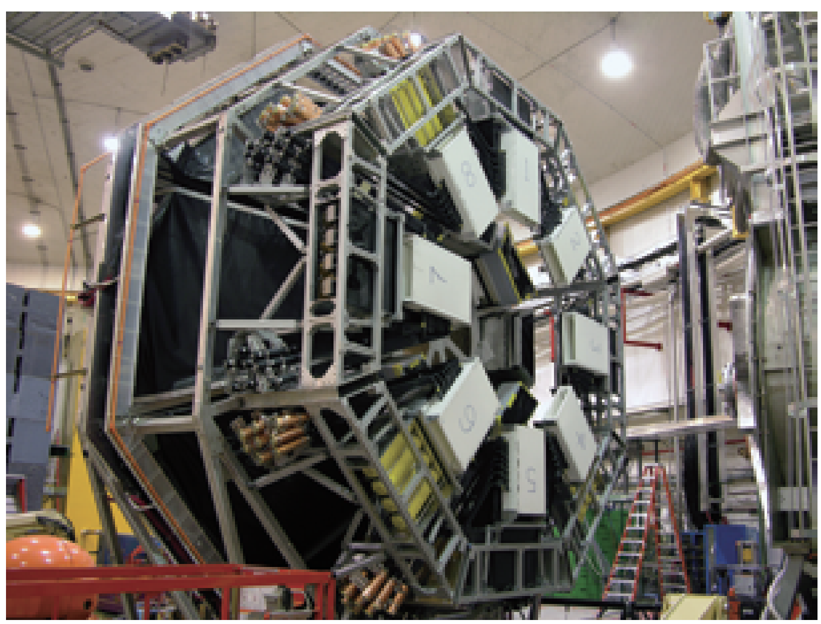

Figure 1: Photograph of the G0 apparatus in the backward-angle configuration with the detector package decoupled and withdrawn from the superconducting toroidal magnet.


### SHELLEY PAGE

*Professor of Physics, University of Manitoba*

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

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

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

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

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# Results and Progress

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

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

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

# Partners

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

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

# TRIUMF's Role

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

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

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

# 4.2.1.2.5.3

# NPDGamma Experiment at Los Alamos

## Introduction

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

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

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

# Description of Dedicated Apparatus

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

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

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

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

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

# Results and Progress

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

# Partners

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

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

# TRIUMF's Role

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

# 4.2.1.3

# Particle and Nuclear Physics Theory

## Introduction

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

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


## ACHIM SCHWENK

***TRIUMF Research Scientist***
***Deputy Theory Group Leader***

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

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

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

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

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

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

# Recent Developments

## Nuclear Physics

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

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

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

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

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

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

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

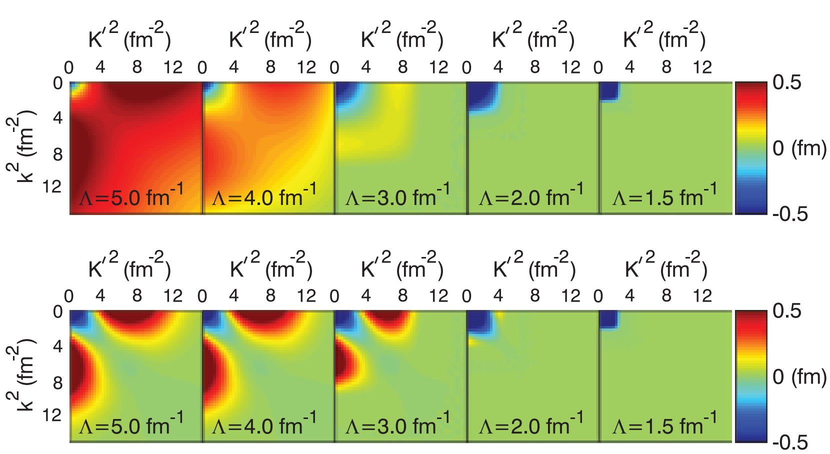


**Figure 1:** Evolution of two different NN potentials to low-momentum interactions $V_{\text{low k}}$ (with $\Lambda$ = 5, 4, 3, 2 and 1.5 fm$^{-1}$) that become universal at low cut-offs.

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

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

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

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

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

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

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

## Chiral Perturbation Theory

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

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

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

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

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

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

## Lattice QCD

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

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

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

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

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

## Particle Physics Phenomenology

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

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

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

### Philosophy of Science

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

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

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

## Partners

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

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

## TRIUMF's Role

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

# 4.2.2

# Life Sciences and Nuclear Medicine

# 4.2.2

# Life Sciences and Nuclear Medicine

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

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

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

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

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

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

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

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

# 4.2.2.1

# Neurology

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

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

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

# Description of Facilities

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

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

**Figure 1:** Radiochemist preparing radiopharmaceuticals at TRIUMF.

# Results and Progress

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

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

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

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

1. A theoretical model outlining the presynaptic basis for motor fluctuations in PD [R. de la Fuente-Fernandez *et al.*, Brain 127: 888-899, 2004] and work describing changes in the temporal pattern of dopamine release in PD with motor complications [R. de la Fuente-Fernandez *et al.*, Brain 127: 247-2754, 2004] were published.

2. Changes in dopamine turnover with disease progression in PD were described [V. Sossi *et al.*, JCBFM 24: 869-876, 2004], based on methodology developed at this centre.

3. The effects of ECT [E. Strome, C. Clark , A. Zis , and D. Doudet, Biol. Psychiatry 57: 1004-1010, 2005] and of retinal pigmented epithelial cell implants [D. Doudet *et al.*, Exp. Neurol. 189: 361-268, 2004] in primates were described.

4. Further development of *in vivo* Scatchard methods to differentiate changes in binding affinity and density were applied to study the effects of pharmacological challenges [D. Doudet *et al.*, JCBFM 26: 28-37, 2005] and quantitative phosphor imaging was applied to studies with PET tracers [E. Strome *et al.*, J. Neurosci. Methods, 141: 143-154, 2005].

5. The effects of negative contrast using different concentrations of sucrose on behaviour and dopamine release were described [R.F. Genn *et al.*, Behav. Neurosci. 118: 869-873, 2004]. The relationship between medial prefrontal cortical dopamine release and performance on a working memory task was described [A.G. Phillips *et al.*, J. Neurosci. 24:547-553, 2004].

# Partners

In Canada: University of British Columbia and Vancouver Coastal Health Authority.

# TRIUMF's Role

TRIUMF provides five key people in the PET chemistry program. It has provided infrastructure support including design, engineering, electronics, the machine shop, and other technical support. TRIUMF's support ensures that the TR-13 cyclotron, the chemistry systems, and the imaging tomographs remain operational so that the imaging program can continue to function. Two TRIUMF research scientists are routinely involved in the design of the studies.

# 4.2.2.2

# Oncology

Ever since the initial studies using microPET, the BCCA has aggressively pursued molecular imaging. The agency has acquired a PET/CT system and plans to have a dedicated research scanner as part of their Phase B Functional Imaging Program. In addition, they have received a Leading Edge Endowment Fund (LEEF) award, with which they have created a chair in molecular imaging. Led by this LEEF BC Leadership Chair in Molecular Imaging, BCCA, in conjunction with the UBC-TRIUMF PET Program, will draw together a unique set of expertise to create a fully integrated radiotracer development and functional imaging program. This program will position BC as a world leader in biomarker development and molecular imaging.

## Description of Facilities

The Functional Imaging Program at the BCCA is a collaboration among the agency, TRIUMF, UBC, and the BC Children's Hospital. Capital acquired through the BC Provincial Health Services Authority Emerging Technologies Fund allowed purchase of the province's first hybrid PET/CT scanner in 2004. The clinical PET/CT program, located at BCCA's Vancouver Centre, was enabled by TRIUMF supplying $^{18}F$, the positron emitting radionuclide used in production of $^{18}F$-fluorodeoxyglucose (FDG). FDG, as a marker of glucose metabolism, is the tracer used in oncologic PET imaging, a diagnostic study which has become a standard of care in the management of many cancer types. A small clean room and shielded chemistry system were installed at the TR-13 cyclotron to produce FDG for the clinical program (see Figure 1). $^{18}F$ is delivered to the automated chemistry box in the shielded clean room, and BCCA staff members produce FDG in the box. Two shipments a day are sent to the BCCA PET facility to scan up to 16 patients with various forms of cancer.

Expanding on early pilot studies carried out with the small animal PET purchased through a previous Canada Foundation for Innovation (CFI) grant, the TRIUMF/UBC team with BCCA is now aggressively pursuing functional imaging as its major research tool to achieve a fully integrated cancer imaging program. This program will address basic biological questions and clinical

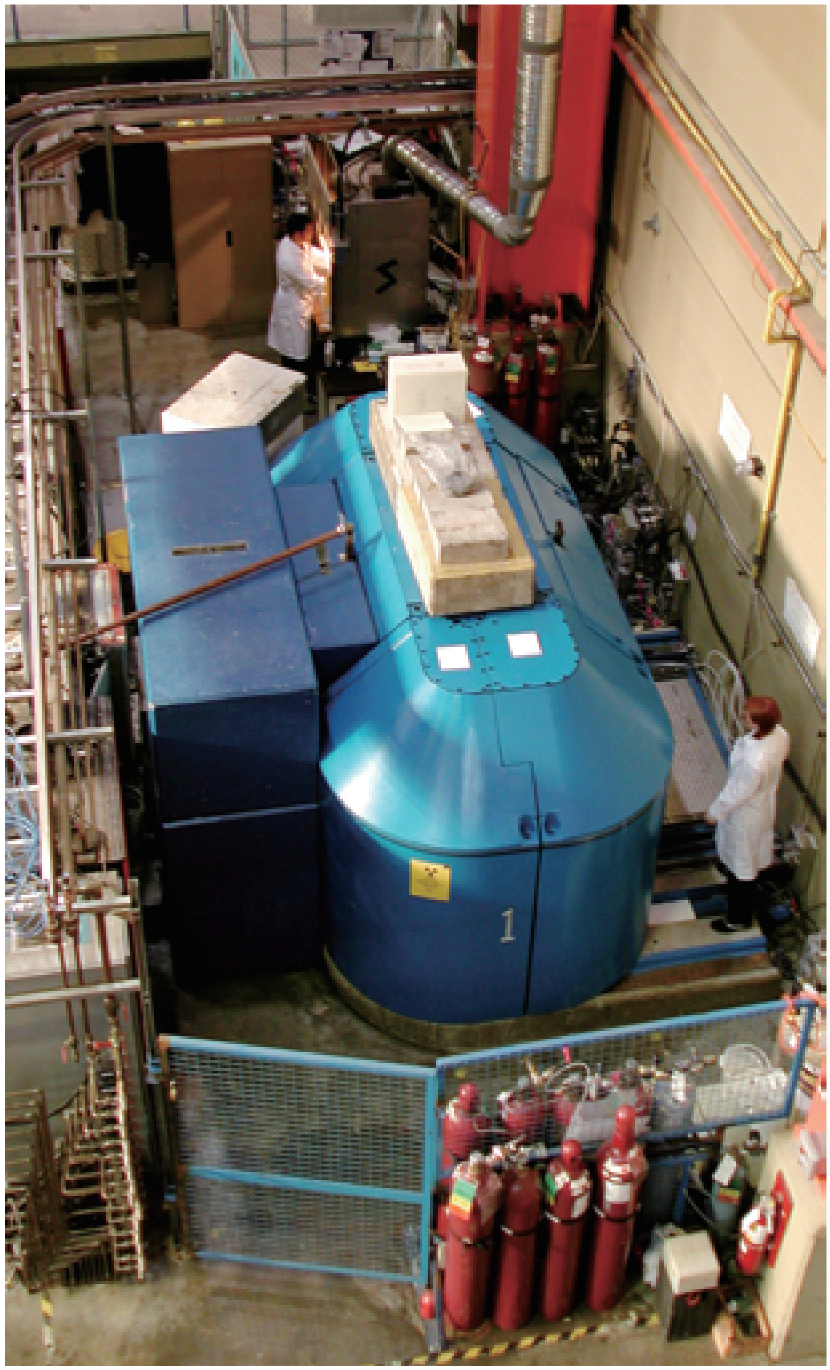


**Figure 1:** Overhead view of the TRIUMF TR-13 cyclotron.

problems in oncology using functional imaging. Central to all aspects of the BC Functional Cancer Imaging Group will be the development of an interdisciplinary radiotracer research program in conjunction with TRIUMF, basic and clinical researchers at UBC and BCCA, and corporate partners that include Advanced Cyclotron Systems, MDS Nordion, AMI (Quebec), Bristol Meyers Squibb, and Siemens, Canada. The expertise attracted to BC by the establishment of the LEEF Chair will enable the province to enhance its leadership position in the areas of radioisotope production, and radiopharmacy, in addition to paving the way for new research in genomics, biophysics, biochemistry, *in vivo* pharmacokinetics, computational biology, bioinformatics, and clinical oncology using radiotracers as biomarkers.

## Results and Progress

Clinical operations began on June 28, 2005, and as of November 15, 2007, 4,769 adult and 275 pediatric oncology patients have been scanned. Referrals to this publically funded program are accepted from physicians across the province with reference to Provincial Tumour Group-approved, evidence-based guidelines for the use of PET/CT in oncology. All PET/CT scans at the Vancouver Centre are performed under Clinical Trials Agreements with Health Canada. The largest groups of patients studied are those with potentially operable non-small cell lung carcinoma (31%), colorectal carcinoma (19%), and lymphoma (14%). Specific approved indications for both adult and pediatric populations are listed on the BCCA's website and include some gynecologic and testicular cancers as well as melanoma and sarcoma. Analysis of the data obtained from referring physicians indicates that PET/CT scan results have led to improved clinical decision making in over 90% of patients and in many cases have led to significant changes in treatment.

A planned physical expansion of the BCCA Vancouver Centre will house a 19 MeV cyclotron, FDG production, and radiochemistry research facilities. Construction began early in 2008, with completion anticipated by early 2009. A small animal PET scanner will be purchased in 2008 and located in the BC Cancer Research Centre, across the street from the Vancouver clinic. Dr. François Benard was recruited as the LEEF BC Leadership Chair in Molecular Imaging and assumed this BCCA/UBC appointment in March 2008.

## Partners

In Canada: UBC, BC Cancer Agency, and BC Children's Hospital.

## TRIUMF's Role

TRIUMF plays a dual role in the regional partnership for oncology research. All of the radioisotopes used in the imaging studies are produced using TRIUMF's accelerators and technical expertise. TRIUMF has the expertise key to combining the radioisotopes with the biomolecules to be used. In addition to this technical contribution, TRIUMF scientists T. Ruth and M. Adam collaborate on a peer-to-peer level with the clinical research programs of the partnering institutions.

# 4.2.2.3

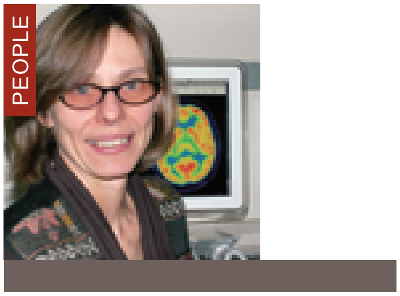
# PET Centre

The PET Program in Vancouver was established in 1980 as a collaboration of several departments within the Faculty of Medicine at the University of British Columbia and with TRIUMF. The program is dedicated to basic research in neurology and psychiatry. The program has been funded continuously for over 25 years. Within the United States, where statistics are more available, it is estimated that there are 20 million nuclear medicine procedures performed annually. PET is becoming an increasingly important imaging technique with 1.4 million PET studies carried out in the US in 2006 along with 240 PET/CT scanners sold in the same year.

## Description of Facilities

The major resources include the TRIUMF-designed TR-13 cyclotron, which delivers 13 MeV protons, and the ECAT 953B PET scanner to detect the tracers. Two previous CFI-funded projects enabled the Pacific Parkinson's Research Centre (PPRC) to acquire the state-of-the-art human brain scanner, the high-resolution research tomograph (HRRT), and to purchase a microPET small animal scanner to establish a functional imaging program for basic biomedical research, with a focus on neuroscience and cancer. A 2.5 km underground pneumatic tube quickly transports the short-lived tracers from TRIUMF to the UBC hospital where two human scanners reside.

The nuclear medicine facilities that support the research program can be segmented into two major portions, those associated with production of the scanning agents—cyclotron and hot cells—and the scanning instruments themselves. TRIUMF has four scanners: three for studies using human subjects, and one dedicated to small animal experiments. This equipment is described below.




## VESNA SOSSI

*Associate Professor, UBC*

Vesna Sossi completed her Ph.D. at the University of British Columbia in 1991. She performed her thesis research at TRIUMF where she studied pion-induced pion production on deuterium. After graduation she joined the UBC/TRIUMF Positron Emission Tomography (PET) imaging group and in 2001 the UBC Physics and Astronomy Department.

Vesna's current research bridges PET imaging techniques with the investigation of neurodegeneration as manifested in Parkinson's disease in humans and animal models.

Dr. Sossi is the recipient of the NSERC University Faculty Award, a Michael Smith Scholar Award, and a Michael Smith Senior Scholar award. ■

### Cyclotron and Hot Cells

The production of the radiotracers used in studying disorders of the monoaminergic pathways relies on the production of specific radionuclides, the conversion of these radionuclides into a useful form, and labelling a biologically active molecule or radiotracer that can be used to probe the system. The production of the radionuclides is performed on the TR-13 cyclotron with gas and liquid targets.

The TR-13 cyclotron is a negative ion cyclotron capable of accelerating two $H^-$ beams simultaneously to 13 MeV where they are extracted into targets containing the appropriate material for the production of $^{11}C$ as methane and $^{18}F$ as fluoride or $F_2$. TRIUMF, in collaboration with Ebco Technologies, designed and built the cyclotron. TRIUMF also designed and built the target systems.

The actual chemistry for producing the radiotracers occurs in lead shielding containers called hot cells. The program has two such hot cells, one dedicated to $^{18}F$ radiotracers and one dedicated to $^{11}C$ radiotracers. Development work is performed in fume hoods with lead bricks for shielding, and there is a lab dedicated to quality control measurements for testing the radiotracers before they are released for injection into human subjects.

Once a radiotracer is prepared, it is sent via a pneumatic pipeline the 2.5 km separating the TRIUMF site and the UBC Hospital where the scanners are located (see Figure 1). TRIUMF personnel maintain the pipeline.

### Scanning Instruments

The Siemens ECAT 953B is a brain-only scanner. The scanner is composed of 16 rings of detectors for a total of 6,144 single crystal elements, yielding 31 image planes that cover an axial field of view of 10.8 cm. The detector material is bismuth germinate (BGO).

This scanner was one of the pioneer instruments in the transition from 2D to 3D acquisition mode, the latter characterized by the additional acceptance of those positron annihilation events where the two emitted gamma rays travel at an oblique angle with respect to the scanner axis. In using 3D acquisition mode, the resulting radiotracer detection sensitivity increased by a factor of 6, from 0.5% to 2%, providing images with better statistical properties. The ability to acquire data in 3D prompted a large increase in the development of suitable image reconstruction and data quantification algorithms, which were aided by the rapid development in computing power and data storage devices. The scanner is capable of a spatial resolution of 5.5 x 5.6 x 6 $mm^3$; in practice, when reconstructing human data sets, smoothing filters are introduced to minimize the impact of statistical noise leading to an effective resolution of approximately 9 x 9 x 6 $mm^3$.

The ECAT has been the workhorse for the UBC-TRIUMF PET group for almost two decades and has been used for several pioneering studies, including a study of Parkinson's disease (PD) etiology and progression, where approximately sixty patients were scanned three times at four-year intervals with three different dopaminergic tracers. This unique data set provided insights into early disease regulatory changes and is currently being completed to provide the full longitudinal data set.

Members of families with PD-associated gene mutation (LRKK2) are being examined on this scanner at UBC in collaboration with the Jacksonville Mayo Clinic. In addition to providing a glimpse into the preclinical stage of PD, this study demonstrates that the neurochemical changes identified in this group are identical to those observed in sporadic PD. Dopamine release associated with the placebo effect was first demonstrated with data acquired on this scanner. Likewise, studies investigating the role of dopamine turnover in PD were first performed on this scanner. Over the course of the years, the ECAT has proved to be very stable and reliable.

The high-resolution research tomograph (HRRT) from Siemens is a double layer LSO/LYSO scanner, currently the most complex brain scanner, which is available in only 17 PET centres worldwide (see Figure 2). The double layer architecture is designed to increase the resolution uniformity across the field of view. The spatial resolution achievable with the scanner is approximately (2.5 mm)$^3$, the detection sensitivity is approximately 6%, and the axial field of view is 25 cm. Due to its hardware complexity (119,800 crystals), there are several challenging aspects to this scanner. For instance, data sets are very large, of the order of several GBytes, thus rendering data storage and reconstruction is demanding from the computational point of view. Frequent hardware calibrations are required, and the impact of patient motion on data accuracy cannot be ignored.

Addressing these challenges contributed to a rapid development of reconstruction and data quantification algorithms, which will not be limited to the HRRT but will ultimately benefit the PET field in general. In spite of its complexity, the HRRT provides data that could not be easily, achievable, if at all, with any other scanner. In particular, a large part of the UBC-TRIUMF PET group research being planned involves the quantification of tracer binding/uptake in the ventral striatum, which is involved in expectation/reward/addiction mechanism. There, the HRRT provides the necessary resolution to avoid

**Figure 1:** Dr. T. Ruth discussing a PET scanning procedure in the medical-imaging suite

partial volume effects for this small structure. Detailed studies investigating the mechanism of placebo effect, psychiatric complication in PD, such as depression and compulsive behaviour, as well as psychiatric manic behaviour will be performed in the HRRT in the next five years.

The recently acquired Advance NXi GEHC PET Scanner is a whole body BGO scanner with a 16 cm axial field of view that has proved to be very reliable and stable. It is meant to be a replacement for the Siemens ECAT scanner, which is showing signs of aging; currently there are no commercial dedicated brain scanners available. The Advance intrinsic resolution in 3D mode is approximately 5 mm in all three directions in the centre and degrades by approximately 50% at 20 cm off centre, while the sensitivity is approximately 2%. Studies that do not require the high resolution provided by the HRRT will be performed on the Advance. In particular, the longitudinal studies started on the ECAT will continue on the Advance after appropriate calibration between the two scanners is performed.

The Siemens microPET Focus 120 is a dedicated rodent LSO tomograph with a 10 cm axial field of view, a resolution of 1.8 $mm^3$ at the center of the field of view and a sensitivity of 6%. The majority of the studies currently performed on the scanner are dedicated to the investigation of the dopaminergic system in the 6-hydroxydopamine-lesion model of Parkinson's disease and survival of retinal cell transplantation as treatment for PD. A pioneer study, which investigated pancreatic islet survival following transplantation, has also been performed on this scanner together with the investigation of hypoxia in tumour mice models. Several pilot studies have been performed to assess the availability of large molecules such as antibodies to the brain. Future planned studies involve the investigation of transgenic mice models of PD and overlap syndrome disease such as PD and dementia.

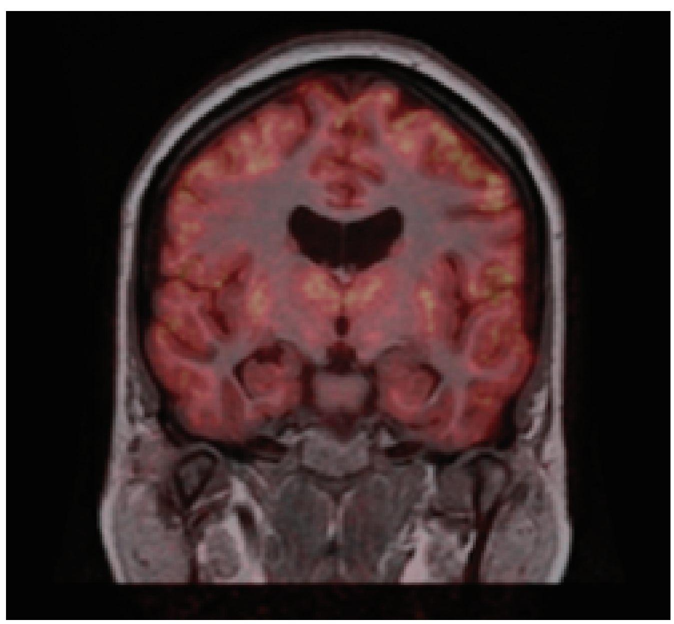


**Figure 2:** A high-resolution PET scan of the brain combined with an image from MRI.

# Results and Progress

TRIUMF's PET program has taken the lead in promoting and assisting other PET centres in Canada. Besides its expert advice, TRIUMF's PET chemistry group provided both the Edmonton Cross Cancer PET Facility and the BCCA with $^{18}F$ prior to the installation of their own cyclotrons. With the acquisition of the microPET small animal scanner, the PET group has broadened its research to include other diseases such as cancer and diabetes. However, significant improvements and upgrades to the life sciences infrastructure at TRIUMF need to be made if the PET program is to continue its leadership position and continue broadening the imaging research program into other diseases.

The program has been funded continuously for over 25 years. Currently, the major resources include the TRIUMF designed TR-13 cyclotron and the ECAT 953B PET scanner to detect the tracer. In addition, the PET group has acquired two relatively new PET scanners: the high resolution research tomograph (HRRT) for human brain studies and the Focus-microPET© small animal scanner. A 2.5 km underground pneumatic tube quickly transports the rapidly decaying tracers from TRIUMF to the UBC hospital where the human and animal scanners reside. The Neurology group is now planning to add another used whole body PET scanner as a backup to the aging ECAT tomograph. In addition to this hardware, the PET chemistry group has three labs in the Chemistry Annex at TRIUMF (rooms 005, 007, and 110) as well as a small quality-control lab (room 103). These labs were all constructed in 1980 and have not been renovated.

A program to develop new imaging agents for the diagnosis and monitoring of enzyme treatments for two lysosomal storage diseases, namely Mucopolysacchridosis I (MPS I) and Gaucher, will be carried out in collaboration with Dr. S. Withers in the UBC Department of Chemistry. These diseases are caused by mutation of genes encoding for the enzymes iduronidase and glucocerebrosidase, respectively. Studies utilizing the small animal PET scanner are proposed to assess the *in vivo* potential of these new tracers in rats or mice. In parallel, they also plan to develop chemical chaperone therapies for these genetic diseases. Dr. C. McIntosh (UBC) has been examining the use of PET coupled with the reporter gene approach developed by Dr. Gambhir to establish an *in vivo* imaging approach to monitor the survival of transplanted pancreatic islets. Based on preliminary results, Dr. McIntosh wishes to pursue this approach in other animal models to ultimately monitor islet transplantation in humans.

Through the PET Centre, TRIUMF and UBC have partnerships with a variety of other research groups to develop PET-based imaging techniques specific to their research problems. PET isotopes are used by other UBC departments including: Botany (for fertilizers, protein enrichment of rice), Chemical Engineering (multiphase fluid dynamics for the pulp and paper industry), Zoology (imaging animal models of physiological systems), and Oceanography ($CO_2$ sequestering via copper catalyzed reactions).

Together with its partners, TRIUMF is uniquely poised to fast-track the establishment of a fully integrated radiotracer program by mobilizing, coordinating, and expanding on resources that currently exist within the biomedical and basic research communities. The region has outstanding programs of research in nuclear physics, engineering, physics, biophysics, chemistry, biochemistry, radiochemistry, radiopharmacy, mathematics, genome sciences, bio-informatics, epidemiology, radiology, clinical oncology, and clinical imaging.

