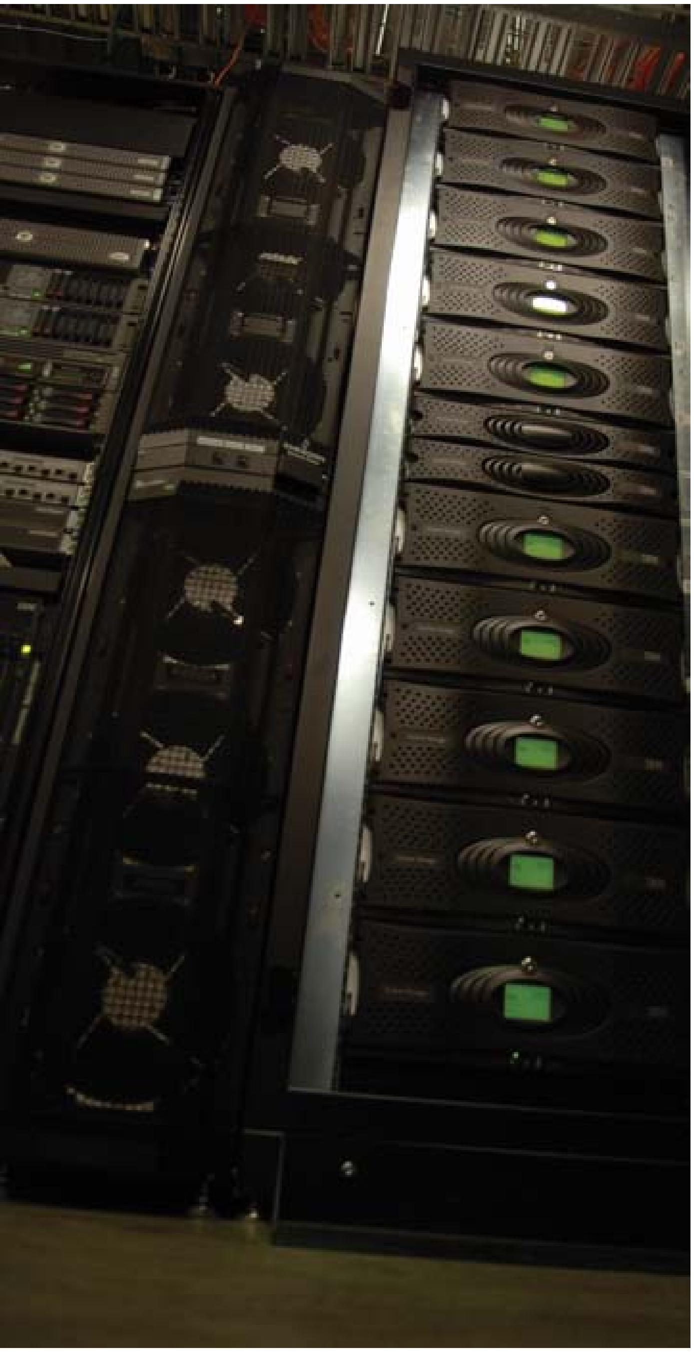
TRIUMF

Annual Financial & Administrative Report

2008-2009

Cover Photo: Dr. Isabel Trigger and a section of the ATLAS Tier-1 Computing Centre.
As part of the world's most advanced network and computing grid, TRIUMF is housing Canada's Tier 1 Computing Centre, one of only ten in the world. For more information on the ATLAS Tier-1 Computing Centre, please see the 2007-2008 Annual Financial and Administrative Report at http://admin.triumf.ca/docs/reports/annual _financial_admin2007/



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Hello, and welcome to the *TRIUMF Annual Financial & Administrative Report* 2008–2009. In these pages you'll find stories highlighting some of our new accomplishments this year as well as our 2008 auditor's report. I can proudly say that 2008 has been a good year for the TRIUMF family: our scientific and technical staff, our university owners, our national and international user communities, our private sector partners, and our graduate and undergraduate co-op students.

TRIUMF Director Nigel Lockyer

The Government of Canada funds TRIUMF on a five-year cycle. Our biggest accomplishment this year was the successful completion of our Five-Year Plan 2010–2015. With the help of hundreds of contributors from TRIUMF and the Canadian university community, we organized and wrote the Plan to be a layered document: the front sections were simple overviews giving the big picture in a page or two, and the more detailed sections later in the book were in-depth chapters imparting more technical knowledge.

Talented people fuel TRIUMF's research, so we also wanted to highlight the people that make us such a success. We did this by providing short biographies of selected individuals and groups who had been recognized by their scientific communities over the past few years: a contribution to the community, an award, or a significant publication. The document, ultimately 840 pages, as well as a shorter, bilingual overview, was published using TRIUMF's new graphics scheme and with a modern design and layout. We are proud of the final product.

With a sub-title of "Building a Vision for the Future," the Plan is meant to be transformational. If fully supported by the Government of Canada, it will take TRIUMF to a new level of scientific performance and impact. It hinges upon two major initiatives: one, to place TRIUMF front and centre on the world stage in the development and study of rare-isotope beams, which is the hot field in nuclear physics, and, two, to provide infrastructure that will allow TRIUMF to lead Canada in the nuclear medicine revolution. Both of these initiatives require significant investment by our university partners, the Provincial Government of BC, the Government of Canada, and our private sector partners.

Nuclear medicine, an important component of the revolution in medicine, has been brought about by molecular imaging, a term used to describe the ability of doctors to study disease at the sub-cellular level. When combined with genomics, molecular imaging is transforming how we treat cancer, and our understanding of neuro-degenerative diseases such as Parkinson's. Nuclear medicine can be described as those medical procedures that take advantage of medical isotopes, either for imaging or therapy. At TRIUMF, we specialize in generating medical isotopes that emit positrons suitable for imaging with PET (positron emission tomography). We also develop the new chemistry, called radiochemistry, needed to connect these isotopes to molecules that travel to specific parts of the body or targeted biochemical pathways in the body. PET is a powerful imaging technique used for determining the stage of a cancer (metastasis). TRIUMF is rapidly expanding its developmental isotope partnerships in PET imaging to include research with the BC Cancer Agency and the Cross Cancer Institute in Alberta as well as with our private sector partner MDS Nordion Inc., a world leader in the supply of medical isotopes.

Vancouver editor Melva McLean was honoured by the Editors' Association of Canada/Association canadienne des réviseurs for her pivotal role in producing TRIUMF's Five-Year Plan, an 840 page report outlining TRIUMF's plans for the future. The job took nine months to complete and involved 50 contributing writers. If you would like to know about TRIUMF's plans, the report can be found at http://www.triumf.ca/home/news-publications/reports.

One foundation for understanding medical isotopes is what nuclear physicists call rare isotope beam (RIB) research. TRIUMF is one of the leading RIB research facilities in the world, and the proposed electron linear accelerator (or e-linac) at TRIUMF will ensure Canada's place as a world leader in this field. This type of basic research has four major goals, which can be characterized by four questions. How and where in the universe are the chemical elements heavier than iron made? Can we formulate a fundamental theory of how to predict the behavior of all nuclei? Can we find new medical isotopes that will have significant health care benefits for both imaging and therapy? Can we understand the properties of exotic materials that have the potential to address energy and environmental issues?

With the existing cyclotron and the proposed new e-linac operating together, TRIUMF will be a unique facility. We will be able to produce and study both neutron-deficient and neutron-rich nuclei, investigate new materials, and advance nuclear medicine. TRIUMF already has several experimental areas that will be able to exploit low-energy rare isotopes useful in ion-trapping experiments and medium- and high-energy experimental areas important for nuclear astrophysics and structure. When combined with the extensive experimental apparatus on the floor at TRIUMF, and the ability to develop new types of beams, TRIUMF will become a destination of choice for the best scientists and students from Canada and around the world.

I invite you to read all the articles in the following pages, to learn a little bit more about TRIUMF, our researchers, and how we bring world-class science to Canada.

Translating TIGRESS

by Greg Hackman

The wave-function composition for the low-lying states in ^{29}Na was explored by measuring their electromagnetic properties using the Coulomb-excitation technique. A beam of ^{29}Na ions, post-accelerated to 70 MeV, bombarded a ^{110}Pd target with a rate of up to 600 particles per second at the recently commissioned ISAC-II facility at TRIUMF. Six segmented HPGe clover detectors of the TIGRESS γ-ray spectrometer were used to detect de-excitation γ-rays in coincidence with scattered or recoiling charged particles in the segmented silicon detector, BAMBINO. The reduced transition matrix element in ^{29}Na was derived to be 0.237(21) eb from the measured γ-ray yields for both projectile and target. This first-time measured value is consistent with the most recent Monte Carlo shell-model calculation, indicating a significant admixture of both sd and pf components in the wave function, and also providing evidence for the narrowing of the neutron sd-pf shell gap from ~ 6 MeV for stable nuclei to ~ 3 MeV for ^{29}Na. (A.M. Hurst et al., Phys. lett. B 674,168 (2009))

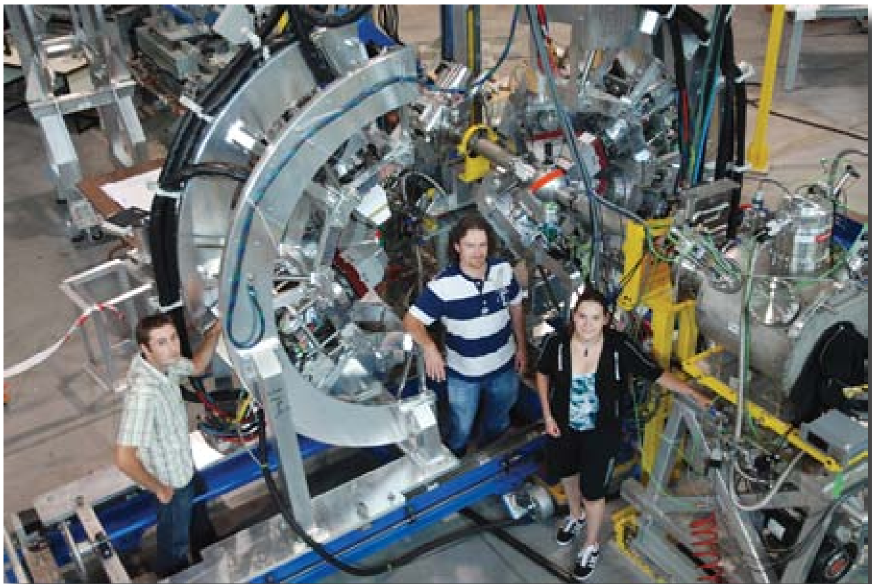


Figure 1: TIGRESS

If you are not a nuclear physicist, the above abstract from a recent article in *Physics Letters B* sounds incomprehensible, doesn't it?

The article was about an experiment with TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer), an experiment that was performed at TRIUMF's ISAC-II in the summer of 2007. In fact, the article detailed the first data taking with TIGRESS. Beyond that, what is the article about? What is Coulomb excitation? What's an *sd–pf* shell gap? What is an admixture of wave functions? And at the end of the day, what does it tell us about Nature that we didn't know before?

"… ^{29}Na …"

The answer to these questions can be explained with a little bit of background about the subject of nuclear structure.

We think we know that the nucleus of an atom contains a whole number of protons (the number is often denoted mathematically as Z) and a whole number of neutrons (N). Each of the chemical elements, and their properties, are associated with a given Z. Protons and neutrons have (very nearly) the same mass, and the total number of nucleons (denoted as A, with A=N+Z) gives the mass number of a single nucleus. Nuclei have been labeled by their element names and masses, mainly because nuclear physics evolved from chemistry. For example, in the abstract above, ^{29}Na refers to nuclei with the elemental properties of sodium (chemical symbol Na, proton number Z=11) and a mass number of A=29. From this we know that there are 11 protons and 18 neutrons in a single ^{29}Na nucleus.

"… wave function composition …"

But what does a nucleus look like? Do the protons and neutrons (together they are called nucleons) stick together to form a bumpy, round ball? The answer to this question is very definitely "no." The nucleus and the nucleons that make it up are small enough that they should be described by quantum mechanics. In particular, the particles that make up the object—the nucleons in the nucleus in this case—are also quantum objects. One important feature of quantum objects, in this case both the nucleus and its component nucleons, is that they can be described either as particles or as waves of matter. Beyond that the question becomes more challenging. Do the waves (particles) act independently of one another, like the orbits of planets around the Sun? Or do the particles (waves) pile up on one another? If they do, does a nucleus end up looking like a drop of wiggling goo or a solid, spinning, pear-shaped lump? The answer to all of the questions is a rather ambiguous "yes and/or no", or the slightly more telling, "depends on the numbers of protons and neutrons."

There are three parts to answering these questions: experimental, empirical, and theoretical. The experimental part is to find, or create, nuclei with a given N and Z and measure their properties, such as energies, spins (a quantum mechanical property analogous to rotation), and parities (does it look the same in a mirror). Empirically, one collects by Greg Hackman

and organizes data from a wide range of N and Z, and establishes trends. Theoretically, the problem is to find an appropriate mathematical abstraction, or a "wave function," to describe what we have seen in experiments and to predict what may happen in future experiments or even in other parts of the universe (such as in explosions of stars). The empirical view reveals that nuclei with 2, 8, 20, and certain higher numbers of either neutrons, protons or both, are extra stable—more tightly bound—than average. These are the lowest five of the "magic" numbers. These magic numbers describe the behaviour of the nuclei of atoms we encounter day-to-day. They do not work on the exotic nuclei that ISAC can produce.

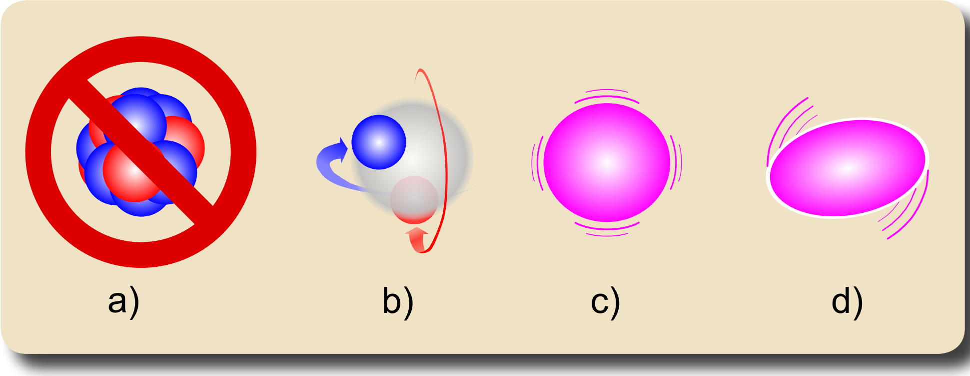


Figure 2: Schematic representations of nuclear behaviour: a) Neutrons and protons stuck together in a static cluster (WRONG!); b) Planet-like orbits around an inert core; c) vibrating or d) rotating blobs of nuclear goo.

"… low-lying states … reduced transition matrix element …"

Because nuclei are quantum systems, they have "states." Each state can be thought of as a step on a staircase. Each step has it its own energy, spin, and parity. The bottom step is the ground state. Higher states are called excited states. Like any other quantum system, nuclei can absorb or release energy in well-defined quantities corresponding to the energy differences between states. When the nucleus absorbs the right amount of energy, it moves to a higher step; when it releases energy, it falls to a lower one. Once it is in the ground state it cannot release any more energy.

One way of releasing energy is by emitting photons; when they come from a nucleus, they are called gamma rays. The energy of the gamma rays directly measures the difference in energies between states. The direction of emission depends on the spins of the states. The average time for the photon to be emitted (the transition rate) depends on a property of the wave functions themselves. The experiment described in the abstract measured this transition rate property of the wave functions of the ground state and first excited state in ^{29}Na.

