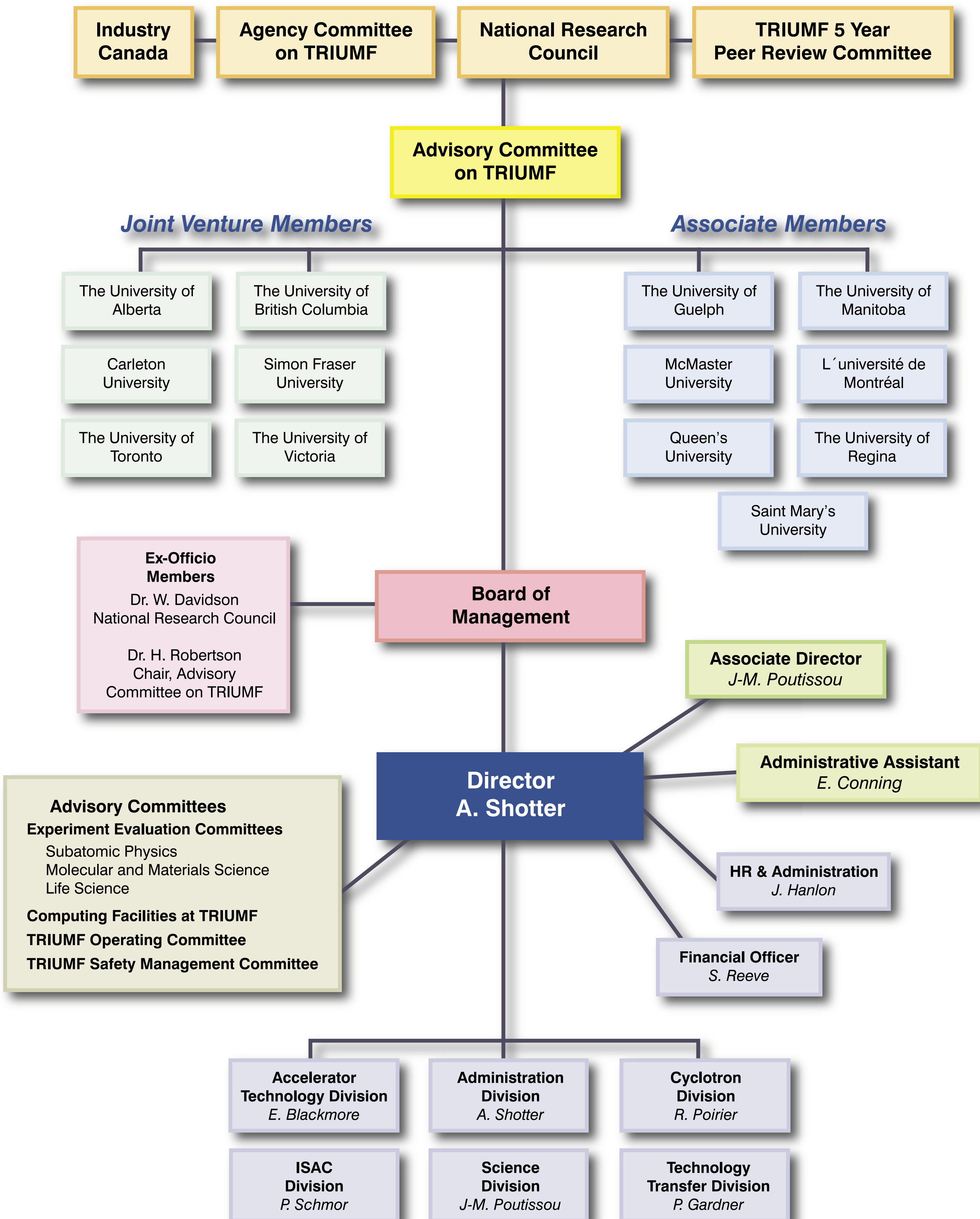
TRIUMF

TRIUMF IS CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

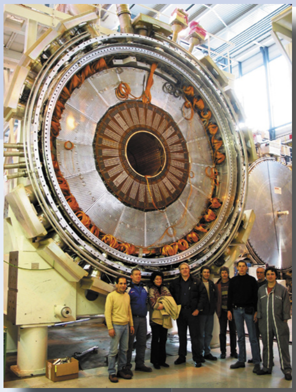
Annual Financial & Administrative Report
2004-2005

TRIUMF Organization Chart

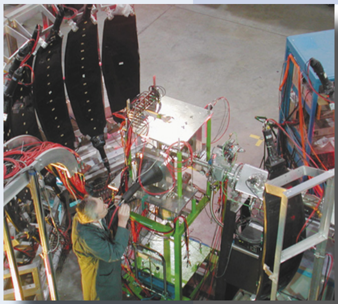


Contents

Back Cover Photos



An endcap calorimeter designed and constructed by Canadian scientists for the ATLAS experiment at CERN



OSAKA experiment at TRIUMF

Alan Shotter presents Suzy Lapi with the Life Science Scholarship

Cover Photo
A cryomodule for the superconducting linear accelerator at TRIUMF

TRIUMF technicans assembling the medium beta cryomodule

Editors: Ken Dawson/Melva McLean
Coordinator: Shirley Reeve
Design/Layout: Mindy Hapke

Director's Report

TRIUMF Director
Alan Shotter

This has been an exciting year for TRIUMF; groundbreaking results are emerging from the scientific program; new facilities are coming on line and TRIUMF is making a significant impact on a new high profile international neutrino experiment. In addition, during the year the University of Toronto joined TRIUMF's consortia of universities as a full member and Saint Mary's University joined as an associate member. TRIUMF now has six full member universities and seven associate member universities, representing every region of Canada.

With so much activity in the laboratory, it is essential that sound financial and administrative procedures be in place to establish firm boundaries, while still allowing for an element of flexibility in TRIUMF's operations. Scientists and engineers need an environment that allows them to work creatively, and TRIUMF's Financial and Human Resources staff are instrumental in helping to create an environment that fosters creativity. TRIUMF is very fortunate to have talented people who, for many years, have overseen the essential financial and administrative activities that make the laboratory so vital. In particular, this report shows that with their assistance, TRIUMF has used its resources very well in the pursuit of excellence in Canadian science.

The mission of scientists is the pursuit of knowledge and understanding of the world and the universe in which we live. Scientists have a responsibility to transfer the knowledge they gain through their work to companies and to individuals who can exploit this knowledge for the benefit of society. TRIUMF encourages this transfer of knowledge through the activities of the TRIUMF Technology Transfer Division. One of TRIUMF's main successes in the area of technology transfer is our long-standing collaboration with MDS Nordion Inc. Using TRIUMF-run cyclotrons, MDS-Nordion Inc. produces medical isotopes, which are distributed across North America and internationally. These isotopes are used for medical therapy and diagnostic purposes. Currently, over two and one-half million patient procedures are carried out each year with isotopes produced at TRIUMF. The Natural Sciences and Engineering Research Council (NSERC) recognized this unique collaboration and its achievements by awarding the 2004 University-Commercial Synergy Award to TRIUMF and MDS Nordion Inc. TRIUMF will use the financial portion of the prize to award scholarships to Life Science students involved in TRIUMF-based Life Science research.

Although this is a financial and administrative report, a large part of the report highlights some of the exciting scientific experiments and projects taking place at TRIUMF. Let me give you a few highlights.

TRIUMF has developed the most advanced beam of the isotope ^{11}Li in the world. This beam has been used to probe the electrical charge distribution of this very exotic nucleus. The Canadian-German scientific team undertaking this work has produced groundbreaking results that are of great interest to scientists around the world.

During the year, TRIUMF established a collaboration with the Japanese accelerator facility J-PARC to undertake an experiment that will help explain the enigmatic nature of one of the most populous particles in the universe, the neutrino. This exciting experiment follows from the successful work carried out at the Canadian Sudbury Neutrino Observatory (SNO).

TRIUMF's ISAC program requires continuous development of new, isotopically pure isotopes. A particularly good method of producing these isotopes, but technically very challenging, is to use high-powered lasers to selectively ionize the short-lived isotopes once they have been produced in the target. During the year, experimenters at TRIUMF used the first laser-ionized, pure isotopic beam. The laser ionization project is over a year ahead of schedule and shows great promise to be the method of choice to produce such beams in the future.

During the year, significant milestones were reached and passed in the construction of the new ISAC-II accelerator. Reaching and passing these milestones is particularly significant because a new type of technology, involving superconducting radio cavities, had to be mastered by the TRIUMF Accelerator Division. It is immensely pleasing that during the year a section of the superconducting accelerator was completed and shown to accelerate successfully alpha particles from a radioactive source. The challenge ahead for TRIUMF is to build all the necessary sections required to complete the full ISAC-II accelerator.

Around the world, nanoscience is emerging as a very important scientific field, showing great promise to transform many aspects of our daily lives. In collaboration with scientists from B.C. universities, TRIUMF has developed a special technique, β-NMR, to probe nanostructures. During the year, important new results demonstrated the tremendous power of this technique, which will undoubtedly contribute very significantly to the development of this new field.

As noted above, for an organization like TRIUMF, good financial and administrative staff are essential, but so are many other support activities. In particular, the skills of the people in the TRIUMF electrical and mechanical engineering fabrication workshops make it possible for TRIUMF to produce much of its scientific equipment on site. It gives me great pleasure to acknowledge the skill and dedication of the technical people that "make things happen" in the TRIUMF workshops.

Students, undergraduates, and postgraduates are our future. As in previous years, TRIUMF was host to many student groups during the year. In particular, a successful Summer Institute was hosted by TRIUMF for young scientists fascinated by the nuclear processes that drive the dynamics of stars. The summer school was planned to coincide with a TRIUMF hosted international conference on astrophysics, the same subject the students were studying.

TRIUMF has had a very successful year. That TRIUMF is attracting young students and scientists is particularly pleasing to me and to all of us at TRIUMF; our success is their future.

AUDITORS' REPORT

To the Joint Venturers of TRIUMF

The accompanying summarized statement of financial position and combined statement of funding/income and expenditures and changes in fund balances are derived from the complete financial statements of TRIUMF as at March 31, 2005 and for the year then ended on which we expressed an opinion without reservation in our report dated May 16, 2005. Those financial statements were prepared to comply with section 7 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 the applicable Assurance Guideline 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 disclosure required by Canadian generally accepted accounting principles. Readers are cautioned that these financial statements may not be appropriate for their purposes. For more information on TRIUMF's financial position, results of operations and changes in fund balances, references should be made to the related complete financial statements.

PricewaterhouseCoopers LLP

Chartered Accountants
Vancouver, B.C.
May 16, 2005

TRIUMF

Statement of Financial Position
As at March 31, 2005

	2005 $	2004 $
Assets		
Cash and temporary investments	5,967,433	4,688,950
Deposits	-	300,000
Funding receivable	1,103,237	924,672
Total assets	7,070,670	5,913,622
Liabilities		
Accounts payable	1,667,229	1,061,965
Funds received in advance	1,462,916	1,278,190
Bank loan	1,519,999	-
	4,650,144	2,340,155
Due to (from) joint venturers		
University of British Columbia	(27,599)	(89,432)
University of Alberta	(2,801)	(2,202)
University of Victoria	(4,886)	(1,523)
Simon Fraser University	4,023	(3,253)
	(31,263)	(96,410)
	4,618,881	2,243,745
Fund Balances		
Restricted		
Natural Sciences and Engineering Research Council Fund	3,001,993	2,628,181
MDS NORDION Inc. Fund	100,000	100,000
Canada Foundation for Innovation	(54,681)	(27,065)
	3,047,312	2,701,116
Other		
Commercial Revenue Fund	1,085,994	355,499
General Fund	3,171	10,574
TRIUMF House Building Fund	(2,413,204)	110,391
Intramural Accounts Fund	728,516	492,297
	(595,523)	968,761
	2,451,789	3,669,877
Total liabilities and fund balances	7,070,670	5,913,622

TRIUMF

Statement of Combined Funding/Income and Expenditures

For the year ended March 31, 2005

	2005 $	2004 $
Funding/income		
National Research Council Fund	40,000,000	40,000,000
Natural Sciences and Engineering Research Council Fund	5,300,363	5,704,966
MDS NORDION Inc. Fund	4,299,391	3,727,465
Canada Foundation for Innovation	1,203,511	1,495,216
Affiliated Institutions Fund	1,249,940	1,391,060
Commercial Revenue Fund	1,433,679	1,048,967
General Fund	140,701	120,281
	53,627,585	53,487,955
Expenditures		
Buildings and improvements	3,088,368	1,642,048
Communications	122,442	157,365
Computer	1,168,475	1,063,457
Equipment	6,563,773	8,478,874
Power	1,890,107	1,843,775
Salaries and benefits	33,014,827	31,760,528
Supplies and other expenses	8,997,681	7,867,075
	54,845,673	52,813,122
(Deficiency) excess of funding/income over expenditures for the year	(1,218,088)	674,833
Fund balances - Beginning of year	3,669,877	2,995,044
Fund balances - End of year	2,451,789	3,669,877

TRIUMF
Statement of Financial Position
As at March 31, 2005

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 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.

Each university owns an undivided 16.7% interest in all the assets and is responsible for 16.7% 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.

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 NORDION Inc. for expenditures undertaken at its 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 Fund

Contributions from unrestricted funds 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

Basis of presentation

These financial statements have been prepared in accordance with section 7 of the joint venture agreement (note 1) 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 Chartered Accountants 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.

TRIUMF Summer Institute

The TRIUMF Summer Institute (TSI) is a long-standing tradition at TRIUMF. Over the years it has attracted many students from Canada and around the world for a series of lectures on a wide variety of topics, all directly related to the leading-edge physics being pursued at TRIUMF. The 2004 TSI, the 16th in the series, took place at TRIUMF from July 5th to 16th and attracted 38 students from four continents. It was titled *Lectures in Nuclear Astrophysics: Experiment, Theory, and Observations*. The Institute is tailored for graduate students and young researchers in the field of particle and nuclear physics. The 2004 Summer Institute was planned to lead into a major international conference, also organized by TRIUMF, which started the following week: The 8th International Symposium on Nuclei in the Cosmos (NIC 8). The combination of a summer institute followed by a conference provided the students with an excellent introduction to the field.

The Institute is structured with formal lectures in the morning, followed by tutorial sessions in the afternoon, where open discussions are encouraged. This interaction between lecturers and students makes for interesting discussions and, at times, arguments. In this way everybody learns from the broad variety of questions raised and from the different viewpoints, both experimental and theoretical, that are expressed by the participants. Many universities recognize the TRIUMF Summer Institute as a formal course, which students can use for credit towards their degrees. This credit is based on successful completion of the Institute's assignments.

This year, in addition to the formal part of the Institute, three excursions were organized, including an ocean kayak trip. These excursions allowed for a more informal interaction between lecturers and students and led to many interesting and enlightening conversations (and some unplanned swimming activity).

Lecturers and their topics this year were:

T. Beers (Michigan State University, USA) Astrophysical Observations

F. Bosch (GSI Darmstadt, Germany) Mass Measurements of Astrophysical Interest

A. Cummings (McGill University) Explosive Nucleosynthesis

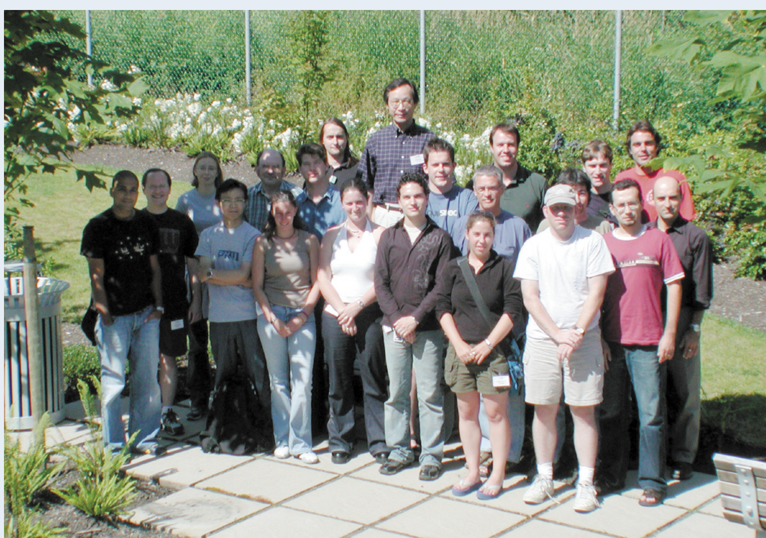
B. Davids (TRIUMF) Indirect Reaction Studies Relevant for Nucleosynthesis

C. Illiadis (University of North Carolina, USA) Direct Reaction Studies

T. Kajino (Natl. Astr. Observatory of Japan, Japan) Big Bang Nucleosynthesis

B. Mayer (Clemson University, USA) Stellar Evolution

A. Mezzacappa (Oak Ridge Natl. Lab, USA) Supernovae and Gamma-Ray Bursts



Lecturers, graduate students and young researchers attending the 2004 TRIUMF Summer Institute.