## Partners

In Canada: BC Cancer Agency, Pacific Parkinson's Research Centre, Simon Fraser University, UBC, UBC Hospital, and University of Victoria.

## TRIUMF's Role

TRIUMF is one of the founding partners of the PET Program and TRIUMF scientists play a key role in the intellectual guidance of the program. TRIUMF contributes the technical capability for producing and tailoring the radioisotope compounds for a wide variety of uses. By training students and other scientists in these techniques, TRIUMF has an even broader impact.

# 4.2.2.4

# Proton Eye Therapy

The Proton Therapy Facility at TRIUMF uses 74 MeV protons extracted from the main cyclotron for the treatment of ocular melanoma. The proton therapy equipment was developed as a collaborative project between TRIUMF scientists, medical physicists and oncologists from the BC Cancer Agency and opthalmologists from the UBC Eye Care Centre.

## Description of Facilities

Choroidal or uveal melanoma is life-threatening but relatively rare disease (about six cases per year per one million population) and can be treated with radioactive plaques or charged-particle therapy. The physicians and medical physicists responsible for proton therapy at TRIUMF also carry out $^{198}$Au plaque therapy, and patients are referred for proton therapy based on tumour size and/or location. Plaque therapy gives excellent results for smaller and favourably placed tumours while protons are used for larger tumours and those located near the back of the eye. A third treatment is enucleation, or removal of the eye, which is the only alternative to proton therapy for medium and large-sized tumors. Of the patients treated to date with protons, the local control rate is about 95%, with the complications rate similar to those observed elsewhere (*cf.*, E. Egger, L. Zografos, A. Schalenbourg, D. Beati, T. Bhringer, L. Chamot, G. Goitein, "Eye retention after proton beam radiotherapy for uveal melanoma," International Journal of Radiation Oncology, Biology, Physics, 55:4, 867-880).Visual acuity is maintained in cases where the vision is good before treatment and where the tumour is away from the optic disc and macula.

Before proton treatment became available at TRIUMF, the usual course of action for Canadian patients with large tumours or ones at the back of the eye was to remove the eye entirely. For smaller tumours, the preferred treatment is still to implant a radioactive disk for a few days. Occasionally it is possible to remove small tumours surgically, but this can be difficult. Any of these alternatives could damage other sensitive parts of the eye and result in some loss of vision. Proton therapy offers the possibility of having the tumours stabilized, the eyes preserved and, depending on the location of the tumour, the vision intact. Iris tumours and benign tumours of the eye called hemangiomas, both even rarer than choroidal melaonoma, are also treated using protons at TRIUMF.

A session of proton therapy is scheduled once per month while the cyclotron is operating. Patients, usually from Western Canada, are referred to the BC Cancer Agency and UBC Eye Care Centre and scheduled for proton treatment if that is deemed the best treatment modality. The tumour size is determined by ultrasound and tantalum markers are surgically implanted by the ophthalmologist to define the location of the tumour. The tantalum clips are visible relative to the beam alignment cross-hairs using X-rays. At TRIUMF a patient mask and bite-block are prepared for each patient and X-rays taken for treatment planning (see Figure 1). Medical physicists determine the optimum eye position and proton beam parameters for treatment.

The 74 MeV proton beam is modified by range modulation, scattering and collimation to provide a uniform dose over the volume of the tumour while sparing, if possible, the critical structures such as the lens and optic nerve. The patient positioning chair, which has six motorized degrees of freedom, the

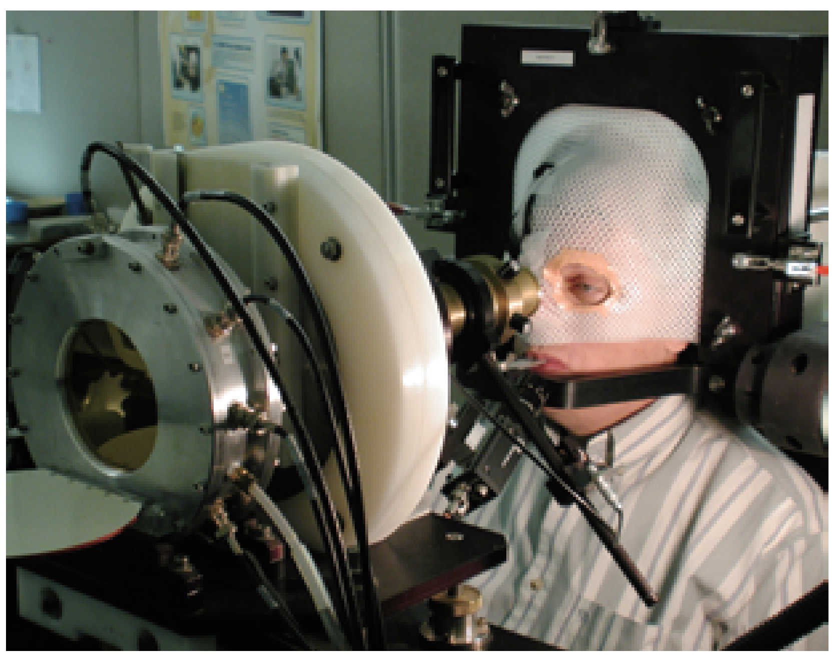


**Figure 1:** A patient being readied for proton therapy. The mask and headrest keep the patient still during the treatment.

patient mask and bite-block, and the X-ray verification system ensure sub-millimeter positioning accuracy. During treatment the patient stares at the blinking light to align the tumour to the beam. The treatment dose of 50 proton-Gy is delivered in four daily fractions, each treatment taking about two minutes.

# Results and Progress

Since 1995, TRIUMF has housed Canada's only clinical proton therapy centre for the treatment of choroidal melanoma, a type of eye cancer. The Proton Eye Therapy Facility is unique in Canada and therefore fills a clinical gap for the treatment of certain eye cancers. Proton therapy continues to save vision in patients. Since the inception of the program, 130 patients have been successfully treated at TRIUMF. About half of the patients are from British Columbia; the other half primarily from the other Western provinces.

The availability of proton and charged-particle therapy is increasing worldwide with several hospital-based facilities operating in the United States and more in Europe and Japan. While ocular melanoma is the most frequently treated cancer with protons, other well-localized cancers near critical structures are particularly suitable for proton therapy.

# Partners

In Canada: BC Cancer Agency and the UBC Eye Care Centre.

# TRIUMF's Role

Without TRIUMF's specialized proton beams, this program would not be possible. TRIUMF's capabilities make the program unique in Canada.

# 4.2.3

# Molecular and Materials Science

# 4.2.3.1

# Centre for Molecular and Materials Science: CMMS

## Introduction

CMMS is the acronym for the Centre for Molecular and Materials Science at TRIUMF. This TRIUMF facility enables an international community of chemists, condensed matter physicists and materials scientists to utilize the powerful experimental capabilities of the muon and polarized nuclei as atomic-scale local probes of matter (please see Figure 1). The research program is multi-faceted, from a broad range of fundamental studies in systems of ever-increasing complexity and sophistication, to the characterization of modern materials and industrial processes. TRIUMF is the sole provider of muon beams in the Americas and one of only four institutions in the world to provide similar experimental capabilities. The three other muon production institutions are RAL (UK), KEK-J-PARC (Japan), which is due to come online in 2010, and PSI (Switzerland). Of these, RAL and J-PARC provide pulsed beams whereas PSI delivers a CW beam similar to that provided by TRIUMF.

The historical core of the CMMS research program utilizes muon spin rotation, relaxation and resonance (μSR) techniques based on the unmatched capability of the positive muon ($\mu^+$) to detect the magnetic field at its microscopic location. It is now well recognized that this capability enables μSR to provide unique information over a very wide range of disciplines. Specifically, μSR has been applied to the study of magnetism, superconductivity, semiconductors and semi-metals, quantum diffusion, molecular bonding states, and fundamental and complex chemical reactions. A recent subset of this work, broadly summarized in Figure 2, is highlighted in this report.

Muons "out of the TRIUMF beam pipe" distribute themselves into condensed matter samples over a depth scale of one half to several millimetres; thus they are a bulk probe and cannot be used in the study of nanoscale structures. Unlike PSI (the Paul Scherrer Institut), with its order-of-magnitude higher proton current, TRIUMF does not have the capability to produce low-energy muon beams of sufficient intensity for a μSR-based nanoscience

**Facilities:**

| | Current | 2010 - 2015 |
|---|---|---|
| Beam lines: | 3 Muon (40 wks) + 2 Rib (3 wks) | 5 Muon (40 wks) + 2 Rib (12 wks) |
| Personnel | 5 fte/MFA grant + 2 fte/TRIUMF | 7 fte/MRS grant + 3 fte/TRIUMF |
| Spectrometers | 5 General Purpose + 5 Specialized | 7 General Purpose + 6 Specialized |
| Dedicated equipment | $4 million | $5 million |

**Users:**

| Nationality/Region | # Users | Institutions |
|---|---|---|
| Canada | 94 | 16 |
| USA | 59 | 25 |
| Japan | 113 | 23 |
| Europe | 52 | 19 |
| South America | 5 | 2 |
| **Total** | **286** | **85** |

**Experiments**

| | |
|---|---|
| January 2004 - December 2007: | 110 |

**Publications**

| | |
|---|---|
| January 2004 - April 2009: | 219 |
| PRL / Nature / JCP etc: | 29 |

**Figure 1:** An Overview of the CMMS Facility, its user community, number of experiments and publications.

program. On the other hand, radioactive nuclei from TRIUMF's ISAC-I can be used to probe materials from 5 – 400 nm below the surface, using the techniques of β-NMR (beta-detected nuclear magnetic resonance) and β-NQR (beta-detected nuclear quadrupolar resonance). The CMMS program now encompasses these techniques. To date, β-NMQR experiments have been successfully carried out on surface and interface proximity effects in normal metals, superconductors, systems with structural and quantum phase transitions, and on the properties of magnetic multi- and monolayers.

Very recently, the β-NMQR infrastructure has been completed, and work is proceeding on rebuilding M9A into a very high luminosity, muons on request (MORE)-enabled, state-of-the-art μSR beam line. However, even with this very welcome additional to TRIUMF's μSR capacity the CMMS was still substantially unable to meet the demands of the growing user community. Therefore, in February 2006, Simon Fraser University (with Dr. P. Percival as Principal Investigator) submitted a proposal to the Canada Foundation for Innovation's (CFI) New Initiatives Fund. TRIUMF and 15 other Canadian universities supported the proposal. CFI approved the proposal in November 2006 and will fund 40% of the $C6 million M20 project (see Figure 3) which will add a second channel, enable the MORE mode, and significantly upgrade the overall beam quality.

In July 2007, it was announced that the British Columbia Knowledge Development Fund (BCKDF) would provide matching funds, and TRIUMF would provide an in-kind contribution equivalent to 20%. The final budget claim for the project was submitted to CFI by SFU in April 2008. TRIUMF and the

**Scientific Scope:**

**High temperature superconductivity (HTSC), definitive measurements & tests:**
- Vortex core structure in type-II superconductors
- Generic magnetic phase diagram of HTSC and hidden order

**Physical, green and materials design chemistry:**
- Reaction kinetics and organic free radicals under hydrothermal conditions
- Catalysis of organic reactions in zeolites
- Ionic liquids, carbenes and related muoniated radicals
- Fundamental molecular reaction rates
- Designing molecular polymer magnets

**Exotic magnetism, strongly correlated systems, quantum phase transitions:**
- Quantum phase transitions, criticality and dynamics in itinerant heli/ferromagnets
- Magnetism in non-fermi-liquid metals
- Heavy fermion (HF) systems & unconventional (non-HT) superconductivity
- SC pair breaking mechanisms via radiation induced defects
- Lack of magnetic ordering in Pu metal
- Multipole ordering in f-electron systems
- Geometric frustration and surface effects
- Magnetic polarons

**Hydrogen-materials interactions:**
- Semiconductors
- Hydrogen storage materials

**Industrial basic research for automobile technology**

**β-NMQR: Probing the interface:**
- Monolayer molecular magnets
- Vortex core size in type-II superconductor
- Thin metal films
- Phase transition probe

**Nuclear quantum electrodynamics**

**Figure 2:** A subset of the scope of CMMS research activities as highlighted in this Report.

CMMS plan to have the beam line installed and operational by April 2011.

This award is an important precedent for TRIUMF. It is the first time a broadly based outside funding agency has committed funding for a major capital component required for development of beam line infrastructure on site. For the CMMS, the national character of the CFI decision marks a watershed because it conveys the clear message that this TRIUMF program is considered, by its peer community, to be one of national importance.

# Description of Dedicated Apparatus

## Beam Lines

### Muon Beam Lines in the Meson Hall

Two dedicated surface muon (29.5 MeV/c) beam lines are in operation. Both M15 and M20 are capable of delivering a separated and/or spin polarization rotated beam via the crossed electric and magnetic field Wien filter/spin rotators. M15 features a modern optical design, invented at TRIUMF, with dual spin rotators separated by a triplet to remove achromatic distortions for efficient beam transport. The older M20 does not have this feature and, when operated in its 90° spin rotated mode, over 50% of the beam is lost. These beam lines are used for condensed matter samples that do not require significant confinement.

For materials that require confinement, *i.e.*, high-pressure studies, the muon decay channel M9B is available, providing muon momenta throughout the range 40–110 MeV/c. The unique feature of this beam line is that it is the sole decay muon channel in the world that provides beams of high transverse spin polarization.

M9A is a new high luminosity beam line, with modern optical design (dual spin rotators), that is currently under construction. This beam line will have a new generation of spin rotators, see Figure 4, which allow for extremely stable high voltage operations. This enhanced feature is accomplished by means of a very innovative electrode design around the edges of the electrostatic plates. The beam line will also feature a fast electrostatic kicker to allow it to be run in the "muons on request" (MORE) mode.

### β-NMR and β-NQR Beam Lines in ISAC-I

Polarized beams of β-emitting unstable light nuclear isotopes can be produced in ISAC-I for transport into its low-energy experimental area and delivered into its condensed matter research facilities. The potentially useful nuclei are $^{8}$Li, $^{11}$Be, $^{12}$O, and $^{17}$Ne, but to date only $^{8}$Li, with a nominal energy of 28 keV

**Simon Fraser University**

| New Initiatives Fund / Fonds des initiatives nouvelles | |
|---|---|
| Muon Beam Line for Molecular and Materials Science at TRIUMF | $2,405,525 |
| **1 project / projet** | **$2,405,525** |

**Figure 3:** The CFI award notification published in Nov. 2006 representing its 40% contribution toward CMMS M20 Beam Line rebuild project at TRIUMF.

and a flux to $10^7$/s, has been delivered. A fast kicker front-end multiplexer then switches the beam to either the β-NMR or β-NQR arms allowing for quasi-simultaneous operation and increased utilization efficiency of the available beams. Each spectrometer is mounted on an isolated HV platform which confers the capability to decelerate the beam to as low as 0.1 keV. The bi-polar β-NMR HV platform can also accelerate the beam to 80 keV. Both beam lines incorporate *in situ* optical imaging of the beam spot for the assessment of their focusing mechanism. The final beam line stages and cryostats operate in a UHV environment that is time consuming to prepare. To that end, sample load locks and an in situ system, in which a multi-sample holder can be placed in the high voltage, have greatly reduced the turnaround time for sample changes.

### New CMMS Devices in the Last Five Years

- A novel μSR high field (5 T) high timing resolution (250 ps) front-end detector array for use in the CMMS dilution refrigerator (base temperature 15 mK) delivers an unprecedented B/T range for μSR studies. Figure 5 illustrates the detector design.
- A general-purpose, extremely flexible spectrometer, OMNI', for use in the M9B decay channel has been commissioned.
- Standardized universal mounting systems for all μSR spectrometers deployed.
- Compact data acquisition electronics for integral μSR designed and implemented.

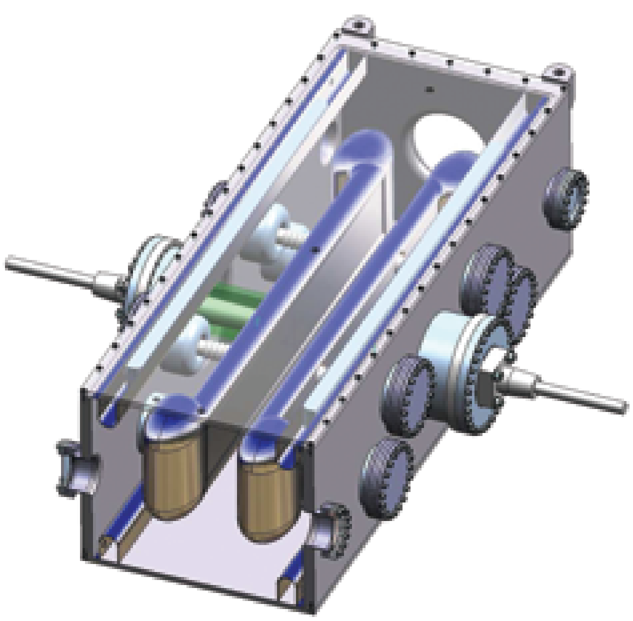


**Figure 4:** A rendering of the vacuum tank, electrostatic plates and high-voltage feedthroughs of the Wien filter / spin rotator being fabricated by Bruker Biospin for the TRIUMF M9A beam line. The design should offer unprecedented stability for the +/- 275 kV operating plate voltages.

- Ceramic temperature stable (2–450 K) 0.8–2.5 GHz microwave resonant cavity for Mu studies designed and implemented.
- High-pressure/temperature apparatus designed and built for supercritical studies.
- High-pressure 2.5 GP piston pressure cells designed and utilized in OMNI’. Figure 6 shows a 3rd generation design which will be used for even higher pressures.
- Cryogenic OMNI’ insert designed and built specifically for optimizing muon polarization in high-pressure cell above.
- Advanced firmware modules for β-NMQR (shown in Figure 7) have been developed to allow random frequency sweeping and complex rf-pulse modulation of capabilities.
- Athermal excitation (optical, electrical, and strain) capabilities have been added to selected experimental configurations.

## Catalogue of Equipment

The equipment belonging to, or available to, the CMMS is includes spectrometers—magnets plus detectors (see Table 1); sample environment control devices—cryostats, ovens, and so on; and ancillary supporting equipment.

### Spectrometers

A spectrometer for the CMMS is a magnet (or magnets) plus an array of counters to detect incoming particles and outgoing electrons/positrons after β-decay. Some spectrometers move from beam line to beam line, some are only used on a specific beam line, and the ISAC-deployed units (β-NMR, β-NQR) are permanently attached to a particular beam line.

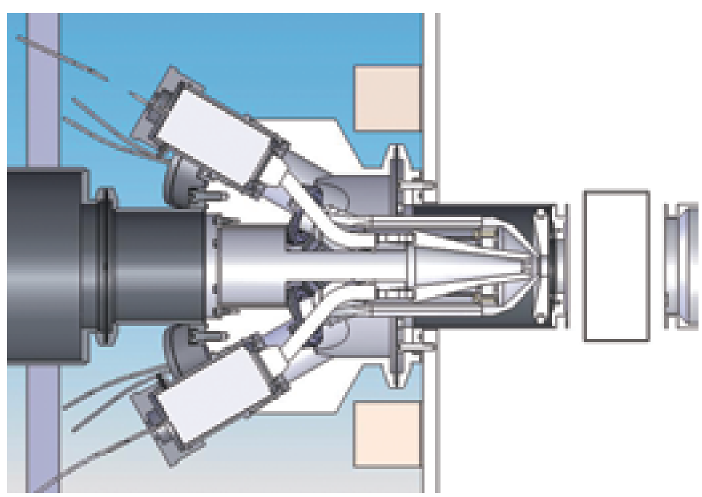


**Figure 5:** Schematic diagram of the scintillators, light guides and photomultiplier arrays in the beam line vacuum that compose the muon CMMS DR front-end detector. The dense design is made possible by the use of wave-shifting scintillators to efficiently bend light around corners.

The magnets are of various types—Helmholtz, solenoid, or solid pole electromagnet, superconducting or normal—and most spectrometers have more than one magnet. The main magnet of a spectrometer is usually oriented so the field is along the beam axis that allows the beam to enter the sample without being turned away. Other coils provide weaker fields in perpendicular directions either for zeroing the field or for applying weak fields (<10 mT) transversely to the beam direction.

Most of the counter systems are movable in various ways, and many follow a general-purpose design of multi-counter modules mounted on tracks on tables attached to the spectrometer. Other counters are fixed components of the spectrometer or sample-holding inserts.

The spectrometer provides the magnetic field, but other experimentally relevant conditions are typically controlled. Temperature is the most important, and samples are usually held within a cryostat or oven. Other variables are pressure, RF/microwave excitation, and electric field.

# Results and Progress

CMMS has contributed to and enabled a number of key advances in molecular and materials science, namely: high-temperature superconductivity; physical, "green," and materials design chemistry; exotic magnetism, strongly correlated systems, and quantum phase transitions; hydrogen-materials interactions; industrial basic research for automobile technology; β-NMQR; and nuclear quantum electrodynamics. Each of these advances is described separately below.

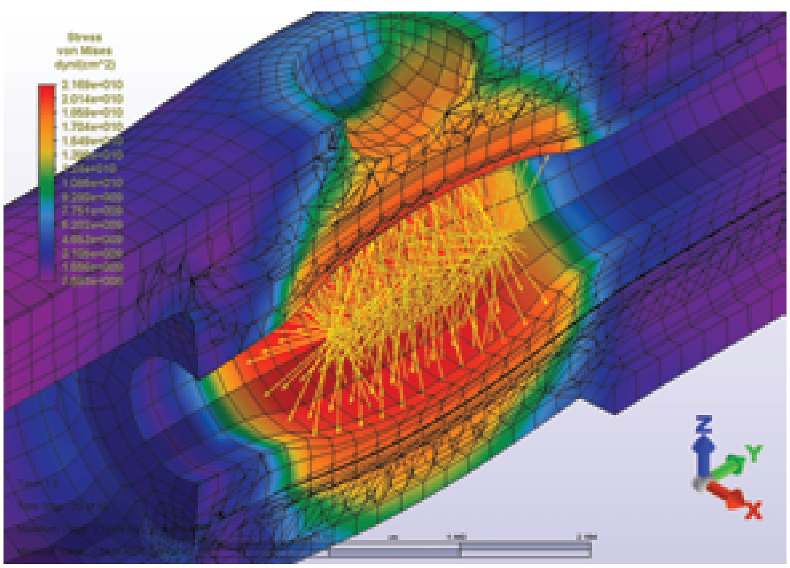



**Figure 6:** A preliminary analysis (T. Ries, TRIUMF) of the stress vs. strain in a double walled pressure cell specifically designed for μSR studies at 3.5GPa. The top dimple reduces the mass density along the muon's path to mitigate multiple scattering and enhance the probability that it will stop in the central target volume.

## High-Temperature Superconductivity: Definitive Measurements & Tests

High-temperature superconductivity (HTSC) has the potential to factor into future energy-saving technologies. μSR has played a prominent role in our current understanding of HTSC, with studies at TRIUMF accounting for the most recognized μSR contributions to this field. Since the discovery of high-$T_c$ cuprates in 1987, μSR has been used to map out significant pieces of their generic phase diagram by exploiting the technique's unique sensitivity to disordered static magnetism, short-range magnetic order, and magnetic phase separation. μSR has also been used to probe low-energy excitations, to establish a definitive relationship between the superconducting carrier density and $T_c$ (the so-called "Uemura plot"), and to provide one of the earliest pieces of evidence for d-wave superconductivity in the bulk. μSR studies on high-$T_c$ cuprates at TRIUMF have provided strong evidence for the existence of a state closely competing with superconductivity, beginning with the reported finding of weak anomalous magnetism [Science 292, 1692 (2001)], and including more recent experiments showing unusual magnetic field-induced effects in the superconducting and normal states. The prominence of μSR in the study of

| Name | Magnet Type | Purpose & Notes |
|---|---|---|
| Helios | Superconducting 6 T | General purpose beam |
| DR | Superconducting 5 T | Low temperatures (see DR sample environment) |
| Hi-time | Superconducting 8 T | High field, high frequency |
| OMNI' | Conventional 0.3 T | Energetic muon beam, thick targets (high pressure) |
| LAMPF | Conventional 0.3 T | Low-field, general purpose |
| SFUmu | Conventional 0.45 T | General purpose and energetic beam |
| β-NMR | Superconducting 7 T | β-NMR studies |
| β-NQR | Conventional 0.01 T | Low-field β-NQR studies |
| Gas cart | Conventional 0.03 T | Very large samples |
| Varian | Conventional 1 T | Energetic beam transverse field. Deprecated since transverse muon polarization developed on M9b beam line |
| OMNI | Conventional 0.2 T | General purpose, deprecated |

**Table 1.** Magnets and detectors and their uses.

HTSC and other unconventional superconducting materials is predominantly due to: (i) the availability of extremely high quality samples from collaborators at UBC; (ii) CMMS spectrometers, which boast unique measurement capabilities not available elsewhere; and (iii) the quality of the research groups involved.

### Vortex Core Structure in Type-II Superconductors

μSR has become the leading experimental probe of the effective size of magnetic vortices in type-II superconductors. The core size and shape (see Figure 8) is a fundamental property of type-II superconductivity that has proven difficult to measure by other methods. The cumulative results, which include studies over the past five years [Physical Review Letters 93, 017002 (2004); Physical Review Letters 95, 197001 (2005); Physical Review B 74, 024513 (2006); Physical Review B 74, 054511 (2006); Physical Review B 76, 134518 (2007), Reports on Progress in Physics 70, 1717 (2007)], have served as a primary motivation for recent advances in the development of a complete microscopic theory of the electronic and magnetic structure of the vortex state in single-band and multi-band superconductors. Recently, the effects of multiband superconductivity on the vortex core size have been demonstrated in the high-$T_c$ superconductor $YBa_2Cu_3O_y$ [Physical Review B 76, 134518 (2007); Physical Review B 77, 024514 (2008)].

### Generic Magnetic Phase Diagram of HTSC and Hidden Order

Within this five year time span, μSR studies at TRIUMF have continued to considerably add to our understanding of the generic magnetic phase diagram of cuprates, which serves as the primary motivation for theoretical ideas on the


**Figure 7:** The β-NMQR rf generator, which contains digital FPGA based DSPs to generate complex modulated pulse shapes to produce sophisticated frequency swept pulses which can be designed to irradiate any discrete set of frequency slices in the spectrum.

microscopic origin of HTSC. The complexity and fragility of HTSC is believed by many to be due to the presence of a hidden order that competes with superconductivity. Zero-field (ZF) μSR is an extremely sensitive probe of weak magnetism associated with a competing state. Very recently, the earlier finding of anomalous weak magnetism in $YBa_2Cu_3O_y$ by ZF-μSR [Science 292, 1692 (2001)] was independently confirmed [Xia *et al.* submitted to Physical Review Letters]. This and new findings from neutron scattering have sparked considerable interest and are driving demand for new μSR measurements. The first new ZF-μSR study of this kind has recently been completed [G.J. MacDougall *et al.* submitted to Physical Review Letters].