"… shell model …"

The wave function of states (ground or excited) in ^{29}Na, or in any nucleus for that matter, can be thought of as a combination of wave functions (and states) of the individual nucleons. In this case, the energy level steps are called "shells," evoking the image of a series of spherical layers growing outward from a central core, like the layers of an onion; the idea of fixed amount of energy to move from one level to another holds equally well for shells as for steps. Each shell can hold a maximum number of nucleons; that number is determined by the wave functions. Furthermore, there are two sets of shells, one for the protons and one for the neutrons.

Shells are named following a convention that dates back to pre-Einstein atomic physics. The lowest energy (innermost) shell is called the *s* shell, has wave functions that can hold up to 2 (two) nucleons (either protons or neutrons in their separate shells). The second shell, call *p*, can hold 6, and the third, the *sd* shell, 12. The next shell is the *pf* shell. The abstract refers to *sd* and *pf*: what it is talking about is in fact the wave functions associated with these respective shells.

The ground state of a given nucleus is formed by filling the shells inside out. When a shell is full it is "closed"; any additional nucleons must occupy a higher (farther out) shell of higher energy, so the system is more energetic and less bound. It is worth noting that these shell occupation numbers directly relate to the first three magic numbers; 2 corresponds to filling the *s* shell, 8 fills both *s* and *p*, and 20 fills *s*, *p*, and *sd*, respectively. The first triumph of the shell model was in correctly explaining higher shell numbers, namely 28, 50, 82 and 126.

In the same way that closed electron shells in chemistry give rise to the inert gases helium, neon and argon, closed nucleon shells are also rather inert. They do not contribute significantly to the behaviour of the nucleus. Nuclear structure is dominated by the valence nucleons, that is, nucleons in partially filled shells. When there is a small number of valence nucleons one can think of them as moving around the shell without running into one another a lot. This is the planet-like, single-particle picture, and the nuclear structure is dominated by the simple wave functions of the single particles. As the valence shell approaches half-full, the particles don't maintain simple single particle behaviour. It's as if they start to bump into one another. Eventually they stop even trying to move independently and instead start vibrating or rotating around the core. This is the "wiggling goo" or "spinning lump" picture. An interesting consequence of quantum mechanics is that a small number of missing particles in an almost-closed shell can act almost the same as particles outside of a core. Put simply, if the core is really inert, a single wave function, added to it as a particle, behaves the same as a single wave function subtracted away. The latter are called "holes."

In ^{29}Na, eight of the eleven protons will fill the *s* and *p* shells; the remaining three will be particles in the *sd* shell. The eighteen neutrons leave the *sd* shell two particles short of being full, so the valence neutrons are regarded as two holes in the *sd* shell. Since neither the neutron shell nor the proton shell is closed, these five valence particles are enough to give rise to collective, rotational behaviour. That is, the wave functions of these valence particles will result in collective wave functions for the low-lying states of the whole ^{29}Na nucleus. However, as discussed below, this is not the full story.

At this point, let's clear up the difference between states, nuclear wave functions, and shell model wave functions. Nuclear states are real; we observe them and measure them. Nuclear wave functions are mathematical abstractions that happen to describe those states. The wave function associated with a shell is *not* directly connected to a state. These *s*, *p*, *sd* and *pf* wave functions are *components* of the nuclear wave function. This is true for both excited states and the ground state. This point will become clearer (and more important) in the following discussion.

"… neutron *sd–pf* shell gap …"

The motivation for this particular experiment lies in the exotic nucleus ^{32}Mg. This nucleus has Z=12 protons and N=20 neutrons. The fully closed neutron shell is expected to drive the proton valence particles into single-particle behaviour, as it does in less exotic nuclei like ^{38}Ar (Z=18, N=20). Instead, ^{32}Mg is highly collective. In fact many nuclei with nearly these particle numbers are more collective than the simple shell model predicts. It is as if in these cases, N=20 is no longer "magic." This feature is becoming increasingly apparent in the so-called neutron-rich nuclei that have far more neutrons than protons.

Why does this happen? One explanation involves breaking the neutron core. By taking two particles out of the N=20 *sd* core and moving them up into the (now not so high) *pf* shell, the valency of ^{32}Mg is now two neutron holes, two neutron particles, and four protons: eight valence nucleons in total. Usually breaking a core requires a lot of energy because you have to move particles up to a higher-energy shell. If, however, the neutron-rich nature of ^{32}Mg means that the *pf* and *sd* shells become very close in energy, then it is possible that the collective behaviour can overcome this step. Then the question becomes, what is it about a neutron rich nucleus that allows it to overcome the magic numbers? In fact, unusual shell effects in neutron-rich nuclei is one of the most vigorous topics of study in experimental, empirical, and theoretical nuclear structure.

The experiment described in the abstract aimed to answer part of the ^{32}Mg puzzle. At what particle numbers does the *pf* shell break down and become important in the low-lying structure of nuclei? And, is it sudden or gradual?

"… Coulomb-excitation technique …"

One way to probe the shell structure of a nucleus is to jiggle the nucleons around in their single-particle levels. To do this, you need to put energy into the nucleus. To put energy into a nucleus, you hit it. At facilities like ISAC, nuclei are ionized, accelerated, and then steered as projectiles onto a target of stationary nuclei. Most of the time the electrical repulsion between the projectile and target is strong enough that the two nuclei never touch, that their wave functions never overlap. If the energy is very high and the collision is nearly head-on, the two nuclei can touch and stick together. These "fusion-evaporation" reactions impart the most energy to the final, residual nucleus, and several gamma rays (and possibly particles) are released in the process. If the wave functions just barely overlap, a "transfer reaction" may occur in which several, or possibly only one or two neutrons or protons move from one nucleus to the other. In these experiments, gamma rays are often valuable for identifying whether the projectile, target, or both are excited, and if so, by how much. Even in near misses, where the nuclei almost but don't quite touch, the violence of the repulsion of the target and projectile may still be enough to "shake" one (or both) into an excited state. Because this process occurs solely due to electric repulsion, it is called "Coulomb excitation." Each of these reaction mechanisms accesses states of different energies, spins, and parities, and shows up different components of the wave functions, that is, each shines a different light on the nucleus. What is common about them is that they all require beams accelerated to the energies provided by ISAC-II, and that the gamma rays are measured with the TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS).

by Greg Hackman

"The reduced transition matrix element in ^{29}Na was derived to be 0.237(21) eb …"

TIGRESS and an auxiliary set of detectors, BAMBINO, have been described in previous annual financial reports. The measurement was successful; the matrix element was measured, and it was measured well enough to learn something about the structure of this nucleus. The first important fact to come out of the experiment was that the matrix element was too large to be explained with only *sd* shell-model wave functions. Something else—like a *pf* admixture into the nuclear wave function—was giving ^{29}Na a larger matrix element.

"… the most recent Monte Carlo shell-model calculation …"

One way of verifying this picture is to calculate some wave functions. The individual equations are straightforward but solving them requires trillions of mathematical operations, many of them equally important, but most of them offsetting one another. Nuclear physicists have developed many methods of simplifying these calculations to make them go faster. The Monte Carlo technique "rolls the dice" and randomly selects which operations to perform; although the method is random, the dice are loaded to favour the important parts. If the calculated wave functions correctly calculate measured experimental properties, such as transition rates, then it is inferred that they will correctly describe other features of the nucleus, such as the wave functions themselves.

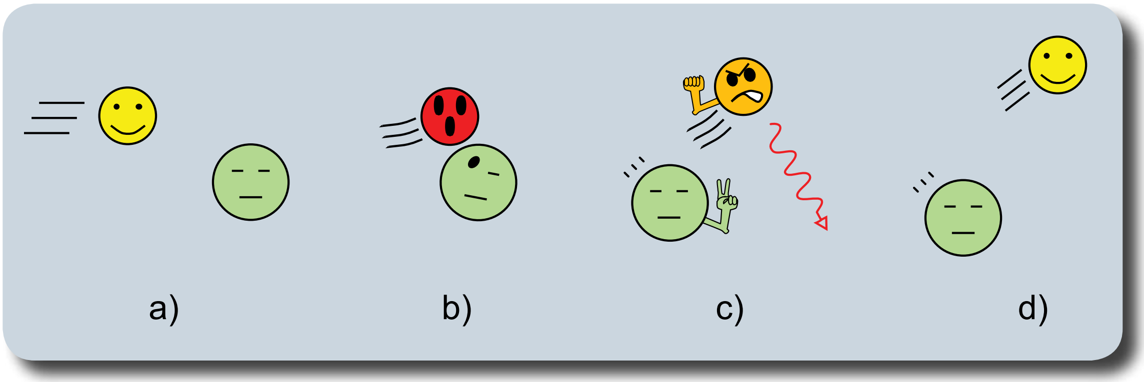


Figure 3: Schematic representations of possible Coulomb excitation: a) accelerated incoming beam nucleus (yellow) and target nucleus rest (green); b) light charges repel, but near collision excites incoming beam nucleus (red); c) excited beam nucleus emits gamma ray; d) beam and target nuclei continue to move away from near-collision site.

"… both *sd* and *pf* components in the wave function …"

The calculations that best match the experimental data are the ones that include *pf* shell-model wave function components in the wave functions for the ^{29}Na states. This says that the increased collectivity of the ^{29}Na states is driven by the *pf* shell, just like in ^{32}Mg. In other words, the nuclear wave function for ^{29}Na includes not just the five shell components suggested early, but that there is also a small but important 9-valence component that makes it even more collective. What does this say about the shells themselves?

"… narrowing of the neutron sd-pf shell gap from ~ 6 MeV for stable nuclei to ~ 3 MeV for ^{29}Na …"

This experiment offers one important point: at ^{29}Na, the shell gap has decreased, but it has not gone completely to zero. With this data, we can partly fill in a picture of Nature; the shell gap that seems to disappear completely in ^{32}Mg has decreased by one-half in ^{29}Na.

As such, this first TIGRESS experiment can be declared a success: our goal was to learn something new about neutron-rich shell structure, and we did. It was part of a program proposed by the experiment leaders to map out the wave function admixtures and shell model gaps leading to ^{32}Mg. Future experiments approved by the TRIUMF Experiment Evaluation Committee would look at ^{31}Mg, ^{28}Na, and heavy neon isotopes. It should be noted that the study of the neutron-rich shell gaps is not confined to TIGRESS. A previous experiment with the 8π (see *"The 8π Gamma Ray Spectrometer: A Versatile Tool for Radioactive Decay Studies at ISAC"* in the *TRIUMF Annual Financial & Administrative Report* 2003-2004) studied excited states in ^{32}Mg itself from the beta decay of ^{32}Na; that experiment resolved a long-standing controversy about spins and parities of certain states, putting the "rotating blob" picture on firmer ground.

The long-term goal is to move beyond ^{32}Mg and find the wave functions and shell model structures at the limits of nuclear existence, that is, at the largest possible neutron numbers. These experiments will take advantage of the continuous and vigorous target and ion-source developments at ISAC (see *"TRILIS: A Unique Ion Source for Radioactive Ion Beam Production"* in the *TRIUMF Annual Financial & Administrative Report* 2005–2006), and upgraded or new detectors at the end of the beam line (see *"ISAC-II Science with MAYA & EMMA"* in the 2007–2008 Report).

Greg Hackman is a TRIUMF Research Scientist, focusing on gamma ray spectroscopy.

How to Make a Rare-Isotope Beam

by Marik Dombsky, Friedhelm Ames, Pierre Bricault, Jens Lassen

TRIUMF's Isotope Separation and Accelerator (ISAC) facility is one of the premier rare-isotope facilities in the world. ISAC produces beams of rare isotopes—short-lived atomic nuclei not normally found in Nature and whose properties can only be inferred with theoretical calculations. Beams of rare isotopes are, however, a challenge to produce. They cannot be made using techniques such as off-line chemical separations because their short half-lives mean that they decay away during the time it takes to extract them.

Dr. Marik Dombsky with the Plenary Ball Mill used for grinding ceramic materials for target construction.

On-Line Isotope Separation

Since the discovery of artificially produced radioactivity in nuclear reactions there has been an interest in producing rare-isotope beams for the characterization of the nuclear chart beyond the domain of stable elements. Over the years, this field has become mature enough to envisage the construction of facilities dedicated solely to the production of rare-isotope beams. The production and study of new isotopes in the lab provides a wide variety of information, from the investigation of the origins of matter to the development of isotopes for medical treatments and applications. But how do we actually make a rare-isotope beam?

There are two main methods used for the production of rare-isotope beams: the in-flight projectile fragmentation and the isotopic separation on-line (ISOL). In the in-flight method, the rare-isotope beams are produced by projectile fragmentation; a heavy ion beam—high Z—impinges on a thin low Z target. The fragments are produced in peripheral collisions and have a momentum very close to that of the initial projectile beam. The wide variety of rare-isotope beams that are produced by this method is analyzed using an electromagnetic separator to form a beam that is more or less pure.

In the ISOL method, the rare-isotope beams are produced during the interaction of a light particle (mainly proton) with a thick high Z target material. The rare isotopes produced are stopped in the bulk of the target material. The target container is closely attached to an ion source that produces an ion beam followed by a mass analysis to select one specific nuclear beam. The main advantage of the ISOL method over the in-flight production is that the rare-isotope beams are produced using ion sources that are similar to those used for stable ion beam production. In short, the beam characteristics are the same, so high quality beams, which are beneficial to all experiments, are possible.

We can summarize the steps of producing a rare-isotope beam (RIB) using the ISOL method as follows:

1. A high-energy driver, such as TRIUMF's 500 MeV cyclotron, accelerates protons, which impinge on an ISOL target material in an enclosed container, which is directly connected to an ion source.
2. The isotopes are produced in nuclear reactions and come to rest embedded in the target material.
3. The isotopes must diffuse, through the target lattice (move between the atoms of the target material) to the surface of the target foils.
4. Once the atoms have reached the target material surface they have to desorb from the surface; any chemical affinity will slow down this process tremendously.

5. The atoms must effuse, bounce around as an atomic gas, out of the target container into the ion source.
6. The isotopes must be ionized and extracted as a charged beam.

In a perfect world, all the steps would be optimized to produce a strong, high-yield beam of the desired isotope without unwanted isotopes to contaminate the beam, but the world of rare-isotope production is never perfect. When the 500 MeV cyclotron-accelerated protons hit the target, the target nuclei are fragmented to produce isotopes. To some extent all nuclei lighter than the target nuclei are produced, and the isotope wanted for the experiment is the "product" while all others are "contaminants." It is possible to choose target materials that will favour the production of the desired product so the contaminants are minimized before the beam is sent to the ion source. Within the conventional ISOL target process, there are three target production reactions of spallation, fragmentation, and fission. At ISAC, all three of these reactions can simultaneously take place, and each one can present challenging problems, which call for challenging solutions.

Spallation

Spallation is the break-up, or fragmentation, of the target, in which the product distribution peaks a few mass units lighter than the target nucleus. Because neutron emission is energetically easier to produce than proton emission, production is skewed to neutron-deficient nuclei lighter than the target. An example of this production mechanism is the use of a niobium metal target material to produce very light rubidium isotopes such as rubidium-74 (^{74}Rb).

Dr. Pierre Bricault with the ECR ion source used to ionize gases for ISAC experiments.

Target Fragmentation

Fragmentation is essentially the obverse side of a spallation reaction in that the product is one of the light fragments. The fragmentation method is advantageous when producing light, neutron-rich products from heavy target nuclei with higher neutron-to-proton ratios. Because of the higher number of neutrons in the heavy target nucleus, the fragments tend to retain a statistical "memory" of the neutron-to-proton ratio and, as a result, have higher neutron-to-proton ratios themselves. An example of such a reaction is the production of lithium-11 (^{11}Li) from tantalum metal targets.