Jens Dilling, a Research Scientist at TRIUMF, chaired the Organizing Committee of the 2004 TRIUMF Summer Institute.

Experiments with ^{11}Li Beams at TRIUMF-ISAC

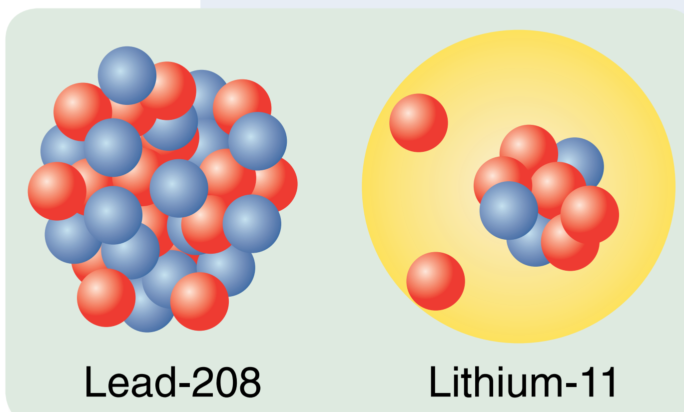
Greg Hackman is a Research Scientist at TRIUMF. He has worked on a variety of experiments in nuclear physics at TRIUMF and at foreign laboratories and has taught university physics. His main focus of research at TRIUMF is the development and construction of the TIGRESS Detector.

When ISAC is complete it will be the premier ISOL-type accelerated radioactive beam facility in North America. Already, when it comes to intensity of beams of the so-called "halo" nucleus ^{11}Li (Lithium-11), ISAC leads the world. A series of experiments with this beam has provided intriguing and important insight into how this halo nucleus behaves. This research has captured the attention of the international community and researchers from around the world are coming to ISAC to perform experiments with ^{11}Li.

To understand why the halo nucleus ^{11}Li is considered exotic, and to appreciate why it has been a centrepiece of nuclear physics research for over two decades, one first needs to understand how normal nuclei behave. It is well known that atomic nuclei are made of protons and neutrons. These subatomic particles are sufficiently similar that they are often referred to as a single type of particle, the nucleon. Their main difference is that protons carry an electric charge equal and opposite to that of the electron, while neutrons are electrically neutral. An atomic nucleus is characterized by its numbers of protons and neutrons, denoted Z and N respectively. The total number of nucleons, A ($=N+Z$), is the dominant factor in the mass of an atom. The size of the nucleus, or more precisely the distribution of nucleonic matter, is referred to as the *mass radius*. In most nuclei, the mass radius is proportional to $A^{1/3}$, as if the nucleus was just A spherical nucleons stuck together. Because the behaviour of the electrons – the atomic structure – is determined by the charge in the nucleus, it depends mainly on the number of protons, Z. How these charge-carrying nucleons are distributed inside the nucleus is reflected in the *charge radius*. In most nuclei, the charge and mass radii are nearly equal, which suggests that the protons are pretty evenly distributed throughout the nucleus. Z and N determine the *nuclear structure*. Different arrangements of protons and neutrons lead to different *states* with different energy levels and different *spins*, a quantum mechanical property roughly analogous to the rotation of a top. The lowest-energy arrangement is referred to as the ground state, while all others are called excited states.

TRIUMF-ISAC currently produces the world's most intense beams of ^{11}Li ions.

Even though protons and neutrons are similar, they populate different energy levels nearly independently. This means that the lowest available energy state of a proton cannot be populated with a neutron and vice versa. As such, combinations with equal numbers of each ($N=Z$) are energetically favoured, especially in light nuclei with less than 20 protons. Systems with too many neutrons will have too much excess energy; if there is too much energy, the nucleus will undergo decay processes to restore the proton-neutron balance. In the most extreme cases, the nucleus emits neutrons. Similarly, a system with a deficiency of neutrons may shed protons. These *particle-unbound* states survive on average for less than a billionth of a trillionth of a second. If there is not enough energy available to emit a neutron, the system will undergo beta decay, where a neutron turns into a proton by emitting an electron and a neutrino. This process can occur on time scales of thousandths of a second (milliseconds, or ms). Both these decay processes may leave the resulting system in an excited state, but with not enough energy to either beta decay or emit neutrons. The excess energy is then released as gamma rays, in average times of typically a trillionth of a second (picoseconds, ps).



Schematic comparison of the size of the "normal" nucleus ^{208}Pb to the exotic halo nucleus ^{11}Li.

The nucleus ^{11}Li, with eight neutrons (N=8) and three protons (Z=3), is particle bound, but undergoes beta decay with a half-life of only 8.3 ms. Over 90% of its decays leave the daughter nucleus ^{11}Be (Beryllium-11 with four protons and seven neutrons) in a highly-excited, particle-unbound state that then decays by emitting a neutron or a more exotic cluster of nucleons. Approximately half of all ^{11}Li decays are also accompanied by the emission of a gamma ray.

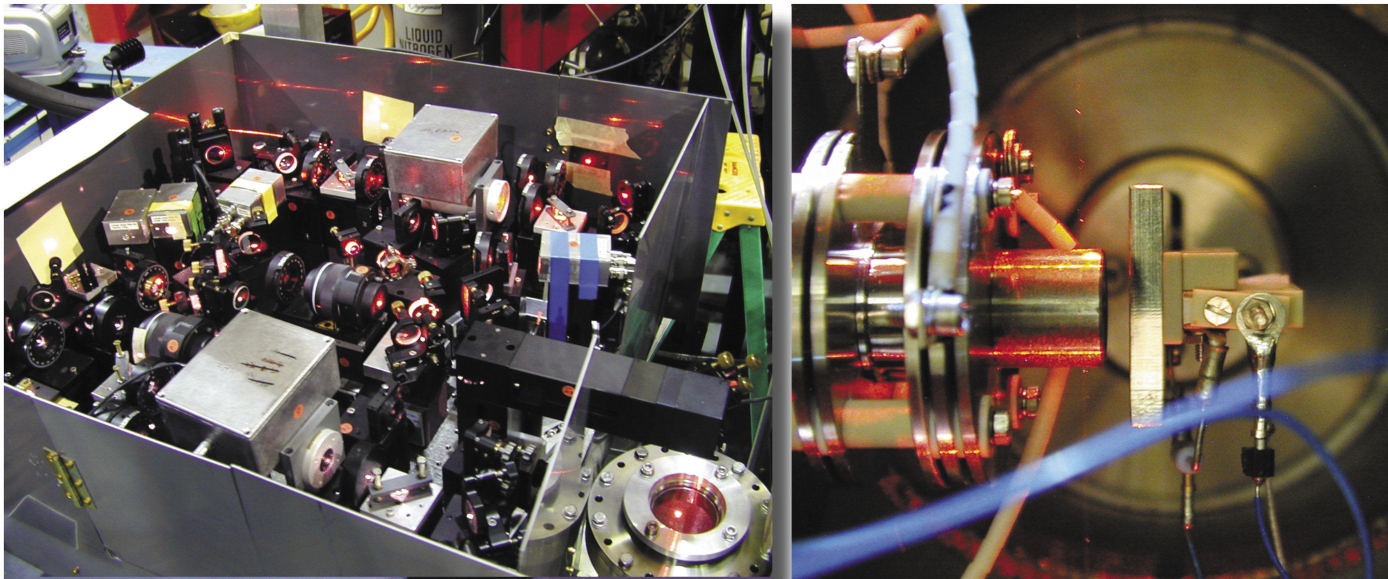
In the mid-1980s, it became clear that ^{11}Li was a special, exotic nucleus. The newest radioactive beam facilities of the day were able to produce a few ^{11}Li ions per second at high velocities. The first experiments with ^{11}Li beams suggested that its mass radius was not only much larger than those of other nuclei of the same A, like the stable nucleus ^{11}B (five protons, six neutrons), but that it was comparable in size to nuclei four times as massive. On further investigation, the evidence suggested that the ^{11}Li nucleus was comprised of a diffuse "halo" of two neutrons surrounding a core that resembled ^{9}Li (Z=3, N=6). In fact, the matter radius of those two neutrons alone was comparable to that of the largest nuclei observed in nature. Clearly, ^{11}Li was not "normal".

Even 20 years later, the neutron halo in ^{11}Li continues to capture the imagination and interest of nuclear structure scientists. The general understanding is the last two neutrons are weakly bound, i.e., they require little energy to be removed, and as a consequence, their mass radius would be large. However, this view raises a number of other questions. The weak binding of the halo suggests that it and the core can be treated as almost independent entities. Is that true? Does the core really behave like ^{9}Li? Equivalently, how does the halo interact with and modify the ^{9}Li core? How do the two neutrons interact with each other? How are nuclear reactions modified by the existence of a diffuse halo? In what other nuclei do these structures appear? The answers to these questions can be found in detailed measurements, for example, of atomic spectra, nuclear decay properties, and nuclear reaction rates. These questions are some of the motivations for investment in major accelerated radioactive beam facilities such as ISAC.

TRIUMF-ISAC currently produces the world's most intense beams of ^{11}Li ions. The ISAC production and ionization system can deliver up to 30,000 ions per second into the experimental area – four orders of magnitude more than delivered to those first experiments in which the halo was first observed. This far superior yield holds the promise of enabling precise and sensitive measurements of ^{11}Li and its decay products. So far, three experiments have been completed. In one, the charge radius of ^{11}Li was measured by atomic spectroscopy, while two separate gamma-ray spectroscopy experiments investigated the population of excited ^{10}Be states following beta and neutron emission. A fourth experiment on the complete spectroscopy of polarized ^{11}Li is ongoing, and experiments with accelerated ^{11}Li are planned for charged-particle decay spectroscopy and nuclear reaction studies.

As mentioned before, atomic structure is dominated by the number of protons, Z. Nevertheless, there is a small but measurable effect on the electronic structure due to the mass A with a tiny additional contribution from the charge radius. The effect appears as a change in the frequency (or colour) of light that can be absorbed by the ^{11}Li atom. The calculations for the mass-related part of the shift are challenging but are now possible, so that the tiny charge radius contribution to the shift can be isolated. Once measured, the charge radius can be used to understand the interaction between the halo and the core. If that interaction is small, then the core will be unchanged by the halo and the charge radius of ^{11}Li will be identical to that of ^{9}Li. In an extreme case where the neutron halo interpretation is in fact wrong, and where the whole of the nuclear matter, including the charge-carrying protons, is diffuse, the charge radius will be as large as the matter radius. The truth will likely fall somewhere in-between. The measured charge radius can then be compared to predictions of a variety of detailed nuclear structure theories. Each of these theories can explain the charge radii of the lithium isotopes from A=6 to 9, but they give different predictions for ^{11}Li itself. The goal is to measure the frequency of light that is absorbed by ^{11}Li atoms, deduce the charge radius of the ^{11}Li nucleus, and determine which theory can best describe the most weakly bound, neutron-rich nuclei.

Over the last five years, a team of German scientists working at GSI Darmstadt has refined the atomic laser-spectroscopic techniques, while Canadian theoreticians have developed the atomic theory needed for this measurement. Lithium ions (stable or otherwise) are implanted into a carbon foil, where they attract an electron to become a neutral atom. The foil is then heated to evaporate the lithium atoms, which then fly into an interaction region where they cross two merged laser beams. One laser is tunable near the correct resonance frequency to excite the atom, i.e., to promote electrons between specific energy levels, while the second laser is designed to strip an electron from only those atoms that have already been excited. The first laser is tuned across a range of frequencies, and the ions are counted. The number of ions rises from near zero to a maximum when

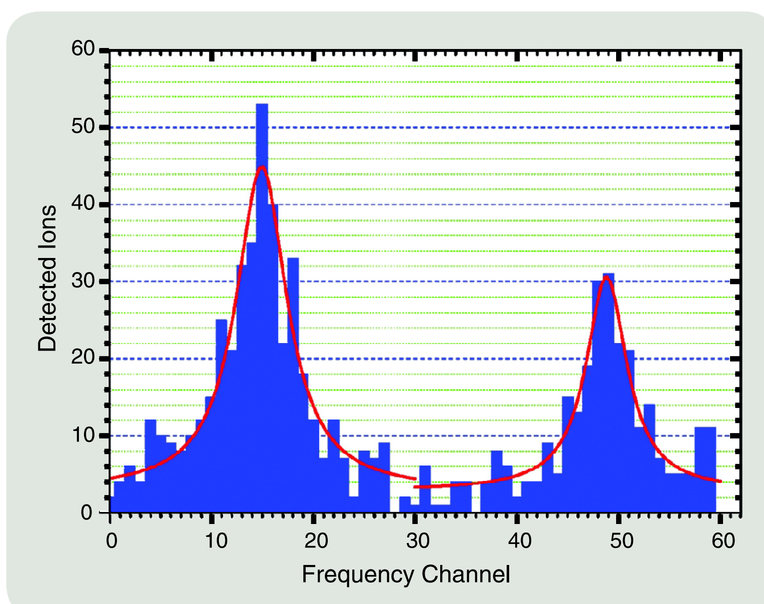


Part of the laser setup (left) and a view into the interaction region (right) for ^{11}Li atomic spectroscopy.

the laser frequency matches an atomic transition energy, i.e., when it is in resonance, then decreases to zero again. The charge radius of the nucleus, then, can be extracted from the difference in frequency between certain pairs of these resonances. The technique has been developed and tested at GSI with both stable (^{6,7}Li) and radioactive (^{8,9}Li) ions. However, extending the measurement to ^{11}Li has faced two challenges. First, because of its short half-life, the whole process of implanting, evaporating, re-ionizing, and detecting these exotic atoms must be fast enough to ensure that the measurements can be made before the atoms have decayed. This optimization has been done at GSI. Second, producing enough ^{11}Li and delivering it to an experiment for implantation in a thin foil is itself a separate challenge. Only TRIUMF-ISAC can deliver enough ^{11}Li at the right energy for this experiment.

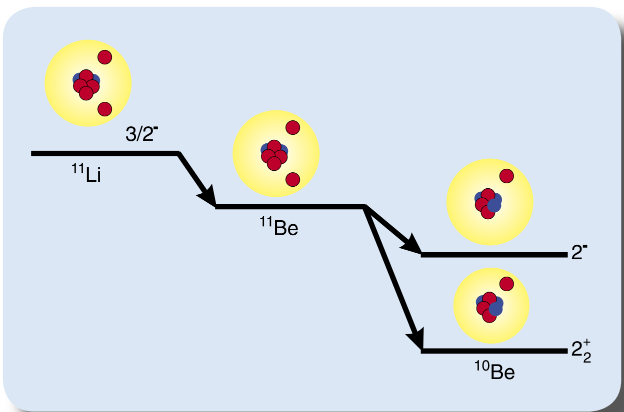
The team, led by Dr. Wilfried Nörtenhäuser of the University of Tübingen, is an international collaboration of German, Canadian and American scientists. The GSI equipment was installed on an ISAC low-energy beam line, and measurements on ^{6,7,8,9}Li were reproduced before the team turned its focus to ^{11}Li in October, 2004. More than 100 spectra of ion counts at different laser frequencies, like the one shown in the figure, were recorded during an experimental run of two weeks in October, 2004. The exact position of the resonance centres contains the information about the nuclear charge radius of ^{11}Li.

The online data have shown that the electric charge of ^{11}Li is indeed concentrated in a ^{9}Li-like core; ^{11}Li definitely has a neutron halo. A statement on the degree of interaction between the halo and core must await full analysis of the data. All spectra are now being carefully analyzed, and the final accuracy of the nuclear charge radius is expected to be on the order of 3%, which will be adequate to distinguish which nuclear theory describes the ^{11}Li system best. This has broader implications. Much of our understanding of how the heaviest elements in the universe are created is based on calculations of the properties of heavier neutron-rich nuclei. These calculations have the same problems as the ^{11}Li calculations; even though they can be fit to describe nuclei we *know*, they predict different answers for the nuclei we *need*. The conclusions from the ^{11}Li measurement will impact how we view the production of heavy elements through neutron-rich channels.