High-$T_c$ superconductors are achieved by doping an antiferromagnetic insulator with charges or holes. ZF-μSR studies, including recent work near the insulator-to-superconductor boundary [Physical Review B 73, 144509 (2006)] indicate that superconductivity struggles against remnants of the magnetic parent compound. In 2003, it was shown for the first time by μSR that local suppression of superconductivity in an electron-doped high-$T_c$ cuprate by a weak magnetic field results in the appearance of magnetic order [Physical Review Letters 91, 147002 (2003)]. Field-induced effects in hole-doped cuprates were further studied by transverse-field (TF) μSR [Physical Review Letters 95, 157001 (2005); Physical Review B 75, 054511 (2007)], and it was shown for the first time that an applied field induces static spin-glass magnetism in the superconducting phase immediately below the critical doping for the so-called "normal-state metal-to-insulator crossover (MIC)" [Physical Review B 76 064522 (2007)]. This discovery identifies the precise location of a hidden quantum phase transition to a state of coexisting superconducting and magnetic orders, and also supports the theoretically predicted occurrence of an "avoided" quantum critical point (QCP) in the HTSC phase diagram. This is the first experimentally established example of an "avoided" QCP in a three-dimensional bulk system.

Recently, an anomalous inhomogeneous magnetic-field response has been observed by TF-μSR above the bulk superconducting transition temperature $T_c$ that tracks the magnetic response of the superconducting state [J.E. Sonier *et al.*, submitted to Physical Review Letters]. The experimental results, shown in Figure 9, are explained by the occurrence of superconducting domains at temperatures extending well above $T_c$. Remarkably, spatial field inhomogene-

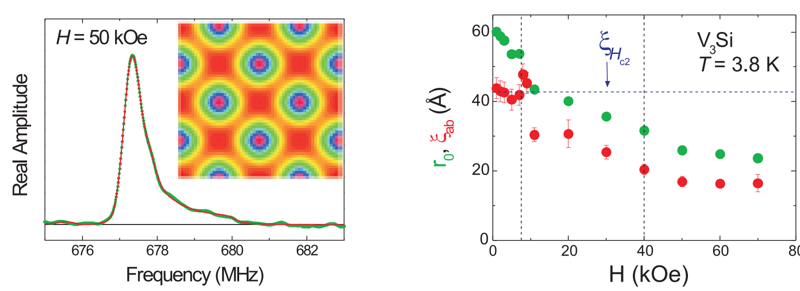



**Figure 8:** Internal magnetic field distribution in the vortex state of superconducting $V_3Si$ (left panel), and the magnetic field dependence of the vortex core size (right panel) due to the delocalisation of bound quasiparticle core states. From [J.E. Sonier et al. Phys. Rev. Lett. 93, 017002 (2004)].

ity above $T_c$ is observed even in ortho-II $YBa_2Cu_3O_6\overline{H}_{50}$, which has highly ordered doping. Hence, the spatial field inhomogeneity above $T_c$ does not appear to be due to local disorder introduced by the chemical dopants but is suggestive of a reorganization of the electronic structure brought about by a closely competing state. The observation of superconducting signatures far above $T_c$ raises the prospect of one day creating a room-temperature superconductor, and future μSR investigations are expected to play a prominent role in elucidating the reason why the bulk superconducting state breaks up into domains above $T_c$.

## Physical, Green, and Materials Design Chemistry

In contrast to the work described in the previous section, which depends on the use of the muon as a microscopic probe of magnetism, applications of μSR to chemistry emphasize the role of the muon as nucleus of the muonium atom (Mu), a spin-labeled light isotope of hydrogen (H). The μSR signature of Mu atoms is very distinct and allows unambiguous measurements of hydrogen atom reactivity and environmental interactions. In some applications, emphasis is on comparison of the behaviour of Mu and H, *i.e.*, isotope effects; others utilize Mu as a substitute for H, to permit studies under conditions where H atom experiments are not possible or the signals cannot be distinguished from background. Incorporation of Mu into a molecule with an unpaired electron (*i.e.*, a free radical) modifies the μSR signature in a manner that provides information on the unpaired electron spin density at the muon location in the molecule. Further aspects of the unpaired spin distribution can be learned by applying another type of muon spin spectroscopy, avoided level-crossing resonance (MuLCR).

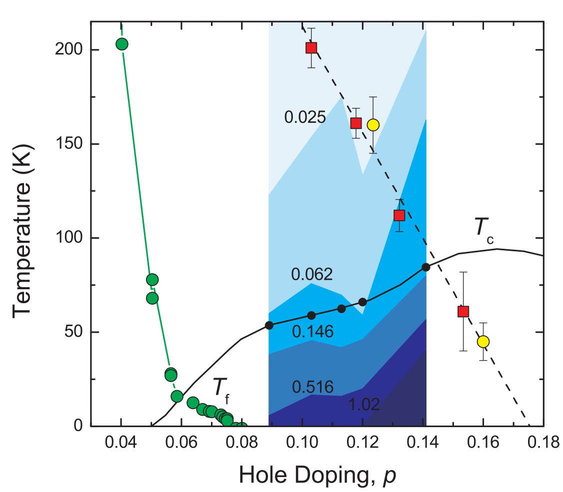



**Figure 9:** The inhomogeneous superconducting behaviour in YBCO at H = 7 T is shown as coloured bands which displays the additional induced relaxation $L - L_{Ag}$. Also shown is the extended spin freezing transition $T_f$ and the onset of magnetic order (yellow circles) determined by ZF-μSR in previous TRIUMF work. From [J.E. Sonier et al., submitted to Physical Review Letters].

PEOPLE

## JUN SUGIYAMA

*Principal Research Scientist*

Jun Sugiyama received a B.Sc. in Chemistry and a M.Sc. in Applied Physics from Nagoya University in 1979 and 1982, respectively. After graduation, he joined the sensor group of Toyota Central R&D Labs (TCRDL), where his work ranged from magnetic sensors to surface acoustic wave devices. From 1989–1993, Jun worked with the materials group of Superconductivity Research Laboratory in Tokyo. He completed his Ph.D. thesis, "Substitution effect on magnetism and superconductivity in Nd2CuO4," in 1992 at Nagoya University.

Dr. Sugiyama returned to the materials division of TCRDL in 1993 to lead the research effort focused on battery-related thermoelectric materials. Emphasis focused on the layered cobalt dioxides which had excellent thermoelectric properties. To that end, Jun has been using TRIUMF's μSR facilities to probe and understand the magnetic character of the complex phases found in these materials.

Jun is currently the leader of the particle beam analysis group of TCRDL. This effort is focused on the development of new materials that have potential applications for future automotive technologies. As a case in point, recent initiatives encompass studies of hydrogen storage materials that promise a means to use clean-burning hydrogen for fuel cell vehicles and other instruments pertinent to a sustainable future "hydrogen economy."

In 1991, Jun received the SRL Technical Research Award. In 2004, he was the co-recipient of a World Young Fellow Meeting Presentation Award presented by the Ceramic Society of Japan, and the recipient of TCRDL's Most Excellent Research Award. ■

In recent years, many of the muonium chemistry projects at TRIUMF have explored problems in reaction kinetics and free radical chemistry which have applications of environmental relevance, for example, the destruction of toxic waste and the development of environmentally friendly industrial processes, or so-called "green chemistry". This Canadian-dominated research effort, from P. Percival (SFU), J. Clyburne (Saint Mary's University), K. Ghandi (Mount Allison University), and D. Fleming (UBC), is the focus of the work reported below.

### Reaction Kinetics and Organic Free Radicals under Hydrothermal Conditions

Developing an understanding of transient free radical reaction dynamics in superheated aqueous solutions is motivated by their relevance and applicability to geochemical production of fossil fuels, biology of submarine volcanic vents, corrosion in pressurized water reactors, the destruction of chemical weapons, and utilization in green industrial processes. However, direct experimental access to the H atom chemistry under these extreme conditions is very difficult, and the use of Mu substitution has provided the experimental means to extract much information of significance.

Measurements of kinetic data for hydrogen atom abstraction and electron transfer reactions in sub- and supercritical water have led to an improved model for the reactions of key intermediates involved in the radiolysis of water in the cooling cycle of nuclear reactors [J. Phys. Chem. A 107: 3005–3008 (2003) "Prediction of Rate Constants for Reactions of the Hydroxyl Radical in Water at High Temperatures and Pressures"]. The data are also relevant to the chemistry involved in the supercritical water oxidation scheme for the destruction of toxic waste [Physica B 326: 55-60 (2003) "Muonium kinetics in sub- and supercritical water"; Rad. Phys. Chem. 76: 1231-1235 (2007) "H atom kinetics in superheated water studied by muon spin spectroscopy"].

Organic free radicals are usually characterized by electron spin resonance (ESR) but this technique is not possible for radicals in superheated water. Thus information gained in the study of muoniated radicals is unique [J. Am. Chem. Soc. 127: 13714-13719 (2005) "Organic Free Radicals in Superheated Water Studied by Muon Spin Spectroscopy"]. An example is the investigation of the equilibrium between keto and enol forms of acetone, where it was found that high temperatures favour the enol, which is only present in minute quantities at room temperature [J. Am. Chem. Soc. 125: 9594-9595 (2003) "Enolization of Acetone in Superheated Water Detected via Radical Formation"].

To carry out these studies on Mu and free radicals in superheated water, specialized apparatus was designed and fabricated to permit μSR and MuLCR measurements under conditions (up to 400°C and 400 bar) not previously attained [Physica B 374-375: 314-316 (2006)].

### Catalysis of Organic Reactions in Zeolites

The use of zeolites as heterogeneous catalysts is ubiquitous, particularly in the petrochemical industry, yet there is still relatively little understanding of the mechanisms involved at the microscopic level, and in particular the roles played by neutral free radicals. Mu easily substitutes in the known organic processing precursors ($C_6H_6$ and $C_2H_4$), forming the radical, which can be detected via the MuLCR technique. The positions, widths, temperatures, and molecular coverage dependencies of the resulting spectra deliver information concerning the binding sites and the dynamics of intra- and inter-site motions of the radicals under study [Physica B 326: 64-67 (2003) "Observation of Muonium in Zeolites"; J. Phys. Chem. C 111: 9779-9793 (2007) "The Interaction and Hyperfine Coupling Constants of the Mu-Ethyl Radical in Faujasites: NaY, HY and USY"; Phys Chem/Chem Phys (2008) "Hyperfine Interactions and Molecular Dynamics of the Mu-cyclohexadienyl Radical in Y-Zeolites"].

### Ionic Liquids, Carbenes and Related Muoniated Radicals

Ionic liquids have attracted significant interest as environmentally friendly solvents. They perform well as acidic reaction media and have very low volatility. One significant aspect of the chemistry of the imidazolium-based ionic liquid is its binary reaction into a pair of carbene molecules, entities with two proximally coordinated unpaired electrons. Until recently, carbenes were considered undetectable due their extreme reactivity, but carbenes incorporating an imidazole ring are relatively stable, and their H atom adducts can be investigated by means of the Mu analogues [J. Am. Chem. Soc. *125:* 11565-1157 (2003) "The Reactions of Imidazol-2-ylidenes with the Hydrogen Atom: A Theoretical Study and Experimental Confirmation with Muonium"; Chem. Comm. DOI:10.1039/ b512462j (2006) "From the reactivity of N-heterocyclic carbenes to new chemistry in ionic liquids"]. Since that initial work, the idea has been extended to study muonium in addition to the even more exotic silylenes and germylenes. H analogues of the ensuing silyl and germyl radicals have not been detected, so the information obtained on their structure and reactivity via μSR is unique, with relevance to the chemical processes used to prepare thin films of silicon and germanium for the semiconductor industry.

### Fundamental Molecular Reaction Rates

The study of the reaction rates of the Mu atom provides for a uniquely sensitive measure of quantum mass effects in chemical reactivity, thereby providing a stringent test of any reaction rate theory describing the process. A good example is the recent study of the Mu+CO reaction, which, in comparison with its isotopic HCO analog, provided an important test of the rates, predicted by the "Isolated Resonance Model". The utility of Mu is due to the enhanced zero-point energy of MuCO, which reduces its density of resonant states by a factor of 30 when compared with HCO [J. Chem. Phys. 125, 014307-13 (2006) "Termolecular kinetics for the Mu+CO+M recombination reaction: A unique test of quantum rate theory"].

### Designing Molecular Polymer Magnets

The intense interest in coordination polymer research can be attributed to the potential to design functional materials by utilizing judiciously chosen building blocks to generate specific structural motifs with targeted physical properties. The group headed by Leznoff (SFU) has been examining metal-cyanide coordination polymers, particularly those based on the dicyanoaurate building blocks. These materials have a wide variety of potential applications as magnetic sensors, birefringent components and gas storage matrices. Recently, a new series of isostructural polymers of the form $M(\mu\text{-}OH_2)_2[Au(CN)_2]_2$ (M = Cu, Ni, Co, Fe, Mn) has been prepared. The $M(\mu\text{-}OH_2)_2M$ aqua-bridged chain motif found in these polymers is unique in cyanometallate materials and is rare in aqueous coordination chemistry. An illustration of the structure, in an aqueous environment and subject to a muon beam, is illustrated in Figure 10. Such new structural motifs are significant as they form the basis for further modification of polymer properties. Utilizing mSR and squid magnetometry, the magnetic properties of these systems were studied as a function of transition-metal moment. A variety of magnetic behaviour, from ferromagnetic to spin-glass meta-magnetic, was found. These results were interpreted in light of the unprecedented structural motif, which features a $M(\mu\text{-}H_2O)_2M$ chain and $H_2O/Au(CN)_2$ hydrogen bonding and will assist in the future design of molecule-based magnetic materials [Chem. Eur. J., 2006, 12, 6748-6761 "A New Basic Motif in Cyanometallate Coordination Polymers: Structural and Magnetic Properties of $M(\mu\text{-}OH_2)_2[Au(CN)_2]_2$ ($M$ = Cu, Ni)" ].

## Exotic Magnetism, Strongly Correlated (SC) Systems, Quantum Phase Transitions

The study of the interplay and competition between the ordering and disordering mechanism in strongly correlated systems at low temperatures is not

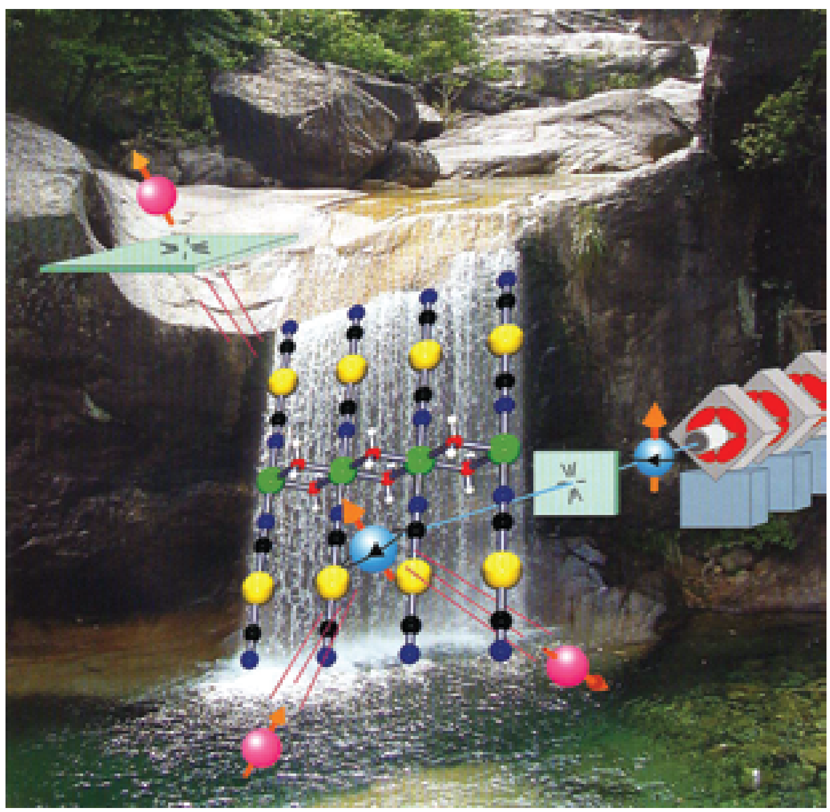


**Figure 10:** Watery bridges play the key role in a new basic structural motif exhibited by $M(\mu\text{-}OH_2)_2[Au(CN)_2]_2$ (M = Cu, Ni, Co, Fe, Mn); a 1D chain propagated by double aqua-bridges. These metal-water chains, shown here cascading down a rock-studded waterfall, aggregate through hydrogen bonds to form stacked ribbons in 3D.

limited to HTSC. Itinerant non-local magnetism, non-Fermi liquid (NFL) magnetism, heavy fermion systems with complex SC and magnetic properties, organic high-pressure SC/antiferromagnetic materials, systems in which geometrical frustration suppresses spin freezing at $T = 0$ due to degeneracy, all can be considered within this general theme. The study of such magnetic systems is the "natural" province of μSR. The muon's magnetic sensitivity, coupled with the capability to conduct experiments from zero to large applied (decoupling) fields, yields an enormously powerful tool to microscopically characterize the statics and dynamics of such complex magnetic behaviour. Only a small sample of what is traditionally the most heavily represented field of study in mSR can be alluded to in the following.

### Quantum Phase Transitions, Criticality and Dynamics in Itinerant Heli/Ferromagnets

It has been demonstrated that in two itinerant ferromagnetic systems, MnSi and $Sr_{1-x}Ca_xRuO_3$, the quantum phase transition from the ferromagnetic state to the paramagnetic state is first order. The magnetic and non-magnetic phases compete for volume fraction near the transition where the ordered magnetic phase is driven to zero temperature, either by pressure (MnSi) or by substitution ($Sr_{1-x}Ca_xRuO_3$). The results suggest that many such quantum phase transitions are first-order, and that nature wants to avoid an actual quantum critical point [Nature Physics 3, 29-35 (2007) "Phase Separation and Suppression of Critical Dynamics at Quantum Transitions of Itinerant Magnets: MnSi and $(Sr_{1-x}Ca_x)RuO_3$"].

### Magnetism in Non-Fermi-Liquid Metals

μSR experiments show that structural disorder is important in many non-Fermi-liquid (NFL) systems. Disorder-driven mechanisms for NFL behaviour are suggested by the observed broad and strongly temperature-dependent μSR (and NMR) linewidths in several NFL compounds and alloys. Local disorder-driven theories are, however, not capable of describing the time-field scaling seen in muon spin relaxation experiments, which suggest cooperative and critical spin fluctuations rather than a distribution of local fluctuation rates. A strong empirical correlation is established between electronic disorder and slow spin fluctuations in NFL materials [J. Phys.: Condens. Matter 16, S4479 (2004) "Disorder, Inhomogeneity and Spin Dynamics in f-electron Non-Fermi Liquid Systems"].

### Heavy Fermion Systems & Unconventional (non-HT) Superconductivity

In strongly correlated electron systems, *s*-wave pairing is difficult to realize, and the study of anisotropic superconductivity is a central feature of such systems. Such systems can further sustain superconducting electron pairing, which are spin-singlet (even-parity) or spin-triplet (odd-parity), the unconventionality of which motivates their extensive study. $PrOs_4Sb_{12}$ is the first known unconventional heavy-fermion SC with a postulated pairing mechanism driven by quadrupole fluctuations. μSR experiments in this material indicate the presence of a small internal field in the SC state along with spin-triplet pairing, a first for a 4f-electron system [Phys. Rev. B 75 020510-1-4 (2007) "Spin-Triplet Superconductivity in $PrOs_4Sb_{12}$ Probed by Muon Knight Shift"].

A natural companion to such work is the investigation of the alloy series $Pr(Os_{1-x}Ru_x)_4Sb_{12}$ and $Pr_{1-y}La_yOs_4Sb_{12}$ in which anomalous dynamic muon spin relaxation has been identified as resulting from the interaction with the enhanced spin of the $^{141}Pr$ nuclei, which is itself caused by the Pr nuclear hyperfine interaction (Bleaney 1973) derived from a Van Vleck-like admixture of magnetic $Pr^{3+}$ crystalline-electric-field-split excited states into the nonmagnetic singlet ground state. The results, therefore, indicate that the electronic spin fluctuations are not directly involved in the dynamic muon spin relaxation [Phys. Rev. B 76, 015427 (2007) "Muon Spin Relaxation and Hyperfine-Enhanced $^{141}Pr$ Nuclear Spin Dynamics in $Pr(Os,Ru)_4Sb_{12}$ and $(Pr,La)Os_4Sb_{12}$"].

The two-fluid model of heavy-fermion formation introduced by Nakatsuji *et al.* has been tested with experiments performed in the heavy fermion material $(Ce,La)_2IrIn_8$. Good agreement was found. A similar analysis of previous data in $UBe_{13}$ was also successfully performed [J. Phys. Chem. Solids, to be published "Study of the Effects of Ce Dilution on the Development of the Heavy-Fermion State in $(Ce,La)_2IrIn_8$,"; J. Magn. Magn. Mat. 310, *e6* (2007) "Two-Fluid Model of Heavy Fermion Formation and μSR Knight Shift Measurements in $UBe_{13}$"].

In superconducting systems, *i.e.*, $CePt_3Si$, $Li_2Pt_3B$, $Li_2Pd_3B$, Uir, without unit cell inversion symmetry, Cooper pairs can have mixed parity, *i.e.*, with an admixture of spin-singlet and triplet amplitudes. Establishing the symmetry of the SC order parameter is therefore an important aspect in the understanding of SC phenomena in such low symmetry materials. μSR Knight shift studies in $CePt_3Si$ shows no temperature dependence below 1K and therefore do not substantiate the theoretical predictions for either spin-singlet or spin-triplet pairing for such systems [J. Phys. Soc. Japan 75, 180 (2006) Supplement "Magnetism and Superconductivity in $CePt_3Si$ Probed by Muon Spin Relaxation"].

### SC Pair Breaking Mechanisms via Radiation-Induced Defects

The effects of radioactive pair breaking on the superconducting properties of $PuCoGa_5$ were investigated through μSR studies on a single crystal sample 25 days after preparation (*i.e.*, fresh) and then 400 days after preparation, allowing radiation damage to accumulate at room temperature. The measured temperature dependence and magnitude of the superfluid density in both samples was compared with a state-of-the-art theory performed as part of the collaboration. It was found that both the fresh and aged samples were consistent with *d*-wave pairing, but that the extreme suppression of the superfluid density in the aged sample is inconsistent with the usual Abrikosov-Gor'kov pair-breaking theory, in which the order parameter is averaged over the defect sites. It was concluded that the aged material is in the limit of a short superconducting coherence length material, consistent with an inhomogeneous order parameter that is suppressed in the region of the defects, similar to the cuprate superconductor YBCO. In order to explain the data, the work extended the theory of inhomogeneous pair breaking to finite temperatures [Phys. Rev. B 76, 064504 (2007) "Muon Spin Rotation Measurements of the Superfluid Density in Fresh and Aged Superconducting $PuCoGa_5$"; J. Phys. Soc. Japan 75, 14 (2006) Supplement "μSR studies of Pu metal and the Pu-based Superconductor $PuCoGa_5$"; J. Phys. Soc. Japan 75, 53 (2006) Supplement "Flux-Line Lattice State in $PuCoGa_5$ Probed by Muon Spin Rotation"].

### Lack of Magnetic Ordering in Pu Metal

Experiments in two alloys of Pu metal ($\alpha$-Pu and $\delta$-Pu) unambiguously demonstrate that no ordered magnetism exists in these materials down to a temperature near 2 K. The results have contradicted previous theoretical predictions of ordered moments in $\delta$-Pu, leading to new physics concerning the configuration of the 5 5-f electrons in Pu [Phys. Rev. B73 094453 (2006) "Limits for ordered magnetism in Pu from muon spin rotation spectroscopy"; J. Alloys and Compounds 444-445, 80-83, 2007 "The Search for Magnetic Order in $\delta$-Pu Metal Using Muon Spin Relaxation"].

### Multipole Ordering in *f*-electron Systems

Due to the compactness of the *f* shells, spin and orbital components of the *f*-electron are strongly coupled, and the relevant degrees of freedom are described by using multipole moments in the localized limit. Early research concentrated on quadrupolar ordering, but it is now recognized that higher multipole ordering can occur. $\mu$SR has been utilized to characterize these orderings in, for example, the intermetallic binary compound $PrPb_3$, which has a non-magnetic ground state with quadrupole and octupole degrees of freedom and is considered to quadrupole order at 0.4 K. ZF-$\mu$SR results suggest a possible contribution from an octupole magnetic moment but TF-$\mu$SR rules this out from symmetry arguments. The results therefore cannot be explained only by the multipole degrees of freedom in the cubic effective field (CEF) ground state and this suggests the importance of excited CEF states [J. Mag. Mag. Mater. 310 743-745 (2007) "Muon Knight Shift Measurements on $PrPb_3$ in Paraquadrupolar State"].

The multipole ordering of $SmRu_4P_{12}$ below its 16.5 K metal to insulator transition ($T_{MI}$) has also been studied indicating that a magnetic dipole and/or octupole ordering occurs at $T_{MI}$. Observed large amplitude fluctuations in the ordered state indicate low-energy excitations of the ordered octupole moment [J. Phys. Soc. Jpn. 76 (2007) 05370 "Evolution of Local Magnetic State in $SmRu_4P_{12}$ Pobed by Muon Spin Relaxation"].

### Geometric Frustration and Surface Effects

In the study of competing ordering and disordering mechanisms, canonical system behaviour is provided by the existence of geometric frustration and spatial inhomogeneity of the underlying ordering interaction. The phenomena of macroscopic quantum ground state degeneracy, *i.e.*, $T$=0 fluctuating spin states, is a theoretically rich, controversial, and very active field of research which is exquisitely experimentally accessible using zero field $\mu$SR. This technique delivers detailed signatures of the static and dynamic nature of the low temperature states in the plethora of possibly co-existing ordered, disordered, and/or fluctuating degenerate states that may be present. The capability extends equally well to powder samples for which alternate techniques, like neutron diffraction, may not be available [J. Magn. Magn. Mater. 310, 1288 (2007) "Co-existence of long range order and spin fluctuation in a new geometric frustration series $M_2Cl(OH)_3$;" Phys. Rev. Lett. 97, 247204 (2006) "Coexisting ferromagnetic order and disorder in a uniform system of hydroxyhalide $Co_2(OH)_3Cl$;" Phys. Rev. Lett. 95, 057201 1-4 (2005) "Coexistence of long-range order and spin fluctuation in geometrically frustrated clinoatacamite $Cu_2Cl(OH)_3$;" Phys. Rev. B 72, 014468 1-8 (2005) "Finite-size effect


## YASUTOMO UEMURA

*Professor, Columbia University*

Yasutomo (Tomo) Uemura obtained his M.Sc. and D.Sc. from the University of Tokyo, in 1979 and 1982, respectively. His thesis entitled "Muon Spin Relaxtion Studies of CuMn and AuFe Spin Glasses" was supervised by Prof. Yamazaki and the work performed at TRIUMF.

Professor Uemura has performed pioneering μSR experiments on various novel magnetic systems. His studies of spin glasses, and the development of phenomenological models for the relaxation functions in these systems, are now considered standards. More recently, he has performed work systemizing μSR penetration-depth data in a wide range of superconductors. He has profoundly demonstrated the value of μSR to the wider condensed matter physics communities. Much of this work has been carried out at TRIUMF.

Between 1983–88, Dr. Uemura worked at Brookhaven National Laboratory with the neutron scattering group, and, in 1988, he joined the Department of Physics at Columbia University.