Fission

Proton-induced fission occurs when the incoming proton deposits sufficient energy in the target nucleus to induce a break-up into two products with roughly equivalent mass. Unlike neutron-induced fission, this reaction method is open to both fissile target nuclei, such as uranium and thorium, and to heavy nuclei such as tantalum, tungsten, lead, and bismuth. Again, because of the higher neutron-to-proton ratio of heavy nuclei, neutron-rich products in the medium mass region can be effectively produced by this reaction mechanism.

Diffusion and Effusion

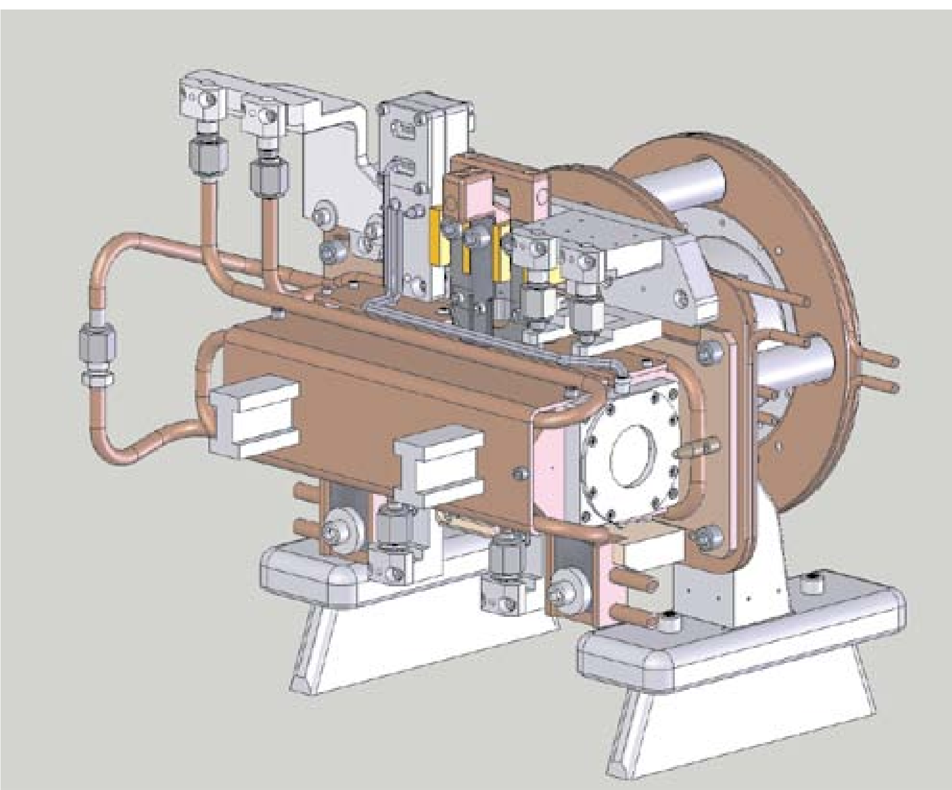
When the isotope is produced by one or more of the three production reactions above, it must both diffuse and effuse out of the target as quickly as possible to reduce the isotope decay losses. Diffusion speed is determined by the interaction of the specific diffusing isotopes moving through the target lattice: the higher the temperature, the faster the diffusion. In effusion, the product atoms are in a gaseous state and randomly bounce around the target container and target material until they enter the ion source. During each collision with a surface, they stick for a time before continuing in a random direction. As with diffusion, a high temperature is required to put the product into a gaseous state and decrease the "sticking" time so the product moves as quickly as possible to the ion source. ISAC target containers are fabricated from tantalum (Ta) and can be operated at temperatures of 2200°C, a temperature suitable for both processes.

Ionization

Ionization is required to convert the product isotope into a charged particle beam, which can then be manipulated and rapidly transported to the experiment. Charged particles can be accelerated, decelerated, focused and steered by means of electrostatic and magnetic fields in order to transport them effectively. Ionization is also key to the "isotope separation" component of ISOL because products that make up the beam are separated by passing the ions through a large dipole magnet. The trajectories of the ions vary depending on their mass-to-charge ratio resulting in a separation analogous to mixed light frequencies passing through an optical prism. Unfortunately, the mass difference for the heavier species is not great enough to ensure complete separation among different elements with the same mass and charge. The result is that beams of a particular mass number are not separated and can be present in a mixed-ion beam after mass separation; however, beam purity can be enhanced by both selective ionization, using ion sources that favour a particular species, and target chemistry, which chooses a target material that will release a particular element but not others.

TRIUMF's Ion Sources

ISAC uses three types of ion sources. The surface ionization source is TRIUMF's simplest source, relying only on a hot surface. Some metals and compounds have a high "work function," the energy depth of the "hole" an electron can drop into when it comes in contact with the metal. Consider a neutral atom of an element making contact with a metallic surface having a high work function. If the "energy hole" (work function) is greater than the ionization potential (energy required to remove an electron) of that specific atom, the electron can be transferred to the surface resulting in an ion. At ISAC, a rhenium (Re) surface is used because Re has a high work function but is malleable and can be heated to 2200°C. The high temperature is required for effusion (as discussed above) to keep the surface clean and because there is a temperature term in the equation for ionization efficiency. Elements that are easily ionized by surface ionization are those with low ionization potentials. These include the alkalis, some alkali earths, the Group 13 elements that include boron, aluminium and gallium, and the lanthanides. A big advantage of surface ionization is that alkali beams can be generated with high efficiency and, at the same time, suppress contaminant beams.



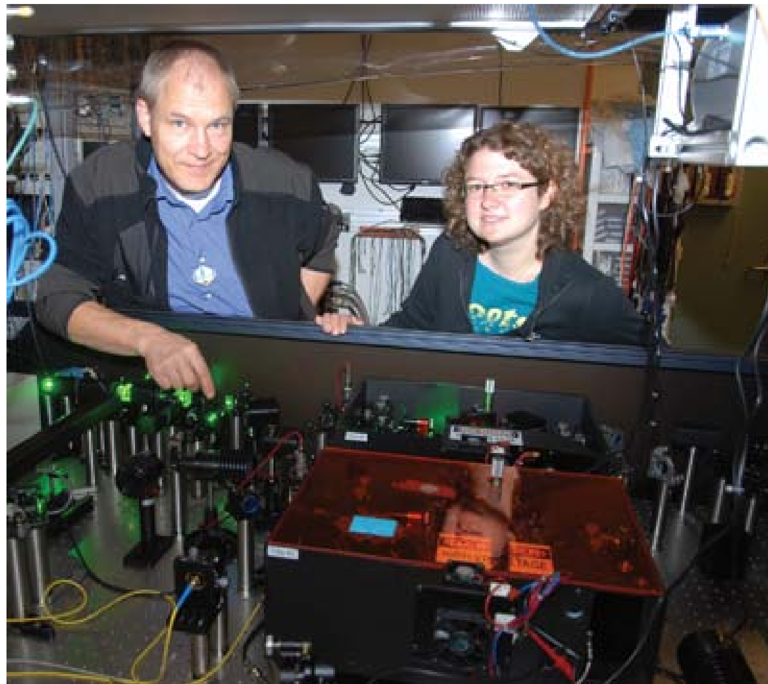
The FEBIAD ion source is a plasma on-line ion source designed and built at TRIUMF.

Plasma (FEBIAD) Ionization Source

Compared to surface ionization, plasma sources are less selective and more complex. They use the principle that atoms (or molecules) effuse from the target into a small, contained volume called the plasma chamber where they are ionized by a beam of electrons. If the electron beam energy is higher than the atom's ionization potential, an atomic electron can be knocked off the atom, resulting in an ion. The electron beam is generated from a hot metal surface, the cathode, and accelerated by an adjacent positively charged anode. The electron energy depends on the potential difference between the cathode and anode. The electron beam is focused using a solenoid magnetic field generated by a coil surrounding the plasma chamber, which has a volume of about 1 cm^3

by Marik Dombsky, Friedhelm Ames, Pierre Bricault, Jens Lassen

and is closely coupled to the target. Plasma sources are not selective. Essentially any element entering the plasma chamber can be ionized by sufficiently energetic electrons, however, some selectivity is possible by varying the electron energy by varying the voltage difference between cathode and anode to account for differences in ionization potentials of desired products and possible contaminants. By adding a cold transfer line between the target and the plasma chamber, we can remove the less volatile contaminants coming from the thick target.



Dr. Jens Lassen and graduate student Andrea Teigelhofer with the on-line laser ion source.

TRIUMF Resonant Laser Ionization Ion Source

The TRIUMF Resonant Laser Ionization Ion Source (TRILIS) has the highest product selectivity but requires the operation of several high power pulsed laser systems and laser beam transport into the isotope production target. Several laser beams of different frequencies are focused into the transport tube from the target to excite an electron from the desired element from one energy level to another. Ultimately, a state is reached where an atomic electron is no longer bound to the atom, resulting in ionization. Because each element has a different electronic structure, with different excited states, matching the frequencies to the energy differences between the states is a highly selective means of ionizing with elemental selectively – a unique feature of resonant laser ionization. Coupled with the mass-charge isotopic separation, a beam of a single mass of only one element is possible. The complexity arises from the requirement of exactly matching several frequencies of laser light and focusing the laser beams, both spatially and temporally, into the transfer tube. At ISAC, the laser path is about 20 m, and the transport tube diameter is about 3 mm, requiring sensitive and stable adjustment. While laser ionization is very selective, beam contamination can still result from abundantly produced species that surface ionize in the hot transfer tube. Intensive development work towards removing these unwanted contaminants is in progress.

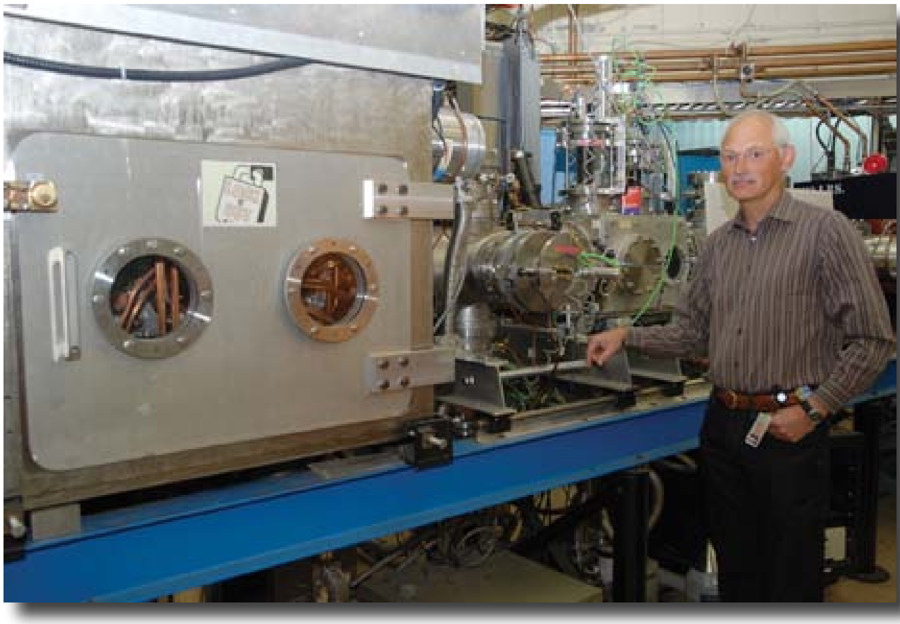
Combining Ion Source Selection & Target Material Selection for Beam Enhancement

TRIUMF enhances the intensity of its desired ion beams by choosing appropriate combinations of ion source and target material. One example is TRIUMF's campaign to produce a gallium-62 (^{62}Ga) beam at ISAC.

Both Rb and Ga can be surface ionized, and one of the first ISAC beam production campaigns was for a beam of ^{74}Rb, which has a half-life of about 65 milli-seconds (ms). This beam was successfully produced from a niobium (Nb) foil target material, using a spallation reaction and a surface ionization source, which is 98% efficient for Rb, giving a yield of 13,000 ions per second. Gallium production from the same target was investigated, and, although the gallium surface ionization efficiency is only 0.5%, the ^{63}Ga, with a half-life of 32 s, yielded 13,000 ions per second; however, no ^{62}Ga, which has a half-life of about 116 ms, was observed. The surface ionization efficiencies cannot account for the lack of ^{62}Ga, but the diffusion and effusion effects can.

Rb does not form compounds with either the Nb target material or the Ta target container, and the ability of Rb to stick to both metals is poor, resulting in relatively fast diffusion and effusion times. Ga does form discrete compounds with both metals; gallide phases such as Nb_5Ga_3 and Ta_5Ga_3 are known. Additionally, Ga adsorption on both metals is stronger than Rb adsorption. The result is that the 116 ms ^{62}Ga diffuses slower and sticks to surfaces longer than the 65 ms ^{74}Rb, and decays away before it can be ionized. The solution to a ^{62}Ga beam was to change the target material and the ion source. For the target material, the compound ZrC was chosen. Although Ga also reacts with Zr metal to form gallides, the carbon to zirconium bond is stronger than the gallium to zirconium bond and gallium reaction with ZrC is not thermodynamically favoured. Additionally, we coated the target container with a layer of TaC, suppressing gallium reaction with tantalum in an analogous manner. This resulted in a measured ^{62}Ga production of 850 per second using a surface source. We then developed a RILIS ionization scheme for gallium, increasing the ionization efficiency from the surface ionization value of 0.5% to a TRILIS ionization value of 6% for a ^{62}Ga production rate of 9,600 per second.

Producing a rare isotope beam has its difficulties, but using the right target materials along with the appropriate ion source can increase the efficiency of the products produced for the experimenters. Once the beam is produced, it must be delivered to the experiment, and that provides TRIUMF's scientists, engineers and technicians a whole new set of challenges. For a discussion on the problems and successes of beam delivery at TRIUMF, see the article "Beam Delivery at TRIUMF's ISAC Facility" in this report.



Dr. Friedhelm Ames with the TRIUMF target test stand.

Marik Dombsky is a Research Scientist, focusing on unique targets and target materials.
Friedhelm Ames is a TRIUMF Research Scientist, focusing on ion sources.
Pierre Bricault is a TRIUMF Research Scientist, focusing on targets and ion sources.
Jens Lassen is a TRIUMF Research Scientist, focusing on laser ion sources and applications.

by Erich Vogt

TRIUMF is only as good as its people. The scientists, engineers and technical staff who choose to make their career with TRIUMF are integral to its success. We honour here two of the key persons who have led TRIUMF since its beginning and are now stepping down from their management positions to devote themselves to their first passion: physics. Ewart Blackmore has been continuously involved with TRIUMF since its inception. Jean-Michel Poutissou joined a decade later when the science program of TRIUMF began. Both have devoted their entire career to TRIUMF and have made outstanding contributions.

TRIUMF began just as the Standard Model (SM) of Nature's basic building blocks and fundamental forces (see Box) was emerging. The SM was all-encompassing and provided many new challenges for experimental physics. To meet these challenges a world network of large new accelerators was built. TRIUMF's long prosperity has, in large measure, resulted from the way it was able to change its experimental program—especially with its muon beams—to meet the SM challenges and to become a Canadian springboard for work at the new accelerators abroad. Both Poutissou and Blackmore have, in their physics, been leaders in the experiments and the design of beamlines and detectors for the work on the SM at TRIUMF and abroad.