A pair of resonance signals in ^{11}Li.

One of the consequences of a weak interaction between the halo and core of ^{11}Li is that the beta decay process could occur in one without perturbing the other. For example, a decay process in the ^{9}Li core could leave the ^{11}Be residual system in a configuration with a ^{9}Be core and an unperturbed two-neutron halo. This would likely be particle unbound and emit one of the halo neutrons immediately. The resulting state in ^{10}Be would also be an excited, halo-like configuration that would emit gamma rays.



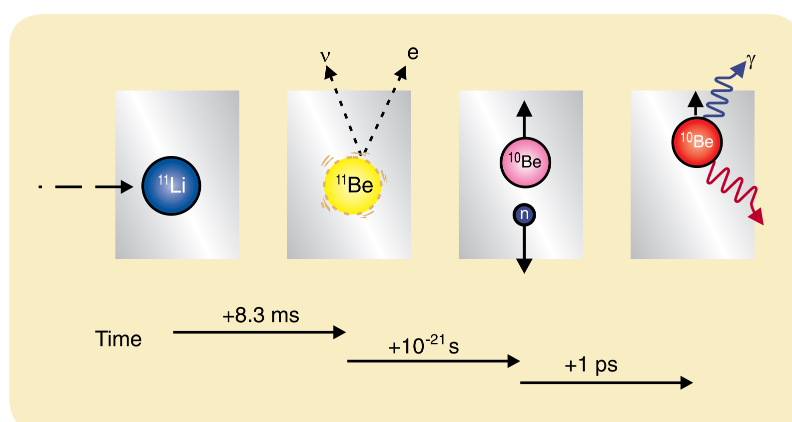
Schematic diagram of a ^{11}Li decay path in which the ^{9}Li core first decays to ^{9}Be, then one of the neutrons in the halo is emitted. The remaining neutron "survives" in a halo-like configuration in ^{10}Be.

In a beta-neutron-gamma decay cascade, the particle decay of the ^{11}Be will impart a recoil velocity to the ^{10}Be. As a result, the gamma rays will be Doppler-shifted. In the same way that a train whistle has a higher pitch when it is moving towards you than when it is moving away, gamma rays emitted in the same direction as the recoil have a higher energy (frequency) than those emitted in the opposite direction; when measured with a high-resolution detector, the gamma rays will appear "blue-shifted" with higher energy if they are emitted in the same direction as the ^{10}Be recoil is moving, or "red-shifted" if they are emitted in the opposite direction. In an experiment, we observe a range of energies, where the maximum width directly shows the initial velocity of the ^{10}Be recoil and, as a result, the total energy involved in the particle decay.

In typical beta-gamma decay experiments, the nucleus is implanted in a thin aluminum foil, where it is allowed to decay. In the case of ^{11}Li, after it decays and the ^{11}Be emits a neutron, the recoiling ^{10}Be will slow down, typically in a trillionth of a second. If an excited state has a long gamma-ray half-life, the ^{10}Be will on average be substantially slowed down before the gamma ray is emitted, and the Doppler-shifted blur will sharpen up. In fact, a detailed analysis of the gamma-ray lineshapes can determine both the energy of the state in ^{11}Be that emitted the neutron and the lifetime of the state in ^{10}Be that emitted the gamma ray. It is important to note that, with this technique, one can indirectly measure neutron energies with resolutions that approach or exceed that which is possible with direct neutron measurements.

These experiments require a high efficiency, high-energy resolution gamma-ray detector. The 8π spectrometer (see Financial Report 2003-2004) is ideal for this task. The first 8π experiment on ^{11}Li decay was performed in August, 2002 and analyzed over the course of two years. The strengths of observed decay branches, and more importantly the fact that certain decay paths were not observed, suggested that in one set of ^{11}Li-^{11}Be-^{10}Be decay paths, the neutron halo does persist. However, the data also suggested that the structure of the intermediate ^{11}Be halo state is more like a two-neutron halo coupled to a ^{9}Be core that is not its ground state but is in an excited configuration instead.

The 2002 data are consistent with the halo survival scenario but are not conclusive. Following publication of the results from the first data set, the experiment was repeated in October, 2004. At that time, SCEPTAR (see Financial Report 2003-2004) was available to positively identify beta-gamma coincidences and reject room backgrounds that had interfered with analysis of the first data set. Prof. Frederic Sarazin of the Colorado School of Mines is leading this effort, which he began when he was a research associate at TRIUMF.

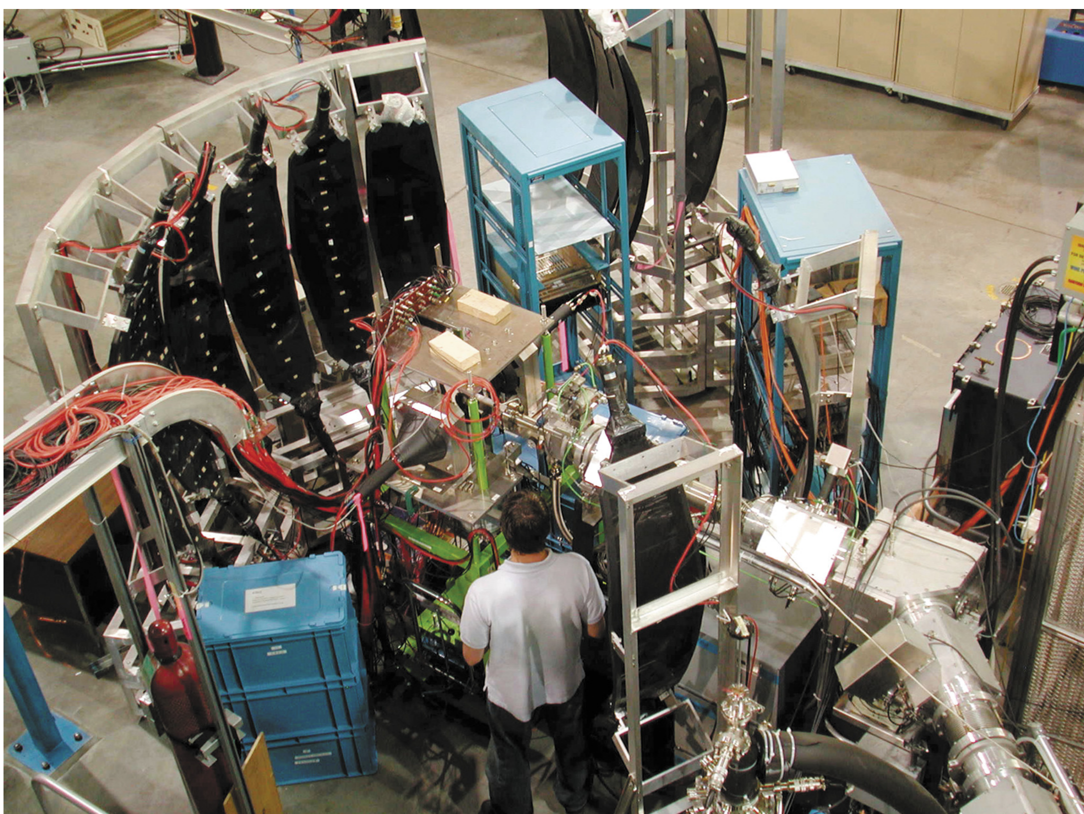


^{11}Li is implanted; it beta decays to ^{11}Be; a neutron is emitted, and ^{10}Be recoils; ^{10}Be slows down and gamma rays are emitted. A gamma ray emitted in roughly the same direction that the ^{10}Be is moving will have its energy increased (blue); if it is emitted backwards, its energy is decreased. The size of the shift depends on the speed of the recoil.

One limitation of the measurements just described is that they do not give a direct indication of the spins of states. The ground state of ^{11}Li has spin; it rotates like a top. In the 8π experiments, these tops are rotating in random directions. However, TRIUMF has unique capabilities for polarizing its radioactive beams, i.e., forcing particles in them to spin in the same direction. With polarized beams it is possible to determine, by direct measurement, the spins of states by measuring the directions in which decay particles are emitted. Prof. Tadashi Shimoda of Osaka University is leading such an experiment. Neutron, gamma, and beta spectrometers are used for direct measurements of the decay of polarized ^{11}Li beams. His interests are, specifically, the structures of so-called "cluster" states in ^{11}Be, which are predicted by a class of theories where nucleons preferentially form distinct structures within the nucleus. Results from the first two experiments have been published.

ISAC's intense ^{11}Li beams are now attracting the attention of teams of scientists from around the world, all attempting to bring their technical expertise to bear on a problem of specific interest to them. Two approved experiments will use ^{11}Li beams *and* the ISAC accelerator chain. In addition to the neutron decay branches of ^{11}Be following ^{11}Li beta decay, more exotic decays involving charged particles occur ~35% of the time. In an experiment led by Dr. Riccardo Raabe of the Katholieke Universiteit Leuven (Belgium), the ^{11}Li ions will be accelerated by ISAC-I and implanted into a charged-particle detector. The accelerated beam ensures that the ^{11}Li is implanted deeply enough so that the charged particles will not escape the detector, so that the full energy of the decays are properly measured. This experiment is scheduled for Spring 2005. Finally, Dr. Walter Loveland of Oregon State University has an approved experiment to study the possible use of accelerated ^{11}Li and other neutron-rich nuclei to produce superheavy elements at ISAC-II.

The world's most intense ^{11}Li beam has been used to complete three experiments, will complete a fourth, and is approved for two more. Today, the ^{11}Li beam is the centrepiece of the TRIUMF-ISAC nuclear structure and reactions programs, and it will remain prominent as the ISAC-II accelerators and experimental facilities are completed.



Apparatus for beta-neutron-gamma coincidence spectroscopy experiment with polarized ^{11}Li beam.

The Tokai-to-Kamioka ("T2K") Neutrino Experiment

Stanley Yen is a Research Scientist at TRIUMF. He has worked on a variety of experiments in nuclear and particle physics at TRIUMF and at foreign laboratories. His present research activity is development of the water-bearing liquid scintillator for the T2K near detector.

Neutrinos

Neutrinos: they are very small
They have no charge; they have no mass;
they do not interact at all.
The Earth is just a silly ball
to them, through which they simply pass
like dustmaids down a drafty hall
or photons through a sheet of glass.
They snub the most exquisite gas,
ignore the most substantial wall,
cold shoulder steel and sounding brass,
insult the stallion in his stall,
and, scorning barriers of class,
infiltrate you and me. Like tall
and painless guillotines they fall
down through our heads into the grass.
At night, they enter at Nepal
and pierce the lover and his lass
from underneath the bed. You call
it wonderful: I call it crass.

by John Updike
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Random House Inc.

Photograph of a ^{6}He nucleus decaying in a cloud chamber.

Introduction to Neutrinos

Particle physics seeks to understand the fundamental particles that constitute all of matter and the fundamental forces that govern how these particles interact. Surely the most intriguing particles are the ghost-like *neutrinos*, designated by the Greek symbol 'nu'(ν). Neutrinos have no electric charge; they have *almost* no mass; they have no measurable size; and they interact *rarely, so* rarely that it would take a wall of lead 5 light-years thick to stop them. Trillions of neutrinos from the Sun pass harmlessly through our bodies every second. Twenty percent of the energy produced by a nuclear power reactor is lost in the form of neutrinos, and 99% of the energy of a supernova explosion is given off in the form of neutrinos. It's important that we understand the properties of those facilities.

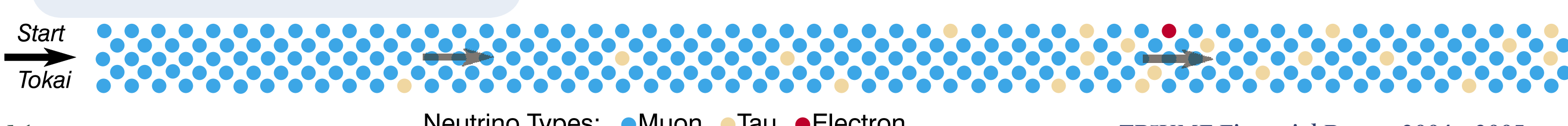
How do we know that such ghostly particles even exist? The story starts back in 1930 when physicists studied a type of nuclear decay called *beta decay*, in which a neutron embedded inside an atomic nucleus spontaneously changes into a proton plus an electron. One example of this is the nucleus ^{6}He (consisting of 2 protons and 4 neutrons), changing into the nucleus ^{6}Li (consisting of 3 protons and 3 neutrons). The equation for this nuclear decay can be written

$$\mathbf{^6He \rightarrow {}^6Li + e^-}$$

The ^{6}He parent nucleus is at rest when it decays. Now, if the right-hand side of the equation really had only two particles, then conservation of momentum would dictate that the ^{6}Li daughter nucleus and the electron would have to fly off in opposite directions. It's just like the situation when a stationary firework explodes; there must be as many fragments flying off in one direction as in the opposite direction. As Newton's third law states "For every reaction there is an equal but opposite reaction".

But photographs of these decays clearly show that the ^{6}Li and the electron do not fly off in opposite directions at all! This indicates that there must be a third, unseen particle emerging from this decay, to carry off the extra momentum. Because this third particle does not leave a visible track, it must have no electric charge, and therefore does not feel the influence of the negatively charged electrons and the positively charged nuclei that make up matter. Only very, very rarely does a neutrino react with other particles. In the language of chemistry, the neutrino is a very inert particle, about a trillion times less reactive than a proton. That means that you could shoot a trillion neutrinos through your body and only about one of them would react with the atoms in your body. All the others just zip right through us, through the walls, and through the whole earth.

Electrons are the most familiar example of a class of subatomic particles called *leptons*. Neutrinos are also leptons. Leptons have no size at all, as far as we can determine. The neutrino produced in the above reaction is an *electron neutrino*, because it is associated with an electron. Two other electron-like particles, which are much heavier than the electron, have been discovered in high-energy particle collisions. These are called the *mu* (μ) and the *tau* (τ).



Each of them has a corresponding neutrino, which are different from each other and different from the electron neutrino. We can arrange these particles in 3 pairs, or 3 "flavours", where each electron-like particle is shown with its corresponding neutrino.

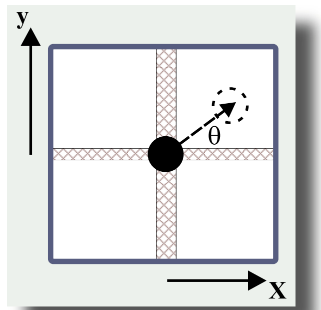
$$(e, \nu_e)\ (\mu, \nu_\mu)\ (\tau, \nu_\tau)$$

Until very recently, it was thought that leptons from one flavour could never change into a lepton of another flavour. This principle was called *lepton flavour conservation*. Neutrinos have very small masses; in fact, until the recent discovery of neutrino oscillations, it was thought that they had exactly zero mass.

Neutrino Oscillations

Using huge underground detectors, physicists are able to detect a few of the electron neutrinos produced by nuclear fusion reactions in the Sun. To their surprise, they have only detected about one-third as many as expected. Either something must be wrong with our understanding of nuclear processes in the Sun, or something must be happening to the neutrinos on the way to the Earth. Most neutrino detectors are sensitive primarily to electron-type neutrinos. The Sudbury Neutrino Observatory, which uses 1000 tons of heavy water located at the bottom of a nickel mine in Sudbury, Ontario, is unique in that it is sensitive to all types of neutrinos rather than only the electron-type. In 2002, scientists who worked with this detector announced that they measured the expected number of solar neutrinos when they counted all types of neutrinos, but observed a deficit when they counted only electron-type neutrinos. The conclusion was that most of the electron-type neutrinos produced in the Sun must have metamorphosed into mu-type or tau-type neutrinos on the way to the Earth. This process, the changing of neutrinos from one type to another, is called *neutrino oscillation*.

We can consider a mechanical analogy to understand how neutrino oscillations occur. Suppose we have a steel ball constrained by weak elastic bands in the horizontal (x) direction, and by stronger elastic bands in the vertical (y) direction, as shown in the next figure. If we displace the ball in the x direction away from its equilibrium position, and then let go, the ball will vibrate back and forth in the x direction, and this vibration will continue unchanged forever in the absence of friction. Similarly, if we start the ball vibrating in the y direction, that vibration will continue unchanged forever, but the frequency of that vibration will be higher than in the x direction because of the stronger force of the elastic bands in that direction. Vibrations like this, which continue unchanged perpetually, are called *normal modes* of a vibrating system.