Tomo is the recipient of the Packard Fellowship and is a Fellow of the American Physical Society. In 2005, he won the first Yamazaki Prize from the International Society for μSR. ■

on Néel temperature in antiferromagnetic nanoparticles"; Phys. Rev. B 69, 214415 (2004) "Random spin freezing in $Ce_2MIn_8$, M = Co, Rh, Ir heavy fermion materials"].

### Magnetic Polarons

Semiconductor electronics to date is based on the quantum transport of charge carriers, while information storage relies mainly on the collective interactions (magnetism) of spins. The promise of new technologies for computational devices motivates the discipline of "spintronics," which proposes to exploit the strong mutual influence of magnetic and electrical properties found in magnetic semiconductors. The mechanism for such phenomena relies on the magnetic polaron, a microscopic cloud of magnetization composed of charge carriers and neighbouring magnetic ions that determines most of the electrical, magnetic, and optical properties of the material. In spite of the importance of this quasiparticle, it has eluded direct observation using more standard techniques. Using the $\mu^+$ in EuS as both a donor centre and a local magnetic probe, the magnetic polaron has been generated and detected. Size and magnetic moment determinations have been made [Physica B 374-375, 430-432 (2006) "Room temperature ferromagnetism in III-V and II-IV-$V_2$ dilute magnetic semiconductors"].

## Hydrogen–Materials Interactions

The applicability of μSR when muons chemically adopt the role of hydrogen is not limited to its use in chemistry but has equal utility in the study of many aspects of hydrogen-materials interactions. In semiconductors, muons exist in a variety of electronic states and site locations, which undergo complex cycles of charge state reactions and/or site migrations. In materials that can accommodate large volumes of hydrogen, muons characterize *in situ*, *i.e.*, as a function of H loading sites, mobility, and host interactions.

### Semiconductors

H is a highly mobile, often unintentional, interstitial impurity in semiconductors. It rapidly forms complexes with, and passivates, other defects and dopants, resulting in dramatic modifications of the electrical and optical properties of the material. Its high diffusivity and reactivity greatly restrict direct measurements on the isolated states of H or the specifics of the passivation reaction. In keeping with the general theme underlying the surrogate utility of Mu, an understanding of the charged states of H can be indirectly obtained via μSR, which many consider to be the main source of information on isolated H in semiconductors.

Utilization of athermal excitation (optical, electric, and uniaxial stress) with μSR leads to powerful ways of studying Mu (H). Significant progress along these directions has been made in GaAs and Si [Physical Review B 72, 33201 (2005) "Nature of Charged Muonium in GaAs with an Applied Electric Field;" Physical Review B 73, 113202 (2006) "Demonstration of the effect of uniaxial stress on the electronic structure of bond-centred muonium in Si;" Physical Review B, submitted (2007) "Optically induced dynamics of muonium centre in Si studied via their precession signatures"].

The discovery of a Mu centre with a very small central hyperfine interaction in GaN suggests that H may also act as an effective shallow donor in this important semiconductor used for optoelectronics [Physical Review Letters 92, 135505 (2004) "Muonium as a shallow centre in GaN"].

The first detailed structural characterization for isolated $H^+$ or $Mu^+$ in any semiconductor with direct confirmation of bond-centre occupancy was conducted with TRIUMF [Physical Review Letters 95, 086404-1 to 4 (2005) "Detailed local structure of isolated positively charged muonium, as an analog for the hydrogen ion, in *p*-type GaAs"].

An extensive effort in a series of semiconductor materials (Si, Ge, GaAs, GaP, 6H-SiC, and SiGe alloys) systematically established the energy of the thermodynamic levels associated with a change in the equilibrium charge-state for the Mu analogs of isolated H. Utilization of RF and μwave muon resonance was critical to quantify the final states. The accumulated data support the theoretical claim in that the midpoint between the acceptor and donor levels for the Mu (H) lies at a constant energy independent of host, except that the experimental value is 0.5 eV above the prediction [Physical Review B 76, 045221_1-5 (2007) "Donor and Acceptor Energies for Muonium in GaAs" is a typical work in the series of 4 publications].

### Hydrogen Storage Materials

Complex hydrides, like the alanate $NaAlH_4$, are one of the most promising hydrogen storage materials to have emerged in recent years. Until recently, slow-cycling kinetics precluded these from consideration as practical onboard hydrogen carriers until Bogdanović's discovery of the remarkable acceleration effects of transition metal dopants, thereby opening the door for new classes of potential H-storage materials. In a seminal work, Kadono and Jensen *et al.* have shown the utility of implanted muons to emulate the Ti catalyzed H dynamics in this material, thereby allowing μSR a definitive role in what will soon be a very active field of research [Phys. Rev. Lett. 100, 026401 (2008) "Hydrogen Bonding in Sodium Alanate: A Muon Spin Rotation Study"].

## Industrial Basic Research for Automobile Technology

Some layered cobalt dioxides $A_xCoO_2$ (A = Li, Na and K) exhibit excellent thermoelectric (TE) properties: they can be used to convert heat directly into electrical power. This unusual property attracted the interest of Jun Sugiyama of Toyota Central R&D Labs to spearhead a vigorous research program at the TRIUMF CMMS. Sugiyama's contention is that the unconventional magnetic properties of $Na_xCoO_2$ (NCO) are critical to understand its thermoelectric efficiency, and that the positive muon's unique sensitivity as a probe is key to understanding these magnetic properties. Over the past few years, this strategy has paid off, as a number of remarkable properties of NCO have been revealed: with $x \sim 0.75$, it is an antiferromagnet (AF); with $x \sim 0.7$, NCO is a superb TE; with $x = 0.5$ it is an AF with a charge-ordering transition; and with $x = 0.35$ and absorbed water, it is a superconductor. Sugiyama's CMMS research defines the leading edge of worldwide efforts to understand the phase diagram of NCO and its related compounds with A = Li and K. All are examples of highly correlated electron systems, akin to the HTc-SC cuprates. Recently, this group's CMMS based research initiative has broadened to encompass hydrogen storage materials, with their well-known impact for modern environmental issues [Phys. Rev. Lett. 92, 017602 (2004) "Dome-shaped magnetic phase diagram of thermoelectric layered cobaltites;" Phys. Rev. Lett. 96, 037206 (2006) "Static magnetic order in metallic $K_0\overline{H}_{49}CoO_2$;" Phys. Rev. Lett. 96, 197206 (2004) "Evidence of two-dimensionality in quasi-one-dimensional cobalt oxides;" Phys. Rev. Lett. 96, 197206 (2004) "Magnetic phase diagram of layered cobalt dioxide $Li_xCoO_2$" plus 12 additional full journal publications 2003-2007].

## β-NMQR: Probing the Interface

The TRIUMF low-energy ISAC-I facility produces and delivers an intense (~$10^7$/s) beam of highly polarized variable energy 28 keV $^8Li^+$ nuclei to the two platforms dedicated for condensed matter physics. The capability to decelerate the beam just prior to implantation allows the $^8$Li nuclei to be ranged into surfaces over a depth profile from 5–400 nm. The combination of high nuclear polarization, 0.84 s half-life, 0.63 kHz/G magnetic moment, spin 2 with a +32 mb electric quadrupole moment; and RF irradiation capabilities of up to 50 MHz dictate that $^8$Li magnetic and quadrupole resonances will be directly sensitive to field fluctuations within the range of 0.1–$10^5$ Hz coupled with capability to carry out measurement in a magnetic field of up to 9 Tesla.

Over the past several years, the art of β-NMQR has been significantly refined at TRIUMF. Capabilities to control the depth of implantation allow for selective layer implantation where the $^8$Li nuclei may be placed in a benign host layer adjacent to the material of interest. RF pulse shaping and random frequency irradiation technology allow for excitation of discrete slices of the spectrum and the elimination of the spectral sweep distortions. The availability of both zero- or low-field β-NQR, and high-field β-NMR, allows for the flexibility to utilize or mitigate the effects of local fluctuating electric fields in non-cubic sites. These and future capabilities, *i.e.*, transverse counters to allow spin echo measurements, bode well for the vigour of the program.

### Monolayer Molecular Magnets

Monodispersed, individually addressable nanoscale magnets are a requirement for technological applications (information storage, quantum computing). With the recent advent of monolayer deposition of single-molecule magnets (SMM), such systems become feasible. Low temperature quantum effects, *i.e.*, magnetization tunnelling, phase interference, and quantum coherence, dramatically affect macroscopic magnetic properties. The small quantity of magnetic material present in a monolayer is well suited for study by β-NMR techniques [Nano Letters 7, 1551 (2007) "Local Magnetic Properties of a Monolayer of $Mn_{12}$ Single Molecule Magnets"].

### Vortex Core Size in Type-II Superconductor

Understanding the size and dynamics of type-II superconductor vortex lattices is a central theme in not only in HTc material but also for normal metal type-II materials. This work examines the vortex size near the surface of the well-studied, multi-band $NbSe_2$ to find that at low fields the vortex cores are anomalously large [Phys. Rev. Lett. 98, 167001 (2007) "Magnetic-field Effects on the Size of Vortices below the Surface of $NbSe_2$"].

### Thin-Metal Films

The β-NMR study of isolated $^8$Li on the surface of nearly ferromagnetic Pd indicates a large negative shift, which scales with the bulk susceptibility above 100K. Below this temperature effects attributed to the Li defect are observed [Phys. Rev. Lett. 98, 047601 (2007) "ß-NMR of isolated lithium in nearly ferromagnetic palladium"].

Knight shift and relaxation data in 5 keV depth-controlled $^8Li^+$ in 50nm of Ag on $SrTiO_3$ using a 5 keV show a thermally activated transition from an octahedral (O) interstitial to a substitutional (S) site at 100 K. Similar work using 30 keV $^8Li^+$ in 100 nm Cu film on MgO indicate both O and S are occupied at low temperature with a similar transition to S above 100 K. In both materials, high temperatures data, *i.e.*, 100% S occupancy, are consistent with the Korringa law for a simple metal [Phys. Rev. Lett. 93, 157601 (2004) "Beta detected NMR of Implanted 8Li in a Thin Silver Film;" Phys. Rev. B. 75, 073405 (2007) "ß-NMR of isolated $^8Li^+$ implanted into a thin copper film"].

### Phase Transition Probe

Structural phase transitions near a surface invariably exhibit broken symmetry in the underlying driving mechanism. As such it is expected that the onset and nature of the transition near the surface will vary from that found in the bulk. The zero field β-NQR study of $^8$Li near the surface of the well-known $SrTiO_3$ second-order structural phase transition presents a textbook case of the utility of this probe. At temperature >150 K, the three $^8$L sites have cubic symmetry and hence no efg (electric field gradient) is present with consequently no spin precession and no strong loss of polarization. As the temperature is lowered and the lattice distortion sets in, two of the three sites develop an efg, and the resulting spin precession destroys that fraction of the polarization. The resulting loss of polarization is closely related to the distortion's temperature dependent distribution profile away from the surface, a distribution probed by the depth profile of the implanted beam. These measurements also emphasize that the rather small quadrupole moment of $^8$Li is not a barrier to using it for β-NQR studies [Phys. Rev. Lett. 96, 147601 (2006) "Near-Surface Structural Phase Transition of $SrTiO_3$ Studied with Zero-Field ß-Detected Nuclear Spin Relaxation and Resonance"].

## Nuclear Quantum Electrodynamics

Using the unique capacity of the M9A decay channel to provide $\mu^-$ with substantial spin polarization, spin precession measurements were carried out on series of muonic nuclei ranging from $^{12}$C to $^{207}$Pb in fields as high as 2.4 T. These fields, more than twice the previous standard, facilitated the measurement of the relativistic shifts of $\mu^-$ g-factors in very high Coulomb fields (*i.e.*, bound to nuclei of intermediate and high atomic number Z) to unprecedented precision. These results promise a new testing ground for quantum electrodynamics under extreme conditions [Phys. Rev. A Brief Rep. 72, 022504-022507 (2005) "Relativistic shifts of bound negative muon precession frequencies"].

# Partners

In Canada: AECL Chalk River, Brock University, Dalhousie University, McMaster University, Mount Allison University, Saint Mary's University, Simon Fraser University, Trent University, University of Alberta, University of British Columbia, University of Saskatchewan, University of Sherbrooke, University of Toronto, and the University of Waterloo.

International Partners: Argentina (2), Austria (1), France (1), Germany (5), Israel (1), Italy (1), Japan (23); Portugal (1), Russia (3), Scotland (1), Sweden (1), Switzerland (2), Turkey (1), United Kingdom (1), and the United States (25)

# TRIUMF's Role

The impact of the CMMS program at TRIUMF is now thoroughly distributed over a variety of pure and applied fields of research. The program has hosted cutting-edge and unique contributions into the underlying aspects of high temperature superconductivity, reactions relevant to environmental and industrial processes, new technological materials, nano-scale interface physics while providing fundamental data to test theories ranging from chemical reaction rates to quantum phase transitions, and even quantum electrodynamics. What was once an esoteric and specialized technique is now a tool sought out by an ever-increasing community of users from across disciplinary boundaries.

In recognition of this fact, TRIUMF, CFI and BCKDF have funded an expansion of CMMS infrastructure to facilitate and more readily distribute the research capabilities supported by this program.

To this end TRIUMF's most notable CMMS infrastructure initiatives have been the development of the nascent β-NMQR experimental platforms and the use and redevelopment of its M9A channel into one dedicated solely for μSR. This latter contribution was no doubt a key indicator leading to the M20 upgrade award by CFI/BCKDF. In addition to such very visible "large scale" measures, TRIUMF's tacit support for the program encompasses the provision of outstanding technical facilities, *i.e.*, engineering, machine shop and detector fabrication resources, budget support for CMMS facility R&D and, more recently, a full-time facility scientist position.

In summary, TRIUMF, CFI and BCKDF have funded an expansion of CMMS infrastructure to facilitate and more readily distribute the research capabilities supported by this program. Together with NSERC, which clearly continues its strong commitment to CMMS involved research groups, this program is poised to further expand its impact on the international Molecular and Materials Science community.

# 4.2.3.2

# Proton Irradiation Effects in Advanced Semiconductor Technologies

## Introduction

Energetic protons in space can cause the degradation of semiconductor devices by several mechanisms, including total dose effects and single-event effects (SEEs). Total dose effects are due to the buildup of charge in oxides induced by the holes and electrons generated as protons lose energy by ionization. Typical effects of this charge buildup in integrated circuits (ICs) are large increases in leakage current and functional failure. Total dose effects are often permanent. SEEs occur as a single proton impinges on a material, generating secondary particles. These secondary particles can deposit sufficient energy per unit depth by ionization to change the state of circuit nodes in a memory circuit and cause false information to be stored as a single-event upset (SEU). A SEU can be corrected by reprogramming the circuit into its correct logic state, but if the error rate is too large, it can result in performance degradation of a system and potentially mission failure. Another class of SEEs, which is not correctable by reprogramming, is termed a hard error. Hard errors include single-event latchups (SELs) and gate ruptures (SEGRs). If a hard error occurs, a circuit element may suffer permanent physical damage.

As IC technology advances, devices become more vulnerable to SEEs. To ensure space system functionality and survivability, it is essential that reliable hardness assurance test protocols and radiation-hardened device technologies are available. Both of these require a sound understanding of the basic mechanisms for proton-induced radiation effects.

Future work will continue to explore new issues as semiconductor technologies advance. For example, IC dimensions are becoming so small that there is now evidence that protons can induce SEEs by direct ionization, which can greatly increase SEU error rates and could make traditional hardening approaches obsolete. New technologies (both electronic and optoelectronic) are also introducing new failure mechanisms. These issues greatly exacerbate problems in developing reliable hardness test protocols and will require continued work to identify the mechanisms for proton radiation effects in these new and advanced technologies.

## Results and Progress

We have made significant advances in the understanding of the mechanisms for proton radiation effects in numerous areas. For example, by combining our work at TRIUMF with high-energy transport calculations, we showed that proton interactions with the high-Z materials used in advanced IC technologies could generate secondary particles that can deposit high levels of charge, making some ICs more prone to SEL. The cross section for these interactions increases at high proton energies. Because of this, we were able to demonstrate the importance of performing SEL proton testing at high proton energies. Other work showed that the circuit designs used for some advanced ICs can lead to considerably higher SEU error rates during space flight due to the effects of total dose exposure.

Advances were also made in the basic understanding of charge collection and propagation characteristics of transient signals generated by secondary particles created by proton/material interactions. These results were correlated to device technology features, thereby providing insight that can be used to fabricate improved radiation-hardened devices.

Based on these results and other results at TRIUMF, we have written a new comprehensive hardness assurance test procedure for proton testing for SEE based on the mechanisms for proton-induced SEE. In other work, we determined that secondary particles generated by proton/silicon interactions can deposit high levels of localized charge in the oxides of power MOSFETs (known as microdose effects), leading to device degradation at extremely low total dose levels. This result has important implications for power MOSFET operation in space environments.

In the area of optoelectronics, we were able to identify point defect mechanisms in optical fibres under proton irradiation. The importance of this research is indicated by the fact these works have led to two Outstanding Paper Awards and two Meritorious Paper Awards at the Nuclear and Space Radiation Effects Conference, out of ~100 papers presented each year.

# Partners

International Partners: France (1) and the United States (1).

# TRIUMF's Role

The TRIUMF spectrum covers almost the entire energy spectrum of trapped protons encountered in near-earth space orbits, and therefore it is an ideal facility for exhaustively characterizing semiconductor devices for space applications. No facility in the United States covers the wide proton energy spectrum covered by TRIUMF. Research Scientist Ewart Blackmore has also provided significant technical support enabling the success of these experiments.

# 4.2.4

# Accelerator Physics

The TRIUMF Accelerator Research Group was formed in October 2004 and given the mandate to provide operational support for the cyclotrons and ISAC, to develop beam physics for higher intensity in the cyclotron, to develop primary and secondary ISAC beam line optics and optics for spectrometers, to undertake beam studies for external projects, and to develop new initiatives such as fixed field alternating gradient (FFAG) accelerators and beta beams.

The Group ensures that the beams required to satisfy the demands of the TRIUMF science program are delivered. The priorities of the Group can be divided into three broad classes: (1) support for operation and development of TRIUMF accelerators and beam lines: (2) support for approved collaborations with other accelerator-based laboratories: and, (3) research in theoretical aspects of accelerator physics. One important activity not captured in this section is the ongoing support for operation. This support includes help with tuning accelerators, beam lines and the ISAC mass separator, development of software to facilitate tuning by operations, and training operators to understand and operate beam line and accelerator components.

The Accelerator Research Group consists of the following scientists: R.A. Baartman, theory, optics, and collective effects; M.K. Craddock, accelerator design; J. Doornbos, secondary channel design; F.W. Jones, multi-particle simulations and parallel computing; S.R. Koscielniak, theory, novel accelerators, and collective effects; Y.-N. Rao, cyclotron and beam line modeling; and L.W. Ro, cyclotron modeling, development, and choppers. Figure 1 summarizes the group's activities.

TRIUMF activities in the operation and development of accelerators and beam lines are discussed next.

# High Current Beam Development for TRIUMF

## Introduction

TRIUMF is pursuing a high current beam development program aimed at increasing the extracted current from its pre-ISAC level of about 200 μA to 300-400 μA. This level is required to operate the ISAC beam lines at maximum intensity without having to lower the current to non-ISAC users.

## Results and Progress

Since 2000, a large fraction of TRIUMF's one-day-per-month beam development shifts has been devoted to using TRIUMF's low- and high-energy probes to measure beam quality and to develop high current/low spill tunes. In 2005, centre region re-alignment work, and the installation of a water-cooled beam stopper on the first turn to prevent overheating of the centre region components, enabled TRIUMF to extract, without incident, an average current of 298 μA for 2.4 hours. This was followed by a week of beam production in 2006 during which 270 μA was extracted without incident. Although the existing beam lines only have a current capacity of 300 μA, in 2003 a peak current of 420 μA at 25 % duty cycle with good transmission was extracted, thus confirming that 400 μA is within the TRIUMF cyclotron's space-charge limit.

Although TRIUMF's high-current ion source I3, which has been dormant for many years, will resume operation in 2009, users won't be able to extract average currents greater than 300 μA until there is more beam dump capacity, improved centre region/ISIS cooling, and perhaps an ISIS vacuum upgrade. In the meantime, 300 μA will be enough to satisfy all of the existing users' requirements, and TRIUMF will continue improving this tune and studying the 400 μA tune at reduced duty cycle.

# Release of $^7$Be from Stripping Foils

## Introduction

The recent improvement in cyclotron beam quality has resulted in a denser beam on the carbon foil used to strip the $H^-$ ions and extract them from the cyclotron. As a result, at the highest extracted current the foil is sufficiently hot that the $^7$Be created by nuclear interactions is released rather than remaining conveniently contained in the foil. This release adds to cleanup time during shutdown. We assigned the task of modeling the heating to a visitor from the Paul Scherrer Institut. The results are clear, but need testing. The testing is ongoing and the activation near the stripper is measured during each shutdown.

## Results and Progress

Most of the foil heating is due to the stripped 270 keV electrons. These travel in spirals along the magnetic field lines, repeatedly traveling through the foil until either they are lost or completely lose their energy through straggling. A new result is that the multiple Coulomb scattering during each foil passage makes thinner foils preferred because, although the scattering angle is smaller for thinner foils, it is a square root effect, not a linear one. This means that for thinner foils the probability is higher that the electron scatters off the foil before it ranges out. The standard foil has been 5 mg/cm$^2$. We are now testing foils down to 1 mg/cm$^2$, and looking for lower activation levels when the lid is raised during shutdown.

| Project | Start - End | Principal | Collaborating Laboratories |
|---|---|---|---|
| High current beam development for TRIUMF | 2000 - 2013 | Root/Baartman/Rao | |
| Release of $^7$Be from stripping foils | 2007 - 2009 | Baartman/Rao | |
| New spiral inflector for TRIUMF | 2007 - 2009 | Root | |
| Redesign of muon beam lines at TRIUMF | 2006 - 2010 | Doornbos | |
| TRIUMF cyclotron extraction and beam line optics | 2004 - 2005 | Rao/Baartman | |
| TRIUMF injection line optics | 2003 - 2008 | Baartman/Rao | |
| Cyclotron computer code development | 2003 - 2007 | Rao | CIAE, Thales, D-Pace |
| Radioactive ion storage ring | 2003 - 2003 | Craddock | |
| Large scale simulations for the CERN LHC using distributed computing | 2005 - 2007 | Kaltchev | CERN |
| LHC collimation system | 1997 - 2004 | Kaltchev | CERN |
| LHC beam-beam effects and parallel codes | 1997 - 2008 | Jones | CERN |
| EURISOL betabeam | 2005 - 2008+ | Jones | CERN |
| T2K experiment at J-PARC | 2000 - 2005 | Doornbos | KEK, JAERI |
| Charged kaon beams at J-PARC | 2005 - 2007 | Doornbos | KEK, JAERI |
| Pellet-beam interactions at HESR | 2003 - 2004 | Rao | GSI |
| Microbunching for KOPIO | 1997 - 2005 | Koscielniak | BNL |
| Impedance and collective-effects at JPARC | 2002 - 2004 | Koscielniak | KEK, JAERI |
| GEANT4 | 2003 - 2008+ | Jones | Int'l GEANT4 Collaboration |
| Development and support activities for ACCSIM | 1986 - 2008+ | Jones | CERN, LANL, KEK, JAERI, BNL, ORNL |
| Space charge simulation codes | 2003 - 2005 | Jones | |
| 60 GeV/c RF separated kaon beam | 2006 - 2006 | Doornbos | FNAL, BNL, CERN |
| FFAG studies | 2003 - 2009+ | Koscielniak | Int'l Muon Collider Collaboration |
| Intensity limitations in cyclotrons | 2006 - 2008 | Baartman | |
| Fringe fields | 2007 - 2009+ | Baartman | |
| Nonlinear transfer maps for charged particle beam transport | 2004 - 2008+ | Kaltchev | University of Maryland |

**Figure 1:** Activities of the TRIUMF Accelerator Research Group showing the extensive and international research program.

# A New Spiral Inflector for TRIUMF

## Introduction

TRIUMF's spiral inflector bends the 300 keV $H^-$ axially injected beam coming from the ion source onto the median plane and centres the beam for injection into the magnet dees. It consists of a pair of 12 in. high spiral-shaped electrodes with a 1 in. gap operating with voltages of 28.7 keV. Although the existing inflector has performed well for over 30 years, the new one will allow TRIUMF to have the old one as a spare, be better engineered mechanically, and perform better because its design will be based on improved magnetic field measurements. As well, with modern CNC machining techniques, construction of the spares is cost effective. This work started in 2007, and installation is planned for the beginning of 2009.

## Results and Progress

TRIUMF's inflector is a non-analytic version of Belmont and Pabot's original Grenoble design. It was designed using AXORB, a TRIUMF computer code, which used a modified version of Belmont and Pabot's electric field and took into account TRIUMF's magnetic field, which varies between 0.5 kG and 3 kG along the inflector's central trajectory.

Due to time constraints, the calculations for the existing TRIUMF inflector were based on magnetic field measurements made on a 10:1 scale model of the magnet. After the inflector was constructed, more accurate axial magnetic field measurements were made on the main magnet. In early 2007, AXORB, which had been dormant for 30 years, was re-written so that it would run on TRIUMF's newer computers. Improved electrode shapes were calculated using the main magnet measurements. The improved electrode shape should increase the spiral inflector's acceptance by 5 to 10%.

The inflector electrodes are routinely removed for maintenance. Mechanical engineering studies are being carried out and are aimed at improving the electrode mounts so that the required mechanical tolerances can more easily be achieved when the electrodes are re-installed after maintenance.

# Re-design of Muon Beam Lines at TRIUMF

## Introduction

The new M9A and M20 are both surface muon beam lines for μSR studies. Surface muons are so-called because the muons result from the decay of pions that have stopped near the surface edge of the pion production target. Only positive muons can be obtained in this way. The maximum momentum is 29.8 MeV/c. The muon polarization is almost 100% longitudinally. They have a well-defined source location unlike muons from the decay of pions in flight. This makes it possible to obtain a small beam spot with high luminosity at the end of the beam.

In 2006 and 2007, the Group completed new designs for M9A and M20 and designed an extension for M13. The M13 extension will be installed in 2008, M9A in 2009, and M20 in 2010.

## Results and Progress

The newly designed M9A and M20 beam lines will be equipped with spin rotators, basically crossed electric and magnetic fields, which can rotate the spin in a direction transverse to the direction of motion. In M9A, the spin will be horizontally transverse. In M20, the spin will be vertically transverse. The spin rotator systems are achromatic, which makes a high momentum acceptance possible. The achromaticity is achieved by using two spin rotators, each rotating the spin through 45° and placing a quadrupole triplet between them. At present, the TRIUMF beam line M15 is the only beam line in the world that has this feature.

An important aspect of both the M9A and M20 beam lines is the Muons On REquest (MORE) feature invented at TRIUMF. As soon as a muon enters the experimental target, the beam is switched away by using a fast electrostatic kicker. In M9A, the beam is discarded. In the case of M20, the beam is directed to another leg. This switching means that two experiments can run simultaneously on M20. The optics in both beams have been designed to give a small beam spot and a high luminosity, which is important because advanced modern experiments are done on small samples, of the order of 1.0 or 2.0 cm diameter. Several slit arrangements in both beams make it possible to limit the background effects.