The Standard Model

The Standard Model pertains to the basic building blocks of Nature and a unification of its four fundamental forces. The forces are gravity (which has eluded unification), electromagnetism and two forces which play a role only for subatomic particles: the Weak Interaction (WI) responsible for radioactive decay and the Strong Interaction (SI) which binds the building blocks into composites. Using Maxwell's electromagnetism as a template—with its beautiful inherent symmetry—a unification of the WI with electromagnetism was accomplished into a single force called the Electroweak Interaction (EI). This unification brought with it the prediction that the quantum of light—the photon—would be joined, in Nature, by three very heavy quanta—the Z^0, W^+ and the W^-—which cause radioactive decay. The epoch-making discovery of these new quanta at CERN in 1983, in a team led by Carlo Rubbia but with TRIUMF's fifth director, Alan Astbury as co-leader, confirmed the SM and achieved the Nobel Prize immediately. In the same year an experiment at TRIUMF established one of the most important properties of the WI: its "handedness" according to which the W's or Z's always spin around their direction of propagation, taken along the thumb, like the fingers of the left-hand. In the SM the basic building blocks are of two kinds: three families of quarks, which participate in both the WI and the SI, and, similarly three families of leptons which engage in the WI but not the SI. Each family has two members and each building block has an "antiparticle" with many of the opposite properties. For the leptons the families are headed by the familiar electron, the muon and the taon, and are completed in each case by a neutrino. The SM has many built-in symmetries and rules. For example, it says that the neutrinos are all massless and that in any reaction the number of members from a family does not change: there is no "family number violation (FNV)". According to this rule a muon must normally decay into an electron accompanied by a muon's neutrino and an electron's antineutrino so that there is no FNV. It is the spirit of physics that once a model has emerged one seeks to go beyond it: to find things that violate it. For two decades the SM withstood all attempts to violate it until deep underground experiments in Japan and in Sudbury, Ontario, discovered that neutrinos do carry a small amount of mass. According to quantum mechanics, this allows the neutrinos to oscillate: an electron's neutrino can change into a muon's neutrino and vice-versa. The quarks of the SM are bound by the SI to produce neutrons and protons, and in turn, atomic nuclei, and, in turn, atoms when nuclei are combined with electrons, and, in turn, molecules and, in turn, everything around us. The symmetry rules also allow the quarks to mix with each other slightly–which was the subject of part of the 2008 Nobel Prize in Physics.

Jean-Michel Poutissou

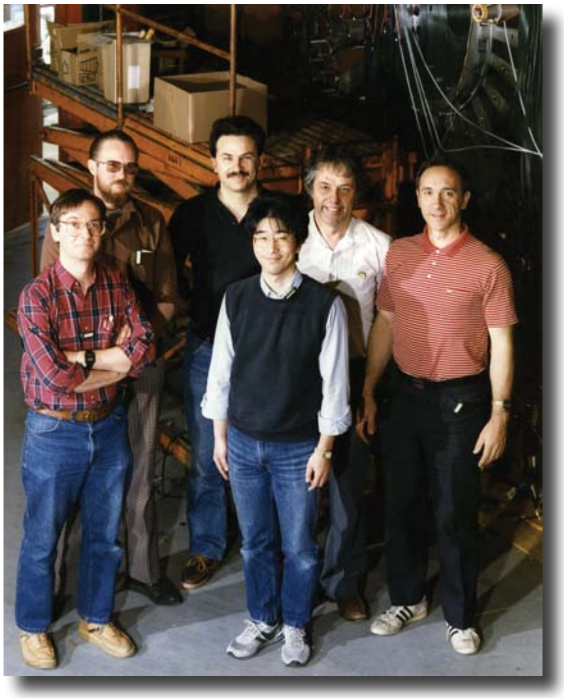
Jean-Michel Poutissou completed his early education in France but came to Canada to fulfill his military obligations to his mother country by becoming a physics graduate student of L'Université de Montréal. He obtained his Ph.D. in 1972 and was retained in Canada by marrying a Canadian physics student,

by Erich Vogt

Renée Poutissou, who has also had her whole scientific career at TRIUMF. He came to UBC in the fall of 1972 attached to the Montéal group of Professor Pierre Depommier which was initiating some of the earliest work in TRIUMF's meson hall for rare muon decays. He participated in the construction of the main beam line in that hall and the M9 muon beam line and also participated in the pion capture program of UBC's David Measday. He joined TRIUMF in 1978 and ten years later was appointed as Associate Director and also as Division Head for Science. Jean-Michel has carried a heavy administrative load through much of this career at TRIUMF, but his passion for physics has kept him involved at the cutting edge of the science, probing the symmetries and rules of the Standard Model (SM, see Box) and, in each experiment in which he participated, he has been central to both the physics and the associated technology.

The intense search for breaks in the SM began, in 1974, with Poutissou's participation in the Montréal group's search for the decay of a muon into an electron and two photons. No such rare decay was found. Shortly after, our competitors in Switzerland announced discovery of events in which a muon decayed into an electron and a photon, thus violating FNV and the SM (see Box). This was a shock and so Poutissou, in 1977, quickly reconfigured the Montréal experiment and established that no such rare decay occurred, at least not within one in ten million decays. Continuing with FNV searches at TRIUMF, Jean-Michel joined the experiment of Doug Bryman and Cliff Hargrove to establish an incredible lower limit (less than one decay in ten billion) for muon conversion which involves the capture of a muon by an atomic nucleus. This experiment was a tour-de-force, involving the first use anywhere of a new particle detector called the "Time-Projection Chamber" (TPC). The TPC was invented in California but TRIUMF's small TPC was a forerunner of the many large TPC's built for the world's large particle physics laboratories.

From 1983-2000 Jean-Michel joined the challenging experiment for rare kaon decays at Brookhaven National Laboratories (BNL) for which TRIUMF's Douglas Bryman was a leader. He supervised the installation of the photon-veto counters for the end caps of the large detector. Several events were found for a kaon decaying into a pion and a neutrino-antineutrino pair—the rarest events ever found in particle physics at that time (one event in ten billion decays). The result contributed greatly to our understanding of quark mixing and to time-reversal-noninvariance. Apparently Nature wants the physics to change when, in the equations, we change the direction in which time flows.



TRIUMF team installing the magnet at Brookhaven, experiment 787 in 1986. John McDonald, Herb Coombs, Larry Felawka, Yoshita Kuno, Peter Kitching and Jean-Michel Poutissou

The TWIST experiment at TRIUMF (1989-2009) involved a large collaboration drawn from Canada, Russia and the United States searching for the "handedness" (see Box) of the Weak Interaction. As a participant in this successful experiment–improving the earlier TRIUMF result by several orders of magnitude—Jean-Michel developed the trigger mechanism for the detector and the degrader to stop muons in thins foils. He was head of the TWIST management committee. He was also part of the collaboration which measured radiative muon capture in hydrogen. This TRIUMF experiment probed special parts of the WI between leptons and protons

Poutissou's most recent passion has been a neutrino-oscillation experiment (see Box) at the newly commissioned J-PARC laboratory in Japan. To prepare for this experiment he formed (1993-1995) a neutrino working group to develop a proposal to search for neutrino oscillations at BNL. In the summer of 1993, the TRIUMF group, with the help of a summer student from the University of Victoria, Jared Anderson, discovered the special properties of neutrino beams taken off axis from the production line. In the end, the BNL experiment was not funded in the United States, but the so-called superbeams developed for it are now coming into use at J-PARC and also at Fermilab in Chicago. Fifty Canadians are playing a large role in the new neutrino oscillation experiment (T2K) in Japan.

When Poutissou was appointed as the Associate Director and the Head of Science Division in 1988 he became the catalyst around which much of TRIUMF's science has been accomplished during the last two decades. Six years later he integrated the TRIUMF applied science group into the science division and made it into a very active research group with its own Life Sciences Project Evaluation Committee (LSPEC). This was one of the circumstances which

by Erich Vogt

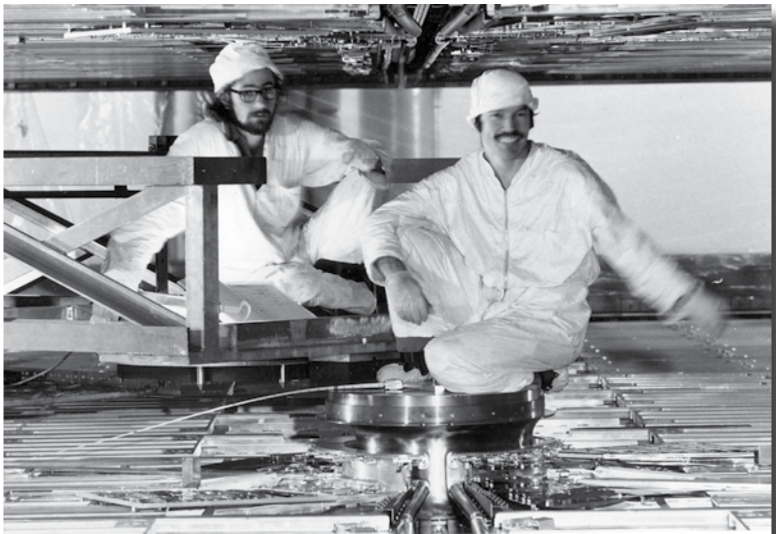
has helped Positron Emission Tomography (PET) research at UBC retain its very strong position During the last twenty years he has personally been involved in many experiments. He is now stepping down from his heavy administrative load to pursue his passion for neutrino experiments. However, he is now helping to set up the newly created TRIUMF Nuclear Medicine Division until a permanent head can be identified. His legacy at TRIUMF is recognized worldwide. In 2006, France recognized Jean-Michel's extraordinary contributions to the development of scientific collaborations by awarding him the rank of Chevalier of the French Légion d'Honneur. TRIUMF has no such honour to bestow, but we have awarded Jean-Michel our deep admiration, respect and our grateful thanks. His deep understanding of the physics, of the people who have a passion for science and for TRIUMF, combined with his patience, sense of humor and a sharp, Jesuit-trained, analytical mind ensured that his decisions rarely went wrong. In short, no single person has had more influence on TRIUMF's experiments at home and abroad than Jean-Michel Poutissou.

The French Ambassador to Canada, Daniel Jouanneau, congratulating Jean-Michel Poutissou after presenting him with the Chevalier de la légion d' honeur.

Ewart Blackmore

Ewart Blackmore came from Northern Ontario/Quebec with a passion for physics, engineering and hockey—all of which he has excelled at throughout his life—and received his undergraduate degree in engineering physics at Queen's University in Kingston in 1963. He then traveled west to UBC and obtained his Ph. D. in nuclear physics on the aging Van de Graaff accelerator while studying with John Warren, a founder of TRIUMF and its first Director. It was here that Ewart learned that accelerators had to work reliably to do physics. After UBC he was awarded a NATO Science Fellowship at the Rutherford Laboratory and spent two years there working in particle physics and detectors. Already in England, in 1968, he was part of the Canadian team which used the Harwell linac to make the first proper measurement of the electric dissociation of negative hydrogen ions in magnetic fields—a measurement which was crucial for determining the loss of beam in the magnetic field of the TRIUMF cyclotron and which therefore determined the size and cost of the cyclotron.

Ewart joined TRIUMF in 1969 and he has been a staff member ever since. He has been a singular master of everything at TRIUMF: the physics, the cyclotron, the beam lines, all of the experimental apparatus, etc. The biggest problem about Ewart for TRIUMF was choosing the best roles in which his universal excellence could be employed. As soon as TRIUMF was funded, it was appreciated that the central region of the large 500 MeV cyclotron—in which the beam is injected into the accelerator and begins its first small, diffident circles—posed the most difficult technical challenges. Ewart was put in charge of building a full-scale model of the central region. In two years his team built the world's largest, most complex 3 MeV cyclotron and its successful operation proved the viability of the injection of the externally-generated negative hydrogen ions, of the inflector and of the rf structures which accelerated the beam through its first turns.



November 1974 Marty Smyth and Ewart Blackmore working in the central region of the 500 MeV cyclotron.

Ewart then moved on to take responsibility for the beam diagnostic probes for the main cyclotron. Professor J. R. Richardson, the second director of TRIUMF—during the challenging period of cyclotron building and commissioning—appointed him as Assistant Director for initial operations (1975-1981) responsible for the operation and maintenance of the cyclotron systems and for beam scheduling, Subsequently he served as head of the Experimental Facilities Division, coordinating the development of pion and muon channels in the Meson Hall, the pion and proton spectrometers and the beginnings of the TISOL facility which was a forerunner of the current new program, ISAC, with radioactive beams.

Like Poutissou, Blackmore played an important role in the rare kaon decay experiment at BNL for which Douglas Bryman of TRIUMF was a leader. The importance of this successful experiment for the Standard Model is given in the Box and in the discussion, above, of Poutissou's physics career. Ewart designed the central tracking detectors for the experiment and then worked with the Canadian/US team that successfully designed and built a new beam line and target that delivered 1.5 million kaons for every pulse of the BNL accelerator—a tenfold increase in the number of kaons delivered to the experiment—without which the measurement of the very rare decay would not have been possible.

During the years 1986-1990 TRIUMF was funded by Ottawa to carry out a major design study for the KAON Factory which was proposed as an addition to TRIUMF. The study was headed by Alan Astbury and Ewart was his deputy, responsible, first, for the experimental areas and then coordinating the technical aspects of the design of the system of accelerators. A very compelling design for KAON emerged but, unfortunately, its funding was eventually turned down by Ottawa soon after the US decided not to proceed with its Supercollider in Texas. The concept of KAON was taken up and expanded by Japan. The Japanese facility, J-PARC, is presently being commissioned and will have its formal opening in July, 2009.

As TRIUMF became a springboard for the work of Canadians abroad at the world network of large accelerator facilities, Ewart has been responsible for coordinating many of the contributions which TRIUMF has made to these facilities. Such contributions have put TRIUMF on the international stage and helped ensure that Canadian scientists are welcome to participate in experiments at the large accelerator facilities anywhere in the world. In 1984 Canada pledged to make the first international contribution to the new HERA facility at the DESY laboratory in Hamburg, Germany. HERA involved the study of the collision of very high-energy proton and electron beams, probing challenges raised by the Standard Model. During the past two decades of its excellent science many Canadian physicists participated in the experiments of HERA. The TRIUMF contribution to HERA was a 50 MeV negative-hydrogen-ion transport line. It was designed by Ewart and his colleagues at TRIUMF, constructed using Canadian industry and commissioned in Hamburg in 1987. This was the first TRIUMF contribution to an international laboratory and won accolades for Canada and TRIUMF, but it was not the last.

In 1996 the Government of Canada awarded TRIUMF funding for a contribution to the Large Hadron Collider (LHC) at CERN, Switzerland, which is currently achieving its first beams. From 1996-2006 Ewart coordinated the design effort carried out by TRIUMF's accelerator experts and oversaw the manufacture of the components by Canadian industry. The projects for LHC included upgrades to the CERN PS booster and PS synchrotron to produce the beam performance required for the LHC, involving magnets, power supplies, beam instrumentation and rf equipment. For the main LHC collider itself there were two large efforts: first the power supplies and pulse forming networks for the LHC injector kickers which were assembled at TRIUMF; then the second and largest contract was for the development of 52 large twin-aperture quadrupole magnets for the beam-cleaning insertions of the LHC. These were manufactured by Alstom Canada, in Tracy, Quebec. The total value of the LHC contributions was $41.5 million

Most recently Ewart has been using the expertise developed twenty years ago for the experimental facilities of the proposed KAON factory, to coordinate TRIUMF and Canada's contribution to the new J-PARC facility in Japan. Working with TRIUMF's remote handling experts—widely recognized internationally—Ewart has organized TRIUMF's contribution of purpose-built remote handling equipment for the J-PARC target hall and neutrino beam, where many Canadians (see Poutissou's story above) are involved in experiments.