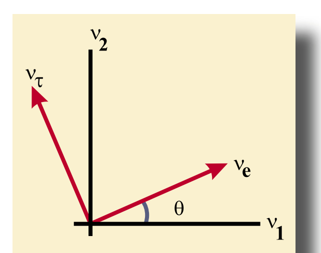


Steel ball and elastic bands: a mechanical analog to neutrino oscillations.

Now suppose we displace the ball from the equilibrium position not along the x or y axes as before, but at some angle θ from the x-axis, as shown by the dashed circle in the diagram. Because the elastic bands along the x-axis pull with a different strength than the elastic bands along the y-axis, the frequency of the component of vibration along the x-axis is also different than the frequency of the component of vibration along the y-axis. The net result is that the ball does NOT continue vibrating at angle θ forever, but the direction of the vibration changes with time.

According to quantum mechanics, all particles have a wave-like nature. The "wavefunction" of a particle vibrates just like this steel ball, and the frequency of the vibration, in cycles per second, varies with the mass of the particle. So, a lightweight particle's wavefunction vibrates with a low frequency, just like vibrations of the ball along the x-axis but a heavier particle's wavefunction vibrates with a higher frequency, just like vibrations of the ball along the y-axis.

By analogy with the steel ball, suppose a neutrino's wavefunction vibrates in one of two normal modes, call them ν_1 and ν_2. In the language of particle physics, these are called *mass eigenstates*. Let's also suppose that there were only two flavours of neutrinos, say ν_e and ν_τ. If an electron neutrino (ν_e) created by a nuclear reaction in the Sun corresponds to one of the mass eigenstates then it would stay that way forever, just like the steel ball vibrating in one of its normal modes. But suppose the ν_e is not emitted as one of the mass eigenstates. Then the ν_e direction is skewed with respect to ν_1 direction by some angle θ, the mixing angle, as shown. Also suppose that the mass of ν_1 is different than the mass of ν_2, so that the two frequencies of vibration are different. This situation is exactly like that of the steel ball; that is the direction of



Neutrino oscillations require that the orientations of v_e and v_τ be tilted with respect to the normal modes of vibration v_1 and v_2, and that the two normal modes vibrate at different frequencies.

vibration changes with time, and a particle which starts out vibrating purely in the ν_e direction will eventually vibrate partly in the orthogonal ν_τ direction. In other words, some of the electron-type neutrinos will change into tau-type neutrinos. This is the basic idea behind the phenomenon of *neutrino oscillation*.

A proper mathematical analysis reveals the probability that a neutrino, which starts out as an electron neutrino, remaining an electron neutrino varies in a periodic way with the distance travelled. This probability starts out at one, a dead certainty, then decreases with distance to a minimum value, then increases back to one again as the distance continues to increase. Further distance increases see this variation repeat itself. The distance over which this variation repeats itself depends upon the mass difference between the two types of neutrino, while the maximum reduction in the probability that the electron neutrino will retain its identity depends on the angle between the ν_e and the ν_1 axes. If either this mixing angle or the mass difference is zero, then the neutrino will retain the identity with which it was created.

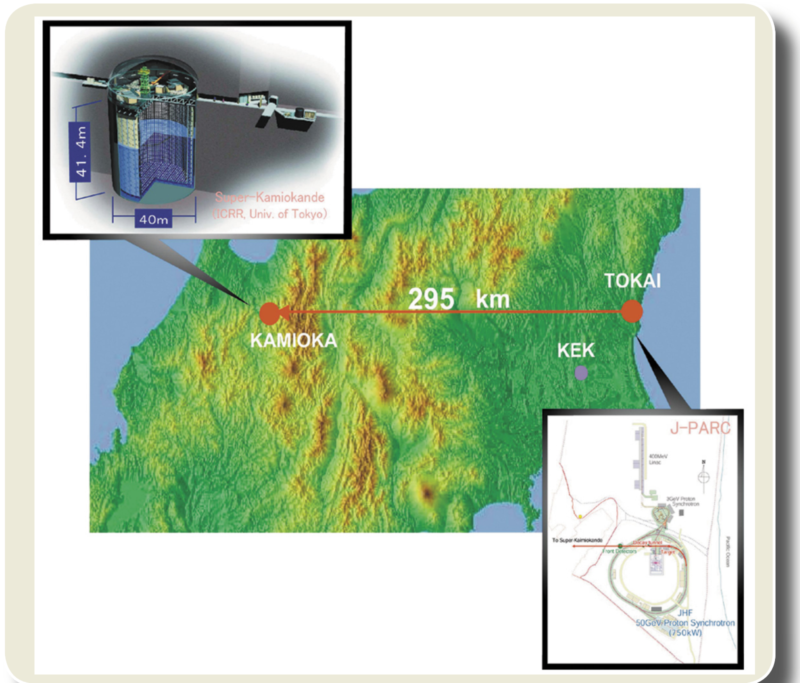
In reality there are three flavours of neutrinos (electron, mu, and tau), which complicates this picture but does not destroy its general validity. The observed oscillation of electron-type neutrinos from the Sun provides very clear evidence that neutrinos, previously thought to be massless do, indeed, have mass.

Evidence for neutrino oscillations also comes from the observation of muon-type neutrinos produced by high-energy cosmic rays hitting the earth's atmosphere. The number of downward-moving neutrinos, produced a few tens of kilometres overhead, can be compared with the number of upward-moving neutrinos, which have traversed the diameter of the Earth. A deficiency is observed in the upward muon neutrinos, which means the muon neutrinos must have oscillated into another type.

While the existence of neutrino oscillations shows that some neutrinos must have non-zero mass, that mass is very, very small. The electron is between 2.5 million and 10 million times heavier than the heaviest neutrino (and the hydrogen atom is about 2,000 times heavier than an electron). Very small indeed! However, since there are a billion times more neutrinos than there are protons in the universe, even a tiny neutrino mass can contribute significantly to the total mass of the universe.

The T2K Neutrino Experiment

Neutrinos from the Sun and neutrinos produced in the atmosphere by cosmic rays cannot be controlled in energy or direction. What we need to measure the mixing angles and masses accurately is an intense beam of man-made neutrinos of known energy, produced by a high-energy particle accelerator. This is the purpose of the 50 GeV synchrotron particle accelerator now under construction at the JPARC laboratory in Tokai, on the east coast of



The T2K experiment will shoot an intese beam of neutrinos from the J-PARC accelerator to the Super-Kamiokande detector 295 km away.

Japan north of Tokyo. This ring accelerator, 1568 m in circumference, will accelerate protons to energies of up to 50 GeV (50 billion electron volts), and produce the world's highest beam power of 0.75 megawatt. This high-energy, high-intensity proton beam will slam into a 0.9 m long graphite target, blowing apart the nuclei of the carbon atoms in the target and releasing vast numbers of subatomic particles called pi mesons. The positive pi mesons will be focused with a magnetic focusing device called a "horn", and made to fly down a 130 metre-long tunnel, during which time most of them decay into positive muons and muon neutrinos via the following reaction.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

The muons are stopped in a 4 metre-thick wall of graphite and copper, but the muon neutrinos go right through the wall. This neutrino beam, which will be the most intense one in the world, will then pass through a "near" detector

Start
Tokai
Neutrino Types: Muon Tau Electron

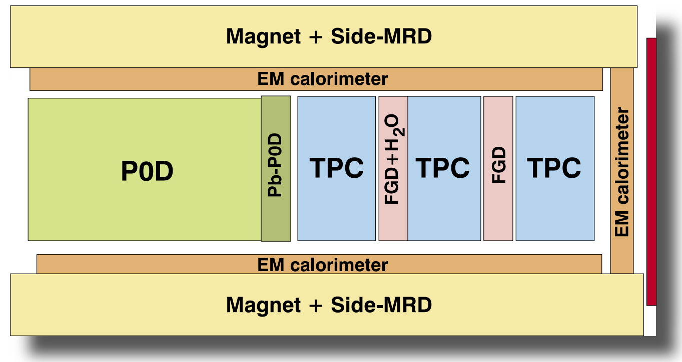
located 280 m from the end of the tunnel, and then fly 295 km to the *west* coast of Japan. There, buried under a mountain near the village of Kamioka, is the existing Super-Kamiokande "far" detector, which consists of 50,000 tons of super-pure water, viewed by 11,200 photomultiplier tubes (figuratively, electronic eyes, each 50 cm in diameter).

When neutrinos collide with the oxygen nuclei in the water, they create energetic muons or electrons: muon-type neutrinos make muons, and electron-type neutrinos make electrons. These muons or electrons make flashes of light called Čerenkov radiation in the water that can be detected by the photomultiplier tubes. The principle of the experiment is that we measure the population of electron-type and muon-type neutrinos in near and far detectors separately and then compare. The presence of neutrino oscillations would change the population of neutrinos in the 295 km between the near and far detectors. The objectives of the experiment are to (1) precisely measure the oscillation pattern for the disappearance of muon neutrinos, and thereby determine the associated mixing angle and mass difference with 10 times more precision than previous experiments; and (2) search for evidence of the appearance of electron neutrinos at the far detector, and thereby determine another, so far unmeasured, mixing angle.

Canada has a strong group of collaborators in the T2K experiment, comprised of physicists and engineers from TRIUMF and the Universities of British Columbia, Victoria, Toronto, York, Carleton, and Montreal. The Canadian contribution will be both to the beamline and to the experimental apparatus. The idea of using off-axis neutrinos to obtain a nearly monoenergetic beam was invented at TRIUMF. TRIUMF accelerator physicists have already contributed to the design of the combined function magnets for the proton beamline. Future beamline contributions will consist of the proton beam monitor, the design of the target stations, remote handling equipment, and radiation shielding. These items mesh well with the existing expertise at TRIUMF in beam and target handling in high- radiation environments.

The experimental apparatus will consist of the existing Super-Kamiokande as the far detector, and a new near detector that is now in the design stage. Canada will make important contributions to both of these. Using the expertise acquired at the Sudbury Neutrino Observatory, the Canadian group has built a movable laserball for calibrating the water Čerenkov near detector for the earlier-generation K2K experiment and will apply this same knowledge to build a calibration apparatus for the Super-K far detector.

The 280 m near detector is presently conceived as shown in the figure below.



The 280 m near detector has many sub-systems, several of which will be built by Canada.

The whole apparatus sits inside a large magnet formerly used for the UA1 experiment at CERN. Here, 'MRD' is a muon range detector, 'P0D' is a neutral pion detector consisting of interleaved plastic scintillator and lead sheet, 'TPC' is a Time Projection Chamber for measurement of the curvature of the particle tracks to calculate the particle momentum, and 'FGD' is a fine-grained detector to allow detection of the recoil protons and the muons from reactions of the type

$$\nu_\mu + n \rightarrow \mu^- + p$$

occurring on neutrons embedded inside atomic nuclei in the detector material. This is the principal reaction that allows us to determine the energy and direction of the incident muon neutrinos in the near detector. Because the far detector is made of water, which has a high oxygen content, we would like a near detector with a high oxygen content as well, in order to avoid systematic nuclear effects. To this end, the Canadian collaborators have devoted considerable effort towards developing water-bearing liquid scintillators for use in the "water+FGD" part of the near detector. Construction of the TPC is also the responsibility of the Canadian group, which takes advantage of the expertise in TPC's that were originally developed for the international linear collider.

The international particle physics community recognizes this experiment as the flagship neutrino experiment. The construction of the accelerator and neutrino beamline are fully funded by the government of Japan. The construction of the near 280 m near detector is a collaborative effort of researchers from Canada, USA, Japan, UK, France, Italy, Spain, and Russia. First beam for the neutrino experiment is expected to be delivered in 2009.

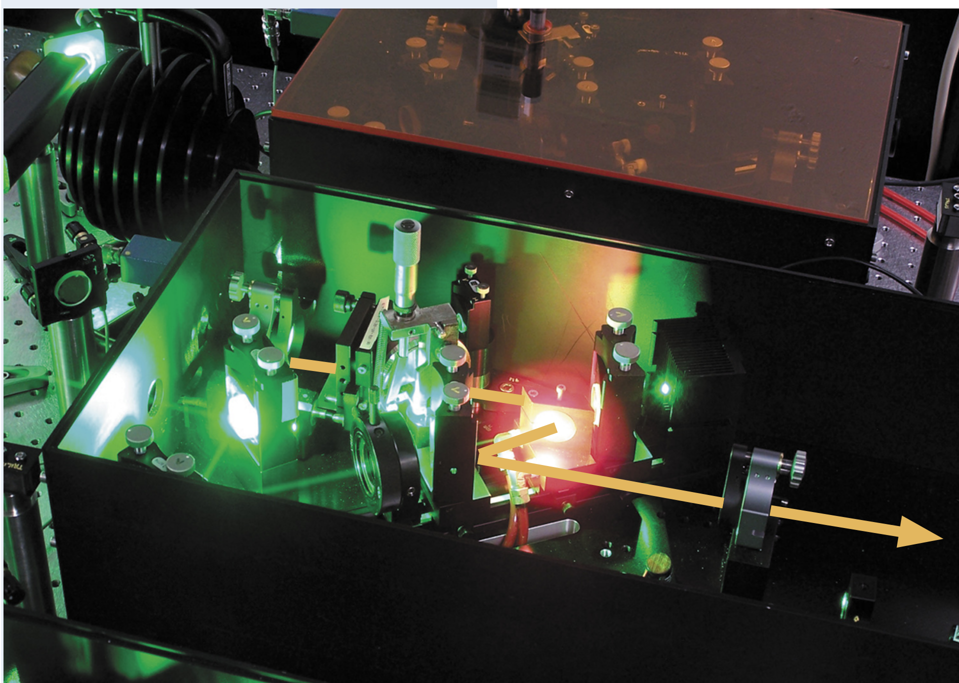
Kamioka

TRILIS A Unique Ion Source for Radioactive Ion Beam Production

Jens Lassen is a Research Scientist at TRIUMF. He has worked on the development and use of resonant laser ionization spectroscopy in the USA, Europe and now TRIUMF. His main focus of research and development at TRIUMF is the construction, application and physics of laser ion sources.

The TRIUMF Isotope Separator and Accelerator (ISAC) facility produces a wide variety of exotic, unstable isotopes for experiments in nuclear physics, nuclear astrophysics, tests of the Standard Model of particle physics, molecular and materials science. At the heart of a radioactive ion beam facility lies a production target. Here the high intensity, 500 MeV proton beam from the TRIUMF cyclotron bombards various target materials. The production target is heated to about 2,000°C, either by the beam itself or by external means. At such high temperatures, the products of the nuclear reactions in the interior of the target rapidly diffuse out to regions where they can be gathered and ionized. All this has to be done in a very hostile environment, one of high temperature and high radiation. Once charged, the isotopes can be formed into beams by electrical and magnetic forces and the beams directed towards the experimental apparatus.

The number of protons in the nucleus characterizes a chemical element, while an isotope is characterized by both the number of protons and the number of neutrons in the nucleus. The mass of a nucleus is given, roughly, by the sum of the number of protons and neutrons it contains. There are subtle, but important, effects upon mass arising from just how this sum is made. Different combinations of proton and neutron numbers having the same sum will form isotopes with slightly different masses, called isobars.

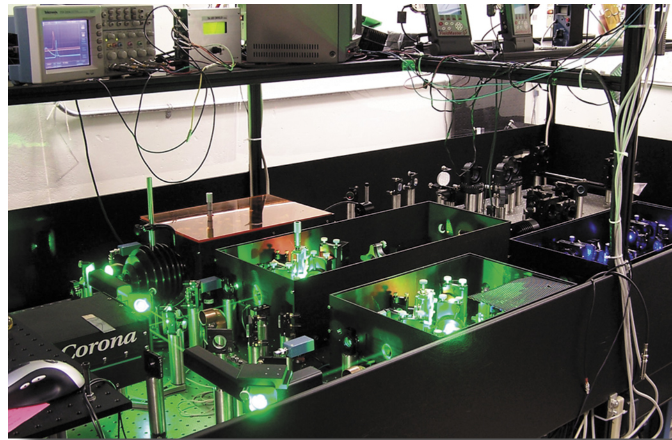


TRILIS titanium sapphire (TiSa) lasers fit into an 11”x17” space. The lasers were originally developed at Mainz University specifically for laser resonance ionization and ultra trace analysis.