The extension of M13 was proposed by the Accelerator Research Group to decrease the background of positrons in the PIENU experiment, which intends to very accurately measure the decay of a positive pion into a positron and a neutrino. The extension consists of a 70º bending magnet and a quadrupole triplet.

# Extraction of the Cyclotron Beam and Beam Line Optics

## Introduction

Because extraction is by $H^-$ stripping, the TRIUMF cyclotron is able to supply multiple beams continuously for multiple experiments. Typically, a 50 kW beam is extracted into a beam line and the beam can be focused to a spot smaller than 2 mm diameter. This gives a sufficiently high energy density to damage the carefully prepared targets. It is therefore essential to accurately characterize the extracted beam and its spot size to avoid target damage.

Work on improving the agreement between calculated and measured beam sizes began at the end of 2004, because beam power on ISAC targets had reached 20 kW and management of the size of the beam spot became essential. New tunes were developed and successfully used in 2005. At the present time, not all aspects of the various modes of operation are understood down to the 1 part in $10^5$ level necessary for running without the spill monitors in beam line 2A tripping the beam off. The Group continues to make the refinements needed for the new mode of operation, where the beam is swept across the ISAC target with AC steering magnets. A good understanding is also needed so that we can optimize the design of the new beam line 4.

### Results and Progress

In 2004, because of target damage from over-dense beams, the Group re-investigated the coding of the equations of motion in the computer program used to track particles from the stripping foil to the beam line. We discovered an error that had existed for 30 years. As a result of this work, for the first time, we have an accurate description of these beam lines. We have obtained agreement of better than 15% everywhere between calculated and measured beam sizes in the beam lines, so we can confidently change the beam spot size to what is required by the target designers. We are currently using GEANT4 to try to understand the beam distribution halo to the level of 10 ppm of the core.

## TRIUMF Injection Line Optics

### Introduction

The space-charge effect is important in the TRIUMF injection line because it strongly affects the fraction of beam that can be accepted by the cyclotron centre region as well as the amount of beam halos that can possibly spill in the cyclotron and beam lines. Research in this area will be used to help design replacement optics needed for future upgrades to > 400 μA extracted from the cyclotron. A series of experiments was performed in 2003–2004 to measure the beam emittance and space-charge neutralization level. Further experiments will be performed in 2008.

### Results and Progress

To achieve improved understanding and also to allow accurate modeling of the 300 keV injection line, we measured important beam parameters such as space-charge neutralization and emittance. This work prepared us for future development and exploration of the injection line for high-current operation, which aims to reach an extracted current of > 400 μA from the cyclotron.

Using software developed at TRIUMF, the Group performed transport calculations in six-dimensional phase space with the linear space-charge force included. Good agreement was achieved between the measured and calculated transverse sizes of the 300 keV beam in the injection line. The emittance is ~0.13 om (normalized) at a dc current of 575 μA. Matching to the periodic sections appears good in the horizontal section, but not good in the vertical section where there are fewer diagnostics and beam-size restraining collimators. With bunching, the local current reaches >3 mA at cyclotron injection; the space-charge effect becomes increasingly dominant as the beam travels along the injection line. For injection line currents above 500 μA, the fraction of beam that can be accepted by the cyclotron centre region begins to fall despite adjustments to the existing bunchers. This could be corrected by introducing an additional first harmonic buncher in the vertical section at ~2.5 m upstream of the inflector. Or, this effect could be partially compensated by increasing the RF dee voltage, thereby increasing the longitudinal cyclotron phase acceptance. Alternatively, injection with dc beam current 5 mA is contemplated.

The choice of the final configuration for 450 μA extracted will be made based on this research and will largely depend on reliability, reproducibility, and stability issues, including the ion source.

# Cyclotron Computer Code Development

## Introduction

Cyclotron FFAG orbit dynamics are different in nature than those of most other accelerators because the model of separated elements (drifts, dipoles, focusing, and so on) is not a good one, and because there is no given reference orbit. Instead, particles must be tracked through varying fields and reference orbits found for each energy by an iterative technique.

From 2003 to 2005, updates were implemented in the orbit codes porting them from obsolete operating systems to the Linux OS. In 2007, modifications were made to enable FFAG lattice studies.

## Results and Progress

Over the years, TRIUMF developed a series of computer codes for cyclotron orbit dynamics research. This is one of the important contributions of TRIUMF to the cyclotron development. These codes are essential for cyclotron design and research and maintaining optimal beam tune. From time to time, TRIUMF receives requests from other laboratories to use these codes for the design of new machines. Maintaining these codes is therefore an ongoing activity

## Partners

In Canada: MDS-Nordion, D-Pace.

Internatioal Partners: Chinese Institute of Atomic Energy, Thales (France).

## TRIUMF's Role

TRIUMF played a leading role in the collaborations with CIAE and D-Pace/Thales in providing intellectual guidance to the cyclotron design and development: to the understanding and optimization of the magnetic field; to the approach of beam probe design; to the consideration and modeling of extraction optics.

# Radioactive Ion Storage Ring

## Introduction

The Accelerator Research Group has studied the design of a storage ring to be fed by radioactive ions from ISAC-II. The low intensities of beams of unstable isotopes make it vital to use them efficiently. Their collection in a storage ring would open up a number of possibilities: 40,000 times higher beam intensities (depending on half-lives and loss mechanisms in the ring), enabling better suppression of background and more accurate measurement of isotopic and ionic properties; higher luminosities, by the use of beam cooling and internal targets; acceleration to higher energies; quasi-simultaneous operation with fixed-target experiments; and colliding- or merging-beam experiments with protons, electrons, muons, etc.

This work was carried out in 2003 but discontinued when it became apparent that TRIUMF's highest priority for RI beam development was the provision of additional targets and beams. When these immediate aims are accomplished, however, a storage ring remains a potentially powerful tool for TRIUMF's further development.

### Results and Progress

There were two main aspects to this study: estimating by what factor the ISAC beam intensity could be amplified by storage, and designing the magnet lattice for the ring itself. For injection of ions with short lifetimes, it was clear that stripping is preferable to multi-turn stacking. Stripping also increases the ions' average charge state, thus lowering the magnet strengths required in the ring, and reduces the fractional width of the charge-state distribution, thus enabling a greater fraction of the beam to be contained. A stripping foil also presents an obstacle to the circulating ions, but it was found that "painting" the incoming beam could reduce the frequency of interceptions to an acceptable once in 400 turns. Moreover, it was found that the ion losses per foil traversal could be kept to 1% provided the charge/momentum acceptance of the ring was at least ~4%. With continuous injection, the stored beam intensity should be maintainable at 40,000 times that delivered by ISAC. Alternatively, pulsed operation could provide a 25,000 times improvement while allowing the beam to be shared with ISAC-I or ISAC-II.

To obtain a ring with large charge/momentum acceptance, low dispersion and low horizontal beta function, a double-bend achromat lattice was chosen. The ring is four-sided, with a diameter of 15 m and the long straights assigned to injection, cooling, acceleration and experiment (or extraction). With a bending power of 2.6 T-m, light ions such as carbon can be accelerated to 80 MeV/u and heavier ones such as the rare earths to 35 MeV/u. Initial tracking studies showed good behaviour for charge or momentum excursions up to about 4%, as required.

TRIUMF's collaborations with other laboratories on accelerator science and technology projects are presented here.

## Large-Scale Simulations for the CERN LHC Using Distributed Computing

### Introduction

In the final design phase of the Large Hadron Collider (LHC), it will be necessary to verify the long-term stability, particularly in the presence of the beam-beam forces that will eventually limit the LHC performance. Due to the very non-linear nature of motion in the LHC, only a detailed numerical simulation can reliably predict the long-term behaviour of the particles.

In 2004, the CERN IT Department developed the LHC@home system based on the Berkeley Open Infrastructure for Network Computing (BOINC). This system provided access to more than 60,000 home computers, donated by more than 30,000 volunteers worldwide. The computing power provided by LHC@home allows experimenters to evaluate the parameter space with maximum accuracy and to find possible problems, which could be missed by a less detailed analysis.

## Results and Progress

The Accelerator Research Group extended the CERN-based automatic procedures for launching tracking jobs with our own tools that automatically process large volumes of tracking data in order to extract information about long-term stability such as dynamic aperture and border of chaos. In 2005–2006, tracking jobs launched from TRIUMF, totalling an estimated 6 million CPU hours, were used by CERN to make the final choice of the LHC crossing scheme, *i.e.*, the plane in which the two beams collide and the LHC working point on the tune diagram, and also to analyze the effect of multipole errors in the interaction point (IP) quadrupoles. In 2007, a similar study was performed, but in conditions corresponding to LHC start-up at injection energy. There is a strong request from CERN for TRIUMF to continue the BOINC-tracking studies.

## Partners

International Partners: CERN, Queen Mary University of London, Niels Bohr Institute and University of Copenhagen, and Helsinki Institute of Physics.

## TRIUMF's Role

Since late 2005, because of our knowledge of the LHC lattice optics, optical databases, and tracking codes, nearly all BOINC-tracking runs have been launched from TRIUMF, following directions for machine studies coordinated with CERN. During 2005–2006, these runs led to the present set of LHC parameters and enabled our CERN colleagues to test additional configurations and to define strategies for the start of the collider

# LHC Collimation System

## Introduction

Even a tiny release of the energy stored in the LHC beam would lead to a serious damage of equipment, hence the importance of the system of collimators whose function is to cut off the amplitudes of the circulating particles at 8 sigma at injection energy and 6 sigma at collision. TRIUMF has played an important role in the design of lattice optics for the betatron- and momentum-collimation sections of the LHC and in the optimization of collimator parameters. Work on collimation continued in 2003; since then a new constraint—impedance—was introduced. The collimation will be first used during LHC commissioning in May 2008.

## Results and Progress

The main objectives were to maximize the beam size at the collimators (and so decrease their contribution to the ring impedance) and generate additional space for longer collimators.

By following the original design approach, by the end of 2003 a new arrangement of collimators was found and implemented in the LHC sequence. The final solution preserved the number of collimators, warm quadrupoles and maximum voltage of the power supplies. It provided a wider domain of betatron phases at intermediate locations, making it possible to position the collimators where the beam envelope is larger. A good cleaning efficiency was simultaneously maintained.

## Partner

CERN.

## TRIUMF's Role

For a number of years, in an extensive collaboration with the LHC team, TRIUMF has been responsible for the software that optimizes collimator parameters and for the design and maintenance of the optics (quadrupole parameters) of the betatron- and momentum-collimation insertions.

# LHC Beam-Beam Effects and Parallel Codes

## Introduction

As part of the Canadian contribution to the LHC, the Accelerator Group has collaborated with CERN on studies of coherent beam-beam effects, which pose limitations to the performance of existing colliders and will play a role in the operation and performance of the LHC.

The first collaborations occurred prior to 2003 and applied TRIUMF-developed space-charge techniques to a prototype beam-beam code. The first 3D parallel code was developed in 2003–2004. The parallel multi-bunch multi-IP code was developed in 2006–2007, with further work on fast-multipole field computation to be done in 2008.

## Results and Progress

Using routines developed by TRIUMF originally for space-charge simulation, TRIUMF and CERN have co-developed the first application of fast multipole methods to beam-beam effects. The availability of parallel computing facilities at the University of Alberta, and later at the Westgrid facilities in Calgary and Vancouver, prompted the collaboration to extend this 2D code to 3D by implementing parallel algorithms to treat the interactions of longitudinal bunch segments as they approach and leave the crossing point of the counter-rotating beams in the LHC. The resulting code BEAMX was among the first of its type to be able to exhibit and estimate longitudinal beam-beam effects such as the crossing angle and the frequency sidebands due to synchrotron motion.

More recently, further advances in the high-speed communications architecture of computing clusters have allowed us to pursue a more ambitious simulation. In the LHC, the two beams consist of trains of thousands of distinct bunches of protons, and these bunches approach and collide with each other at four IPs where the four LHC experiments are sited, whereas existing beam-beam simulation codes were limited to a single pair of bunches and a single IP. For operational reasons the bunch trains have gaps in them and, in general, the two beams do not have exactly the same gap structure.

In the LHC and other collider communities, there is strong interest in being able to simulate the full complexity of collision patterns that arise from gaps and differences in the beam. Our Group formulated plans for a new parallel simulation code that would track multiple bunches through multiple IPs. This project was approved for access to high-performance computing systems at École Polytechnique Fédérale de Lausanne: a MYRINET-based commodity cluster on which development, benchmarking, and production were done, and an IBM Blue Gene supercomputer where very large-scale performance tests could be done. The first production version of the code was completed and showed good parallel efficiency and excellent scaling properties. The code input and parallel communications scheme have been designed in a very general way, allowing arbitrary bunch patterns and extension to arbitrary numbers of bunches and IPs, limited only by the number of processors available in the computing cluster. Further enhancements of the simulation options and the field solution methods are planned.

### Partners

International Partners: CERN, École Polytechnique Fédérale de Lausanne.

### TRIUMF's Role

TRIUMF provides knowledge and expertise in accelerator simulation, and undertakes the software conceptual design, application of numerical methods, parallel programming, testing and debugging, and collaborates on the production and analysis of results.

# EURISOL Betabeam

### Introduction

The Sixth Framework Programme of the European Union funds the EURISOL Design Study. Its mandate is to define a next-generation ISOL-based radioactive beam facility to be sited in Europe and to support a large and diverse research program. As a high-intensity source of radioactive ions, the EURISOL facility may act as the first stage of a neutrino factory based on the acceleration of these ions to high energies and their accumulation in a large racetrack-shaped storage ring where they emit neutrinos through the beta decay process.

Betabeam is a potential key to future long baseline neutrino experiments because it relies on known technology and is able to produce a neutrino beam of precise timing, low divergence, and low-energy spread, as opposed to the technical challenges and high costs associated with the beam production and beam cooling in muon-based facilities. TRIUMF participates in the Betabeam task of the EURISOL study, which will produce a conceptual design study incorporating all aspects of the Betabeam accelerator complex and its operation.

## Results and Progress

Our beam dynamics group was invited to collaborate with Betabeam study members who had noted that the code ACCSIM was a good candidate for a platform on which to build a comprehensive simulation of the decay ring, incorporating ion injection, RF capture, tracking, decay, and detection and quantification of losses of the decay products.

At early Betabeam meetings, TRIUMF presented a survey of the available computing tools and methods, and a plan for the software developments needed to meet the simulation requirements. Initially, we worked with CEA Saclay personnel, who were designing the optics and magnet lattice of the decay ring. Together, we worked to establish the parameters and operating conditions of the ring and determine how they would be imported into the simulation, and how simulation results could be folded back into their optimization process for the ring design. We also worked with CERN members to specify the simulation parameters for the injection, RF system, and stacking mechanisms that were envisaged for accumulation of radioactive ions in the decay ring.

This definition stage was followed by work on a three-part upgrade package for ACCSIM, comprising: (1) generalization of tracking and acceleration for arbitrary ions; (2) physics and tracking model for ion decay process; and (3) accurate tracking and loss detection of secondary ions. In the latter task, we developed some new tracking techniques that involved transfer matrix scaling and direct computation of dipole trajectories.

With this package complete, the application to the decay ring was pursued as a joint TRIUMF-CERN project in which data sets of secondary ion losses were produced by ACCSIM runs and then were post-processed by the FLUKA code to account for ion interactions with the accelerator components, in particular the superconducting dipoles. The publication of these results represents a first look at Betabeam decay-ring operation from the point of view of ion losses, radiation exposure of ring hardware, and especially the heat deposition in the dipoles that may result in magnet quenching. The latter result has led to a new design effort to specify an open-coil dipole that will be resistant to quenching via ion losses.

The new ACCSIM version has also been distributed to other Betabeam members who are using it to estimate losses and space-charge effects in the post-ISOL accelerators (CERN PS and SPS in the baseline scenario).

## Partners

International Partners: CERN, CEA Saclay (France).

## TRIUMF’s Role

TRIUMF provides the design and programming of simulation tools needed for Betabeam studies, configuration for current lattice and operational parameters, and streamlining of simulation data flow to post-processing applications.

# T2K Experiment at J-PARC

## Introduction

The T2K (Tokai to Kamioka) experiment needs a fast extracted proton beam from the 50 GeV J-PARC (Japan Proton Accelerator Research Complex) accelerator. The design work was finished in 2005. The J-PARC 50 GeV ring is under construction.

## Results and Progress

The beam line bends the beam through 90°. It consists of an arc of superconducting combined-function magnets, which combine quadrupole and dipole fields. The arc is preceded by a normal conducting preparation section, and followed by a normal conducting targeting section. Extreme care had to be taken to prevent the proton beam triggering the quenching of the magnets in the arc. The beam line is presently being built at J-PARC.

## Partners

International Partners: KEK, JAERI.

## TRIUMF's Role

TRIUMF was the main designer of the optics for the 200 m long transfer line between the accelerator and the target where the neutrinos are produced. The design work was finished in 2005. The J-PARC 50 GeV ring is under construction.

# Charged Kaon Beams at J-PARC

## Introduction

In 2006 and 2007, the J-PARC Physics Advisory Committee asked TRIUMF to perform an extensive external review of the designs for the proposed 1.8 GeV/c and 1.1 GeV/c kaon beams. These are clean kaon beams where the intensities of the various background particles, mainly pions and muons, are reduced by a factor of several thousands by two stages of separation using DC separators. The very delicate and critical second- and third-order optics are corrected with sextupoles and octupoles. The beams will be used for the study of hyper-nuclear physics.

## Results and Progress

TRIUMF's expertise in the design of clean kaon beams continues to be called upon. An example of that expertise was the beam line built at Brookhaven National Laboratory [J. Doornbos *et al.*, Nucl. Instrum. Methods A444, 546-556, (2000)]. TRIUMF also designed an 800 MeV/c single-stage separated beam as a branch of the 1.1 GeV/c beam. Although it has only a single stage of separation, the beam is clean because, at the beginning of the beam line, there is an extra focus where the beam-defining slit can be placed. This beam is required by J-PARC's TREK experiment, which measures the polarization of the muon resulting from the Kμ3 decay. This experiment is the only one in the world that directly measures T-violation, unlike experiments that deduce T-violation from CP-violation, assuming CPT invariance.

### Partners

International Partners: KEK, JAERI.

### TRIUMF's Role

TRIUMF's expert advice has helped J-PARC develop credible plans for moving forward with the production of clean kaon beams.

## Pellet-Beam Interactions at HESR

### Introduction

TRIUMF provided pellet target and beam interaction Monte Carlo simulations to the 14.5 GeV high-energy storage ring (HESR) at the international Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt, Germany for the future PANDA experiment. A crucial question for the operation of HESR is the effect of target heating, which will, in combination with the stochastic/electron cooling, define the equilibrium beam conditions. This equilibrium is strongly dependent on the mechanisms of cooling.

For the envisaged luminosity at PANDA, the average target thickness will be a few times $10^{15}$ atoms/cm$^2$. The question of whether the density distribution of the target may also affect the heating is important here, because in contrast to, for example, a cluster-jet target, the target density is not homogeneous but concentrated in pellets of a few tens of micron diameter; the local thickness reaches values of a few times $10^{19}$ atoms/cm$^2$. Though this effect was investigated for the CELSIUS ring and found to be small, dedicated Monte Carlo simulations were made for the situations at the HESR.

TRIUMF was invited to join the PANDA collaboration as part of the Uppsala group in Sweden in October 2004 to do the Monte Carlo studies. Work ceased after the technical progress for PANDA was completed in 2005.

### Results and Progress

For the first time, the simulations were done using a beam of $T_{[\overline{P}]} = 800$ MeV and $T_{[\overline{P}]} = 14.5$ GeV; the lowest and highest energies respectively at which the HESR could operate. For the target, two different scenarios were used: discrete pellet and continuous distribution, of the same effective thickness of 2.8Å—$10^{15}$ atoms/cm$^2$. The results of the Monte Carlo runs show that the growth in emittance does not deviate significantly for the two cases. This result supports the earlier findings of studies in CELSIUS and COSY rings in which the effect of the strongly inhomogeneous distribution of a pellet target could not be distinguished from a homogeneous distribution of the same effective thickness.

### Partners

International Partners: TSL (Uppsala), GSI.

### TRIUMF's Role

TRIUMF contributed Monte Carlo simulations dedicated for the HESR. This has been included in the PANDA Technical Progress Report.

# Microbunching for KOPIO

## Introduction

TRIUMF performed beam-dynamics simulations of a new slow-extraction technique, called microbunching, for the CP-violation rare decay experiment KOPIO to be performed at the Brookhaven National Laboratory (BNL) AGS using $10^{14}$ protons per pulse.

From its inception in 1996 to cancellation in July 2005 for financial reasons, the KOPIO project spanned a decade. A series of microbunching demonstration experiments was performed at the AGS from 1997 to 2005. TRIUMF provided accelerator physics expertise on microbunched slow-extraction from 2000 to 2005.

## Description

An experiment was designed to run at the BNL alternating gradient synchrotron (AGS) that would make use of a microbunched slow extracted proton beam for studies of the rare decay $K_L^0 \rightarrow \pi_0 \nu[(\bar{\nu})]$. This experiment, called KOPIO, would use time of flight to measure the momentum of $K_L$ that decay in flight inside the detector. 25 MHz RF cavities in the AGS ring would be used to confine the resonantly extracted proton beam into microbunches with RMS widths of about 150 ps every 40 ns. Elimination of backgrounds from other $K_L$ decays, generated outside of the microbunches, translated into the requirement that the intra-bunch extinguishment be less than $10^{-3}$ of the bunch intensity. The beam dynamics challenge was two-fold: to produce very short bunches without excessive cavity voltage, and to achieve extremely low leakage of the extraction scheme.

## Results and Progress

Microbunching relies on the interplay of a chromatic 1/3-integer extraction process and the longitudinal cusps of proton intensity that occur near the fixed-points when RF buckets perform phase-space displacement acceleration. TRIUMF developed software to perform a detailed two-dimensional simulation of the extraction process, both as a tool to understanding experiments performed on the AGS and as a means to develop and optimize the technique to a level suitable for KOPIO.

TRIUMF proposed a combination of 25 MHz fundamental and anti-phased fourth harmonic RF acceleration to achieve the necessary bunch length with modest voltages and constructed a prototype of the 25 MHz RF cavity, scaled from a 27 MHz design for the RHIC. The BNL slow-extraction team performed a variety of beam experiments first with 93 MHz cavities verifying the calculated bunch lengths, and later used 4.5 MHz RF cavities to verify the intrabunch extinction of $\cong 10^{-5}$. Both were in good agreement with the TRIUMF simulations. The last series of results was reported in a NIM journal paper [N. Alberola *et al.*, Nucl. Instrum. Methods A560, 224-232 (2006)].

## Partners

International Partners: United States (4), Institute for High Energy Physics, Protvino, Russia.

### TRIUMF's Role

TRIUMF was responsible for developing the microbunching technique, originally conceived at BNL, to a level where it could meet the demanding specification of the KOPIO experiment. TRIUMF wrote simulation software, calibrated it against known slow-extraction properties of the AGS and, based on extensive exploration of design parameters, perfected the extraction scheme. Had the operation of the AGS for rare decay physics not been terminated in 2005, TRIUMF would have constructed the 25 MHz RF cavity.

## Impedance and Collective-Effects at J-PARC

### Introduction

J-PARC pursues frontier science in particle physics, nuclear physics, materials science, life sciences, and nuclear technology, using a new proton accelerator complex. J-PARC consists of a 180 MeV linac followed by 3 GeV and 50 GeV rapid cycling synchrotrons. TRIUMF was asked to consult on ring impedance estimates and advise on the potential for beam instability.

TRIUMF was invited to prepare estimates of collective effects in October 2002 and presented results and recommendations to the Accelerator Technical Advisory Committee (ATAC) in March 2003 and March 2004, at which time the work ceased.

### Results and Progress

A wide variety of impedance sources were considered; in particular kicker magnets with reactive terminations, for which there were no previously existing formulae. Both bunched and coasting beam, longitudinal and transverse, instability thresholds, and growth rates were estimated. The study was complicated by the fact that there are vastly different parameter sets during injection, ramping, and the fast and slow extractions. For the bunched beams, a key issue was to understand the stability of high-order head-tail modes at very large chromatic tune shifts.

Recommendations made to the ATAC included: (1) methods of beam-load compensation for the RF cavities; (2) not to operate the ring with near zero chromaticity during slow extraction; (3) to be wary of introducing resonant transverse impedances into pumping-port enclosures and RF cavities by careless design; and (4) to add small resistive loads, or at least one matched termination to the TW-type kicker magnets to reduce troublesome reflections, etc. The head-tail modes were found to be stable throughout most of the main ring acceleration cycle, with the exception of a short period at injection.

### Partners

International Partners: KEK, JAERI

### TRIUMF's Role

TRIUMF provided beam-impedance and collective-effects calculation expertise to the 3 GeV booster and 50 GeV main ring at J-PARC.

TRIUMF's research in theoretical aspects of accelerator physics is dicussed next.

# GEANT4

## Introduction

Motivated by our local expertise in medium-energy hadronic reactions and in computing and simulation, TRIUMF was invited to join the GEANT4 collaboration during its formative stage. Since joining, TRIUMF has made major contributions to the design and implementation of GEANT4, has hosted two international GEANT4 workshops and continues to provide new functionality and user support for this ongoing software collaboration.

In recent years, we have seen significant efforts in the area of GEANT4 studies of beam lines, including detailed geometries of magnetic elements and other hardware. These have chiefly been in the areas of beam delivery systems for colliders (LHC and ILC), where experimental backgrounds need to be accurately predicted, and in muon cooling lines and experiments such as Muon Ionisation Cooling Experiment (MICE) at the Rutherford ISIS Spallation Neutron Source. In works related to spectrometers and nanobeams, it has been demonstrated that GEANT4 can accurately model magnetic elements and overlapping fringe fields, and that tracking is highly accurate, scalable, and can compete with dedicated ray-tracing codes.

GEANT4 is structured as a software toolkit and various beam-line tools based on GEANT4 have emerged, such as Fermi Beamtools, BDSIM, GMAD, and G4Beamline. The Muon Ionisation Cooling Experiment (MICE) appears to be the most advanced of these and is applicable to a number of TRIUMF systems, but it has essentially been designed around muon cooling systems. There are a number of additional needs and avenues of further development to be considered for the future of this or similar codes.

## Results and Progress

There are now prototype models of several TRIUMF beam lines in GEANT4 or G4Beamline. In 2008, a G4Beamline application for extraction line BL2A will be developed with as high a level of optical accuracy as the knowledge of the hardware (particularly magnetic field data) will permit. The models give an opportunity to understand better the beam line behaviour and possibly to improve performance. G4beamline offers a number of features useful for this-application, but current indications are that further development of G4beamline would be needed to make it maximally useful for this and other TRIUMF beam lines. G4beamline is a product of the private company Muons Inc., but it is essentially written and supported by one person and is freely available with open source and GPL licensing. In principle, therefore, we can modify the source code to meet our needs, but doing so raises the question of whether these should be *ad hoc* modifications or whether there should be a more formal contribution to the evolution of the code or a product derivative of it.

### TRIUMF's Role

TRIUMF's membership in GEANT4 brings obligations but also privileges, including direct access and involvement in the evolution of the code (instead of just public release packages), as well as an inside track on issues of support, feature requests, and the opportunity to learn and discuss with experts about all aspects of the GEANT4 toolkit. These privileges and opportunities, along with the laboratory's expertise in particle and nuclear physics, computing, and accelerators and beam lines, position TRIUMF to pursue advanced accelerator and beam-line tools and applications built from GEANT4.