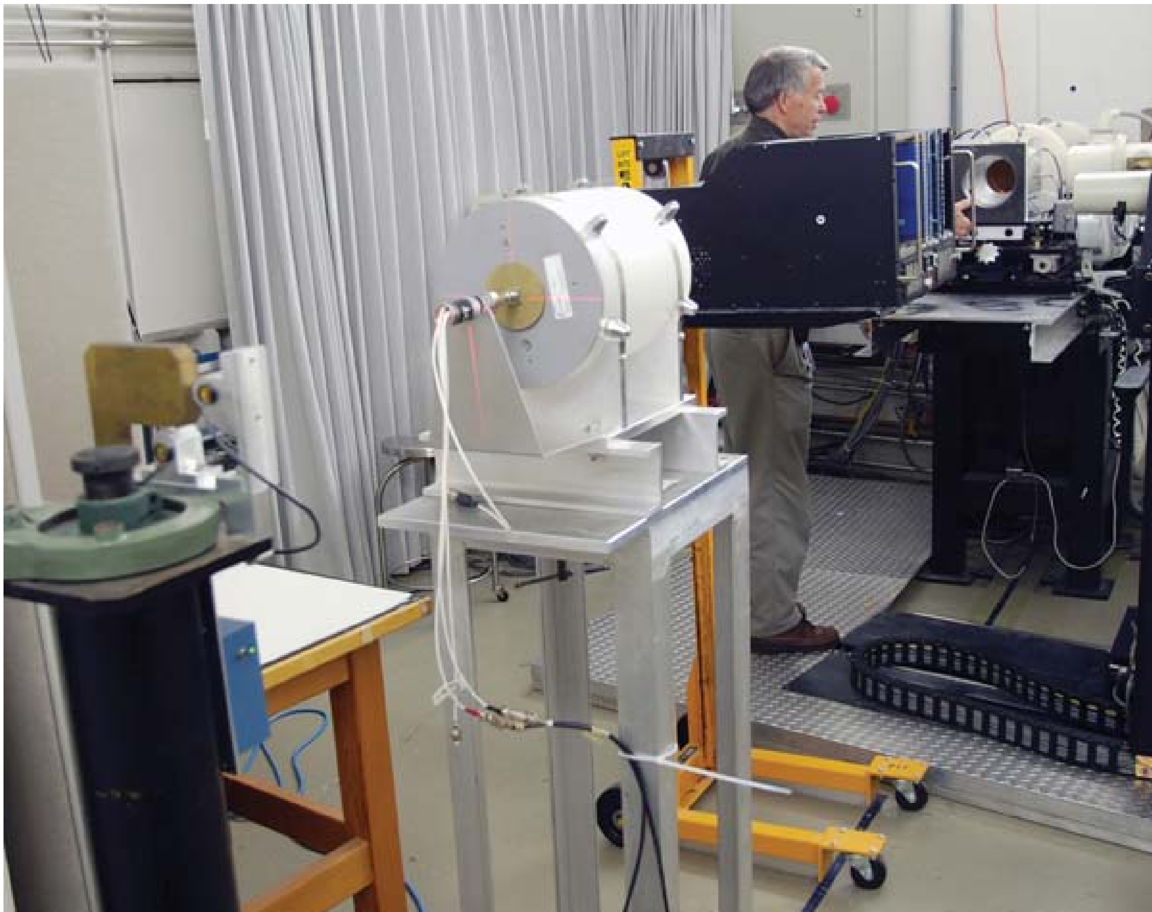
Ewart has always had an interest in medical physics and recognized the possibilities of using TRIUMF's unique capabilities for producing beams for specific medical

TRIUMF and Ewart Blackmore have pioneered the use of proton therapy for the treatment of ocular melanoma.

by Erich Vogt

applications. TRIUMF has a strong relationship with the BC Cancer Agency (BCCA), a relationship which initially focused on using beams of negatively charged pions for the treatment of deep-seated tumors in experiments carried out in the 1980's. It became clear that although the pion therapy worked, proton beams were easier to produce and experience elsewhere in proton therapy identified certain sites where protons were particularly effective. Starting in 1993 Ewart designed and constructed the TRIUMF proton therapy beam line, with a grant from the Woodward's Foundation, for the treatment of ocular melanomas, a rare form of eye cancer. To date about 140 patients have been treated at TRIUMF and many lives have been saved.

As a passionate engineering physicist— like his mentor John Warren—Ewart used his free time on weekends to take on other projects. Electronic components sent into space or used here on earth are subject to background radiation from



The TRIUMF irradiation facility development by Ewart Blackmore tests radiation effects on electronic components for space, aircraft and ground level applications.

cosmic rays which can damage or destroy them. There are a few laboratories around the world that can carry out proton and neutron irradiations to test for radiation effects in electronic components, but none of them have TRIUMF's flexibility in beam energy and intensity. For example, a ten-year dose of proton irradiation for the International Space Station can be delivered in ten minutes at TRIUMF, or, if desired, the rate can be reduced by many orders of magnitude. Neutrons cause radiation effects in aircraft and at ground level. Ewart developed the TRIUMF Proton Irradiation Facility (PIF) and Neutron Irradiation Facility (NIF). These facilities are now used each year by about 25 companies from around the world to test space, aircraft and ground level electronic systems for the effects of radiation.

For forty years Ewart has held senior administrative posts at TRIUMF. He has now stepped down, in November 2008, from his most recent post as head of TRIUMF's Engineering Division and he plans to pursue his scientific interests in medical physics and PIF and NIF. Like Poutissou, he has served on a number of Canadian and International review committees. We are all watching where Ewart's talents will be used next for TRIUMF and for Canadian science.

Dr. Erich Vogt, OC, OBC, FRSC, is a Professor Emeritus of Physics of the University of British Columbia and past Director of TRIUMF.

Superconducting Technology and PAVAC

by Robert Laxdal

TRIUMF typically uses its expertise in accelerator technology in accelerator design, fabrication, installation, and operation to support its science program. At other times, TRIUMF employs accelerator technology expertise in international collaborations to support accelerator installations at facilities such as CERN in Switzerland or the Japan Proton Accelerator Research Complex (J-PARC). These collaborations secure Canadian physicists' access to unique accelerator capabilities not available in Canada. In addition, part of TRIUMF's mission is the transfer of high technology, where required, to Canadian industry. Sometimes there is a perfect match between a company's expansion goals and TRIUMF's requirements. Such is the case in the collaboration between TRIUMF and PAVAC Industries Inc. of Richmond, BC.

In the ISAC facility, 500 MeV protons from the TRIUMF cyclotron slice through a production target producing a myriad of exotic fragments as the target nucleii are splintered or "spallated." These exotic particles migrate as a gas through a heated tube to an ion source where one electron is removed to charge or "ionize" the resultant particle. The mixture of ionized fragments is then separated into like masses by bending in a magnetic field to form a "pure beam" of one particular exotic ion. Experimentalists can study this exotic beam at energies produced in the source (less than 60 kV), or the beam can be injected into the ISAC linear accelerator chain to achieve beams of much higher energy to enable a different category of experimental characterizations. These accelerators use electromagnetic energy at radio frequencies to accelerate the charged particles. The first two linear accelerators installed at ISAC operate at room

Six niobium cavities from PAVAC as assembled for installation into an ISAC-II linear accelerator cryomodule.

by Robert Laxdal

temperature using water-cooled copper to conduct the high radio frequency (RF) power required for acceleration. In 2006, a superconducting heavy ion linac was added to further boost the velocity of the ions.

In a superconducting linac, the RF structures or "cavities," which produce the accelerating fields, are made from niobium. Niobium is a metal that becomes superconducting at temperatures below 9.2 K (nine degrees above absolute zero) and is the material of choice for modern superconducting cavities. These cavities are technically challenging to produce but, when done correctly, can provide large accelerating fields for very little electrical power. For example, the RF surface resistance of niobium in a superconducting state is five orders of magnitude less than for copper at room temperature. Thus, a cavity requiring 100,000 watts of RF power at room temperature could attain the same accelerating field with only a few watts at superconducting temperatures.

Superconducting RF (SRF) performance is strongly dependent on the purity of the niobium surface because any foreign material imbedded in the material will absorb power and heat the cavity. Only highly refined ultra-pure niobium is used for cavity production. It is imperative that other materials or gas do not infect the material during manufacture, and, for this reason, the niobium is welded with an electron beam in a vacuum. Because the niobium surface can be infected with other materials by machining or forming, the parts are etched in a strong acid before welding. There are only a few companies in the world that have mastered the technology required to successfully fabricate niobium cavities for particle acceleration.


Niobium surfaces are etched with a strong acid solution before being welded with an electron beam in a vacuum environment.

The ISAC-II linear accelerator installed in 2006 was assembled from 20 niobium cavities made in Italian industry. The next stage, which will consist of the addition of twenty more niobium cavities, is scheduled for installation in 2009. Seeking a "made-in-Canada" solution for this phase, TRIUMF looked around for a vendor with the confidence to tackle a challenging new technology. At the same time, PAVAC Industries Inc. was looking to expand their operation beyond that of a small company producing electron beam welders. Ralf Edinger, the president of PAVAC, had the idea that the patented LASTRON technology used in PAVAC's electron beam welders could be coupled with a small accelerator to produce a product for pollution control. A meeting at TRIUMF started the ball rolling, and TRIUMF and PAVAC began collaborating to produce the first SRF cavities to be built in Canada.

Three years later the collaboration has been very successful. Two full-scale prototype cavities have been fabricated, and six of twenty production cavities have been delivered. Along the way, two copper prototypes have been produced to establish the required forming, machining, and welding fixtures. RF engineers worked with PAVAC engineers to establish the correct fabrication sequence to arrive at the final cavity dimensions required to produce the exact RF frequency. A new laboratory was added to the technical infrastructure supporting the SRF group at TRIUMF. The Chemical Etching Laboratory is used to "super clean" ultra-pure niobium both before welding during the cavity fabrication process and after the cavity is complete.

PAVAC and TRIUMF's venture into superconducting technology extends into the global market. For example, TRIUMF's Memorandum of Understanding with the Variable Energy Cyclotron Center (VECC) in Kolkata, India includes the collaborative design and fabrication of two electron linacs, one each for TRIUMF and VECC, with PAVAC supplying the cavities. In another example, Fermilab in Chicago and TRIUMF are formalizing an agreement that aims to qualify PAVAC as a North American vendor for the 16,000 cavities needed for the 30 km-long International Linear Collider (ILC). PAVAC and TRIUMF are now collaborating on a prototype of this cavity, with initial forming and welding studies in copper.

The PAVAC/TRIUMF collaboration has definitely been successful for both parties. PAVAC has mastered a difficult technology that has opened up new markets and allowed them to follow future development and expansion initiatives, and TRIUMF now has a dependable supplier "next door," one that will allow the SRF group to follow its own research and development initiatives in an exciting and rapidly advancing field.

Robert Laxdal is a TRIUMF Research Scientist, focusing on superconducting equipment and applications.

Shedding Light on Radioisotope Production

by Tom Ruth

Almost from the moment of its discovery, radioactivity was used as a tracer. As the story goes, Hungarian physician George de Hevesy became convinced that his landlady was reusing leftovers. When questioned, she indignantly denied serving anything but fresh food every day. Still not convinced, de Hevesy spiked his leftovers with radioactive material. His suspicions proved correct when he used an electroscope and detected the radioactivity in a subsequent meal.

Today, radioactivity is used for many purposes, but the most widely known use is in medical diagnoses. Every day, more than 70,000 medical procedures are performed worldwide to aid in the care of patients, and, of these, 85% make use of the radionuclide ^{99m}Tc. The wide use of this radioisotope is possible because it is produced in the radioactive decay of molybdenum-99 (^{99}Mo). With a half-life of 66 hours, the Moly, as this isotope of molybdenum is called, is prepared in a generator where the decay product ^{99m}Tc accumulates and is then retrieved by a process referred to as "milking." With only 5 reactors responsible for producing more than 95% of the world's supply, and with its short half-life, Moly must be generated on a weekly basis.

The ^{99}Mo/^{99m}Tc generator system accounts for $5B in sales every year, with the National Research Universal (NRU) reactor at Chalk River Laboratories in Canada and the Nuclear Research and Consultancy Group (NRG) reactor in the Netherlands producing about 80% of the Moly between them. Yet, the general public was unaware of its production until November 2007 when the NRU was not allowed to restart after routine maintenance by the Canadian Nuclear Safety Commission (CNSC) who pointed out that the Atomic Energy of Canada Limited (AECL), the operator of the NRU, had not completed a backup system for the reactor and was thus unsafe for routine operation. The shutdown deprived the medical community of a supply of this medical isotope and raised concern because it pointed out the fragile nature of the supply network.

This shortage lasted several weeks until the Canadian government intervened and ordered the CNSC to allow the restart of the NRU and allow it to begin producing Moly, but the fragile nature of the supply was again illustrated in August of 2008 when the Dutch reactor was shut down due to a leak in one of the coolant pipes. This shutdown lasted until April of 2009, causing delays and cancellations of diagnostic procedures throughout Europe. During this period, disaster within the medical community was diverted only because the NRU had excess capacity and could supply 70% of the world's needs.

The hopes for the ultimate solution to the reliable supply of Moly were further dashed when the Maple Project at Chalk River was cancelled by the AECL. This project would have built two dedicated reactors for the sole purpose of producing medical isotopes, in particular ^{99}Mo. The Maple project began in 1998 and was cancelled in 2008 without receiving the license to operate because of unresolved problems with the reactor operation. Each one of the two Maple reactors would have had the capacity to produce the world's demand for Moly, and with the Maple project looking like it was moving forward, the medical community saw no need for additional sources. At present, the 5 remaining reactors which produce Moly are all over 40 years old, and the 2 major ones—NRU and NRG—are both over 50 years old.

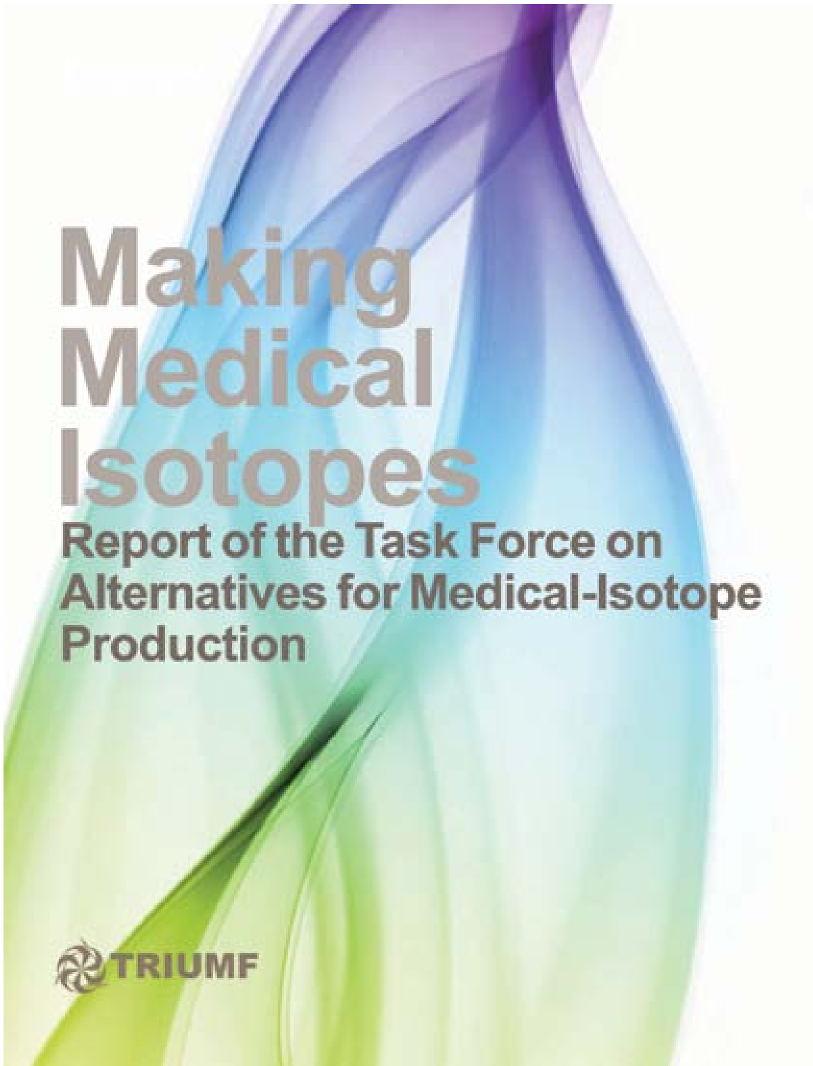
If all of this is not complicated enough, all of these reactors make use of highly enriched uranium (HEU, typically >93% ^{235}U). HEU is considered a security risk because a nuclear bomb of the size used in World War II can be made with about 20 kg. The International Atomic Energy Agency (IAEA) and the US National Nuclear Safeguards Administration (NNSA) have been working for decades to remove HEU from civilian use, and, in particular, from medical isotope production. In a recent report, the National Academy of Sciences (NAS) indicated that there were no technical or financial impediments to the conversion of reactors to producing medical isotopes by using low enriched uranium (LEU, <20% ^{235}U). (LEU is preferable because it is practically impossible to make a nuclear bomb with this material.) Based on the NAS report, it is expected that the US Congress will require medical isotope suppliers to convert to LEU targets in order to receive the uranium required for production.