Other than by choice of the target material, we have no control over the many different isotopes that are produced in the target. Calculated production rates, in nuclei per second, of the different isotopes produced when a 500 MeV proton beam bombards a uranium target are shown as a function of proton and neutron number (see figure on page 22). It illustrates how the target material usually breaks up asymmetrically into two fragments. Production rates are high for isotopes near the centre of the chart, which are mainly stable, long-lived isotopes, and fall off by over a factor of a million for those near the edges. The isotopes at the edges of the chart are exotic; some live for only a few milli-seconds. Each experiment requires that one specific isotope from one of the many low-yield, short-lived, exotic isotopes created be selected with high efficiency. In other words, the selection process must deliver only those nuclei that have both the required number of protons and the required number of neutrons.

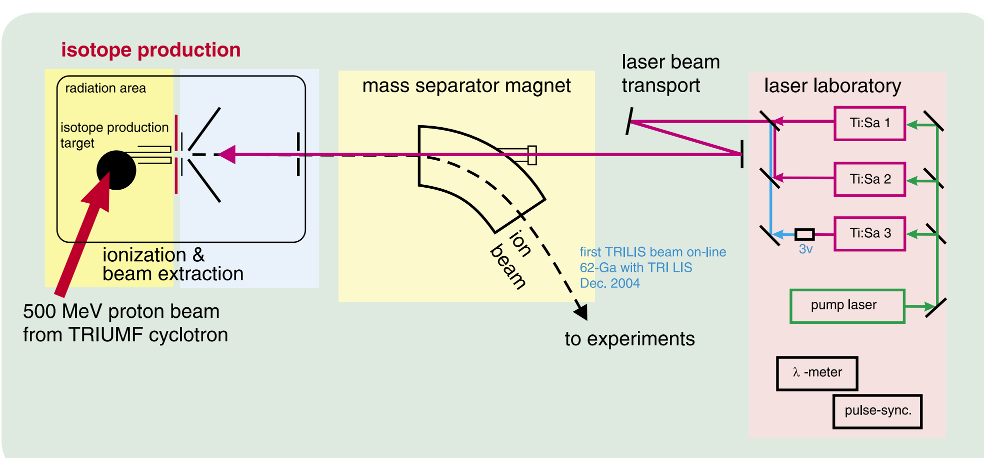
A universal ion source would simply ionize all isotopes emerging from the target, leaving the problem of selecting the particular one of interest to a high-throughput, high-resolution mass spectrometer. Isotope selection in such a device is based upon the ratio of the isotope's charge to its mass. In general, the lower the mass, the easier it is to efficiently select a single isotope. However, as the mass increases, relative differences in the charge-to-mass ratios decrease, leading to a requirement for increased resolution in the spectrometer. In addition, high resolution can be obtained only at the expense of reducing the throughput of the desired isotope to unacceptably low levels. High efficiency in selecting a particular isotope can be better obtained by combining the unique elemental selectivity of resonant laser ionization with low resolution, high throughput mass separation. In a resonant ionization laser ion source (RILIS), the selection of the desired element is based on the interaction of laser light with the atoms' valence electrons. The number of protons in the nucleus mainly determines the properties of the electrons circling around the nucleus of an atom; the properties of the electrons are specific to the type of element.

Electrons orbit around the nucleus of an atom in orbits that have well-defined energies and differ markedly for each element. Ionization occurs when one or more of these electrons is completely removed from an atom, leaving it with a net positive charge. Energetic collisions with other atoms, or the photoelectric effect in which a photon of light transfers its energy to an orbiting electron, can lead to ionization. Because electrons in orbit have well-defined energies, there is an energy below which ionization cannot occur. Any energy in excess of this ionization energy is given to the ejected electron. If the collision energy is less than the minimum for ionization, the electron can be moved to a higher energy, but still bound, orbit.



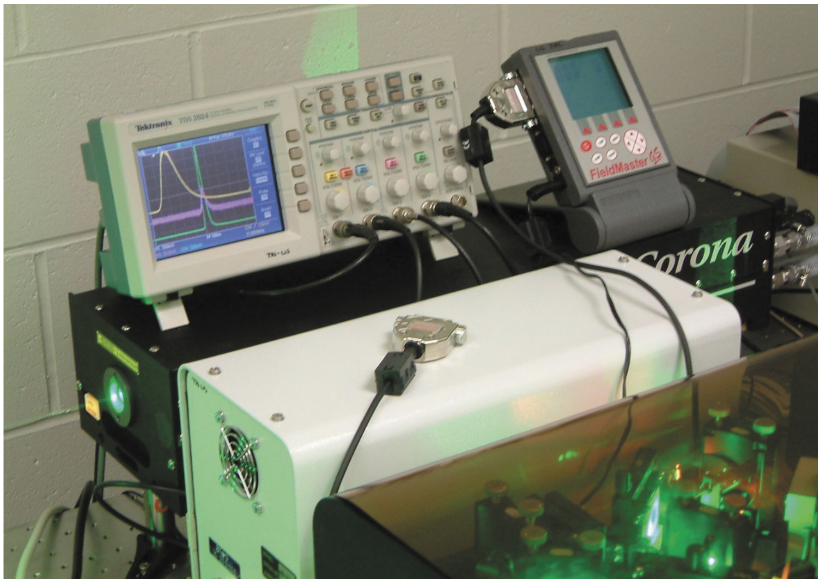
Lasers and frequency-tripling in operation at TRIUMF for the first on-line delivery of radioactive beams by resonant laser ionization in December 2004.

Rather than carrying out ionization in a single step, a RILIS uses several steps to improve efficiency and selectivity. A typical multi step laser excitation scheme is shown next to the periodic chart. Laser beams, which consist of photons of very well-defined energy (frequency), are used to add energy to an electron and move it from one orbit to a higher energy, less well-bound one. To do this, the photon energy and electron orbit energy difference must be exactly matched. This energy difference is a characteristic of each element, and it is this uniqueness that provides the element selectivity. What is done next depends upon the energy levels of the electrons in the selected isotope. It is possible that the photons from a second laser are capable of imparting sufficient energy to eject the electron, which has just been moved to a higher orbit, from the element and ionizing it. It is also possible for a second laser beam of well-defined energy to add more energy to the electron, raising it to an even higher energy, just below that required for ionization (Rydberg states). From there, the electron can be pulled off the isotope by a strong electric field. Whatever the second step, the basic idea is the same: first, selection of an element by resonant absorption of photons, and then ionization, using an energy insufficient to ionize all those isotopes not selected in the first step. The output of the RILIS is therefore, a mixture of the different isotopes of a given element. These differ



The TRILIS system consists of the laser system, beam transport and focusing of the lasers into the ionization region at the exit of the isotope production target. The laser light selectively ionizes isotopes of a particular element from the abundance of isotopes produced. A magnetic mass separator is used to analyze the ion beam and to select the isotope of interest to be sent to the experiments.

appreciably in mass. A magnetic spectrometer can be used with high efficiency to select from this mixture the isotope of interest.

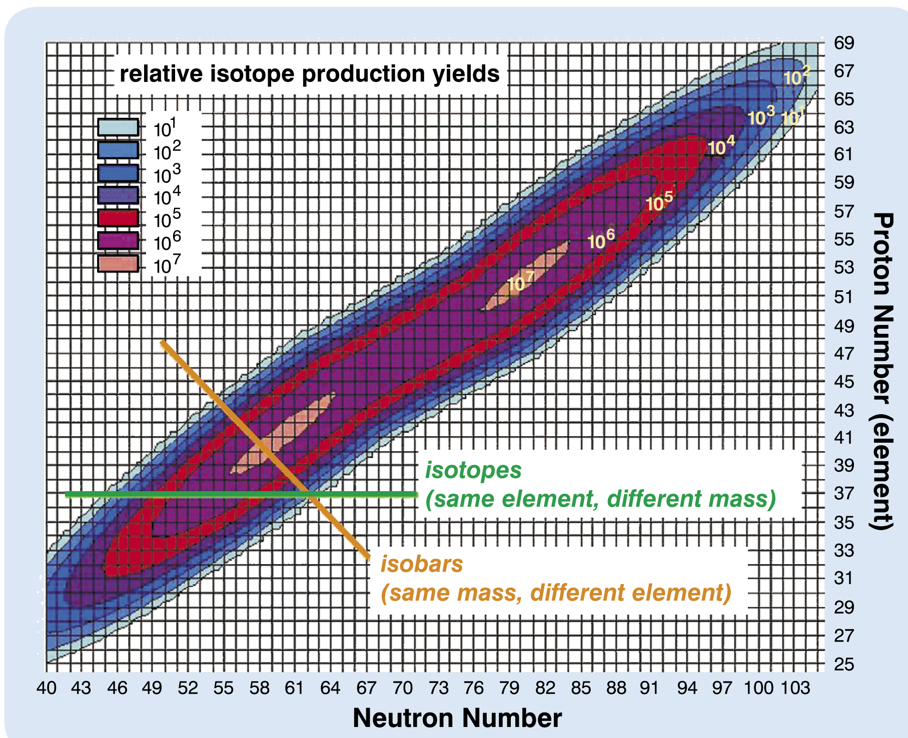


Compact, high-power solid-state pump laser, precision wavelength meter and pulse synchronization equipment. The long pump pulse (yellow trace, 160 ns) into the crystals of the TiSa lasers precedes the synchronized TiSa laser pulses (magenta and green trace).

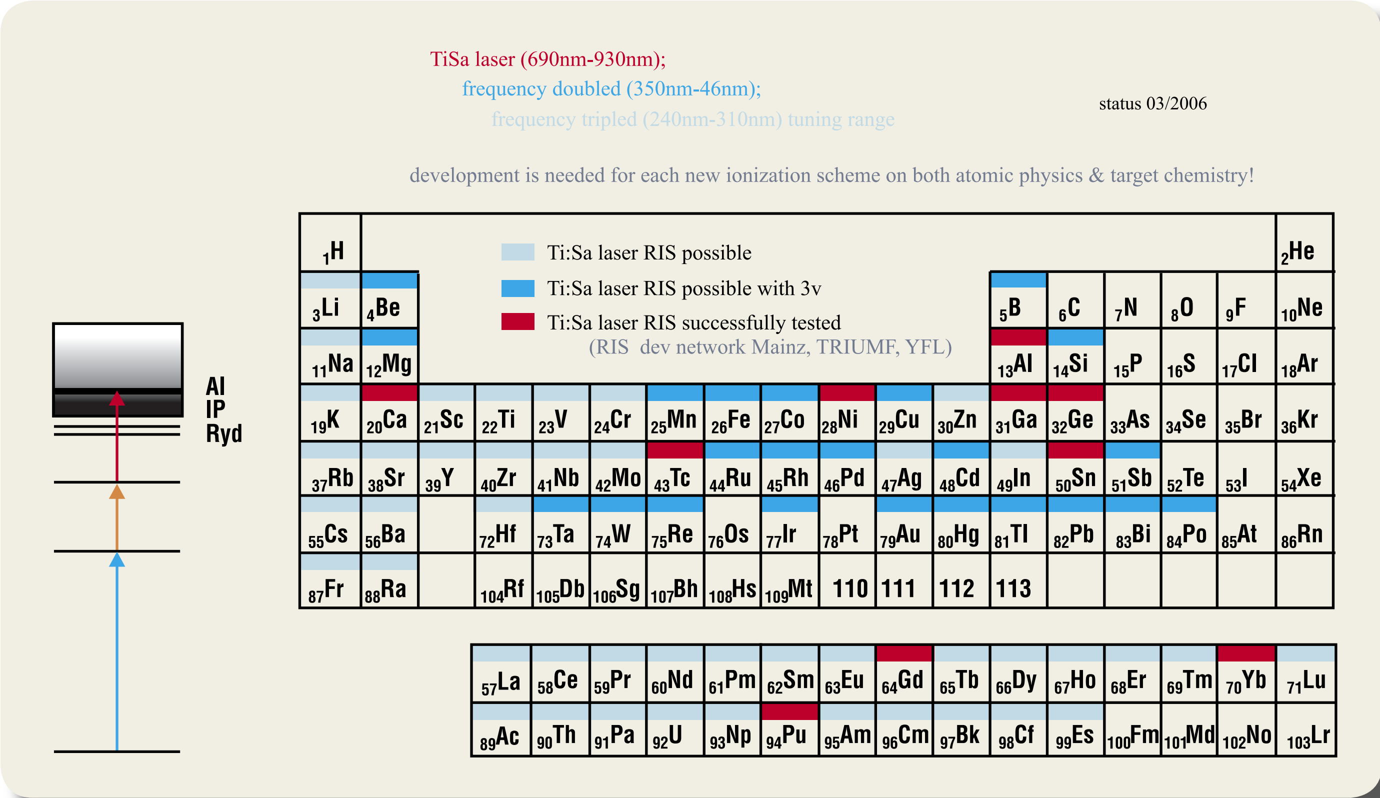
RILIS, besides producing exotic isotope beams of high purity and yield, has the further advantage that its equipment can be far removed from the very hostile radiation environment of the production target. The laser beams, which by their nature are very well collimated, can be directed into the production target from a location that is easily accessible for maintenance. The problem of having to deal with installations close to highly radioactive materials at high temperature is therefore avoided.

In 2002, the decision was made to develop, install and operate a modern laser ion source, with the goal to have the first on-line radioactive ion beam available by the end of 2005. The system was to rely on state-of-the-art, all-solid-state laser systems for reliable, low-maintenance operation. While industrial grade solid-state pump lasers were available, the necessary tunable (i.e., variable energy), high repetition rate, pulsed titanium-sapphire (TiSa) lasers were not, and had to be developed as part of this project. In close collaboration with the group of Dr. K. Wendt from Mainz University, the leading group in resonance ionization spectroscopy in Europe, a unique, all-solid-state laser system, with frequency doubling and tripling, was designed, built and installed at TRIUMF. The TRIUMF Resonant Laser Ion Source (TRILIS), not only greatly improves beam delivery by increasing the variety, purity and intensity of the isotopes used for ISAC experiments; it also pushes the application of modern laser technology. The experience with TRILIS has given direction to modern laser ion source development for radioactive ion beam facilities around the world.

TRILIS has the important capability of being able to ionize the transition metal elements, the lanthanides and actinides in addition to all the elements that are accessible with surface ionization, the current workhorse ion source at TRIUMF. The highlighted portions on the periodic chart shown above indicate the possibilities for TiSa laser-based RILIS beams.



This map shows the calculated relative yield of the many isotopes produced when protons bombard uranium carbide. The break-up is asymmetric, with heavy and light fragments being produced. TRILIS allows the interesting exotic, short-lived and stable isotopes of one element to be selected over the much more abundant, long-lived and stable isotopes.



Resonant laser ionization is unique in its element selectivity. This is achieved by resonantly exciting the atom's valence electron from energy level to energy level until it overcomes the ionization energy barrier (IP). The periodic chart indicates the potential for RILIS to provide selective ionization of radioactive isotopes produced with the unique ISAC isotope production target.

The first tests of the lasers and laser ionization schemes were carried out on stable isotopes. Then, in December 2004 and almost one year ahead of schedule, the first tests of scheduled radioactive ion beam delivery with TRILIS were made. A beam of ^{62}Ga (Gallium-62) was produced at 1500 atoms per second, representing an increase in yield by a factor of 2, combined with a 20-fold suppression of the isobaric ^{62}Cu (Copper-62) over conventional surface ion source operation. This higher intensity and purer beam allowed the first detailed study of the branching ratios in the decay of the superallowed beta decay of ^{62}Ga, well before competing groups from Europe and the U.S. were able to perform these measurements. This was the first time that such an all-solid-state laser system was used for on-line production of radioactive beams.