## Development and Support Activities for ACCSIM

### Introduction

The Accelerator Design Group developed the tracking and simulation code ACCSIM and has benefited from its expertise in accelerators and beam lines as well as experience from previous well-known TRIUMF codes such as COMA and REVMOC. Like these codes, the emphasis for the ACCSIM team is on usability by those users who may not have advanced computing skills, and on direct interaction and consultation with users to determine the needed functionality and the path of further development.

### Results and Progress

With its free availability and comprehensive documentation, ACCSIM has been used in a variety of applications, which has led to collaborations between TRIUMF and other accelerator labs such as CERN, LANL, KEK, BNL, ORNL, and J-PARC. Specifically, ACCSIM played a role in the design effort for the J-PARC 3 GeV rapid-cycling synchrotron and for the ORNL SNS 1 GeV accumulator ring, both recently constructed and either being commissioned or in operation. In addition, ACCSIM was the vehicle or catalyst for two tasks in the beam dynamics component of the Canadian contribution to the LHC, and has facilitated strong long-term relationships with a number of accelerator experts at CERN.

Other notable applications include several studies of the LANL PSR and its upgrades, simulation of the proposed LINAC IV $H^-$ injection in the CERN PS Booster (part of the LHC upgrade program), the EURISOL Betabeam, and tracking in the KEK 12 GeV PS under high-current operation for KEK-to-Kamiokande neutrino production. The latter study included one of the few direct comparisons that have been made between a space-charge tracking code and actual measured beam profiles in a ring (with good agreement being observed).

### Partners

International Partners: KEK, JAERI, (Japan); CERN; United States (3).

## TRIUMF's Role

TRIUMF is the home base of ACCSIM where development, documentation and support is done, although the code has gained much by expert input and sharing of ideas from CERN and other laboratories. We have also engaged in direct collaborations with users towards new applications and enhancements to the code.

# Space-Charge Simulation Codes

## Introduction

The simulation of intense proton beams in synchrotrons and storage rings has been of widespread interest in recent years, in studies and designs of hadron facilities, spallation neutron sources, and proton drivers for future neutrino and muon facilities. The space-charge simulation code ACCSIM, developed at TRIUMF with input from a number of experts, is one of a generation of innovative codes, created at various institutes, which are devoted to modeling these intense proton machines.

## Results and Progress

After a seminal ICFA workshop in Oxford, where much information on code development and progress was exchanged, the authors of several codes including ACCSIM, SIMPSONS, ORBIT, and others undertook a long-term collaboration to compare, test, and validate these codes using common baseline configurations, with the CERN PS being the first reference lattice to be considered. Although these codes tend to run at the practical limits of current computing hardware, data sets were obtained and comparisons and analyses were published for a number of simulation cases and levels of accuracy. This led both to insights about the behaviour and applicability of the codes, and to new questions about differences between the codes. The Group expects that there will be further phases of this collaboration that will lead to refinements of our methodologies and better understanding of numerical issues and physics models.

## Partners

International Partners: CERN, GSI, KEK, Rutherford Appleton Laboratory.

In the United States: Oak Ridge National Laboratory, Brookhaven National Laboratory, Fermilab, Lawrence Berkeley National Laboratory.

## TRIUMF's Role

The space-charge simulation codes field is a relatively small but active field of research in which the code authors have been able to establish long-term relationships and have collaborated with each other on various studies of actual and planned accelerators. In particular, with CERN and ORNL, TRIUMF's development and support of ACCSIM is valued, and our continued participation will be appreciated.

# 60 GeV/c RF Separated Kaon Beam

## Introduction

High-energy RF separated kaon beams were built decades ago. They had very small intensities because of the large momentum-related higher order optics aberrations and the small electric gradients in the room temperature cavities. Nowadays, it is possible to make high gradient superconducting cavities that can be used in slow extracted beams.

## Results and Progress

A solution to the aberrations problem was found at TRIUMF. The consequence of this solution and the higher gradients is that now RF separated beams can be built at high energies with phase space acceptances more than an order of magnitude higher than in the past. Therefore, RF separated beams can now be built that approach the intensities of unseparated beams, but without large contamination by pions and protons.

These techniques were applied at TRIUMF to design for a 22 GeV/c RF separated $K^+$ beam for the Cabbibo-Kobayashi-Maskawa (CKM) experiment at Fermilab. This experiment aimed to measure 100 events of the decay in flight of the kaon into a pion and two neutrinos. The E787 experiment at BNL had already measured three such events, but its continuation was cancelled. Unfortunately the development of the CKM experiment was also terminated.

Due to new detection techniques developed by the CERN NA48 collaboration that can handle very high particle rates, an attempt is now being made at CERN to measure the decay in a 75 GeV/c un-separated beam. In this way, they hope to measure 100 events. It was thought there that a separated beam would have too small a phase space acceptance. In order to demonstrate the feasibility of a separated beam at such high momenta, in 2006 an optics design was made at TRIUMF for a 60 GeV/c RF separated kaon beam with very high acceptance, using superconducting X-band cavities. If the presently intended experiment with an unseparated beam succeeds, the thinking is that a follow-up experiment using an RF separated beam, with the same rate as the unseparated beam, but now mainly kaons, will make it possible to measure 1,000 events.

## Partners

International Partners: CERN, Brookhaven National Laboratory, Fermilab.

## TRIUMF's Role

Initial ideas originated at TRIUMF, and we are still consulted on new designs.

# FFAG Studies

## Introduction

TRIUMF is engaged in designs for a new and novel type of charged-particle accelerator, the non-scaling fixed field alternating gradient (FFAG) accelerator, which promises more cost-effective accelerations of muons for HEP and of low-energy hadrons for cancer therapy. A demonstration model, EMMA

(Electron Model with Many Applications), is under construction at Daresbury, UK.

The TRIUMF involvement with FFAGs began in October 2003, with US-led designs for a future neutrino factory and muon collider. We quickly discovered that FFAGs were a cost-effective alternative to recirculating linear accelerators, such as CEBAF, because their enormous momentum acceptance meant that the costly multiple return arcs and much of the costly ionization cooling could be dispensed with. Later, the studies blossomed to include a demonstration model using low-energy electrons and proton and carbon accelerators for cancer therapy. The work is ongoing, at least through 2009.

## Results and Progress

American and European scientists are developing FFAG research programs, and the TRUIMF Accelerator Physics Group has worked with them to achieve a breakthrough in understanding how FFAG designs may be simplified as well as the restrictions imposed by scaling avoided. In particular, we introduced "serpentine" acceleration (essential for muons), developed a theoretical model explaining the momentum dependence of orbit shape and period, and are now helping to guide the design of the 10–20 MeV electron model, EMMA. As with traditional isochronous cyclotrons, which are a type of non-scaling FFAG, this "first generation" machine has the demerit of resonance crossing due to the variation of the transverse betatron tune. Looking forward to the medical applications, and a much slower rate of acceleration than muons, we are actively working on designs involving wedge-shaped, combined-function magnets in which the contributions of increased path length and edge focusing are used to stabilize the transverse tunes. If the design proves feasible, the UK consortium intends construction of PAMELA, a medical prototype.

## Partners

TRIUMF is a member both of the US-led Neutrino Factory and Muon Collider Collaboration, and of the UK-led CONFORM consortium of laboratories and universities building the EMMA model and studying alternatives for a proton or carbon medical accelerator design.

## TRIUMF's Role

TRIUMF continues to play a key role in FFAG studies, particularly in these areas: providing intellectual and creative leadership to the development of non-scaling FFAGs to the understanding and optimization of the magnetic lattices, notably the extreme momentum compaction to the cyclotron-like method of bucketless RF acceleration to introducing the use of cyclotron orbit codes for FFAGs in place of synchrotron codes, which are awkward to use for spiral-orbit accelerators; to practical aspects of the EMMA design, such as selection of the L-band cavity design; and to a high-gradient small-aperture version of the PAMELA concept.

# Intensity Limitations in Cyclotrons

## Introduction

The 500 MeV TRIUMF cyclotron's limitation on peak intensity is due to repulsive space-charge forces overpowering the vertical focusing forces in the central region where beam energy is lowest. For upgrading to higher intensity, it is necessary to understand the limitation. Therefore, we plan to re-build the vertical section of the injection line. A study will determine optimum matching conditions into the cyclotron and therefore must be completed in 2008 so that the new injection line can be completed within the scope of the current Five-Year Plan.

## Results and Progress

The dynamics in an isochronous accelerator is non-intuitive as the space-charge forces cannot relieve themselves by lengthening the bunches. In a sense, particles act as if they have infinite mass. One can model the dynamics using individual macro-particles, but the optimization is not transparent. A much more efficient formalism exists, one which is statistical in nature: the 21 six-dimensional second moments of the particle bunch distributions are followed rather than the motion of millions of individual particles. This formalism has never been used to study the effects of space charge in the first few turns of a cyclotron. Besides transport in six-dimensional phase space, acceleration must also be correctly handled. An error has been found in one standard code (TRACE-3D).

At sufficiently high intensity, the bunches become vortices, circular when observed from above the median plane. A new discovery is that this tendency alleviates the harmful influence of the "gap-crossing resonance" which causes a stretching of the beam in the median plane. This aspect is currently under study; it may result in higher charge per bunch than envisaged when the cyclotron was originally designed.

## Partners

International Partners: Chinese Institute of Atomic Energy (CIAE).

## TRIUMF's Role

This research is critical to cyclotron-upgrade plans, so TRIUMF plays the lead role.

# Fringe Fields

## Introduction

A highly accurate understanding of the focusing effects of dipoles and quadrupoles pays dividends in tuning time saved. If the elements are quite long compared with aperture, accuracy is easily obtained. On the other hand, when the fringe field is relatively long, its effect must be well understood. This understanding applies both to linear effects and aberrations.

New beam lines are now designed with the knowledge of the effect of fringe fields, so they are relatively more easily commissioned than in the past. Older beam lines, which have always been tuned empirically, are one-by-one becoming treated more scientifically.

### Results and Progress

It is of course possible to use the element field map in a ray-tracing code, but this makes simple optics calculations very cumbersome. If only the linear and lowest order aberration are important, one can ask, "How much of the detail of the field map is needed?" The answer, it turns out is "very little." For example, the linear effect of the quadrupole can be summarized exactly using only three parameters: effective length, effective strength, and a fringe field parameter. And the lowest order (cubic force) aberration depends not at all on the fringe field shape.

These results are used to distil the field maps into a simple and efficient form. For example, of the hundreds of electrostatic quadrupoles used in both ISAC-I and ISIS (the cyclotron injection line), almost all are set to their theoretical values in spite of the fact that many are short compared with their aperture. Magnetic quadrupoles are also being treated in this way, which makes the beam optics calculations sufficiently efficient that beam envelopes can be calculated continuously in a graphical user interface as the operator tunes the elements.

### Partners

Individual contact among collaborating research scientists around the world.

### TRIUMF's Role

TRIUMF has contributed to the international body of knowledge with the publication of key research papers and presentations at confenreces.

## Nonlinear Transfer Maps for Charged-Particle Beam Transport

### Introduction

Charged-particle beam transport can be described with a Taylor map, which, in the linear case, coincides with the familiar beam-transfer matrix. Traditional accelerator design codes, such as TRANSPORT of K. Brown and MAD, developed by CERN, utilize the next (second) order map while methods to construct maps of higher order and use them for nonlinear analysis were developed in the 1980s by Dragt, Forest, Irwin, Berz and others. Such are the Lie-algebraic method, which fully accounts for the Hamiltonian (symplectic) nature of motion, or the differential algebra method, where the map is extracted directly from the equations of motion. In terms of mathematical apparatus, both these approaches, and especially the second one, require extensive numerical manipulations of polynomial functions. For this, the techniques of the truncated power series algebra (TPSA) are applied (also called automatic differentiation).

At present, increased power of analytic computational systems (such as Mathematica) provide the flexibility and speed needed to implement all the map-building methods described above. Nonlinear problems can then be studied with dedicated notebooks in a local environment. Work in this direction, pursued also by researches in many accelerator laboratories, has recently been initiated at TRIUMF. We have developed two packages - LieMath and DARK possessing many features and functions of two well-established codes: MARYLIE (of A. Dragt) and COSY (of M. Berz).

## Results and Progress

### Lie-algebra Applications

In 2004 and 2005, the TRIUMF Accelerator Group wrote LieMath, a code that builds a symplectic six-dimensional map in either Lie-factor, or Taylor form. The input to the code is a beam line of optical elements written in the most popular MAD-input format. The code provides nonlinear optimization and normal form analysis to octupole order. As of 2006, a TPSA module is installed to speed up operations on polynomials.

In 2004, an early version of LieMath was used to produce a seventh-order, off-momentum map for the basic cell of the FFAG. It is in full agreement with the corresponding map generated by COSY.

In 2006, Lie-algebraic theory was applied to test and refine the existing CERN program for multipole correction of the LHC interaction-region quadrupoles, or so-called triplet correction.

In 2007, Lie-algebraic treatment of weak-strong beam-beam interaction produced the effective Hamiltonian in the case of an arbitrary number of collisions or IPs. This result is related to the long-standing question of whether the beam-beam resonances may be cancelled by choosing some appropriate betatron phase advance between ATLAS and CMS, the two main IPs of the LHC. Such resonances, manifesting themselves as dips in dynamic aperture positioned dangerously close to the LHC tune working point, were clearly seen in the tracking data. As a result, we found that not all, but only some kinds of resonances would be cancelled, and that the conditions for cancellation are rather stringent. The idea to tune the machine to a specific phase between the IPs has been, at least for now, abandoned.

### Differential Algebra Applications

DARK (Differential Algebra + Runge-Kutta) is a Mathematica package that applies the TPSA method to compute the transfer map for arbitrary equations of motion describing an optical system. It has the same interface as LieMath, so the Taylor maps produced by these two codes can be compared directly, but it can also tackle the case when the focusing strength of an optical element is not constant along its axis, *i.e.*, the case of fringe fields. The algorithm used is very similar to the one used in the code COSY.

In mathematical terms, DARK is a differential algebra integrator, a numerical solver of the complete variational equations describing an optical system.

The code has been tested against numerical integration of individual trajectories and, for magnetic quadrupoles with fringe fields, against high-order maps generated with COSY.

Possible applications include nonlinear optimization of beam lines, FFAG, a linear collider interaction region, existence of third-order achromats, etc. DARK was used recently to study fixed points and transition to chaos of the Duffing equation.

## Partners

International Partners: CERN, University of Maryland.

## TRIUMF's Role

In 2005, the LieMath package was added to the web-based dynamic accelerator physics software repository. Currently DARK is being used to study fixed points and transition to chaos of the Duffing equation. This is intended for Section 18.11 (Taylor Approximations) in the book "Lie Methods for Nonlinear Dynamics with Applications to Accelerator Physics" which is being prepared by Prof. A. Dragt.

# 4.2.5

# Detector Development and Fabrication

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

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

Detectors exploit several technological approaches. One example is scintillating materials that emit a flash of light when stimulated by impact or passage of an energetic particle. The intensity of light is typically proportional to the energy of the particle deposited in the material, thereby leading to arrays of such scintillators being known as calorimeters. The light can be collected and detected by a variety of devices, which themselves are a topic of recent advances. The scintillator material can be organic or inorganic, a solid, liquid or gas, and is chosen from an array of established possibilities to optimize the precision in time or energy of the measurement while minimizing the cost. New materials with improved properties continue to be developed, for example, liquid xenon, which is a topic of future work by the detector group and is described below.

Another widely used detector technology exploits the trail of ions and free electrons produced in the track of a charged particle typically passing through gases, but also through certain liquids, to determine the spatial location of that track to a precision that may be as thin as the diameter of a human hair. The electrons are collected on a lattice or array of many electrodes in the medium. The tiny electrical signal on each electrode is amplified by an avalanche process in the high electric fields near the electrode and is detected by a sensitive electronic device. Such tracking detectors are often used in magnetic fields of large magnets in which the tracks of charged particles are curved to a degree proportional to their momenta. Measuring a track's curvature thus determines the particle's momentum. In addition, the density of the ionization along the track can be recorded and used to identify the type of charged particle.

All particle detectors ultimately produce information in the form of electrical signals that must be processed by electronic circuits, digitized to produce numerical data, which in turn may be further processed in real time and then recorded for further analysis. The initial signals may be so tiny that they need to be amplified by sensitive devices that have very little intrinsic noise. Continuing advances, in both this analog technology as well as in the digital processing devices and techniques, have played crucial roles in rapid enhancements in the capabilities of detector systems.

## Description of Facilities

The facilities for detector construction occupy four substantial areas on the TRIUMF site. Two of these house three new machine tools: a Haas VF-5/40XT CNC vertical milling centre with a 5-axis spindle and 2-axis rotary table yielding a precision of ± 5 µm over a working volume of 1.5 m x 0.66 m x 0.64 m; a Haas TL-3 CNC lathe with a maximum cutting diameter of 0.5 m and a maximum cutting length of 1.5 m; and a Multicam CNC router with a precision of ± 50 µm over a working volume of 3 m x 3 m x 0.4 m.

All of these new machine tools are housed in temperature-controlled areas, with dust extraction systems suitable for machining the composite materials that play a major role in the fabrication of modern instruments. In addition, there are available three temperature-controlled class-1000 clean rooms, with volumes 7.8 m x 11.5 m x 5 m, 8 m x 10 m x 2.4 m, and 8 m x 9 m x 2.8 m, for assembling instruments of all sizes. One of these contains a 3 m x 2.4 m precise granite slab with a pneumatic press. Finally, there is a 10 m x 27 m detector test area equipped with several high-purity gas mixture manifolds. The replacement value of the entire infrastructure of the detector facility for construction is about $C1 million.

# Particle Physics Experiments

## KOPIO

The KOPIO experiment was an international project to be based at the Brookhaven National Laboratory in the United States. The collaboration had worked for about a decade to develop a detailed design and funding scenario, and had passed essentially all the stages of scientific and technical review. Unfortunately, the US National Science Foundation cancelled the project in 2005.

TRIUMF had responsibility for the challenging design and construction of the pre-radiator detector, which consisted of a sandwich of scintillator bars and wire chambers. The scintillator bars were to be produced at a local firm called CELCO. The production technique developed by TRIUMF in collaboration with CELCO led to a patent. This collaboration subsequently produced the fine-grained detector (FGD) bars for T2K (see below).

In addition, a collaboration with l'Université de Montréal developed an electronic digitizing system based on 50 MHz flash ADCs. This 48-channel VME board (VF48) is now used by a variety of experiments including liquid-xenon PET medical imaging, the ALPHA experiment at CERN, and the PIENU and TACTIC experiments at TRIUMF. A modified version running at 200 MHz is also used by the TIGRESS experiment at TRIUMF.

## TWIST

The recently completed TWIST experiment at TRIUMF measured, with dramatically improved precision, the Michel parameters describing the weak decay of muons to electrons, thereby imposing much stronger limits on possible deficiencies or extensions to the standard model that embodies our present fundamental understanding of particle physics. Such discrepancies are sought because they would be clear indications of new physics that could be clues to a more profound and general model.

The core of the TWIST experiment, a tracking gas detector that challenged the limits on precision in construction, was built in the TRIUMF detector facility between 1999 and 2001. In 2004 a time expansion chamber, and associated gas purification and pressure control system, was installed to study the properties of the muon beam entering the main TWIST detector apparatus. Maintenance of the wire chambers and time expansion chamber was provided until the experiment was completed at the end of 2007.

## T2K

The T2K (Tokai to Kamioka) experiment in Japan is an international effort that will pursue the widely recognized logical next step in unraveling the profound mystery of neutrino mass and flavour oscillation. Canada is contributing the central core of the Near Detector (ND280), which consists of two types of sub-detector: three identical tracking detectors called time projection chambers (TPCs), and two almost identical one-ton scintillator matrices or FGDs. The detectors are scheduled to be installed at the Japan Proton Accelerator Research Complex (J-PARC) laboratory in the middle of 2009.

The TPCs are gas-filled volumes of roughly 2 x 2 x 0.3 $m^3$, lined with precise electrodes to produce a strong electric field of high uniformity. Free electrons produced by particle tracks in this volume drift towards sensitive detection arrays on one side of each half-box, over a maximum drift length of 1 m.

The mechanical construction of the TPCs at the TRIUMF detector facility depends on new infrastructure acquired through the CFI-supported Laboratory for Advanced Detector Development (LADD). A prototype was also built in 2005 by the detector facility. LADD also provided electronics, power supplies, and a laser for the prototype tests, performed at the University of Victoria. The sophisticated system for purifying and re-circulating the special gas mixtures required for the TPCs at precisely controlled pressures was designed and is being constructed by the detector facility.

The FGD consists of 8,500 scintillator bars that were extruded at the local CELCO plant in 2007. The scintillation light produced in each bar is captured by a 1 mm diameter wavelength-shifting fibre in an axial extruded hole. One end of each fibre is optically coupled to a recently developed type of light detector called a multi-pixel photon counter (MPPC). The MPPC is a kind of Geiger-mode photon detector (GPD) produced by Hamamatsu Photonics. Characterization of these new devices was performed using LADD equipment and manpower and will lead to publication of several technical papers. The intricate FGD mechanical design depended on the skill and experience of the leader of the detector facility, and fabrication in the facility used new equipment purchased through LADD. The FGD signal-acquisition electronics was designed and fabricated under the leadership of the LADD group.

### PIENU

The PIENU experiment is a project to improve, by about a factor of ten, the precision with which electron-muon universality has been tested experimentally in the decay of pions. If this symmetry were found to be broken, it would be a clear signal of departures from the standard model of particle physics. The measurement will exploit the excellent properties of the pion beam available from the M13 beam line at TRIUMF.

The design of the PIENU experiment started in 2006, and the start of actual measurements is expected in fall 2008. PIENU requires a combination of scintillator detectors, which are used to detect charged particles and stopped pions, wire chamber and silicon strip detectors measuring charged-particle positions, and a calorimeter measuring energies of the positron or photon from the pion decay. All scintillator detectors and wire chambers are being built by the detector facility. The signal-acquisition system for the calorimeters and silicon strips is based on the VF48 design developed initially for KOPIO.

### G0

The goal of the G0 experiment at Jefferson Laboratory in the US is to learn more about how the various flavours of quarks in the proton or neutron contribute to its distributions of electric charge and magnetization.

A Canadian group led by the University of Manitoba made indispensable contributions to the design and construction of the experiment. In particular, the TRIUMF scintillator shop constructed large arrays of plastic scintillators and light guides. The first phase of the experiment was completed successfully, and the results published.

## Nuclear Physics Experiments at TRIUMF

### SCEPTAR

One of the main detection tools for nuclear physics at ISAC is the 8π spectrometer, the only existing large, high-resolution, high-efficiency γ-ray spectrometer for characterizing the decay of stationary radioactive nuclei. TRIUMF's Detector Group contributed both design and construction efforts towards the enhancement of this facility with ancillary detectors for beta particles or conversion electrons produced in time coincidence with the γ-rays. The leading example is SCEPTAR (SCintilator Electron-Positron Tagging Array), which is a segmented sphere of 20 thin plastic scintillators, one in front of each of the 20 high-purity germanium (HPGe) high-resolution γ detectors of the 8π.

SCEPTAR is intricate because its delicate elements must be supported precisely inside the HPGe array with a minimum of obscuring material, while connected to a tube of slim acrylic strips carrying the scintillation light out of the vacuum vessel to external sensors. This system's design and construction challenged the skill and experience of TRIUMF's Detector Group. The detector was installed successfully and has performed well.

### TACTIC

TACTIC is a cylindrical time projection chamber (TPC) designed to study nuclear reactions that are important inside stars, at the relevant very low energies where the reactions occur with low probability. An ISAC beam of short-lived nuclei passes along the axis of the gas-filled cylinder, and the ionization tracks of the products of any interactions with the low-pressure gas are collected on the cylindrical walls. These walls are lined with gas electron multipliers (GEMs), which amplify the signals so that their intensities and arrival times can be recorded. This innovative TPC was designed by the Detector Group and built by the University of York in the United Kingdom. The signals are digitized and recorded by the VF48 boards of the type mentioned above.

### MAYA

The MAYA detector is a unique device, on loan from GANIL in France, being applied at TRIUMF to study exotic halo nuclei. It was the very first experiment carried out in the new ISAC-II, in 2007. MAYA is essentially a small TPC in which the tracking gas serves also as the target material, a so-called active target. The Detector Group designed and assembled a system to provide the required high-purity gas mixtures.

### TIGRESS

The Detector Group provided equipment, clean room, and testing facilities in support of the development of the new TIGRESS facility for the study of nuclear structure and basic symmetries at ISAC-II.

## Medical Imaging

Complementing the TRIUMF Life Sciences program, the Detector Group is active in developing an innovative technology for medical imaging, an effort that began in 2004 with the now-subsumed LADD. Positron emission tomography (PET) is a widely applied medical method for three-dimensional imaging of internal organs. In this method, a short-lived radioactive isotope, chemically substituted in a biologically active molecule, is administered to the patient. The isotope is chosen to be one that decays by emitting a low-energy positron with a short range in tissue. The positron annihilates with an atomic electron, producing a collinear back-to-back pair of γ-rays, each with an energy of 511 keV. The patient is surrounded by an array of detectors that record the positions of the interaction of the γ-rays in the detectors, thereby defining a line through the point of annihilation. Sophisticated analysis of the two-dimensional information from a large number of such events yields a three-dimensional image of the concentration density of the isotope, which might reveal, for example, anomalous local deficiencies in metabolism of the carrier molecule.

The quality of the medical information available from PET images depends on both the number of events recorded (statistical precision) and the spatial resolution of the detectors. The recording rate is limited by the detector time and energy resolutions with which coincident γ-rays can be identified as coming from the same annihilation event. Today's conventional PET systems employ inorganic scintillators such as LSO.

While arrays of such scintillators have high detection efficiency, their resolution in time and space is limited by their granularity and lack of information about the depth into the scintillator of the interaction location where each γ-ray is absorbed, producing the scintillation light. An ideal detector would provide a fast timing signal as well as precise three-dimensional spatial information about each interaction. The detection medium of liquid xenon offers this possibility, as the interactions produced both prompt scintillation light to define the time with a precision of 1 ns and mobile ionization electrons to define the position via the TPC technique to within 1 mm.

These advantages have motivated work on applying liquid xenon detectors to particle physics. The focus of the TRIUMF Detector Group has been on demonstrating the feasibility of such a detector for PET. Simulations were performed to investigate how to identify Compton (quasi-elastic) scattering of γ-rays from electrons, which would otherwise limit the performance. The feasibility of simultaneously measuring light and ionization charge was demonstrated in a small test chamber.

Present efforts are focused on the design and construction of one prototype segment of an eventual 12-segment microPET ring detector suitable for small animals. The components have been fabricated, and the assembly will be completed in 2008. The cryostat and controls to maintain the required very high xenon purity have been built and tested. Avalanche photodiodes have been chosen as the most appropriate light detector and have been acquired and characterized. The electronics to sense and record the signals from the 32 photodiodes and 192 TPC electrodes has been developed and built. The prototype segment will be operated and studied through 2008. The group expects to demonstrate the feasibility of a PET detector based on liquid xenon by 2010. The success of this effort will be another example of the application of ideas emerging from basic research in particle and nuclear physics to enhance and even save the lives of the citizens funding this research.