Thus, the supply of Moly is again placed under pressure, and one has to ask, "What solutions can we expect over the short term and over the long term?" The Maple experience does not lend confidence to the user community. Although the Jules Horowitz multi-purpose research reactor in France is due to come on line in 2014 and will help with the supply, it can not match the output of either the NRU or NRG. There are discussions about modifying the Missouri University Research Reactor, but these modifications to the reactor will take up to 5 years to complete and only be able to supply about 30% of the North American demand. Building any new reactor requires up to a decade, when one takes siting issues as well as actual construction into consideration.

The good news is that TRIUMF has come up with a solution. In its five-year plan for 2010–2015, TRIUMF articulated its strategy to build an electron linear accelerator (e-linac) to generate a beam of energetic photons that will be used to

Shedding Light on Radioisotope Production

by Tom Ruth



produce fission in ^{238}U to generate a wide array of neutron-rich isotopes for use in TRIUMF-based programs in astrophysics and nuclear physics. During the safety analysis for this production system, it became obvious that one of the major products from photo-fission of ^{238}U is ^{99}Mo. In fact, the isotope distribution from this fission process is nearly identical to that from the thermal neutron fission of ^{235}U that is used in the reactors. The difficulty is that the yield from photo-fission is approximately a thousand times less than from neutron-induced fission. In addition, the biggest challenge from a technical perspective is the design of the converter that will be required to convert the power of the electron beam into photons that will involve several megawatts of heat dissipation.

In 2008, TRIUMF organized a workshop—sponsored by the Ministry of Natural Resources Canada, the newly formed Advanced Applied Physics Solutions, and the University of British Columbia—to explore the concept in more detail. The outcome of the workshop was a recommendation to pursue the initiative to the level of a proof-of-principle demonstration in order to determine the actual requirements for a production system that would probably require several e-linacs.

The interest in this accelerator approach is growing because there are several significant advantages to the e-linac concept. First of all, the target used can either be natural uranium (0.7% ^{235}U) or depleted uranium (<0.3% ^{235}U), either of which bypasses the issue of weapons-grade uranium. In addition, because the fission yield from the two processes is almost identical, the chemistry used in isolating the Moly will be similar, if not identical, and will minimize the regulatory approval process, which should be rapid and straightforward. Another major advantage is the lower decommissioning cost of an accelerator in comparison to those associated with a reactor.

MDS Nordion has expressed interest in the accelerator approach and has indicated that it would assist with a proof-of-principle demonstration of the overall concept (producing Moly from the photon-induced fission of natural uranium to determine the yield and specific activity of the ^{99}Mo). In order to perform such a test, TRIUMF would have to build its e-linac as soon as possible. While the design of the science-driven e-linac is not that of a medical isotope–producing system, the power density could simulate that of the high-power accelerator to address some of the technical questions for a production system. While the accelerator approach may be able to provide a solution to the medical isotope problem, it is not the answer to the scientific needs of the community: neutrons for research that are produced in reactors.

TRIUMF management is pursuing a number of avenues that will enable us to fast track the construction of its e-linac within the next two years. This development is further proof of how basic science has direct and invaluable benefits to society.

Tom Ruth is a TRIUMF Research Scientist in Nuclear Medicine and past Director of the TRIUMF/UBC PET Programe.

Beam Delivery at TRIUMF's ISAC Facility

by Colin Morton

TRIUMF's Isotope Separator and Accelerator (ISAC) is one of the world's premier rare-isotope beam (RIB) facilities. Energetic protons from TRIUMF's main cyclotron are used to produce exotic nuclei that are delivered in beam form to experiments in the ISAC experimental halls. Without these beams, the experimental program at ISAC cannot proceed.

Beam delivery represents a significant challenge at any particle accelerator laboratory. At a RIB facility such as ISAC, the challenges are magnified. ISAC uses the isotope separator on-line, or ISOL, method to produce RIBs. With this approach, protons from TRIUMF's main cyclotron are steered onto a thick production target of material with a relatively high atomic mass. Lighter nuclei are produced in reactions between the protons and the target material. These nuclei pick up electrons from the surrounding environment to form neutral atoms. Some of the atoms produced occur naturally but many do not, and it is these "exotic" species that are of particular interest to researchers.

The atoms produced within the target diffuse from the target material into the container holding the target, then drift into an ion source where they are re-ionized, i.e., where one or more electrons are removed from the atom forming positively charged ions. The target is held at high voltage, typically a few tens of kilovolts, relative to ground so that the ions produced are accelerated out of the ion source by electrostatic forces.

The resulting beam of ions, still at low energies by typical accelerated-beam standards, is focused through a pair of magnets to separate the ions by their charge-to-mass ratio. This is the "on-line" part of ISOL: isotopes are separated as they are extracted from a production target operating on-line, i.e., with proton beam on target rather than off-line after irradiation. After mass separation, a beam of ions with a single charge-to-mass ratio is available either to be steered to a low-energy experimental area or to be injected into the ISAC accelerator chain for acceleration to a few percent of the speed of light. These accelerated beams are then used to carry out higher energy experiments in the ISAC-I high-energy experimental area or at ISAC-II. For beam delivery to be successful, each of these elements, from the cyclotron and its related systems to the experiment itself, has to function properly.

^{11}Li and the "Spanish Experiment"

Halo nuclei are those nuclei with extreme ratios of protons to neutrons such that the nuclear radius is much greater than would otherwise be expected (see R. Kanungo, "The Magic of Star Dust—Exploring Exotic Nuclei," *TRIUMF Annual Financial & Administrative Report 2007–2008* for details). Lithium-11 (or ^{11}Li), with a half-life of 8.6 milliseconds, is one such nucleus. Despite having only 11 nucleons, its radius is comparable to that of ^{208}Pb (lead-208), with 208 nucleons. Several experiments have been carried out at ISAC to study ^{11}Li and similar nuclei at both low and high energies. At this time, ISAC is arguably the best lab in the world for studying ^{11}Li because the proton currents available from TRIUMF's main cyclotron allow higher production yields than those observed elsewhere, while the direct injection of low-energy beams into the ISAC accelerator chain allows even short-lived species such as ^{11}Li to be accelerated to energies of interest to those studying nuclear structure.

Setting up the E1104 experiment, July 2008. The inset shows the inside of the chamber with the 4 detector telescopes, each of which comprises 256 3x3 mm pixels.

In 2008, a group of researchers led by scientists from the Universities of Huelva and Sevilla and the Spanish National Research Council (Consejo Superior de Investigacione Cientificas, or CSIC) in Madrid mounted an experiment to study ^{11}Li by elastic scattering. Their plan was to take a RIB of ^{11}Li ions, accelerate it to a few percent the speed of light using the ISAC-I and ISAC-II accelerators, impinge it on a ^{208}Pb target, and observe the scattered nuclei in a series of charged-particle detectors placed around the target. By measuring the number of scattered particles by Colin Morton

observed at different angles to the incoming beam, it would be possible to determine the reaction probability or "cross-section" as a function of angle and beam energy. As halo nuclei should be easily polarized, i.e., distorted as the halo neutrons (in the case of ^{11}Li) move in opposition to the core of the nucleus in an electric field. A reduction in the elastic scattering cross-section would be expected, in particular for those events where the ^{11}Li nucleus was scattered backwards. The goal of the experiment, TRIUMF experiment S1104, was to observe and measure this reduction.

The Beam Delivery Process

Early in July, members of TRIUMF's Beam Delivery Group (BDG) met with members of the S1104 collaboration to review the state of the experimental setup (which had been flown from Spain and installed in the ISAC-II experimental hall) and to develop a detailed plan for the run. At this point, roughly ten days before the first RIB would be delivered, several items still remained to be completed. The detector system to be used for the experiment was still being set up. A decision had yet to be made regarding the use of an upstream detector for triggering the data acquisition system. A timing signal from the accelerators' RF system—the system that generates the rapidly oscillating electric fields that accelerate the ion beam—was still needed. Most importantly, the production target to be used for producing the exotic beams of ^{11}Li and ^{9}Li (included in the experimental proposal to provide a basis for comparison with a non-halo nucleus) had to be brought on-line while the ISAC accelerators needed to be set up to deliver the requested beams.

The process of bringing the new target on-line began roughly three days before RIB was to be delivered. Accelerator tuning with a stable beam of ^{18}O (with the same charge-to-mass ratio as the ^{9}Li RIB) from the off-line ion source began at about the same time. Like most accelerated beam experiments at ISAC, the S1104 group also used this stable beam to check their own setup prior to the start of the experiment. While they were doing this, the proton current on the on-line target was slowly increased to 70 µA, about 4×10^{14} protons/second. As this was being done, a major problem became apparent: the yields of exotic nuclei measured from the target were lower, and in the case of ^{11}Li much, much lower, than expected. (The poor yields were exacerbated in the case of ^{11}Li by its short half-life: 8.6 ms, vs. 178 ms for ^{9}Li.) Without yields comparable to those observed from previous targets, the experiment would not be possible in the time allotted.

The tantalum production target that was used for this experiment was a new design that was intended to take full advantage of the 100 µA proton beam available at ISAC. Unfortunately, the combination of target and high beam currents did not produce RIB as expected. (An inspection of the target after the run would show significant damage to the target, including breaks in its structure that would have allowed nuclei produced within the target to escape without entering the ion source. If that had happened, they would have stuck to the nearest cold surface or been pumped away into the target vacuum system rather than be ionized, extracted, and delivered to an experiment.) The result was that the yield of ^{9}Li, while low, was at least useable from an experimental standpoint. That of ^{11}Li was, at best, questionable. With that in mind, the collaboration chose to continue as planned, starting with ^{9}Li in order to obtain a reference measurement and then proceeding to ^{11}Li.

The Experiment

The experiment began on July 18. The first part went well. The collaboration had requested a rate of 10^6 ^{9}Li/s at the location of the experiment but was willing, if necessary, to accept a rate an order of magnitude lower in order to carry out the ^{9}Li measurement in two days. After two days, the average rate was nearly what had been requested: about 9.8×10^5/s, with very little downtime. The second part did not go nearly as smoothly. The Group and experimental spokespersons had agreed to a rate of 2000 ^{11}Li/s at the experiment. The rate measured at the ISAC yield station was about 1200/s. Taking the beam through the ISAC accelerators reduced this to about 300/s, although a few hours' worth of tuning increased this to about 700/s, which was still barely a third of what had been agreed to.

The experiment ran with these rates for about a day and a half. At this point, the beam delivery and ISAC target development groups took advantage of scheduled time for cyclotron beam development (which was scrapped at ISAC's request) to squeeze what they could out of the target. The proton current was increased to 100 µA, resulting in a five-fold improvement in the ^{11}Li yield, before a failure of the beam line 2A extraction probe, i.e., the mechanism holding the carbon foils used to extract the proton beam from the cyclotron to ISAC, shut down ISAC early the next morning.

After repairing the probe during that day's scheduled maintenance, beam was restored to the experiment. The rate at the experiment was no better than it had been before the development and maintenance shifts. To make matters worse, a power bump knocked both the cyclotron and ISAC off-line early that afternoon. By the time RIB was restored, a full 24 hours had been lost. The ^{11}Li rate was back to about 700/s but didn't last; overnight, it dropped by a factor of two. The delivery and development groups then spent 24 hours trying to restore the rate, to no avail. The run limped along for another two days with barely 100 ^{11}Li/s reaching the experiment before ending three days earlier than scheduled, leaving the experiment with only about a tenth of the data expected.

Success After All

Because TRIUMF schedules two running periods each year, the Spanish collaboration did not have to wait long for a second chance. S1104 was the first experiment scheduled for the fall running period, less than ten weeks after the first run ended. Where the initial run had been scheduled for 216 hours (or 18 twelve-hour shifts) with 48 hours of setup time beforehand, the new one was granted 240 hours (20 shifts) with an additional 72 hours of setup time. The target was a standard high-power (i.e., high-proton-current) tantalum target, capable of running with proton currents of 70–80 μa for extended periods, and the run was scheduled to have only a brief, four-hour interruption for maintenance (and even that was on a strictly if-needed basis). The goal of the run was simple: finish the ^{11}Li measurement and complete the experiment.

ISAC-II experimental hall. Experiment S1104 was mounted on the beam line at centre of this photo.

Setup for the second attempt began on October 6 as a routine two-week maintenance period ended. The accelerators were tuned with a beam of stable ^{22}Ne (with the same charge-to-mass ratio as ^{11}Li) while the preparation of the new target for on-line use was wrapping up. The target went on-line on October 8. Two days later, with 65 μA of protons on target, ^{11}Li was delivered to the experiment at a rate close to 3000/s. By the time the run ended 11 days later, rates of over 7000/s were seen. Even with another power bump costing nearly 24 hours of beam time, the total number of ^{11}Li ions delivered to the experiment was more than double what would have been expected at the agreed-to rate of 2000/s (see Figure 1).

The analysis of the data from both the ^{9}Li and ^{11}Li measurements is currently underway. Commenting on the experiment, Maria José G^{a} Borge (CSIC Madrid), one of the spokespersons for the experiment, said, "We were very pleased with the results and the extra opportunity we had in October." Despite the losses associated with accelerating RIB—typically two-thirds or more of the yields measured at the ISAC yield station—the peak rates of accelerated ^{11}Li observed at the experiment were higher than those typically observed at low-energy ISOL facilities. More importantly, we were able to maintain these high rates—5000/s or more—for several days. This combination of high production and delivery yields and reliability gives ISAC a significant advantage over other facilities.

This experiment was extremely challenging, even without target problems and power bumps. The short half-life of ^{11}Li makes any experiment with the nucleus difficult, even at low energies where the beam does not have to be accelerated. Planning an experiment requiring an accelerated beam of ^{11}Li with rates of a few thousand per second would be unheard of at most ISOL facilities. That's why the S1104 collaboration chose to come halfway around the world to pursue their experiment. It would not have been possible anywhere but at ISAC.

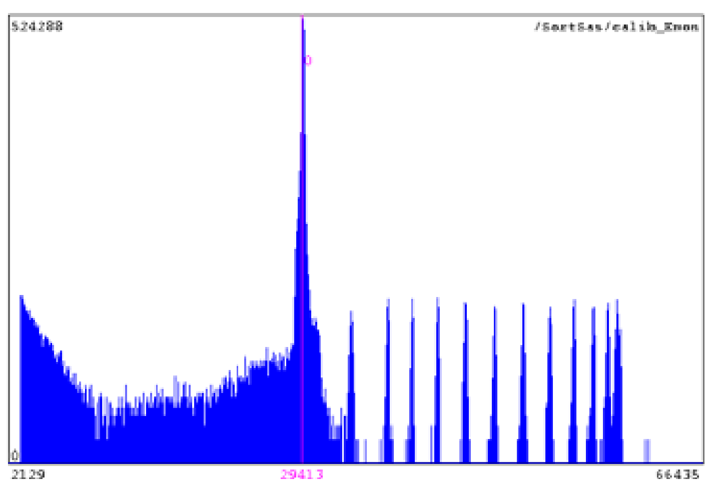


Figure 1: Energy spectrum of accelerated ^{11}Li as observed in a downstream monitor detector (not shown). No target was in place, and the beam structure can be seen up to double the energy at the main peak.