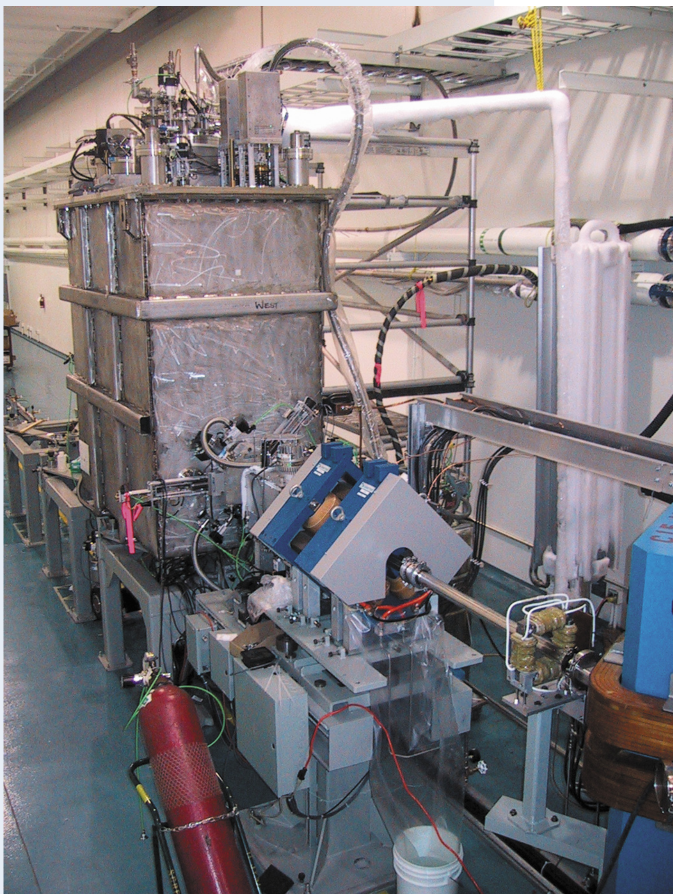
The successful laser ion source operation for an experiment means that experimenters can now request laser ion source beam development for a host of new beams including Sn (Tin), Ni (Nickel), Ca (Calcium), Tc (Technetium), Ga (Gallium), and Ge (Germanium), with Al (Aluminum) under development for experiments to be performed in 2005. The electronic structure of each isotope requires that a unique laser excitation scheme and laser wavelengths be devised for each beam. The development is done off-line at TRIUMF, in collaboration with LIS groups in Finland and at Mainz University. With all major components of TRILIS operational, ISAC is in a position to develop and produce new radioactive ion beams of high intensity and purity, ensuring that TRIUMF-ISAC continues to be a leading radioactive ion beam facility.

TRILIS now plays a key role in expanding the beam delivery capabilities of ISAC and will continue to do so for a long time to come. This makes ISAC an even more attractive and productive place to carry out research using exotic radioactive beams.

The Superconducting Linear Accelerator at TRIUMF

Robert Laxdal is a Research Scientist at TRIUMF, who has worked on a variety of particle and nuclear physics projects. His current activity focuses on the design and construction of the Medium Beta Cryomodules for ISAC-II at TRIUMF.

A new accelerator is being installed at TRIUMF and it is cool, even cold – well, very cold. To explain: An accelerator accelerates charged particles such as electrons, protons, or heavier ions, by a combination of electric and magnetic fields. Usually radio-frequency electric fields are used to accelerate the charged particles, and magnetic fields are used to direct and focus the particles as they are accelerated. In a linear accelerator (LINAC), the accelerating structure consists of a straight series of spaced hollow metallic tubes through which the beam passes. An alternating electric voltage at high frequency (RF) is applied across the gaps between the tubes. For each type (mass and charge) of particle to be accelerated, there is a definite relationship among the length of the tubes, the gaps between them, and the frequency of the applied electric field. When the beam, which consists of a series of short bursts or bunches, travels through one of the metallic tubes, it feels no electric forces, but when it emerges from the end of a tube, it is exposed to the voltage difference between adjacent tubes. If the length of the tube and the RF frequency are properly related, then the beam bunch will experience an accelerating electric force. During the time that it would feel a decelerating electric field, the burst is "hidden" inside the tube. As the velocity of the ions increase down the LINAC, the length of the tubes is increased, so their arrival at each gap between tubes is timed to coincide with the maximum RF voltage.

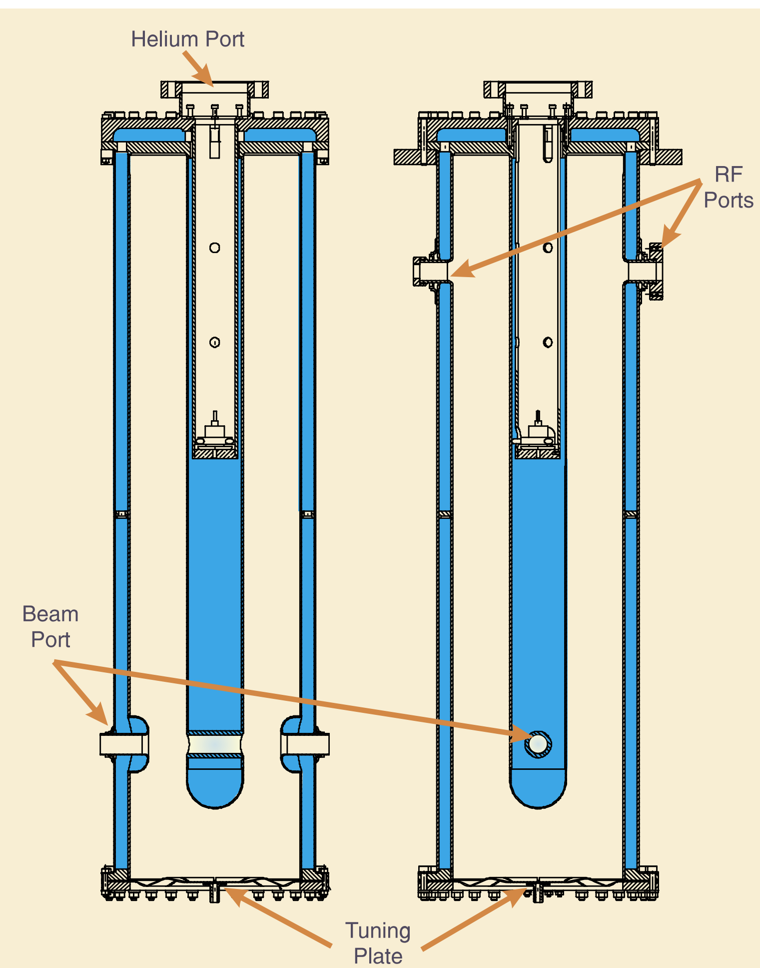


Medium beta cryomodule during installation in the ISAC-II hall.

Accelerators are complex and expensive to build and operate. To reduce the capital costs, physicists and engineers seek to optimize the acceleration process in ways that shorten the overall LINAC length without compromising reliability and operating costs. For example, a higher peak electric voltage between tubes would mean a fewer number of tubes and a shorter LINAC. Higher voltages also mean higher resistive power losses and an increase in engineering difficulties. An analysis shows that long multi-gap RF structures are best for power efficiency. Because gap spacing and RF frequency are determined by a particle's velocity, these structures are only optimized for the acceleration of one family of ions. Instead, lighter ions, which could be accelerated to a higher velocity for a given field, must follow a fixed velocity profile and a lower energy. Shorter two- or three-gap structures, although power hungry, can be independently phased to match the velocity of a wider variety of ions and constitute an accelerator for wide application. An effective but technically challenging way around this problem is to make the RF cavities electrically superconducting to reduce wall losses to almost nothing and allow the LINAC designer to use shorter structures capable of efficiently accelerating a wider range of ions.

The ISAC-I linear accelerators presently deliver beams of radioactive and stable ions to experiments with final energies variable between 150 thousand and 1.5 million electron volts per atomic mass unit (150 keV/u to 1.5 MeV/u), corresponding to velocities from 1.8% to 5.6% the speed of light. TRIUMF is now constructing an extension to the ISAC facility, ISAC-II, to further accelerate the ions from 1.5 MeV/u to energies of at least 6.5 MeV/u (11.7% the speed of light). At the heart of the installation is a new superconducting linear accelerator. It is composed of resonant RF structures called cavities and superconducting solenoids that provide periodic focusing for the accelerating beams. The cavities and solenoids are housed in box-like structures called cryomodules, providing good thermal isolation for the cold elements of the LINAC. The LINAC is grouped into medium and high beta (velocity) sections. An initial installation of twenty medium beta cavities, corresponding to an accelerating voltage of 20MV, is due for commissioning by the end of 2005. The first major milestone, achieved in November 2004 and reported here, is the demonstration of the acceleration of ions with a single cryomodule.

The cavities are simple cylindrical structures with two accelerating gaps formed between the outer conducting wall and a baseball bat shaped inner conductor (see figure below).



The ISAC-II medium beta cavity.

The inner conductor has a hole near the tip through which the beam passes. RF energy is coupled into the cavity via a port in the side of the cavity near the top. The dimensions of the cavity are chosen so that the induced fields resonate at a particular RF frequency with maximum RF voltage built up at the tip of the inner conductor near the beam ports. A demountable flange on the cavity bottom supports a tuning plate, which is used to adjust the resonant frequency over a limited range. The cavity transverse dimensions are chosen to match a certain particle velocity, so the time a particle takes to cross from one gap to the next corresponds approximately to half an RF cycle and acceleration occurs at both gaps.

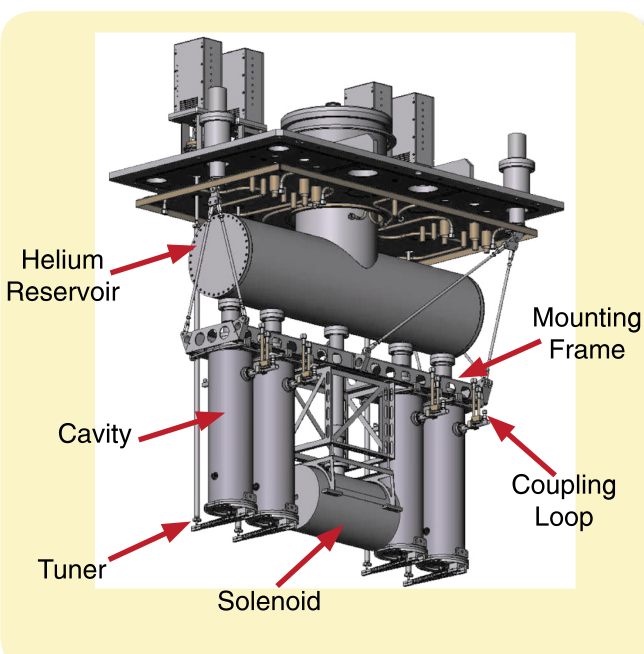
The cavities are fabricated from sheets of highly refined niobium, a Type I superconductor with a critical temperature of 9^{o} K. Each cavity has its own jacket outside the outer conducting wall and, together with the hollow inner conductor, forms a volume to contain a bath of liquid helium. The liquid helium maintains the RF surface at a stable temperature of 4.2^{o} K. When properly constructed, the cavity surface resistance is only a few billionths of an ohm. This means that RF voltages of 500kV can be induced on the inner conductor with as little as a few watts of power loss. In a room temperature cavity, it would take over 100,000 watts to sustain the same voltage. Furthermore, at room temperature, the voltages would have to be kept significantly lower because of the resultant surface heating.

While superconducting technology can produce high accelerating gradients at low power, there are significant technical challenges. The highly refined niobium must be treated very carefully during fabrication. All welding must be done with an electron beam welder in an evacuated chamber to avoid inclusions of other materials in the surface. Even very small inclusions of non-superconducting material can increase the local resistance on the RF surface, promoting heating of the niobium surrounding the inclusion and limiting the cavity performance. After fabrication, the cavities are chemically polished, then rinsed with high-pressure de-ionized water, and then dried in a clean room before mounting in the accelerator module. The resonating frequency of each cavity, 106 million cycles per second, must be set with high accuracy. To do so, TRIUMF has developed a mechanical tuner capable of both coarse (a few kilocycles) and fine (a few cycles) frequency adjustments. The demonstrated mechanical resolution of the tuner is better than 0.001 of a millimetre. All cables and mechanical connections to the cavity must be thermally isolated or stage cooled with liquid nitrogen to avoid thermal losses on the liquid helium.

Our development and engineering has led to very efficient and effective cavities, which can generate an acceleration voltage of 1.1 megaVolts across their effective length of 18 cm, a significant improvement over other heavy ion facilities in the world.

Two pairs of these cavities are grouped together with a superconducting solenoid placed between them. The solenoid, used to focus the beam, is designed to operate at fields up to 9 Tesla, 200,000 times the earth's magnetic field. At each end of the main coil, an oppositely wound smaller coil serves to minimize the magnetic field that could interfere with the operation of neighbouring cavities.

The four cavities and solenoid are housed in a cryomodule that provides a vacuum to shield the cold mass from a molecular heating load. A liquid nitrogen cooled box enclosure inside the vacuum wall reduces the radiative thermal load. The stainless steel vacuum tank has dimensions 2m x 2m x 1m. Cavity performance is reduced if the cavities are cooled in the presence of a magnetic field; magnetic shielding in the form of sheets of high permeability alloy is placed between the warm wall and the cold shield. The shielding is designed to reduce the earth's magnetic field by a factor of twenty.



The top assembly of the medium beta cryomodule.

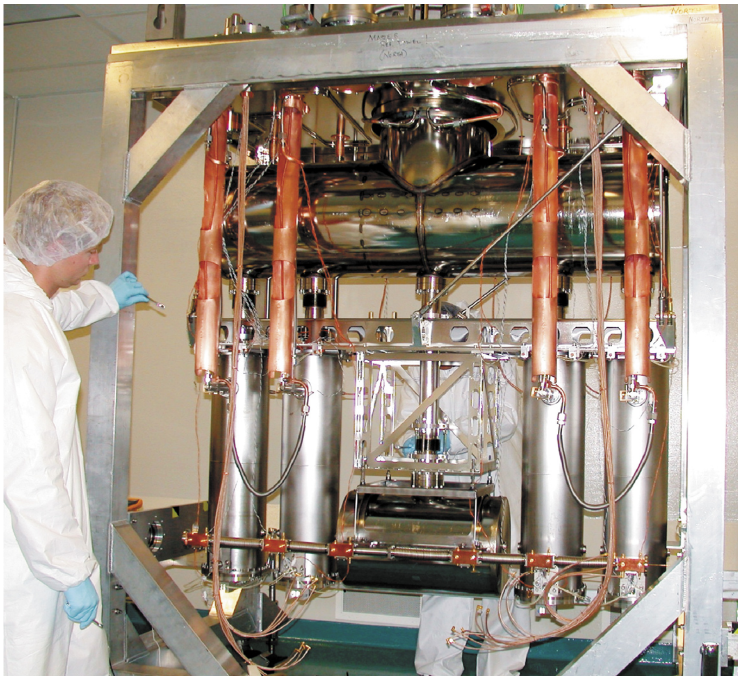
The superconducting elements are supported on a beam that is suspended from the lid by struts. The struts are slung from three support points, two upstream and one downstream, that are laterally and vertically adjustable. There is an independently mounted liquid helium reservoir (120 litre capacity) suspended from the lid, which feeds liquid helium to the cold elements during operation (see figure below). Five of these cryomodules are required to achieve the desired final energy.

Correct acceleration requires precise alignment of the cavities and solenoid with respect to the beam axis: within ±0.4 mm for the cavities and ±0.2 mm for the solenoid. Aligning to this tolerance at temperatures slightly above absolute zero presents an interesting engineering challenge as assembly of the cryomodule has to take place at room temperature. The temperature drop of some 300^{o}C causes all the internal assembly to shrink in length, in different amounts for different components. For example, the centre of the solenoid moves upward by about 5 mm while the accelerating gaps in the cavities move somewhat less, by 3.8 mm. In order to provide a pair of eyes inside the cryomodule, an electric positioning system has been devised to chart the position of the cold mass during cooldown cycles and determine the magnitude and repeatability of the contraction. Each cold mass element is outfitted with a position monitor. A wire running parallel to the beam axis and through the monitors carries an RF signal that is measured by the monitors and is converted to an x-y position.

Each cryomodule has a single vacuum system for thermal isolation and beam acceleration. This demands extreme cleanliness of all internal components and precludes the use of volatile lubricants and flux, as well as any particulate generators, to avoid contaminating the superconducting surfaces. Assembly and commissioning tests are done in the new ISAC-II clean laboratory area. A mounting frame is used to assemble the tank internals to the lid and, initially to align the components.

The first stage of the ISAC-II accelerator, to be completed in December 2005, will see the installation of five of the medium beta cryomodules. Each cryomodule is first assembled in an open 'dirty' lab space, then disassembled, cleaned and reassembled in the 'clean room'. After re-assembly, the modules are tested in the lab before being certified for installation on line.