# Partners

In Canada: Guelph University, University of British Columbia, l'Université de Montréal, University of Regina, University of Victoria, University of Manitoba, and York University.

International Partners: France (2), Japan (1), Switzerland (1), the United Kingdom (3), and the United States (3).

# TRIUMF's Role

The present TRIUMF detector group is the result of the 2007 amalgamation of the existing detector facility for design and construction with LADD, which was created with special funding from the Canadian Foundation for Innovation (CFI). Led by an experienced designer, R. Henderson, the detector construction facility has internationally recognized expertise and accomplishments in two main areas: gas detectors and scintillator detectors. CFI funding of LADD provided new infrastructure and enabled the hiring of two physicists, F. Retiere and L. Kurchaninov, with strong interests and experience in detector and electronics research and development. The focus of their research has been on detector and electronics development for particle physics and medical imaging.

# 4.3

# Creating Future Leaders

# 4.3.1

# Outreach and Public Engagement

## Introduction

As a world-leading research laboratory, TRIUMF takes its commitment to the citizens of Canada seriously. A key component of that commitment is a formal outreach program with a mission of promoting science and research in the public arena. TRIUMF's outreach activities are also designed to tell Canadian students, teachers, and the public about the excitement of curiosity-driven research and about how a laboratory like TRIUMF adds value to Canada in new technologies, medical applications, and highly qualified people.

In 2003, funding from the Vancouver Foundation and the Life Members Organization of the Engineering Institute of Canada (now Canadian Society of Senior Engineers (CSSE)) allowed TRIUMF to broaden the laboratory's outreach activities. In just a few years, TRIUMF's Outreach Program developed a number of successful educational initiatives that have established the laboratory as a major contributor to Canada's science promotion community.

The TRIUMF Outreach Program uses the laboratory's facilities to provide stimulating and educational opportunities for students of all ages but most especially high-school teachers and their students. Programs have been created to stimulate the interest of students in the physical sciences, and to support science teachers with materials and experiences relevant to the classroom. These programs were developed both in-house and through partnerships with local and national science promotion agencies. Through these programs, TRIUMF is attracting a new generation of scientists into the wonder and excitement of fundamental research and its possibilities.

## Programs for Teachers

Students respond to high quality video content as part of their learning experience. One of TRIUMF's most compelling outreach initiatives has been the production of animated physics education videos for schools. The Physics in Action series is intended as a supplementary teaching aid to show how the concepts and formulas taught in middle- and high-school physics are not purely abstract concepts; they are, in fact, in use every day and govern the performance of sophisticated equipment.

The Vancouver Foundation funded the first video, on the topic of special relativity. TRIUMF built on this first video's success with a second video on the applications of electromagnetism and circular motion in the cyclotron. This second video was made possible with funding from NSERC's PromoScience and was released with some fanfare at Catalyst 2008, a conference of the British Columbia teachers of science. Both videos are available, free, to every high school in Canada.

Teachers are often responsible for providing instruction on topics for which they have little or no practical experience. TRIUMF developed two programs to provide teachers with real-world research experience they could transfer to

**Figure 1:** High-school teachers visiting TRIUMF and learning about a beam line during the Fall Professional Development Day.

the classroom. Every other year, the British Columbia Association of Physics Teachers and the British Columbia Science Teachers Association organize a Fall Professional Development Day at TRIUMF. This event attracts approximately one hundred teachers from across the province (see Figure 1). TRIUMF provides the teachers with a full day of tours, talks, and hands-on physics demonstrations. For teachers who appreciate a more in-depth look into the world of TRIUMF physics, TRIUMF recently launched an internship program that offers high-school educators a three- to seven-day research experience working as part of an experimental research team on a running experiment (see Figure 2).

TRIUMF has also collaborated with the Universities of Alberta and Victoria and the US laboratory Fermilab to bring an authentic research experience into the classroom through the Alberta Large-area Time-Coincidence Array and QuarkNet programs. These programs bring into schools compact cosmic-ray detector equipment that can be operated and maintained by teachers and students. These systems integrate into a North American network of schools studying large-scale cosmic-ray showers. TRIUMF has helped develop the next-generation data acquisition systems for these systems, which are now ready to be deployed at schools across the province. To date, the cosmic-ray detector project and the internship program have been supported by funds from the Vancouver Foundation and the CSSE.

## Programs for Students

TRIUMF is a favourite field-trip destination for high-school science classes and receives about 660 student visits per year. Field trips provide students with an overview of the laboratory, but some very interested students want more. In 2004, TRIUMF and the B.C. Innovation Council initiated a scholarship program that offers exceptional high-school science students a hands-on experience as a participating member of a research team. Graduating students going on to university science programs are eligible for the six-week research experience at TRIUMF, along with a $3,000 scholarship. The High-School Fellowship program attracts 100 applications per year, and the program has been a major success: of the six scholarship winners to date, three have chosen to return to TRIUMF as undergraduate co-op students (see Figure 3).

**Figure 2:** Pitt Meadows high-school teacher Michael Bruins assisting SFU Professor Jeff Sonier on an experiment.

# Programs for the General Public

TRIUMF offers public tours twice daily from May through August and twice a week the rest of the year. Each year, TRIUMF attracts an average of 440 visitors who come specifically for the public tours program.

In response to an overwhelming demand, TRIUMF created the Saturday Morning Lecture Series, a monthly lecture featuring talks by scientists from TRIUMF, the University of British Columbia, Simon Fraser University, and the National Research Council's Fuel Cell Program as well as other notable visitors to TRIUMF. The lectures are aimed at high-school students but are well attended by adults interested in science. These lectures have proved to be very popular, with some lectures attracting capacity crowds of 100 or more (see Figure 4).

The scope and scale of science outreach is far too large to be tackled alone. To develop new outreach programs, TRIUMF has built strong relationships with other institutions involved in science outreach. These include: the BC Innovation Council (BCIC); the BC Association of Physics Teachers (BCAPT); the BC Science Teachers Association (BCScTA); outreach and science promotion programs at the University of Alberta, University of Victoria, and UBC; the Perimeter Institute for Theoretical Physics; QuarkNet at Fermilab in the US, Telus World of Science; the H.R. Macmillan Space Centre in Vancouver; Capilano College in Sechelt, B.C.; and NSERC-Pacific in Vancouver. Most of TRIUMF's outreach programs have been developed and/or delivered in conjunction with one of these partners.

TRIUMF has also supported the science promotion community through its support of the Scientists in Schools program at Telus World of Science in Vancouver, the Regional Science Fair (and the Canada-Wide Science Fair in 2005) run by the Youth Science Foundation Canada, the UBC Undergraduate Science Conference, the Canadian Undergraduate Physics Journal, BCScTA's journal Momentum, the Canadian Journal of High School Science; and others.

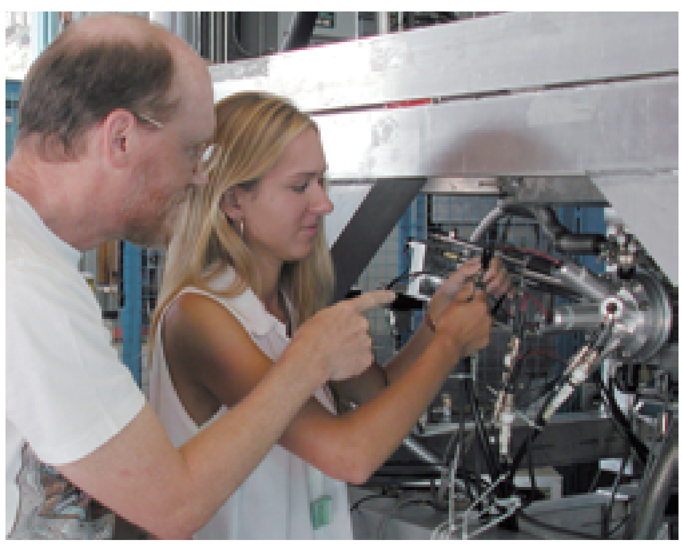


**Figure 3:** UBC Professor Jess Brewer working with Reka Moldovan of Kelowna, BC during her High-School Fellowship experience.

TRIUMF approaches outreach from many directions: as a creator of content linking the excitement of TRIUMF's curiosity driven research to the high-school classroom; as a facilitator, providing teachers unique tools to teach their students about fundamental science; and as a communicator, telling students, teachers and the public about the scientific, social, and economic impacts a fundamental research laboratory like TRIUMF has on Canada.

## Partners

In Canada: British Columbia Association of Physics Teachers, British Columbia Innovation Council, British Columbia Science Teachers Association, Canadian Association of Physicists, NSERC Promo Science, Perimeter Institute, University of British Columbia, Vancouver Foundation, and others. Internationally, a number of key laboratories are involved, often through the mechanism of the InterActions Collaboration.

## TRIUMF's Role

TRIUMF supports one roughly full-time position as Outreach Coordinator. The majority of the effort in this program comes from individual staff members at TRIUMF who work within the Outreach Program framework to make contributions. In recent years, the Outreach Coordinator has been working closely with the newly created communications office.

**Figure 4:** Packed auditorium listening to one of TRIUMF's Saturday Morning Lectures.

# 4.3.2

# Training and Educating Students

## Introduction

An important and integral part of TRIUMF's mission is educating and training Canadians. The educational experiences that TRIUMF makes available to young Canadians are not available anywhere else in Canada. As a national and international laboratory for subatomic physics, TRIUMF provides research facilities and educational opportunities that no single university could provide. They are available to the entire Canadian university community. In return, TRIUMF gains intellectual and technical strength from its ongoing relationships with the university community's highly qualified, talented, and innovative faculty and staff as well as access to their students, the scientific leaders of the future. This synergy between TRIUMF and the Canadian universities benefits all of us, but most particularly benefits Canadian students.

TRIUMF has an ongoing commitment to education at all levels. Student programs target high-school students, undergraduate, and graduate students, as well as post-doctoral and research assistant positions. TRIUMF provides scholarships, on-site educational opportunities, and student-focused conferences and initiatives. As well as academically focused educational opportunities, TRIUMF provides training for technical and trades careers through co-op programs.

## Co-operative Education and Summer Students

TRIUMF works closely with Canadian universities to provide work experience to undergraduate students, mostly through the Co-operative Education Program. There are three work terms per year: January–April May–August, and September–December. Universities that do not have year-round co-op programs are invited to submit student applications for the summer work term, providing an equal opportunity for a TRIUMF work-term experience to all Canadian undergraduate students.

Academic co-op students receive a salary commensurate with their academic and work experience. TRIUMF also pays the cost of transportation between the student's university and Vancouver, ensuring that the best students from across Canada are able to apply for a TRIUMF co-op position without the financial penalty of paying for transportation costs to and from Vancouver. Figure 1 shows the geographical distribution of students.

Educational opportunities at TRIUMF are not limited to university students. Highly qualified technical people are critical to the success of Canadian industry as well as scientific research. For many years TRIUMF, has supported a small co-op program for technical students from local colleges and technical institutes. TRIUMF itself produces highly qualified technical people. In high demand, some of these technical people may leave TRIUMF for positions in industry.

Between 2003 and 2008, 319 undergraduate students worked at TRIUMF: 73 worked in the spring term, 174 in the summer term, and 72 in the fall term. The students worked on a wide range of activities at TRIUMF, including participation in the building of beam lines, programming computers, synthesizing radio-pharmaceuticals, guiding facility tours, constructing and testing particle

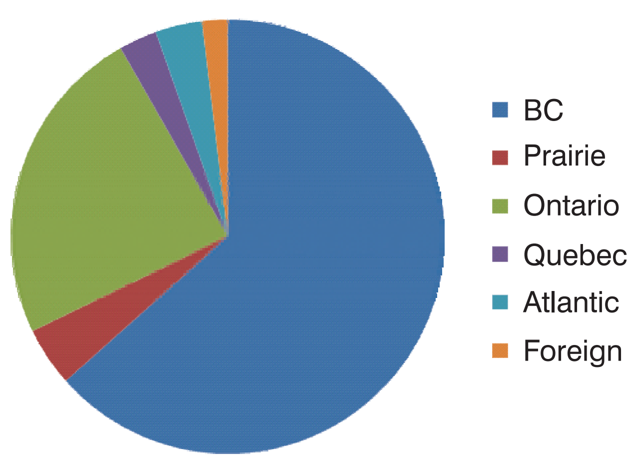



**Figure 1:** Distribution of TRIUMF co-op students by region of origin.

detectors, analyzing data, and working on electrical systems. The distribution of student activity by area of work is shown in Figure 2.

The summer students have the opportunity to learn about the wide spectrum of research that takes place at TRIUMF through special weekly lectures, specifically designed for undergrads by TRIUMF. This lecture series sets the TRIUMF co-op experience apart from others because it broadens the learning experience beyond the particular project on which each student is working.

During each summer co-op term, TRIUMF organizes a contest designed to teach students the presentation skills that will be necessary to their success in whatever career path they finally choose. The students are coached on the techniques and skills required for successful presentations and then compete with each other in presenting ten minute lectures on their TRIUMF project. The winner receives a scholarship to participate the Winter Nuclear and Particle Physics Conference at Banff, where he/she presents their paper. The opportunity for students from across Canada to get to know each other and develop networking and social relationships is also an important part of their work term at TRIUMF.

Employing co-op students benefits the employer as well as the students. Students bring new skills and points of view as well as enthusiasm and curiosity to their work. Patrick Bonnick (see Figure 3) is an example of this mutually beneficial relationship. Patrick was enrolled in the Chemical Physics program at the University of Guelph and had worked in a previous term at Bubble Technologies Inc., on gel detectors for nuclear radiation. Upon his arrival at TRIUMF, he was employed by the T2K neutrino group to help develop water-based scintillating liquid and gel detectors. The skills he learned at Bubble Technologies and the university lab were a key asset to the physicists directing the TRIUMF project. In turn, Patrick received encouragement, coaching, and instruction from TRIUMF's experts in this technology and hands-on experi-

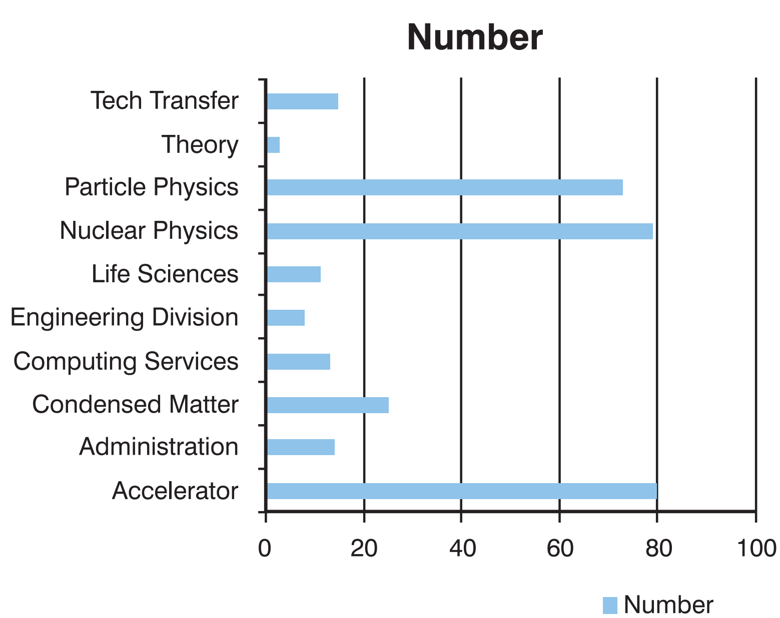



**Figure 2:** Distribution of TRIUMF co-op students by work topics.

ence in scientific state-of-the-art research. After completing two work terms at TRIUMF and successfully developing a scintillating gel, Patrick completed his B.Sc. in Chemical Physics and is now in the Department of Physics at Dalhousie University, doing graduate work on improving the efficiency of fuel cells.

In Patrick's words, "TRIUMF was easily the highlight of my undergraduate career. The opportunity to do cutting-edge research as an undergrad was unbeatable. By working alongside my supervisor, I developed all the skills you need to do research, but don't learn in school. I worked independently much of the time, and improved my own work ethic immensely…Our group also had weekly meetings, so I gained quite a bit of practice at presenting. Additionally, I participated in TRIUMF's summer presentation contest, which taught us proper presentation skills in a formal manner (*i.e.*, classroom setting). My experience [at TRIUMF] … ultimately led to my receiving an NSERC scholarship to perform my Masters at Dalhousie University."

## Undergraduate Summer Research Awards

TRIUMF presents five prestigious Summer Research Awards annually to exceptional Canadian undergraduate students, one for each of the five regions of Canada. The scholarship program promotes subatomic physics research across Canada. In order to qualify, the applicants must have completed at least two years of an undergraduate program (or equivalent). One scholarship is awarded in each region: Atlantic, Quebec, Ontario, the Prairies, and British Columbia. The recipients work at TRIUMF for one term and receive the regu-

**Figure 3:** Patrick Bonnick during his work term at TRIUMF.

lar student salary, plus a $2,000 scholarship payable upon completion of a report on their term's research.

The scholarship program has been very successful in engaging students from universities who are not members of the TRIUMF joint venture. For example, prior to 2001, Saint Mary's University, Halifax, had a strong astrophysics program but only modest involvement with TRIUMF. With encouragement from the faculty at the university, summer, Sean McGee, a student from Saint Mary's applied for and won the TRIUMF Summer Research Award for the Atlantic Region in 2001. He chose to work on the DRAGON nuclear astrophysics program at TRIUMF. Upon returning to Saint Mary's, Sean wrote his B.Sc Honours Astrophysics thesis on his TRIUMF research and presented seminars on his work to fellow students and faculty. The following summer, two Saint Mary's professors, M. Butler and A. Sarty, visited TRIUMF and discussed starting a formal relationship between the institutions. Since then, Saint Mary's has joined the TRIUMF consortium as an associate member and has expanded its nuclear physics program by adding two new faculty members in nuclear physics, whose research programs are now centred at TRIUMF's facilities.

# Graduate Students

Graduate students are a crucial component of TRIUMF's commitment to education. Students working on their Masters and Ph.D. degrees gain hands-on research experience at TRIUMF and learn to work in teams as part of a research group, a learning experience not often available at their university. Research performed at the graduate student level trains the scientists of the future.

In the period 2003–2008, the number of graduate students who completed theses based completely or partially on research performed at TRIUMF is summarized in the chart below.

| Area | Ph.D | Masters |
|---|---|---|
| Subatomic Physics | 65 | 126 |
| Molecular & Materials Sciences | 32 | 69 |
| Accelerator Technology | 1 | 3 |
| Life Sciences | 6 | 25 |

**Table 1:** Graduate students at TRIUMF from 2003-2008 by area of study.

The graduate students at TRIUMF come from Canadian universities and international universities and laboratories that use the research facilities of TRIUMF. Figure 4 shows the geographical distribution of these students. It is worth noting the strong representation from Canadian universities, though the majority of graduate students using TRIUMF facilities are from foreign countries. This is the hallmark of a laboratory with world-class facilities and an international reputation for excellence in both science and educational opportunities.

PEOPLE

## GRAEME LUKE

*Professor, McMaster University*

Graeme Luke received his B.Sc. in Engineering Physics from Queen's University in 1984 and his Ph.D. from UBC in 1988. While completing his Ph.D., "Quantum Diffusion of Positive Muons in Copper," at TRIUMF under the supervision of J. Brewer working at TRIUMF, he joined the first muon spin rotation experiments on the high-$T_c$ cuprates.

After graduation, Dr. Luke moved to New York to start an NSERC post-doctoral fellowship at Columbia University. Over the next ten years, he continued his studies in high-$T_c$ and other highly correlated superconductors. In 1998, he joined the Department of Physics and Astronomy at McMaster University. He also joined the Canadian Institute for Advanced Research Superconductivity Program, which has now evolved into a program in Quantum Materials.

Graeme currently studies superconducting states that are characterized by broken time reversal symmetry or, in other words, are intrinsically magnetic, which is usually forbidden for superconductors. Using the exquisite sensitivity of muon spin relaxation, he has illuminated the magnetic properties of these exotic superconductors. He has also begun studying the use of hydrostatic pressure to tune the electronic/magnetic ground state of various systems.

Dr. Luke's work on these extremely demanding experiments have, he feels, greatly benefited from the technical expertise of the TRIUMF-CMMS support staff. ■

# Post-doctoral Fellows and Research Associates

Upon completion of their Ph.D.s, scientists at the beginning of their careers will often join a research group for a term of two to three years as a post-doctoral fellow (PDF) or a research associate (RA). This career phase is an important step to experience new and different scientific opportunities and acquire additional skills and experience. Researchers are then better prepared as they move toward career positions in academia, research, or industry. Between 2003 and 2008, TRIUMF was host to 88 PDFs and RAs. Many of these work full time at TRIUMF, while others spend most of their time at their home institutes and come to TRIUMF only for limited periods of time, usually when their research group has been allocated experimental beam time or they are building or preparing experimental equipment.

# University Teaching

In addition to providing educational opportunities for students at TRIUMF, some of the scientific staff teach courses for some of the member universities. The proximal universities obviously have an advantage in this regard, but the video conferencing technologies now available have allowed some courses to be taught across Canada. TRIUMF scientist B. Jennings has taught courses on nuclear structure that were simultaneously available to the University of British Columbia and Simon Fraser University students as well as broadcast by video link to universities in Eastern and Central Canada. The video link allowed students from McMaster University, the University of Guelph, and Dalhousie University/Saint Mary's University to watch the lectures and ask questions in real time. This technology allows the teaching of courses in multiple institutions, permitting universities to provide educational opportunities that might not be possible for them because of small enrollment or lack of faculty to teach the course. This is an example of how a national laboratory like TRIUMF can use resources to benefit all of its member universities.

In addition, some TRIUMF research scientists have adjunct professor positions at member universities. These individuals are: J. Behr, J. Dilling, J. Ng, and S. Yen at the University of British Columbia; B. Davids, G. Ball, B. Jennings, and R. Woloshyn at Simon Fraser University; and H. Fearing and A. Olin at the University of Victoria. These adjunct positions allow the TRIUMF researchers to share their expertise by teaching courses and supervising graduate students.

University students have also benefited from field trips to TRIUMF for "hands-on" learning. In the fall of 2006 and again in 2007, the "Particle Detectors" class at the University of Victoria came to TRIUMF for a two-day learning experience using particles from the M11 beam channel, under the supervision of S. Yen. The students attended a lecture about the TRIUMF cyclotron and beam channels and then conducted experiments on particle identification, using time-of-flight and energy loss measurements. The students also studied relativistic mechanics by examining the velocity and momentum parameters of relativistic pions and muons, determining the pion mass, and measuring the lifetime of the pion.

Some courses taught by TRIUMF research scientists are listed in Table 2.

# TRIUMF Summer Institute

Recognizing the important role that a national laboratory with extensive intellectual and physical resources can play in education, for the past 20 years TRIUMF has organized a summer course for graduate students called the TRIUMF Summer Institute (TSI). This two-week summer school is designed to provide graduate students and young researchers with an in-depth course covering one of the areas of research pursued at TRIUMF and elsewhere around the world. Local and international experts give the lectures and spend the two weeks with the students, answering their questions and fostering their interest in the research topic. Typically, the schedule provides three hours of

| Date | University | Course | Title | TRIUMF staff |
|---|---|---|---|---|
| 2002 | UBC | Physics 505 | Graduate Introduction to Nuclear Physics | S. Yen |
| 2003 | UBC | Physics 514 | Electrodynamics | J. Ng |
| 2004 | UBC, Saint Mary's | Physics 505 | Graduate Introduction to Nuclear Physics | S. Yen, J. Dilling |
| 2004 | UBC | Physics 526 | Quantum Electrodynamics | J. Ng |
| 2005 | UBC, Dalhousie | Remote | Graduate Nuclear Structure | B. Jennings |
| 2005 | UBC | Physics 508 | Quantum Field Theory | J. Ng |
| 2006 | SFU | Physics 390 | Introduction to Astrophysics | B. Davids |
| 2006 | UBC/SFU (at TRIUMF) | Phys 522/842 | Modern Techniques for Nuclear Science | J. Behr, L. Buchmann, J. Caggiano, J. Dilling, J. Ressler |
| 2006 | UBC | Physics 528 | Elementary Particles | J. Ng |
| 2006 | UBC | Physics 505 | Graduate Introduction to Nuclear Physics | J. Behr, S. Yen |
| 2007 | UBC | Physics 508 | Quantum Field Theory | J. Ng |
| 2007 | UBC/SFU/Guelph/McMaster | Remote | Graduate Nuclear Structure | B. Jennings |
| 2007 | | | Fundamentals of Scientific Instrument Making | J. Lassen |
| 2008 | SFU | Nuclear Science 344 | Nucleosynthesis and Distribution of the Elements | B. Davids |
| 2008 | UBC | Physics 508 | Quantum Field Theory | J. Ng |

**Table 2.** University courses taught by TRIUMF scientists.

lectures in the morning, and informal tutorials, problem-solving sessions, and discussions in the afternoons. Students have the option of participating in TSI for university credit, in which case homework is assigned and marked. A poster session is scheduled during the TSI to give students the opportunity to present their research and learn about the research their peers are doing.

The Summer Institute typically attracts about 40 students, mostly from Canada and the United States, with the occasional student from overseas. The topics of past Summer Institutes were:

- 2003: CKM and MNS: Quark and Lepton Mixings
- 2004: Nuclear Astrophysics: Experiment, Theory and Observations
- 2005: Atom and Ion Traps: Theory and Applications
- 2006: Collider and Energy Frontier Physics
- 2007: Radiation Detectors: Applications in Nuclear and Particle Physics and Medical Imaging

TRIUMF strongly encourages students to interact and learn from each other in informal settings with each other and the lecturers, so field trips and group activities are an important part of the TRIUMF Summer Institute. These events typically include ocean kayaking, volleyball games, a bike tour, or a barbeque. The TSI provides an excellent opportunity for graduate students to learn from the best experts in the world, as well as become acquainted with each others' research and build lasting friendships.

## Winter Nuclear and Particle Physics Conference

The Winter Nuclear and Particle Physics Conference (WNPPC) is an annual conference aimed specifically at providing a forum for young researchers (students and PDFs). Formerly known as the Western Regional Nuclear Physics Conference, it has evolved into a national meeting for the Canadian subatomic

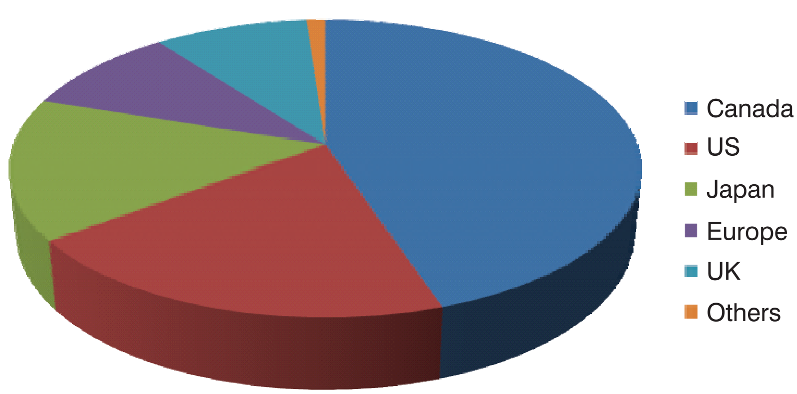



**Figure 4:** Distribution TRIUMF graduate students by region of origin.

physics community. WNPPC features both student presentations and invited talks by experts in the field. Awards are given to the top three student presentations. TRIUMF has been and continues to be involved in overseeing the organization and logistical support for this conference.