Colin Morton is a TRIUMF Research Scientist, responsible for experimental beam delivery.

Remote Handling at TRIUMF

by Clive Mark

Even before its first accelerated beams, TRIUMF recognized that a dedicated group of engineers and technicians could best address site-wide concerns for both handling radioactive components and working in radiation areas.

The Remote Handling Group (RHG) was formed and, armed with a broad mandate, has evolved into widely diverse systems including a remote cyclotron servicing system, a Meson Hall hot cells facility, primary beam lines remote maintenance, a machine shop and welding facility for radioactive materials, and, most recently, the ISAC Target Hall handling system with its remotely operated overhead crane and dedicated hot cell facility. The RHG performs much of the work required on radioactive components and provides remote handling expertise and assistance to other groups.

Cyclotron Servicing

While lower energy beams, such as X-ray machines, only produce prompt radiation when energized, that is, until the power is switched off, high-energy accelerators, like the TRIUMF cyclotron, produce ionizing proton beams of sufficiently high energy to displace electrons from atoms in whatever they impact. Attempts by these "altered" atoms to re-achieve a stable state results in the emission of low-level non-ionizing radioactivity. This induced secondary radiation often has long decay periods during which serious health physics concerns for laboratory personnel can arise.

The cyclotron's motorized aluminum service bridge, along with a family of remote-controlled trolleys and closed circuit television cameras and monitors, provides for dedicated remote operations inside the cyclotron.

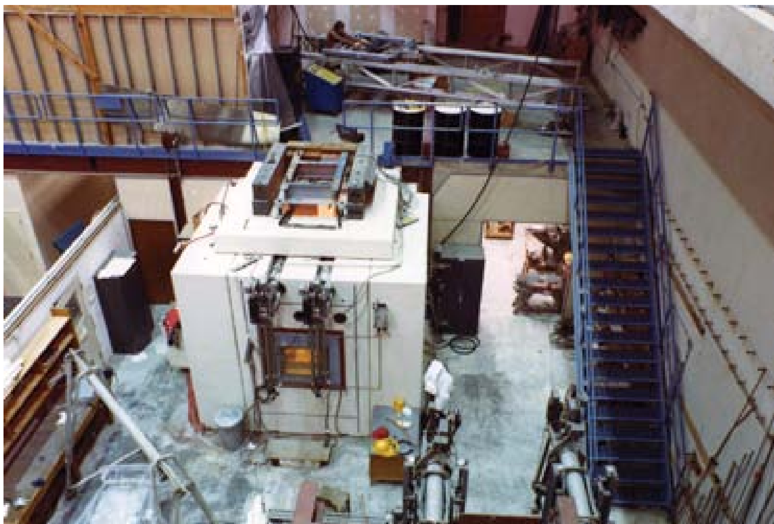
The heart of TRIUMF is its primary particle accelerator. The largest cyclotron in the world, it accelerates hydrogen ion particles to nearly 3/4 the speed of light, attaining an energy potential of over 500 MeV (500 million electron volts). While the actual mass of hydrogen is indeed very small, the final energy attained is significant. During their lengthy flight around the cyclotron, a small percentage of hydrogen ions have their additional bound electron knocked off by striking stray molecules of gas inside the otherwise high-vacuum cyclotron tank, or ripped off by the sheer strength of the surrounding magnetic field. These careening particles, now high in energy themselves, are deposited randomly in the cyclotron, resulting in areas of high, residual, secondary radiation, even after the cyclotron beam is turned off. After extraction from the cyclotron, accelerated particles continue down the beam lines with a small percentage of beam halo striking nearby components and area shielding, rendering them radioactive. As the main proton beam strikes the production target, the "smashing atoms" spray and deposit vast energy in both the target and surrounding materials. Areas of high radioactivity are produced by these interactions. Even the final beam, much of it passing clean through the dense target without any interaction, continues on to a water-cooled beam dump to dissipate its enormous energy. All of these areas, as well as the targets themselves, with their residual radiation, must be safely handled for maintenance, repair, and replacement. The high levels of residual radiation, however, limit the time that personnel can spend working in the area while still staying below strict safety guidelines imposed for radiation workers at TRIUMF.

The Cyclotron Servicing System started with an aluminum bridge structure, which was motorized, and a family of remote-controlled trolleys designed to travel on top as well as to crawl along its sides, to provide dedicated remote operations inside the cyclotron. Closed circuit television cameras and monitors were installed for remote viewing. The original control console for this system pre-dated affordable computer control so hard-wired electrical relay logic provided control interlock functions. Upgrading to a then revolutionary computer control system utilizing an early 8086-PC computer took place in the late 1970s. The system evolved again in 1982 with the construction of a three-story Remote Handling Building, with its own fully equipped machine shop and welding facility, which was sealed off from the cyclotron vault by a 2 m-thick iron and concrete rolling shield door.

Today, all remote servicing inside the cyclotron is performed from a control room in the building. At the beginning of every cyclotron maintenance shutdown, the tank lid is raised, and remote servicing equipment is installed. After 7 highly radioactive beam blockers are removed from the tank, 66 individual 50-mm thick lead shields are installed around the periphery of the tank. Installation of this 10 tonnes of personnel safety shielding reduces the residual radiation levels in the cyclotron tank by a factor of 3, significantly reducing personnel radiation dose exposures. Similarly, by using these remote operated trolleys, many other components within the cyclotron can be removed and replaced without the need for manual in-tank intervention.

Meson Hall Servicing

To service radioactive beam line targets and components in the Meson Hall, the Group constructed a hot cell that employed thick, lead glass shielding windows and remote tele-operated manipulators. A unique design used concrete interlocking modular building blocks, a method that proved valuable years later when reorganization of experimental areas required moving the 30-tonne hot cell.



The 30-tonne Meson Hall hot cell services radioactive beam line targets and components. The unique design uses interlocking concrete blocks.

All targets, monitors and safety interlocked beam blockers in the TRIUMF Meson Hall are of a tall slender smokestack design with the radiation components on the bottom ends of steel shielding plugs that allows personnel access and conventional organic materials to be employed at the upper ends. These units are transported by crane through the hall in a tall, lead-shielded bottom-loading transport flask, which mates with a roof portal in the hot cell. An elevating, rotating turntable was designed for the cells both to support the large components being serviced as well as to rotate and elevate them for even greater access by the limited stiff-arm geometry of remote operable manipulators.

Primary high-current beam lines and target stations in the Meson Hall are surrounded by large concrete shielding blocks stacked by crane over the entire 50 m length from the cyclotron vault to the beam dump. Unstacking these blocks to expose a section of radioactive beam line results in wide, inverted, pyramid-shaped openings. Short-length bridge spans, with removable lead-shielded floor sections span the wide openings of these "canyons" and reduce personnel exposure both by shielding and by elevation distance above the radioactive areas. For service and repair of components deep within the canyons, a series of extra-long tooling along with specialized services connections was developed. These, along with a remote-handling vacuum joint flange designed for TRIUMF, occupy a minimum of invaluable beam line length and allow full remote replacement of all radioactive components along the beam line.

ISAC Servicing

The ISAC (Isotope Separator and Accelerator) rare isotope beams facility uses proton beam from the original existing 500 MeV cyclotron to split the nuclei of selected targets into rare exotic short-lived isotopes for research in nuclear astrophysics, condensed matter physics, nuclear medicine, the biosciences and applied research. From the beginning, the RHG was instrumental in the philosophy and design of the new, uniquely complex target stations and their handling. Unlike existing targets at TRIUMF, which required only water cooling, the ISAC targets also required high voltage up to 60 kV, high current up to 1,000 volts, the injection of exotic gases with many more controls, diagnostics and interlocks, all to operate in a strict high-vacuum environment. The size of these new target assemblies, now known as modules, also grew immensely from the original modest TRIUMF smokestack designs. The concept of tall, shielded devices, with radioactive components on the bottom, was retained; however, the reality of transporting these new modules in an externally shielded flask was not feasible for ISAC. The sheer size of each of the modules, at 1 m x 1 m square and 3 m high required a transport flask of enormous size and weight. In addition, a single module weighs over 12 tonnes, and with additional transport shielding, the weight would easily triple.

The solution was to build the Target Hall, with 1.2 m thick sold concete walls, that it would provide the necessary shielding, and use a remotely operated crane to transport the radioactive target modules to hot cells, which were also incorporated in the hall. Two target stations were constructed, each composed of five similar modules, situated within a by Clive Mark

Installing a cold target in ISAC-I target hall.

T-shaped, five-chambered vacuum vessel, surrounded by steel and concrete shielding with removable cover beams. Two target stations were constructed at one end of the hall, with interim storage in the middle, a pair of top loading hot cells, and an air-lock entry port at the far end.

Remote handling technicians, working with the Mechanical Engineering Group, were responsible for building the two target stations inside the Target Hall as well as for the manufacture and assembly of the five initial Target Station Modules. Recognizing that the Group would have a vested interest in the operation of these modules provided added incentive and assured that they were built correctly.

The overhead crane operating in this 5.4 m x 42 m shielded Target Hall required fully remote operation to transport radioactive modules without exposure to personnel. Reliability of this crane system is critical. Any kind of crane failure during suspension of a radioactive load would be disastrous because personnel would be unable to approach the crane for repair. Working with both a local industrial crane supplier and the international parent company supplying the crane hoist and drive components, the RHG devised a suitable crane system based on conventional crane components. For increased crane reliability all drive systems must be fully redundant, with dual, independently driven hoist drums, dual trolley drives, and four separate gantry drives specified. Conventional crane systems mount all electronic controllers for the motor drives on the crane itself. Concern for both the complexity of electronics as well as potential radiation damage to sensitive micro-electronics in the controllers suggested that the motor controllers be removed from the bridge and relocated in the crane remote-control room outside the Target Hall. Each of the motor drives was also independently hard wired directly from a controller via a looped wire festooning system. Thus the failure of any one motor could either be overcome by its redundant drive ability or be serviced in the shielded control room.

The remote control of the crane was not an operation available through the manufacture, so, with their blessing, we turned in-house for a control system. Engineers from the TRIUMF controls group interfaced a PC computer with the crane's own Programmable Logic Controller to provide variable joystick control of all crane functions through a control panel built by the RHG. Video switching and pan-tilt controllers for cameras were also designed and built by the Group.

The control console for the crane is equipped with video monitors fed by closed-circuit television cameras mounted on the crane and at strategic locations within the Hall. The crane itself is operable in remote function only after the Target Hall is locked out to assure no personnel remain inside. A defined walk-about route, with strategically located pushbutton stations provides a thorough sweep of the entire hall. Only after this procedure is completed, and the hall locked out is the crane enabled for remote removal of a radioactive payload. The target handling hot cell facility for ISAC utilizes a top-loading entry portal inside the Target Hall, with thick lead glass shielding windows, and mechanical tele-operated manipulators accessed from outside the hall.

Production targets at ISAC deplete their irradiated material during operation, requiring frequent replacement, which is also performed remotely in the hot cell. Spent rare isotope production targets are highly radioactive and must be stored for an interim basis allowing adequate decay of radioactive half-life prior to off-site shipment to the designated Canadian repository in Ontario. A procedure has been developed that promptly places spent targets into sealed steel pails inside the hot cell and then transports them from the cell to a dedicated, shielded Spent Target Storage Vault inside the Target Hall. The fully remote procedures that accomplish this task have strict controls that prevent the spread of loose contamination from either the targets or the hot cell itself.

International Collaboration

In 2004, during a peer review of the Tokai to Kamioka (T2K) long baseline neutrino experiment facility being built by the National Laboratory for High Energy Physics (KEK) in Japan, it was noted that neither the proton beam monitors by Clive Mark

positioned directly upstream from their target, or the target itself were designed for remote replacement. Because the neutrino group at KEK did not possess the remote handling expertise, TRIUMF agreed, within the scope of international collaboration with KEK, to design and build a Final Focus Monitor assembly and to provide for a shielded hot cell facility that would permit remote replacement of both the two upstream monitors as well as the helium-cooled graphite target.

Drawing on its experience, the Remote Handling Group designed and built a 3 m tall vacuum vessel, shield plug and mechanisms necessary for remote replacement of a wire grid monitor and a non-intercept beam profile monitor. Both monitors were designed and built in Japan by KEK. The Group also incorporated an expandable vacuum seal, manufactured in Japan, to connect the monitor vacuum vessel with the upstream proton beam line vacuum. This seal was also designed for remote insertion and removal using remote handling procedures. As part of their collaborative contribution, the Rutherford Appleton Laboratory (RAL) in England designed and built a cooled beam window between the monitor vessel and the main target vessel. The Group worked directly with RAL personnel to provide support on the monitor vessel for this window and also designed the procedures and tooling for remote installation and removal of the window, helium recirculating, and vacuum pumping lines.

TRIUMF's Remote Handling Group designed and built a 3 metre tall vacuum vessel and related equipment necessary for remote replacement of monitors for the Japanese T2K experiment. The design was unique; the space available to install the equipment was very small and narrow.

The Group was also responsible for the design of a shielded hot cell wall to be incorporated into the existing design for the T2K Target Building. Due to the restricted availability of space in the area, we again used a unique modular design to permit vertical installation of both the lead-glass shielding window, which was supplied by TRIUMF, as well as the tele-operated manipulators that were included in our contribution to the project. Again, working in concert with RAL engineers who were supplying the actual graphite target, we came up with a remote handling design for target replacement, built by RAL and initially commissioned in Japan in November 2008.

Installing hot cell equipment designed by TRIUMF remote handling for Japan's T2K experiment.

In conclusion, having a defined group of engineers and technicians dedicated to the needs of radioactive materials handling at TRIUMF since the earliest days of operation has allowed us to develop a wide range of integrated procedures, tooling and expertise to provide remote handling support both on site at TRIUMF and off site through international collaboration and exchange of information.

Clive Mark is a TRIUMF Engineer, focusing on remote handling equipment and applications.

TRIUMF and MDS Nordion - Work to Discover Innovative Diagnostic Imaging Agents Based on Radiometals

by Mike Adam

After approximately 30 years working on the same site, MDS Nordion and TRIUMF, with support from the Natural Sciences and Engineering Research Council of Canada (NSERC), have partnered for their first collaborative research and development project for the discovery of innovative diagnostic imaging agents. With the sale of imaging agents at multi-billion dollar levels worldwide, new radiopharmaceuticals may be of significant economic value to Canada.

Developing new medical radioisotopes for use as tools in non-invasive imaging techniques for the detection of disease is the goal of TRIUMF's Nuclear Medicine Division. Dr. Mike Adam left, and graduate student Eric Price right.

Working with the University of British Columbia (UBC), the team will pursue the development of new medical isotope products using technology based on radiometals and chelates. This collaboration combines the fundamental strengths of TRIUMF's expertise in radiopharmaceutical development and radiochemistry research with MDS Nordion's strength as a world leader in radioisotope production. This collaboration is focused on achieving a long-term, medical isotope solution to meet the evolving needs of the global nuclear medicine community.