The first cryomodule served as prototype. After assembly, a series of three cold tests were performed to characterize the module. In April, 2004, the first cold tests, without RF ancillaries installed, characterized cryogenic performance

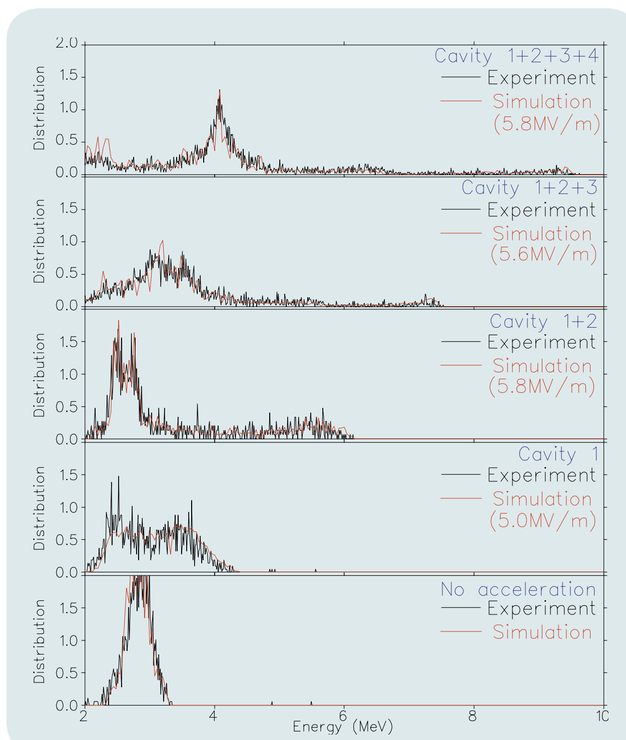


Medium beta cryomodule assembly in the assembly frame.

For the third cold test, the cavities were removed from the assembly and given a final high-pressure rinse. The goal was to duplicate the operating conditions of a functioning LINAC module. The test was a complete success. All cavities were operated simultaneously at the ISAC-II operating frequency and voltage. As a proof of principle, alpha particles from an external radioactive source were injected through a thin foil into the cryomodule, and a silicon detector to measure alpha particle energy was placed at the exit of the cryomodule. Starting from the upstream end, the cavities were turned on sequentially and phased to maximize the final energy. The energy spectra obtained when 0 through 4 cavities were powered is shown in the figure below. Because emission of the alpha particles is not synchronized to the RF, a large fraction of them are not optimally accelerated, adding a large low energy component to the spectra; it is the particles with maximum energy that demonstrate the accelerating voltage in the cavities. The exciting result is that the measured maximum energy of 9.4 MeV is within 6% of the expected final energy for cavity voltages at the ISAC-II specification. This is the first demonstration of acceleration using superconducting RF cavities at TRIUMF and marks the beginning of a new and exciting area of accelerator physics and technology.

and determined the warm offset required to achieve cold alignment. The cryogenic performance of the cryomodule is characterized by measuring the helium boiloff under static load (no RF power) conditions and by measuring the LN_2 consumption required to sufficiently cool the side shield. Temperature sensors are placed in the cryomodule to provide test information. Cryogenically, the cryomodule performed well, with a helium static load of 13W and liquid nitrogen consumption of 5 liquid-litres per hour, both near the expected values. The test also determined the repeatability of the alignment during cooldown and established offset values for each cavity and the solenoid to enable warm positioning compatible with alignment at cold temperatures. The positions of the cold masses were measured over three cooldown cycles and found to be repeatable to within ±0.05 mm vertically and ±0.1 mm horizontally. The results of the first test are then used to adjust the final warm alignment of the cavities and solenoid to be compatible with alignment at cold temperatures.

The second cold test confirmed the integrity of the RF systems and controls. During this test, the four cavities and solenoid were powered together, and locking of the four cavities to an external frequency was demonstrated. Operation of the high-field solenoid did not appreciably affect cavity performance. As expected, the surface resistance of the cavities proved the effectiveness of the magnetic shielding.



Measured spectra of alpha particles accelerated by the first medium beta cryomodule.

The TRIUMF Cryogenic Refrigeration System

Robert Laxdal is a Research Scientist at TRIUMF, who has worked on a variety of particle and nuclear physics projects. His current activity focuses on the design and construction of the Medium Beta Cryomodules for ISAC-II at TRIUMF.

If you are building a superconducting LINAC (*See Superconducting Linear Accelerator at TRIUMF in this issue)*, how do you keep it cold? You build a cryogenic refrigeration system of course, and that is what TRIUMF is doing.

A cryogenic refrigeration system produces liquid helium to cool the cryomodules in the LINAC to temperatures of 4 degrees above absolute zero. The system includes a refrigerator or cold box, high-pressure warm piping, vacuum insulated transfer lines, a high-pressure storage tank, a liquid helium dewar, and a high-power compressor, all in a very large size. The operation also requires a control system to perform gas management and liquid helium flow monitoring and control.

ISAC-II refrigerator rooms: Refrigerator (right side) and liquid helium dewar (left side).

So how does a cryogenic refrigeration system work? A large 250 kW compressor provides the muscle, taking room temperature helium gas and pressurizing it to 13 Bar (13 times atmospheric pressure). The high-pressure gas is transported via warm stainless steel piping to the refrigerator where the gas expands in two high-speed turbines. The expansion cools the helium to liquid, which is transferred to a separate 1,000-litre liquid helium dewar. Plant efficiency is boosted in two ways. Firstly, liquid nitrogen is used to pre-cool the high-pressure stream of warm helium in the input heat exchanger. Secondly, two other heat exchangers in the cold box use the cold low-pressure return gas from the dewar to further cool the high-pressure incoming stream. The plant is capable of liquefying 150 litres of liquid helium per hour.

The liquid helium is delivered to the cryomodule through specially designed transfer lines. Because even small heat leaks will vaporize the liquid and render it inefficient for cooling the cryomodules, the lines are very well insulated. They consist of tubes within tubes within tubes. The central tube carries the liquid helium. Surrounding the inner tube is a thermal shielding tube cooled with liquid nitrogen. The outer tube forms the vacuum jacket to provide thermal insulation to the contents inside. All inner tubes are wrapped in many layers of very thin superinsulating material. A main liquid helium supply line runs from the dewar in the cryogenic room to a trunk line in the accelerator hall. The trunk supply line acts as the main manifold for the cold distribution with parallel supply lines branching off to feed each cryomodule. The cold boil-off gas from the cryomodules is fed back to the refrigerator via the same type of insulated lines. This cold gas is used by the refrigerator to provide extra cooling to the high-pressure stream and improve plant efficiency.

ISAC-II compressor room with main compressor (left) and recovery compressor (right).

Each of the five cryomodules has an inventory of ~180 litres of liquid helium. The liquid helium dewar would normally operate with an inventory of ~800 litres. This gives a total liquid inventory of almost 2,000 litres. Consider that when the liquid is converted back to warm gas it expands 750 times, or to a warm volume at 1 atmosphere of 1.5 million litres. The helium gas inventory is expensive, and in the event of a power outage or shutdown, there must be a means to recover the complete inventory in a storage device. A large 120,000-litre storage (buffer) tank has been installed east of ISAC-II near the compressor room. The tank is rated to handle pressures up to 13 Bar and can accommodate the full helium inventory. In the event of a LINAC warm-up, a recovery compressor independent from the main compressor will turn on and compress the boil-off gas into the buffer tank. In addition, during operation a gas management system senses the pressure in the compressor suction line and either adds or removes gas from the system using the buffer tank and load/unload valves for the regulation.

The refrigerator has its own local controller that is designed to operate the compressor, gas management and cold box safely. TRIUMF is designing a remote global control system that will monitor the local controller plus provide control and monitoring of the helium delivery system and cryomodule temperatures and levels. Inherent in operation with cryogenic fluids are equipment and personnel concerns mainly dealing with the capacity of the liquid to expand if accidentally warmed. All enclosed volumes must be equipped with relief valves to allow the gas expansion without building up destructive or unsafe pressures. The interlocks of the global control system are designed to protect the system in all running modes.

The complexity of the cryogenic refrigerator is such that TRIUMF purchased the refrigerator, main and recovery compressors and the oil removal system from one of only two companies in the world that can build such systems. TRIUMF assumed the responsibility for the installation of the refrigerator components as well as contracted with a local refrigeration company for the installation of the high-pressure piping. TRIUMF also purchased and installed the buffer tanks and helium dewars and contracted out the construction of the cold distribution system based on a TRIUMF design.

The complete system was installed and commissioned in February, 2005 with results well within TRIUMF's specifications. The first closed-cycle refrigeration into a cryomodule was completed successfully in June, 2005, and the vacuum jacketed cold distribution piping into the vault is scheduled for installation and commissioning in November, 2005 to meet TRIUMF's goal of accelerated beam from the LINAC to the end of the vault by December, 2005. In the future, TRIUMF plans to add a second part of the superconducting LINAC to boost the final beam energy. This will require the installation of another similar sized refrigeration system in 2007 to accommodate the larger liquid helium requirements.

ISAC-II helium buffer tank.

Thin Films and Nanostructures Studied by β-NMR

Zaher Salman is a Research Associate at TRIUMF. His research focus is molecular and materials science, particularly the β-NMR facility at ISAC.

Nanoscience and nanostructures are evolving at a fast pace. A nanostructure is a material system whose size is intermediate between that of atoms or molecules and that of bulk solids. A nanostructure may be defined as any structure with at least one dimension of the order of one thousandth of a micrometre (10^{-9} metre). These novel materials, which modern techniques of synthesis and processing can now produce, have physical properties that are different from those of the bulk parent compounds, yet also differ from those of the constituent atoms and molecules. Their properties are controlled by the laws of quantum mechanics and are strongly dependent upon size and shape of the nanostructure. In addition to the basic scientific questions of how materials behave at the nanometre scale, research in nanostructures opens up new opportunities for the design and optimization of material properties for specific technological purposes and applications, such as electronics, optoelectronics, and memory devices.

A current technological trend is to minimize the size of electronic components in order to increase functionality, increase portability and decrease power consumption, and nanostructures have an important role to play in advancing these new technologies. Interest in understanding nanostructures is focused generally on the ability to modify materials so they have properties unavailable in bulk materials; properties which can be tuned for a specific technological application, including electronic, structural, magnetic, optical and superconductive properties.

Figure 1

The β-NMR experimental apparatus uses polarized ^{8}Li to measure magnetic fields in nanostructures.

Magnetic fields arise when there are moving electric charges. For example, an electric current going through a coil of wire makes the coil into an electromagnet. The effect occurs at all size levels, from the large electromagnet to a single atom or nucleus. This holds at all scales, from the large electromagnet to single atoms or nuclei. Nuclei consist of positively charged protons and electrically neutral neutrons arranged in characteristic nuclear structures. These structures carry an intrinsic angular momentum called spin, which, as each carries a net charge, gives rise to a nuclear magnetic moment. Usually the orientation of nuclei in a sample is completely random, resulting in a cancellation of magnet effects in bulk materials. In certain materials, however, it is possible to remove some of this randomness by applying an external magnetic field. The nuclear moments tend to align along the applied magnetic field. When the external magnetic field is removed, the material still shows magnetic properties, as the orientation of the spins is no longer random; (i.e., the

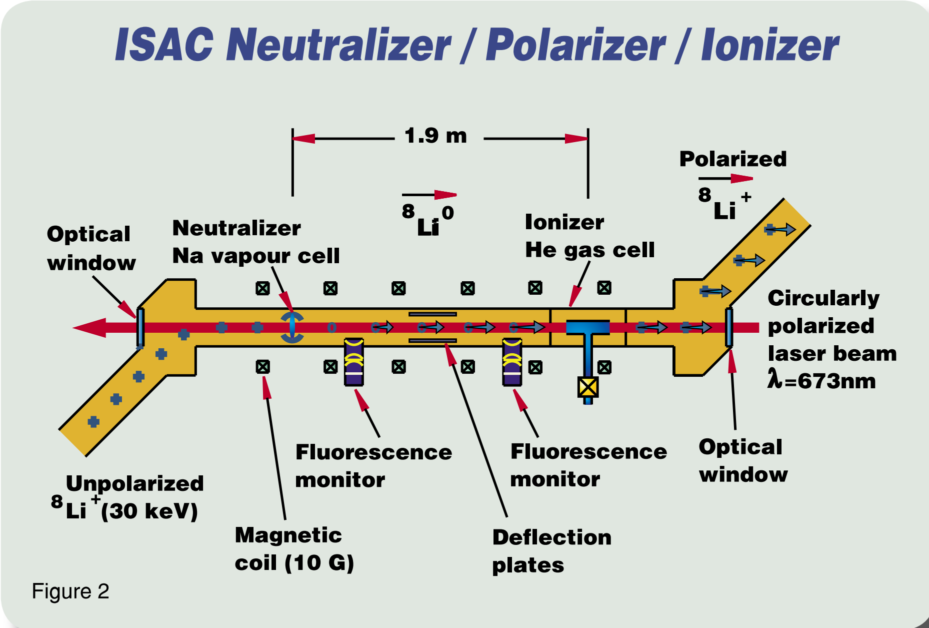


Figure 2

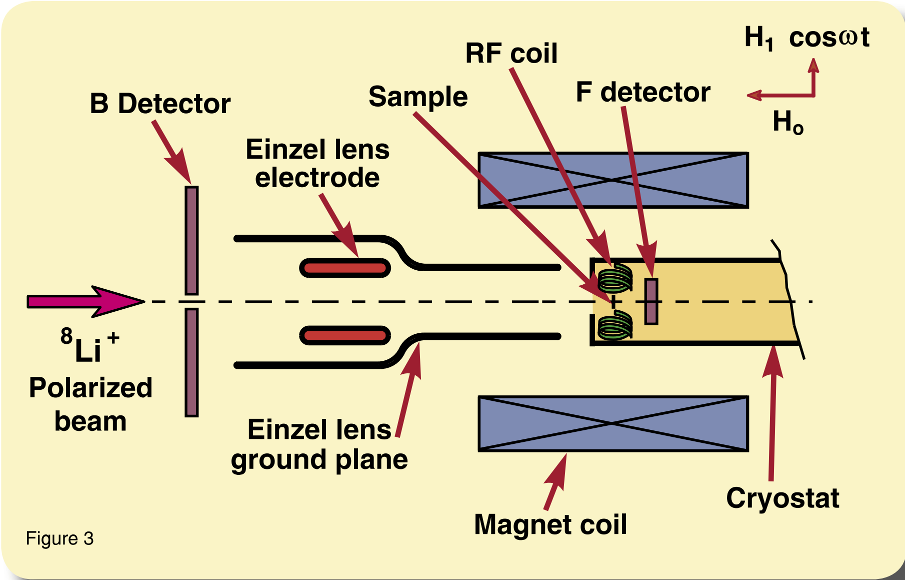
A schematic of the β-NMR polarization process. The amount of polarization using this method is 70%, one thousand times higher than polarization using conventional NMR methods.

nuclei are polarized) their individual magnetic effects add up, and we have some persistent magnetism. Just how persistent the magnetism is depends on the material and its subsequent treatment. Some materials naturally lose their magnetism more quickly than others; the rate at which they do this gives information about their internal magnetic and electronic properties.

In order to understand and exploit the properties of nanostructures, we measure these properties. The technique used is called Nuclear Magnetic Resonance (NMR), and is the basis for Magnetic Resonance Imaging (MRI) used in medical diagnostics. In all forms of magnetic resonance, nuclear spin polarization of a constituent of the material is produced and then its subsequent behaviour, in time, is observed as it interacts with its electric and magnetic environment. NMR is a powerful technique for probing the local electronic and magnetic properties of materials, but it requires a large number, about 10^{20} of partially oriented spins, in order to generate a measurable signal, so it is most widely used in studies of bulk materials. Given the small size and mass of nanostructures, studying their electronic and magnetic properties with conventional bulk measurement techniques such as NMR is impossible. New techniques, specifically designed for these structures, are required. Much greater sensitivity can be obtained with closely related nuclear methods such as beta-detected nuclear magnetic resonance (β-NMR), where the signal comes from the decay properties of a radioactive nucleus. For example, in the case of ^{8}Li, which has a mean lifetime of 1.2 seconds, an energetic decay electron (referred to as β particle), is emitted in the opposite direction of the nuclear spin polarization, and can be used to detect the spin direction at the time of the decay with extreme sensitivity. TRIUMF has recently created a state-of-the-art beam of low-energy, highly polarized radioactive $^{8}Li^{+}$ for doing β-NMR and other experiments (see Fig. 1). Since a factor of 10^{13} less spins, compared to conventional NMR, are needed to generate a measurable signal, β-NMR is well suited for studies of nanostructures or thin films where there are relatively few host nuclear spins.