## Students at TRIUMF Conferences

There is a strong focus on including students in TRIUMF-hosted national and international conferences. It is important for students to have the opportunity to interact with researchers and students from Canada and abroad, learn the information being presented at the conferences and learn to present their own research in a formal setting.

For example, during the Linear Accelerator Conference in the fall of 2008, a special poster session has been scheduled for students. The poster session will be held in conjunction with the welcome reception to ensure the greatest possible exposure for the students among the delegates. Prizes will be awarded for the best presentations, and the winner will be invited to give an oral presentation during the conference.

Most of the national and international conferences hosted by TRIUMF provide a subsidy or grant for student registration fees. Many laboratories and universities are reluctant to send students to conferences because they are not guaranteed a return on their investment to the same extent as they do with scientists. By providing student registration subsidies and grants, a large part of the expense for the universities and laboratories is reduced or eliminated, thus allowing more students to attend. In addition to a student registration budget, TRIUMF now encourages sponsorship of students by industrial vendors displaying their products at the conferences.

Many of these same initiatives will be in place for the Particle Accelerator Conference in the spring of 2009. In addition, for the first time, this large international conference will have a full student program including lectures and a dedicated student poster session.

It is evident that TRIUMF's many and diverse education initiatives are contributing to the creation of highly qualified people who will become the scientists, teachers and leaders that will have a major impact in the future of government, industry and academic institutions in Canada and abroad. TRIUMF pushes the frontiers of fundamental science with the use of innovative technologies and partnerships. TRIUMF's innovative approach to education and the creation of highly qualified people also pushes the frontiers of education in partnership with the Canadian universities and academic communities.

# 4.4

# Generating Economic and Social Benefits

## Introduction

Discoveries in fundamental physics research often result in major advances in technology that benefit society, from Lord Thompson's 1898 discovery of the electron to Sir Tim Berners-Lee's 1990 invention of key protocols for client and server to communicate via the Internet. The first discovery led to the commercial cathode ray tube used in older televisions; the second to the World Wide Web.

If fundamental research is to result in commercial applications, the commercial possibilities of the research must be recognized and extensive development efforts over many years are usually required before the project is ready for the marketplace. TRIUMF has developed a successful, internationally recognized program for the development and transfer of the knowledge resulting from its research that translates into social and economic activity benefiting all Canadians. TRIUMF's "technology transfer" now encompasses a broad and diverse spectrum, ranging from the commercialization of viable technology opportunities to the outreach activities that transfer the knowledge behind the technology and foster understanding of the research performed at TRIUMF.

Since the establishment of the TRIUMF Business Development Plan in 1996, one of TRIUMF's mandates, as set out in the National Research Council (NRC) Contribution Agreement is "to maximize the economic benefits of the Federal Government's investments in TRIUMF to Canadian companies through pro-active technology transfer activities, contracts, and procurement policies." Over the past twelve years, TRIUMF has established itself as the most successful facility in Canada for the commercialization of technology arising from fundamental research.

TRIUMF has also contributed its scientific knowledge to high-value Canadian products now sold around the world. For example, twenty-four hours of every day, from Asia to Europe to North America, TRIUMF-designed and Canadian-built commercial cyclotrons are producing short-lived isotopes for medical imaging, diagnosis, and treatment of disease. At the TRIUMF laboratory, scientists, engineers, and technical personnel have made discoveries and advances that benefit Canada's medical, pharmaceutical, and agricultural industries. The world's satellite communications and terrestrial flights are safer and more reliable because of TRIUMF's ability to test radiation effects on electronic equipment.

TRIUMF's Technology Transfer Division (TTD) is responsible for the laboratory's commercial activities. It is the responsibility of the Technology Transfer Office (TTO) staff to ensure TRIUMF is accountable for, and complies with, the Federal Government's mandate to pursue "all financially and technically viable opportunities for commercializing technologies derived from the research at TRIUMF." In addition, the TTD is responsible for the Applied Technology Group (ATG), the highly qualified technical personnel who maintain and operate the on-site commercial cyclotrons for one of TRIUMF's major licensees, MDS Nordion.

# Recent Results

The term "technology transfer" is the conventional term used to describe the movement of ideas, equipment, and people among institutions of higher learning, the commercial sector, and the public. The conventional approach to technology transfer is now evolving into the broader concept of "knowledge transfer," which describes the movement of knowledge, ideas, concepts, and techniques from a formative location, generally an institution of advanced education or a laboratory such as TRIUMF, to all areas of the social and economic environment. Over the years, TRIUMF has increased the number of its partnerships with businesses and organzations in Canada and around the world by applying the concepts of technology and knowledge transfer and now works with many different organizations on a commercial basis.

## MDS Nordion

Among TRIUMF's many successes, the TRIUMF-MDS Nordion relationship is internationally recognized as a leading example of technology transfer from a research laboratory. In 1978, TRIUMF and the Commercial Products Division of Atomic Energy Canada Limited (AECL) signed an agreement to produce medical isotopes for AECL. The AECL Commercial Products Division became Nordion Ltd., which in turn was purchased by MDS, creating the company MDS Nordion, TRIUMF's current licensee in the production of medical isotopes. A first TR30 cyclotron was commissioned around 1992. In 2003, increasing demand for medical isotopes led MDS Nordion to invest $20 million in a new TR30 cyclotron and related infrastructure, including buildings, on the TRIUMF site. MDS Nordion currently has three operating cyclotrons at the Vancouver site, supplying over 50,000 doses of medical isotopes a week for the diagnosis and treatment of disease (see Section 3.3). MDS Nordion employs 62 full-time staff and contracts with TRIUMF for an additional 35 highly qualified technical and professional staff to maintain and operate their cyclotrons. The demand for medical isotopes is projected to rise as diagnostic techniques improve and screening capabilities increase, and TRIUMF and MDS Nordion are prepared to meet the demand.

## British Columbia Cancer Agency (BCCA)

TRIUMF and the BCCA have a long-standing partnership. In 1996, BCCA and the Woodward's Foundation made TRIUMF their facility of choice to construct the only Proton Therapy Facility in Canada. This facility is designed to treat ocular melanomas, a potentially life threatening cancer. As of May 30, 2008, 134 patients from Canada and the US have been successfully treated at TRIUMF's Proton Therapy Facility.

In addition to the Proton Therapy Facility, TRIUMF is provides BCCA with florine-18 to use in its new positron emission tomography/computed tomography (PET/CT) scanner. The scanner is used for clinical medical imaging for the diagnosis and treatment of cancer. A PET/CT machine contains both PET and CT cameras, producing images that show both chemical (functional) and anatomical (structural) information. The scanner has the ability not only to identify cells with a high metabolism that may be cancerous, but also to show the size and location of these cell groupings. In 2005, the PET/CT scanner was installed in the BCCA's Centre of Excellence for Functional Cancer Imaging but needed a regular and assured supply of the isotope $^{18}$F to perform the clinical trial work. The ultimate goal of the BCCA is to acquire and operate its own PET cyclotron and radio-pharmacy but setting up a dedicated PET pharmacy is a long and complex task. In May 2005, the BCCA and TRIUMF entered into a supply agreement for the isotope $^{18}$F. The initial one shipment per day has increased to two shipments, and the BCCA goal is to perform 3,000 scans per year on an ongoing basis. From inception until March 31, 2008, it has performed 6,202 scans.

## Canadian Space Agency

In the late 1990s, the Canadian Space Agency approached TRIUMF to develop a proton irradiation facility (PIF) to conduct tests on the radiation hardness of space equipment. The PIF facility has been extremely successful and now includes a neutron irradiation facility (NIF) for terrestrial equipment testing, both of which are described below. TRIUMF's success with the Canadian Space Agency has attracted major and diverse industrial customers from Europe and North America including, among others, CISCO Systems, Sandia National Laboratories, Boeing, NASA, CEA, MD Robotics, Argus Tech, QinetiQ, Lockheed Aerospace, Goodrich and IROC. Testing of materials and products is done on a fee-for-service basis unless the researcher has received approval from one of TRIUMF's Experiments Evaluation Committees.

## Proton Irradiation Facility (PIF)

TRIUMF's PIF facility is a truly unique facility for radiation testing of electronic devices and components with protons. The energy range of the TRIUMF 20 MeV to 500 MeV $H^-$ cyclotron matches the proton energies that are of most concern for electronics used in space, and this range of energies is not available at any other single accelerator laboratory in the world.

All equipment sent into space is subject to much higher fluxes of protons and cosmic rays than at ground level, and all electronic equipment, including computers, lasers, and motor controllers, must be checked for sensitivity to radiation. Radiation damage can occur from single event upsets, a problem caused by a single energetic particle interacting in the silicon device, or by an accumulation of radiation, called total dose damage. In addition, there are a number of different types of radiation (gamma rays, electrons, protons, neutrons, heavy ions) and electronic equipment will respond differently to each type of radiation. The PIF facility at TRIUMF makes use of two beam lines, which enter the same test area, one covering the energy range from 65 M3V to 116 MeV and the other from 180 MeV to 500 MeV. Lower energies can be obtained by using variable thickness plastic degraders. The TRIUMF PIF facility can deliver the typical ten-year radiation dose for the International Space Station in ten minutes, or more slowly if desired. The testing results in significant cost savings to the users.

## Neutron Irradiation Facility (NIF)

Atmospheric radiation, caused by cosmic rays from space interacting with Earth's atmosphere, consists of neutrons and other particles that can also interfere with the functioning of electronic devices. TRIUMF's Neutron Irradiation Facility (NIF) offers a neutron beam that simulates exposure to atmospheric radiation and can be used for testing avionics and ground-based electronic systems. The NIF has an energy spectrum matched to the atmospheric neutron spectrum, and can simulate the radiation effects of ten years of atmospheric exposure in a matter of minutes. The facility's neutron flux, or the number of neutrons per square centimeter per second passing through a material, is comparable to that at the Los Alamos Neutron Science Center (LANSCE) in New Mexico. The neutrons produced at TRIUMF have energies up to 400 MeV, with the additional feature that thermal neutrons from the water moderator are also present. TRIUMF and Los Alamos are the only two facilities in North America that offer such a wide range of neutron energies.

## Innovative Diamond-Like Carbon (DLC) Foils

Carbon foils are used at particle accelerators as extractor or stripper foils and, as such, are important to many of the experiments and production activities that take place at TRIUMF. Triggered by an interruption in foreign suppliers, two TRIUMF scientists invented a process to make them in-house, using a well-known process called "carbon arc deposition," that offered a dramatic (and now patented) improvement on the devices. The process involves the sublimation of a material, in this case amorphous carbon, onto glass slides, so that a film can be deposited and removed easily and afterwards used to extract beams. In their attempt to find an adequate film for MDS Nordion's cyclotrons, these two scientists, along with a colleague from Texas, discovered the benefits of layering foils in a sandwich-like manner with diamond-like carbon in the centre of two amorphous carbon layers.

With this new technique, the laboratory can construct various types of film. Not only can the scientist using the film change the number and order of the layers, he/she can also change the relative thickness of the layers according to the desired performance of the composite film. Typically, thin foils can be made to measure 5 $\mu g/cm^2$ to 100 $\mu g/cm^2$; however, the new foils made at TRIUMF are at an astounding weight of 200 $\mu g/cm^2$ to 300 $\mu g/cm^2$. Other benefits of using diamond-like carbon foils include extreme hardness, optical transparency, chemical inertness, and high-wear resistance, all of which enable longer foil lifetimes. Because the film is more durable, the replacement time diminishes, allowing decreased radiation exposure to maintenance personnel and lower foil replacement costs. Having these higher-quality foils also allows researchers to use higher beam densities in their experiments while causing less graphitization of the carbon in the foil.

Official patent applications have been filed for this technology, and there is now strong commercial interest from isotope producers and accelerator manufacturers. Given the performance characteristics of DLC films and the current market conditions, they are expected to capture the majority of the market share within several years. Commercialization of DLC extractor films will establish Canada as the undisputed leader in the micro-niche market for extractor foils, and other uses for the manufacturing technique are being investigated and may lead to much larger markets. Possible future applications include nuclear medicine, PET centres, the radiopharmaceutical industry, and laser ablation techniques.

## D-Pace

In 1995 Dr. M. Dehnel was a graduate student at TRIUMF writing a Ph.D. thesis on charged particle physics. The thesis led Dr. Dehnel to the idea of designing and manufacturing a variety of diagnostic devices for commercial and laboratory beam line injection systems. Dehnel – Particle Accelerator Components and Engineering, Inc. (D-Pace) is a rapidly growing Canadian supplier of the latest cyclotron components and peripherals, and a good example of an innovative Canadian company based on the licensing and transfer of technology from TRIUMF.

D-Pace has doubled its sales every year for the past several years. With customers from Chicago to Seoul, D-Pace, along with TRIUMF, is recognized worldwide as a supplier of technologically advanced, physics-related products. Customers of its semiconductor industry products include: Bristol-Myers Squibb (USA), CERN (Europe); Daiichi Radioisotope Laboratories Ltd. (Japan); the Institute of Nuclear Energy Research (INER, Taiwan), Thales Corporation (France), and Tyco-Mallinckrodt (USA). D-Pace recently formalized a preferred supplier status with Thales for several TRIUMF licensed products.

## Other Partnerships

In addition to the partnerships mentioned above, TRIUMF routinely works with or assists other organizations in many capacities. These collaborations can often lead in directions not originally foreseen by either TRIUMF or the company we are working with. One of many examples is a Vancouver company, UMA Engineering, who has worked with TRIUMF on several projects, including the construction of the ISAC-I and ISAC-II experimental buildings. UMA gained a knowledge and expertise working with TRIUMF which they were able to use to successfully bid on Project Management contracts for laboratories in many parts of the world, including the Canadian Light Source (CLS), and laboratories in North Carolina, Hawaii, and Australia.

In other examples, TRIUMF is playing a leadership role in the international collaboration of the experimental physics and industrial control system (EPICS) and hosting the 2009 meeting. Research at TRIUMF also contributed to the development of the EXTREMA general-purpose graphics and analysis package. EXTREMA is a powerful visualization and data analysis tool that enables researchers to distill quickly large, complex data sets into meaningful information; it is in widespread use around the world.

TRIUMF is also a facility with a broad reach and a strong social conscience and many groups approach TRIUMF for assistance with physics related problems. Solving these problems does not necessarily translate into economic benefit for TRIUMF, but does provide social benefits to Canada. For example, recently the Royal Canadian Mounted Police detachment in North Vancouver developed a problem with their vacuum metal deposition chamber, an advanced fingerprint coater that uses vacuum technology. It is the only one in Western Canada and several court cases were dependent on results from this equipment. The RCMP contacted TRIUMF for assistance. The laboratory provided and installed a spare pump to keep the chamber operational; TRIUMF staff volunteered to quickly repair the pump and vacuum chamber and continued to liaise with the detachment to maintain the pump and vacuum chamber until they were fully operational.

## Evaluating Performance

TRIUMF has adopted an approach to performance metrics based on output rather than input. TRIUMF focuses on achievements instead of effort expended and measures its knowledge transfer activity with quantifiable economic metrics. In addition to those commonly used by other publicly funded research organizations, TRIUMF strives to use innovative measures of effectiveness. Although these metrics do not have an obvious impact on revenues, they indicate the effective transfer of knowledge resulting from TRIUMF activities.

In addition, TRIUMF has developed an increasingly sophisticated set of metrics to monitor its contribution to commercialization and economic development. Table 1 shows 17 such statistics that are being collected. In evaluating the targets, it is important to remember that TRIUMF is primarily a facility for fundamental research in sub-atomic physics. Unlike commercial enterprises, TRIUMF does not produce "research products" at a constant rate, or with a constant rate of growth. If a target is either under- or over-achieved in one year, it should not be assumed that this has any implication regarding the possibility of under- or over-achieving in the following year.

| Item | Description | | 2001/2002 | 2002/2003 | 2003/2004 | 2004/2005 | 2005/2006 | 2006/2007 | 4 Year Total |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Dollar Value of Sponsored Research for the Year | TARGET | $10,000,000 | *$10,000,000 | *$11,000,000 | *$11,000,000 | $6,000,000 | $6,000,000 | |
| | | ACTUAL | $4,783,305 | $6,078,010 | $5,605,575 | $6,578,992 | $5,601,572 | $5,766,630 | $23,552,769 |
| 2 | Number of Disclosures During the Year | TARGET | 15 | *15 | *16 | *16 | 10 | 10 | |
| | | ACTUAL | 14 | 11 | 12 | 7 | 4 | 6 | 29 |
| 3 | Number of Disclosures Reviewed During the Year | TARGET | 4 | *4 | *5 | *5 | 9 | 9 | |
| | | ACTUAL | 2 | 3 | 9 | 6 | 3 | 6 | 24 |
| 4 | Number of Disclosures Funded During the Year | TARGET | 2 | *2 | *3 | *3 | 5 | 5 | |
| | | ACTUAL | 2 | 2 | 0 | 3 | 3 | 3 | 9 |
| 5 | Value of Funding for Disclosures During the Year | TARGET | $25,000 | *$25,000 | *$30,000 | *$30,000 | $60,000 | $65,000 | |
| | | ACTUAL | $13,000 | $28,000 | $0 | $60,000 | $60,000 | $17,000 | $137,000 |
| 6 | Number of Patents Applied for During the Year | TARGET | 5 | *5 | *6 | *6 | 8 | 9 | |
| | | ACTUAL | 5 | 12 | 8 | 13 | 15 | 35 | 71 |
| 7 | Number of Patents Granted During the Year | TARGET | 2 | *2 | *3 | *3 | 5 | 6 | |
| | | ACTUAL | 2 | 8 | 12 | 3 | 2 | 11 | 28 |
| 8 | Value of Purchase Orders Placed by TRIUMF in Canada During the Year | TARGET | $18,000,000 | *$18,000,000 | *$20,000,000 | *$20,000,000 | $12,000,000 | $12,000,000 | |
| | | ACTUAL | $25,013,874 | $28,304,164 | $14,327,977 | $13,727,400 | $11,450,338 | $14,040,118 | $53,545,833 |
| 9 | Value of Purchase Orders Placed by TRIUMF in Foreign Markets During the Year | ACTUAL | - | - | $7,315,642 | $8,201,214 | - | $6,410,518 | |
| 10 | Number of Start-up Companies During the Year | TARGET | 1 | 2 | 2 | 3 | 2 | 2 | |
| | | ACTUAL | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | Number of Spin-out Companies During the Year | TARGET | 1 | *1 | 2 | *2 | 2 | 1 | |
| | | ACTUAL | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | Number of Licenses Granted During the Year | TARGET | 3 | 4 | 5 | 6 | 3 | 2 | |
| | | ACTUAL | 3 | 1 | 0 | 0 | 1 | 1 | 2 |
| 13 | Cumulative Number of *Active Licenses | TARGET | *9 | *10 | *11 | *12 | 14 | 16 | |
| | | ACTUAL | 5 | 11 | 9 | 9 | 9 | 10 | 37 |
| 14 | Royalty Income for the Year | TARGET | $500,000 | *$500,000 | *$600,000 | *$600,000 | $1,200,000 | $1,250,000 | |
| | | ACTUAL | $427,819 | $694,414 | $1,070,000 | $1,402,995 | $1,307,900 | $833,459 | $4,614,354 |
| 15 | Contract Income for the Year | TARGET | $100,000 | *150,000 | *$150,000 | *$200,000 | $150,000 | $250,000 | |
| | | ACTUAL | $208,000 | $144,106 | $98,000 | $80,000 | $776,832 | $880,707 | $1,835,539 |
| 16 | Value of TRIUMF Sponsored Canadian Conferences during the Year | TARGET | *$1,000,000 | *$1,500,000 | *$1,500,000 | *$1,500,000 | $800,000 | $800,000 | |
| | | ACTUAL | $227,100 | $774,900 | $488,800 | $1,117,600 | $1,689,600 | $1,169,600 | $4,465,600 |
| 17 | Number of Industrial Alliances During the Year | ACTUAL | - | - | - | - | - | 48 | 48 |

**Table 1.** Performance versus targets for the years 2002 to 2007.

### Purchase Order Analysis 2006/2007

TRIUMF's purchasing has a direct impact on the Canadian economy. Figure 1 summarizes TRIUMF's total purchases, excluding expenditures on power and construction funded by the provincial government. TRIUMF's procurement policy gives preference to Canadian vendors, but only if price and quality are comparable. Given the highly specialized nature of certain purchases, foreign supply is sometimes the only viable option.

### Commercial Revenues

During the period 2005 through 2010, it is projected that annual commercial revenue to TRIUMF, in Canadian dollars, will increase from \$1.1 million to \$2.5 million. Based on its success to date, by 2010 TRIUMF is projected to have received total cumulative commercial revenue approaching \$25 million. The yearly breakdown for 2003-2008 is given in Figure 2.

The growth in annual commercial revenue to TRIUMF from 2005 through 2010 suggests that, by fiscal year 2009/2010, TRIUMF is projected to generate over \$2.5 million of total commercial revenue. This represents a 25% return on the approximately \$10 million annual research budget and a 5.7% return on the \$44 million annual investment from the federal government. This level of return places TRIUMF performance in the top grouping for universities and fundamental research institutions in Canada and around the world.

### Accumulation and Protection of TRIUMF's Intellectual Property

Beginning with two patents 15 years ago, TRIUMF now has over 50 patent families and more than 150 patents in process worldwide (see Figure 3). This significant increase in patents has led to a systemized approach in evaluating scientific or technical disclosures with commercial potential. After approval by a review panel, the innovation is processed for protection of the Intellectual Property (IP).

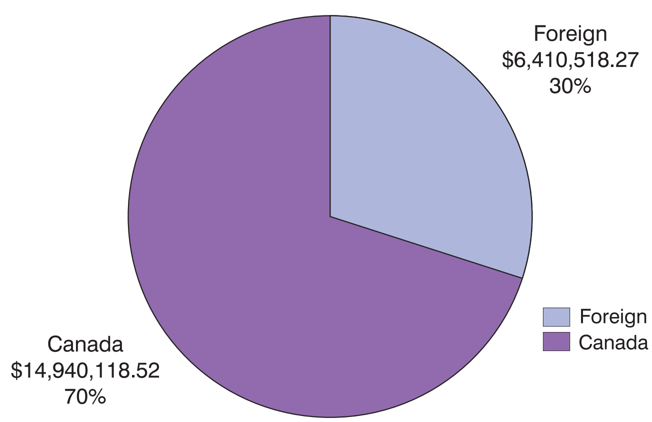



**Figure 1:** Purchasing Order Analysis – 2006/2007, by geographical location of selected vendor.

## Awards and Recognition

Between 2003 and 2008, TRIUMF received several awards for its performance in transferring knowledge to industry and commercializing its technologies. In 2004, TRIUMF and MDS Nordion were awarded the prestigious Natural Sciences and Engineering Research Council of Canada (NSERC) Synergy Award for Innovation. The Synergy Award recognizes outstanding achievements in university-industry collaborations, and is judged on three criteria: partnership, effective use of resources, and tangible benefits. In 2007, TRIUMF again won the NSERC Synergy Award, this time with D-Pace, the Canadian supplier of accelerator components and peripherals.

In February 2008, TRIUMF's application to the Networks of Centres of Excellence for Commercialization and Research Program was successful, and Advanced Applied Physics Solutions, Inc. (AAPS), was awarded a C$14.95 million grant. The AAPS mission is to "improve the quality of life of people around the globe by developing technologies emerging from worldwide subatomic physics research." AAPS will collaborate with academic, government, and industry stakeholders to research and develop promising technologies to a commercially viable stage, including a new underground imaging system to improve productivity in the natural resource sector, and other technologies with a range of applications, including medical-isotope production and pollution mitigation.

# Conclusion

Knowledge transfer extends beyond evaluating the quantifiable economic outputs of TRIUMF. It must include the numerous social and economic benefits that result from the laboratory's research. Measuring and recording the impact of research activities is becoming prevalent around the world, although in

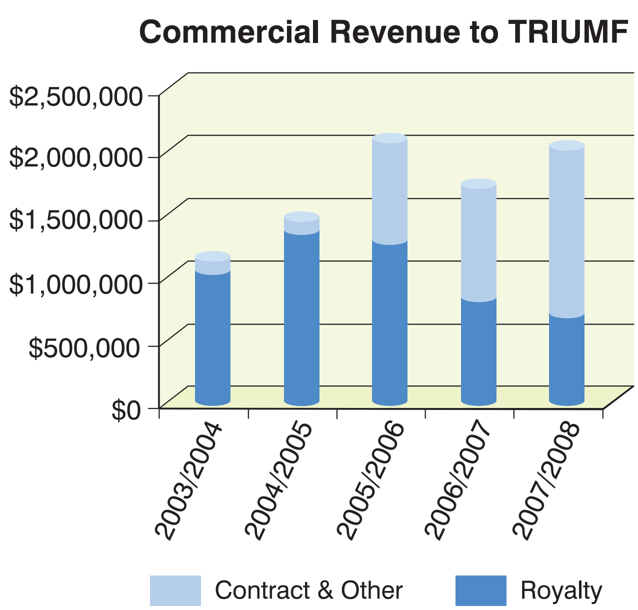



**Figure 2:** History of commercial revenues accumulated by TRIUMF.

many respects, the methods of measurement are still evolving. The TRIUMF approach described here is also evolving and will evolve still further in the years ahead.

Since the inception of the first Business Development Plan in 1996, TRIUMF has demonstrated the significant social and economic impact it has on Canada. The 2010–2015 Five-Year Plan builds on past successes to further expand the scope of TRIUMF's social and economic impact.

TRIUMF has an enviable record within Canada and internationally for its scientific achievements, its commercialization of technology, and the impact of the laboratory on Canadian society and the Canadian economy. The next five years will build on the achievements of the past to prepare for the future.

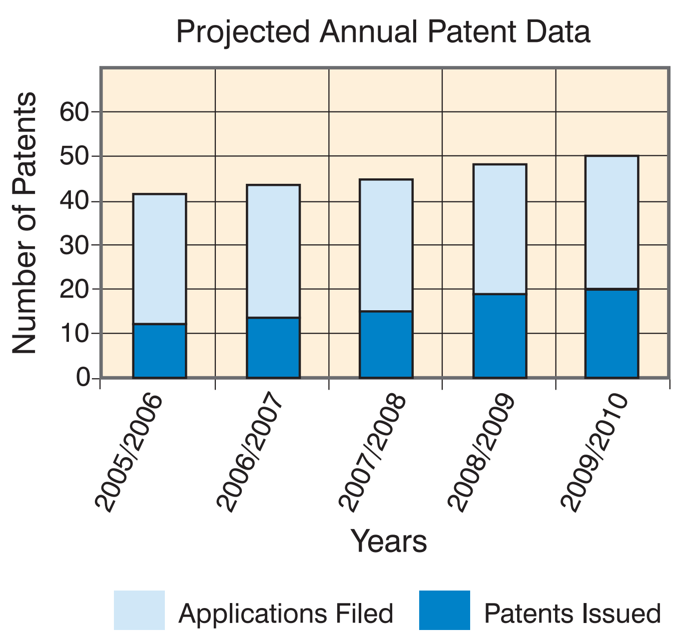



**Figure 3:** Annual number of patent applications filed and issued.