New non-invasive imaging tools are becoming increasingly important to our aging population. The development of new radiopharmaceuticals to diagnose disease in its early stages is the expected goal of this proposal. The PET-FDG method has already demonstrated itself to be the "gold standard" for the detection of cancer. Radiometals, a type of medical isotope, have been the backbone of nuclear medicine for decades; the most heavily used and commercially successful radiometal is technetium-99m (^{99m}Tc), currently used in 80% of 15 million diagnostic procedures for cardiac imaging in North America annually. The development of new agents, perhaps based on radiometals, holds a great deal of promise given the variety of radiometals available, their varying physical properties and highly flexible inorganic chemistry. Research into the application of radiometals in nuclear medicine is also of significant interest to MDS Nordion because such research adds value to the growing family of radiometal isotopes they produce.

While the development of new radiopharmaceuticals based on ^{99m}Tc is still important, two other radiometals, ^{68}Ga and ^{111}In, have significant potential because they provide unique properties that are under utilized and require more

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development. Several contributing factors make these two isotopes of research and commercial interest. One factor is that ^{68}Ga is short lived (half-life ~ one hour) but can be derived from a longer-lived ^{68}Ge (half-life 270 days) via a generator facilitating its distribution to hospital centres. Another factor is that ^{111}In has a relatively long half-life (67.5 hours) and can be used for both imaging and therapy. Scientists will combine select radiometals with newly developed chelates—substances that bind to radiometals and protect them as they are carried through the body—with the goal of providing new agents for the diagnosis and treatment of cancers and heart disease.

This collaboration combines resources, and a new research laboratory will be built in the basement of the Meson Hall Extension Service Annex at TRIUMF. The site planning is now underway, and construction is expected to start this year. The lab will eventually contain four high-level state-of-the-art hot cells and will be equipped to carry out cutting-edge research on the development of radiometal radiophamaceuticals for medical imaging. To start the research a NSERC Collaboration and Research Development grant was awarded in March 2009 entitled, "Enabling Technologies for Metallic Radioisotopes in Nuclear Medicine." This grant will allow TRIUMF and MDS Nordion researchers to focus on the development of new ^{68}Ga and ^{111}In chelate compounds as imaging agents or as radiometal pendent groups for conjugation to larger biomolecules such as antibodies and proteins. This development will considerably expand the reach of nuclear medicine.

Dr. Chris Orvig, UBC Department of Chemistry

The proposed project is largely a chemistry-based proposal that will require special expertise in inorganic chemistry, medicinal inorganic chemistry, radiochemistry and organic chemistry as well as isotope production and selection. The combined expertise from TRIUMF, UBC and MDS Nordion is key to achieving the goals of the project. As leader of the team, I am pleased to be able to bring my 29 years of experience in synthesizing and developing radiotracers for PET (positron emission tomography) and SPECT (single photon emission computed tomography) to the project. Other members of the team include Dr. Chris Orvig, (UBC Department of Chemistry), who, with 32 years of experience in medicinal inorganic chemistry, has focused a large part of his career on bioinorganic chemistry and the use of metals in medicine. Drs. Dennis Wester and Cara Ferreira of MDS Nordion will also join us. Dr. Wester has 30 years of experience in radiochemistry, radioisotope production, and radiopharmaceutical development. Dr. Ferreira carried out her Ph.D. research under the supervision of Dr. Orvig and myself. She has worked in the Applied Research and Development Department of MDS Nordion for three years. Students and young researchers taking part in the project will receive experience in and/or be exposed to synthetic chemistry, inorganic chemistry, radiosynthesis, and medical imaging through their own research activities.

Drs. Cara Ferreira and Dennis Wester, MDS Nordion Inc.

This new joined research and development project will further cement the already strong linkages between academia and industry in the TRIUMF/MDS Nordion partnership, which was awarded the prestigious NSERC Synergy Award for Innovation in 2004.

Mike Adam is a TRIUMF Research Scientist in Nuclear Medicine, focusing on new radioisotopes for diagnosis and treatment.

AUDITORS' REPORT

To the Joint Venturers of TRIUMF

The accompanying summarized statement of financial position and statement of combined funding/Income and Expenditures and Changes in Fund Balances are derived from the complete financial statements of TRIUMF as at March 31, 2009 and for the year then ended on which we expressed an opinion without reservation in our report dated June 19, 2009. Those financial statements were prepared to comply with section 11b of the TRIUMF joint venture agreement and the contribution agreement with the National Research Council of Canada, and are prepared using the basis of accounting as referred to in note 2 to the accompanying financial statements. The fair summarization of the complete financial statements is the responsibility of management. Our responsibility, in accordance with Assurance Guideline 25 of the Canadian Institute of Chartered Accountants, is to report on the summarized financial statements.

In our opinion, the accompanying financial statements fairly summarize, in all material respects, the related complete financial statements of TRIUMF in accordance with the criteria described in the Guideline referred to above.

The summarized financial statements, which have not been, and were not intended to be, prepared in accordance with Canadian generally accepted accounting principles, are intended for the information and use of the Joint Venturers and the National Research Council of Canada. Furthermore, the summarized financial statements do not contain all the disclosures required by Canadian generally accepted accounting principles. Readers are cautioned that these financial statements may not be appropriate for their purposes. For more information of TRIUMF's financial position, results of operations and changes in fund balances, reference should be made to the related complete financial statements.

PricewaterhouseCoopers LLP

Chartered Accountants
Vancouver, B.C.
June 19, 2009

TRIUMF

Statement of Financial Position
As at March 31, 2009

	2009 $	2008 $
Assets		
Cash and cash equivalents	6,517,371	7,749,517
Restricted cash	8,859,614	7,615,683
Due from Joint Venturers	386,104	335,644
Funding receivable	1,302,573	905,750
	17,065,662	16,606,594
Liabilities		
Accounts payable	1,664,960	1,060,687
Funds received in advance	3,180,910	2,788,881
Decommissioning Fund	8,859,614	7,615,683
	13,705,484	11,465,251
Fund Balances		
Restricted		
Natural Sciences and Engineering Research Council Fund	3,242,076	3,540,315
MDS NORDION Inc. Fund	100,000	100,000
Canada Foundation for Innovation	(203,209)	(269,252)
	3,138,867	3,371,063
Other		
Commercial Revenue Fund	(41,450)	1,145
General Fund	137,110	57,572
TRIUMF House Building Fund	(628,795)	(628,795)
Intramural Accounts Fund	754,446	2,340,358
	221,311	1,770,280
	3,360,178	5,141,343
Total liabilities and fund balances	17,065,662	16,606,594

TRIUMF

Statement of Combined Funding/Income and Expenditures and Changes in Fund Balance

For the year ended March 31, 2009

	2009 $	2008 $
Funding/income		
National Research Council Fund	43,500,000	51,500,000
Natural Sciences and Engineering Research Council Fund	5,970,896	6,374,929
MDS NORDION Inc. Fund	4,370,636	3,938,506
Advanced Applied Physics Solutions Inc. Fund	1,033,968	-
Canada Foundation for Innovation	1,114,884	1,867,939
Affiliated Institutions Fund	2,092,220	1,815,124
Commercial Revenue Fund	1,529,721	1,711,706
General Fund	175,071	461,169
	59,787,396	67,669,373
Expenditures		
Buildings and improvements	1,176,123	505,470
Communications	158,169	144,872
Computer	903,876	1,022,417
Facility conformity costs	1,000,000	7,200,000
Equipment	4,116,790	6,834,656
Power	2,343,671	1,905,098
Salaries and benefits	35,554,475	35,794,712
Supplies and other expenses	16,315,457	12,953,653
	61,568,561	66,360,878
(Deficit) surplus of funding over expenditures for the year	(1,781,165)	1,308,495
Fund balances - Beginning of year	5,141,343	3,832,848
Fund balances - End of year	3,360,178	5,141,343

TRIUMF
Notes to Financial Statement

1 Nature of operations

TRIUMF is Canada's national laboratory for particle and nuclear physics, owned and operated as a joint venture by the University of Alberta, Carleton University, the University of Victoria, Simon Fraser University, the University of British Columbia, L'Université de Montréal and the University of Toronto, under a contribution from the National Research Council of Canada. As a registered charity, TRIUMF is not subject to income tax.

At March 31, 2009, each university owned an undivided 14.3% interest in all the assets and was responsible for 14.3% of all liabilities and obligations of TRIUMF, except for the land and buildings occupied by TRIUMF, which are owned by the University of British Columbia. On April 1, 2009, The University of Manitoba became a joint venturer; each venturer's interest is now 12.5%.

These financial statements include only the assets, liabilities, funding and expenditures of the activities carried on under the control of TRIUMF and do not include the other assets, liabilities, revenues and expenditures of the individual joint venturers. Sources of funding include grants and contributions from the National Research Council of Canada, the Natural Sciences and Engineering Research Council, and governments; advances and reimbursements from other sources; royalty income; and investment income. TRIUMF has established a number of separate funds to account for the various funding sources. The sources and purposes of these funds are:

National Research Council Fund (NRC)
Funding of operations, improvements and development; expansion of technical facilities (buildings excluded); and general support for experiments.

Natural Sciences and Engineering Research Council Fund (NSERC)
Funding to grantees for experiments related to TRIUMF activities. These funds are administered by TRIUMF on behalf of the grantees.

MDS NORDION Inc. Fund
Advances and reimbursements from MDS NORDIAN Inc. for expenditures undertaken at its TRIUMF site.

Advanced Applied Physics Solutions Inc.
Advances and reimbursements from Advanced Applied Physics Solutions Inc. for expenditures undertaken at the TRIUMF site.

Canada Foundation for Innovation (CFI)
Funding to grantees for capital projects related to TRIUMF activities. These funds are administered by TRIUMF on behalf of the grantees.

Affiliated Institutions Fund
Advances and reimbursements for expenditures undertaken on behalf of various institutions from Canada and abroad for scientific projects and experiments carried out at TRIUMF.

Commercial Revenue Fund
Royalties, revenue and expenditures relating to commercial activities and technology transfer.

General Fund
Investment income for discretionary expenditures incurred by TRIUMF.

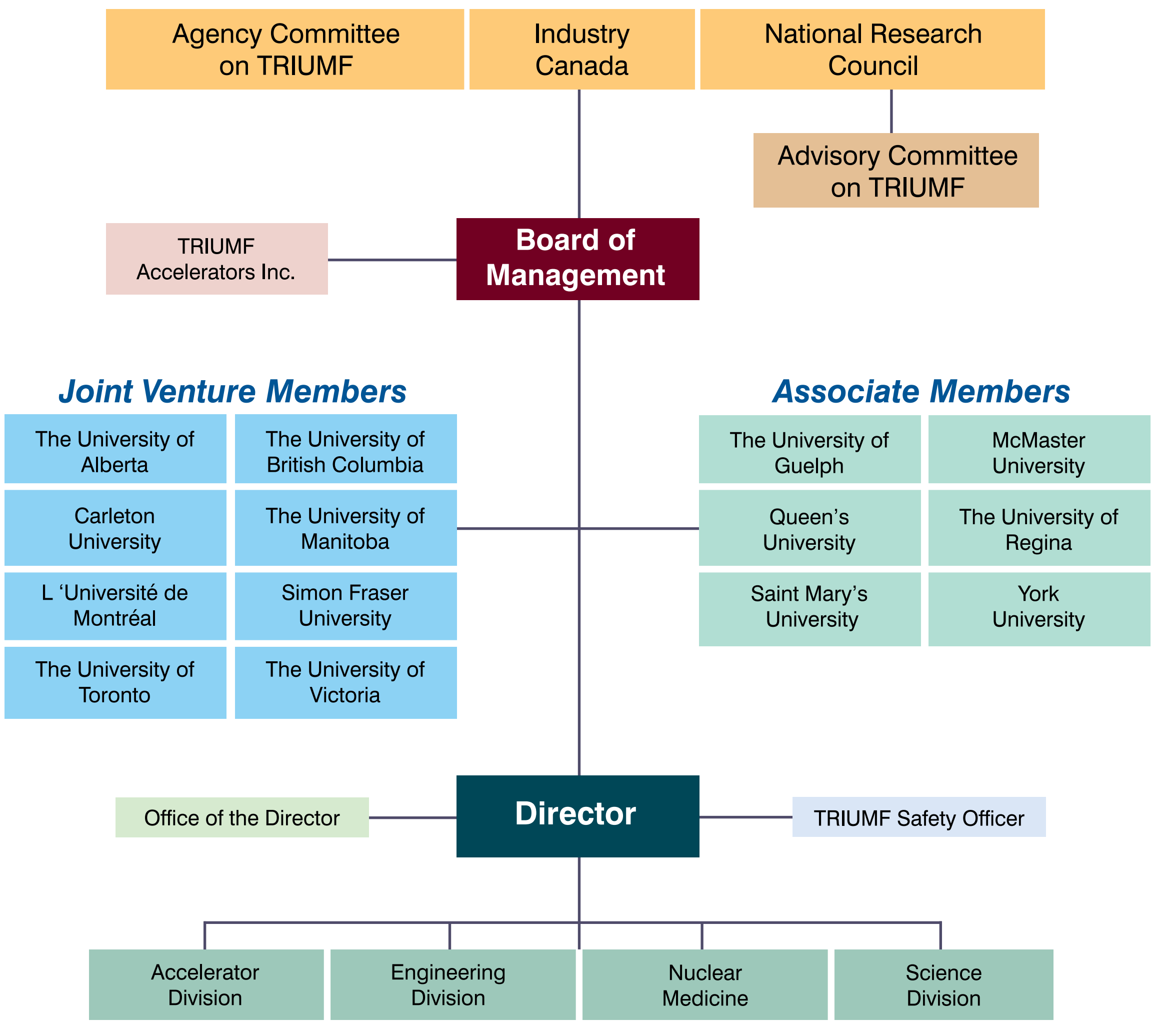
TRIUMF House Building Fund
Contributions from unrestricted funds and expenditures for the construction of TRIUMF House.

Intramural Accounts Fund
Net recoveries for internal projects and services. The recoveries of expenditures are charged to the appropriate TRIUMF funding source by Intramural Accounts.

2. Significant accounting policies

These financial statements have been prepared in accordance with section 11b of the TRIUMF joint venture agreement and the contribution agreement with the National Research Council of Canada, and follow Canadian generally accepted accounting principles for not-for-profit organizations as referred to in the Canadian Institute of Cahrtered Accountants (CICA) Handbook, except that all property, plant and equipment purchased or constructed for use at TRIUMF and related decommissioning costs (if any) are expensed in the period in which the costs are incurred.

These financial statements do not include the accounts of TRIUMF Accelerators Inc. (TAI), a not-for-profit federal corporation incorporated in 2006 and controlled by TRIUMF. The only asset held by TAI is the operating license issued by the Canadian Nuclear Safety Commission, which was recorded at the exchange value of nil. Since inception TAI has not incurred any expenses or liabilities and has not recognized any revenue.


Agency Committee on TRIUMF
Industry Canada
National Research Council
Advisory Committee on TRIUMF
TRIUMF Accelerators Inc.
Board of Management
Joint Venture Members
The University of Alberta
The University of British Columbia
Carleton University
The University of Manitoba
L ‘Université de Montréal
Simon Fraser University
The University of Toronto
The University of Victoria
Associate Members
The University of Guelph
McMaster University
Queen’s University
The University of Regina
Saint Mary’s University
York University
Office of the Director
Director
TRIUMF Safety Officer
Accelerator Division
Engineering Division
Nuclear Medicine
Science Division

Participants at the International Symposium on Radiohalogens (6ISR) hosted by TRIUMF in Whistler, British Columbia.

Participants at the ALPHA Collaboration Workshop at TRIUMF.

Some of the 450 conference participants at the XXIV International Linear Accelerator Conference (LINAC08) hosted by TRIUMF in Victoria, British Columbia.

TRIUMF

Canada's National Laboratory for Particle and Nuclear Physics

TRIUMF is owned and operated as a joint venture by a consortium of Canadian universities via a contribution from the Government of Canada through the National Research Council of Canada.

The Province of British Columbia provides capital funding for the construction of buildings for the TRIUMF laboratory.

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