The information about the local electronic and magnetic environment obtained from a β-NMR measurement can be applied to designing better nanostructures, suited for a specific technological application. For example, in the case of magnetic recording applications, the read/write heads of computer hard drives are in the form of a series of magnetic and non-magnetic conducting layers. The conduction of the head changes dramatically, depending on the magnetization state of the memory unit being read, a phenomenon called Giant Magneto-Resistance (GMR). Therefore, a measurement of the conduction of the head reflects the state of that memory bit, which is the read process of the stored memory. In order to improve the sensitivity of the head, reduce its size and consequently the size of a magnetic memory unit, a better understanding of the interaction between the different layers is essential. β-NMR is a very powerful technique that can provide this understanding.

β-NMR is done by implanting ISAC's low energy, highly polarized $^{8}Li^{+}$ beam into the sample to be studied. Initially, the ^{8}Li nuclei has no polarization. The polarization is produced using an optical pumping method, which uses a laser beam to orient the ^{8}Li nuclear spins along the direction of the beam. The amount of polarization obtained using this method is 70%, which is one thousand times higher than that used in conventional NMR. The details of the polarization process are presented in Fig. 2. The polarized beam is then implanted into the studied sample. Because the nuclear spins of the implanted ^{8}Li are affected by the surrounding distribution of nuclei and electrons in the sample, they become a very sensitive probe of the electronic and magnetic properties of the studied sample.



A schematic of the β-NMR spectrometer. The TRIUMF β-NMR spectrometer is unique in its ability to adjust implantation energy of the ^{8}Li beam, making it a powerful tool for studying nanostructures.

One of the unique properties of the TRIUMF β-NMR spectrometer is the ability to adjust the implantation energy of the ^{8}Li beam. This property is the main feature that makes β-NMR a powerful tool for studying nanostructures, because it allows us to perform measurements in nanostructures as thin as 1 nm (nanometre) by reducing the energy of the ^{8}Li beam enough to stop it in such a thin sample or, alternatively, to study the different layer of the sample by adjusting the energy of the beam to stop it at a specific depth. The 30 keV nominal energy of the beam corresponds to an average implantation depth of about 200 nm. However, it is possible to decelerate such a beam down to 100 eV or less by placing the spectrometer on a high-voltage platform. Varying this voltage allows stopping the Li beam at a depth in the range of 1 to 200 nm.

One type of a β-NMR measurement is performed by applying a static external magnetic field (H_0) along the initial nuclear polarization direction, and a small oscillating magnetic field (H_1), perpendicular to it. The oscillation frequency is stepped through a range of values, and the polarization is reconstructed from the geometrical distribution of the emitted electrons at each frequency value. Using this type of measurement, we can infer information about the local field experienced by the ^{8}Li.

A schematic of the β-NMR spectrometer is shown in Fig. 3. The studied sample is placed in an ultra high vacuum (UHV) chamber (not shown) to prevent the low energy ^{8}Li from stopping in any residual air molecule. The beam enters the UHV chamber and is focused onto the sample by an Einzel lens. A small coil is used to apply an oscillating magnetic field (H_1) in the vertical direction, perpendicular to both the beam and initial polarization. Using a superconducting magnet, a uniform magnetic field H_0 can be applied along the initial polarization direction. The energetic electrons from the decay of ^{8}Li have sufficient energy to easily pass through thin stainless steel windows, out of the UHV chamber, and reach the forward and back detectors, labeled F and B. Since the β's are emitted opposite to the direction of the ^{8}Li nuclear spin, the nuclear polarization at any time can be determined from the directions of the emitted β particles. The polarization at any moment is reflected in the ratio of counts in the two detectors.

β-NMR is being used to study many topics in condensed matter physics, including superconductivity, Li impurities in semi-conductors, single molecule magnets, finite size effects and magnetic multilayers. Recently, depth profiling of the internal magnetic field was demonstrated using β-NMR, by implanting the ^{8}Li beam in a magnetic multilayer structure. This structure is in the form of multilayers of magnetic/non-magnetic conducting layers, similar to the read/write heads of computer hard drives. The conduction electrons in the non-magnetic conducting layer can be polarized by the neighboring magnetic layers and mediate the magnetic interaction between two magnetic layers on either side. The strength of this magnetic interaction depends on the type of materials used and the width of the non-magnetic layer. For applications in the magnetic recording industry, the aim is to find combinations of magnetic/non-magnetic materials which produce higher polarization of the conduction electrons, and therefore higher internal magnetic fields in the non-magnetic layer, and stronger magnetic interaction mediated by the non-magnetic layer needed to produce read/write heads with higher sensitivity. β-NMR is an excellent way to probe the induced internal magnetic field in the non-magnetic layers to allow better understanding of the nature of the GMR effect, responsible for the interplay between magnetic interactions and electric conductivity.

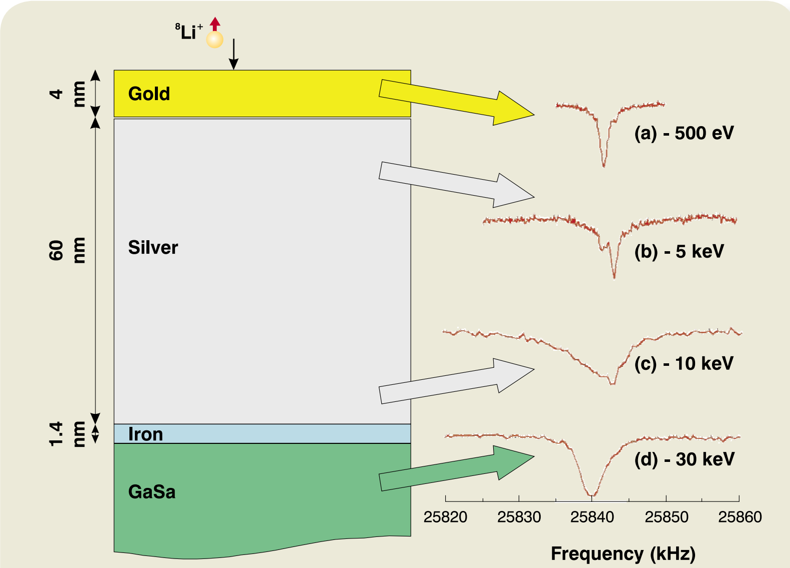


Figure 4

An example of the high-depth resolution achieved by β-NMR when ^{8}Li was implanted in a multilayer film, allowing easy measurement of magnetic fields in the different layers at a scale of a few nanometres.

An example of these multilayer structures is presented in Fig. 4, where ^{8}Li was implanted in a multilayer film of 4 nm gold / 60 nm silver / 1.4 nm of iron deposited on a gallium arsenate (GaAs) substrate. The β-NMR spectra presented in Fig. 4 are obtained at different implantation energies:

(a) 500 eV: At a very low implantation energy of 500 eV, most of the ^{8}Li stops in the 4 nm of gold, giving a resonance signal from the thin gold overlayer, a signal which would be impossible to obtain with most other resonance techniques.

(b) 5 keV: At 5 keV implantation energy, most of the ^{8}Li stops in the silver far from the iron layer, and therefore far from the induced internal magnetic field in the silver, due to the iron magnetic layer. This is why only a narrow resonance line is observed.

(c) 10 keV: At 10 keV implantation energy, most of the ^{8}Li stops in the silver, but close to the iron/silver interface, where the induced internal magnetic field is highest. Although resonances (b) and (c) are both from ^{8}Li in silver, the resonance (c) is significantly broader due to the large induced internal magnetic field in the silver, near the iron/silver interface.

(d) 30 keV: At the nominal 30 keV implantation energy, most of the ^{8}Li stops in the GaAs substrate, and the resonance obtained is typical to ^{8}Li in GaAs.

These results show the high depth resolution achieved by β-NMR, allowing us to easily measure internal magnetic fields in the different layers, at a scale of a few nanometres. This is impossible using conventional resonance techniques, making β-NMR a unique and powerful technique for depth-resolved measurements in ultra-thin films and nanostructures.

In the past two years, TRIUMF has commissioned a new β-NMR spectrometer, specially designed for measurement at zero and low magnetic fields. Currently, we are preparing to augment this system with its own dedicated high-voltage deceleration platform to provide for variable depth implantation capabilities similar to the existing high field spectrometer. In addition, we will develop the capability to illuminate the studied sample by light or a laser beam. This will open the door to study the effect of light exposure in thin films and nanostructures.

The number of new projects in nanoscience research being undertaken by physicists, chemists, materials scientists, engineers and biologists is increasing rapidly. Because this area of scientific inquiry is concerned with a length scale that is of interest to all these disciplines, there are excellent opportunities for collaboration among these diverse groups. The β-NMR group at TRIUMF has been working in collaboration with scientists from universities in Canada, the United States, the Netherlands, Italy and Japan.

TRIUMF Machine and Fabrication Shop

Ivor Yhap is the Machine Shop Supervisor and Ewart Blackmore is head of the Accelerator Technology Division.

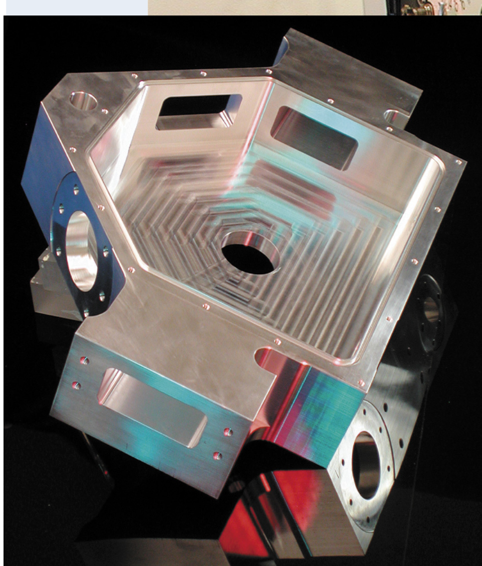
Surface treatments of metals are needed for many different applications: eletropolishing of stainless steel for high vacuum, hard anodizing of aluminum for resistance to wear, nickel plating of copper for low temperatures and powder coating for resistance to corrosion.

TRIUMF's success in developing new accelerator components, detectors and experimental equipment depends not only on its scientists and engineers but also on the skills of the machinists and welders in the TRIUMF Machine Shop. This group of skilled craftsmen is continuously faced with new challenges in fabrication, new materials to machine, and new technologies and techniques to explore and master.

At present, the shop personnel consists of a supervisor, two shift supervisors, seventeen journeyman machinists, two welders and one apprentice. Every day of the week, the staff meets the demands of operations or experiments as they arise. In addition to an array of standard lathes and milling machines, the shop has two CNC (Computer Numerical Control) vertical machining centres that can be used to produce more complex parts with improved precision and repeatability. Recruitment of experienced programmer/machinists and the conversion of the TRIUMF Design Office software to SolidWorks have enabled more efficient use of the Cam software, with the full capability of fourth and fifth axis machining. Scientists, engineers and designers now have more flexibility and can be more creative when designing components required for their projects.

Specialized welding is another important service of the TRIUMF Machine Shop. High vacuum is required for all of the accelerators and beamlines and leak-free welding of a wide array of containment vessels and vacuum boxes, in stainless steel or aluminum, is essential. TRIUMF frequently requires large structures for holding heavy magnets and similar devices for which high quality structural welding is needed. TRIUMF's electron beam welder,

The two CNC machines in operation.

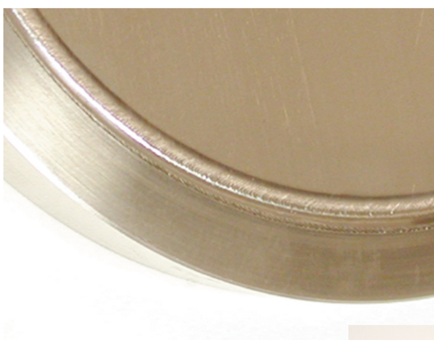


Using the CNC machine, a complicated part can be fabricated from a solid block of material.

where a powerful beam of electrons in a vacuum fuses the parts being welded, is a crucial step in fabricating the many types of targets used at TRIUMF. Targets for isotope production using MDS Nordion Inc cyclotrons, targets for meson production and the many types of target technologies required for ISAC radioactive ion beam production, are all produced using electron beam welding. Typically, these targets require either exotic materials such as tantalum or molybdenum, or very thin foils where electron beam welding is the only assembly technique possible.

With these fabrication skills, TRIUMF machinists can be part of the design team, making suggestions or providing ideas on manufacturing, suggesting preferred methods for machining a complicated device and giving practical advice on how to machine new materials. Although most parts required at TRIUMF are made from stainless steel, aluminum or copper, there are many other materials that must be machined, from assorted plastics and composites

Positioning an ISAC target in the electron beam welder.



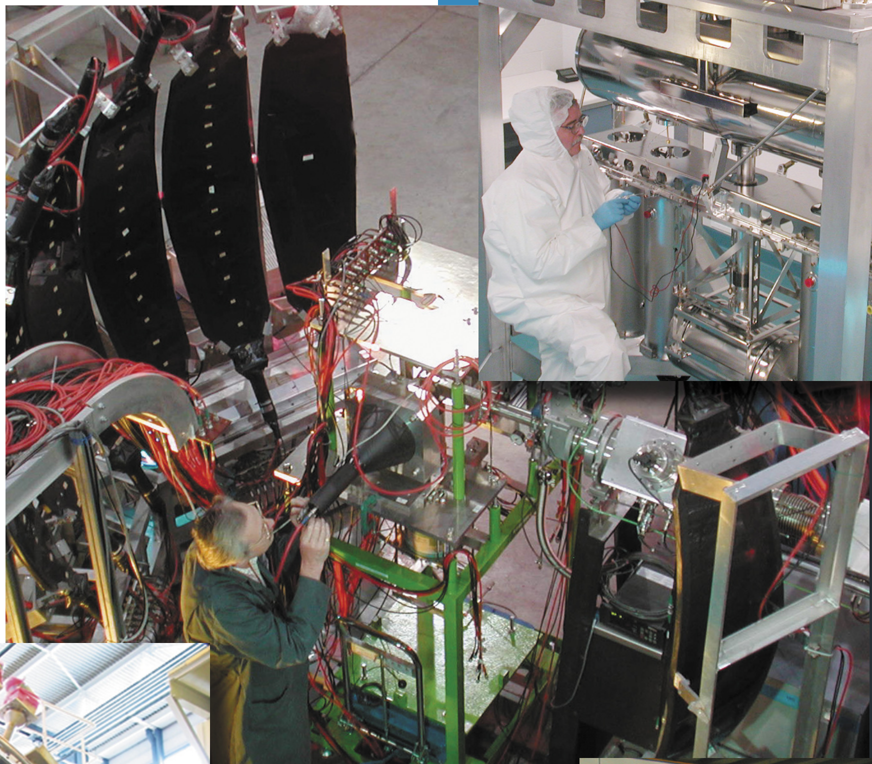
Electron beam welding of thin foil on isotope production target.

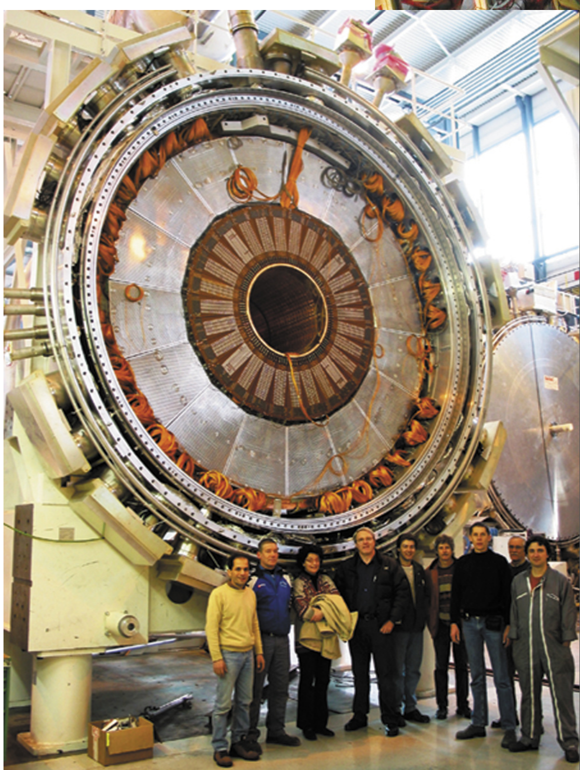
to high-temperature materials to superconducting materials. Frequently, specially shaped ceramics are required, and fabricating them from machinable ceramics is much less expensive than having them produced by molding and firing.

The work of the TRIUMF laboratory has also placed demands and challenges on the machine and fabrication shops in the Vancouver area and across Canada. There are some components, such as the vacuum tanks for the ISAC-II cryomodules, that were too large to be fabricated in the TRIUMF Machine Shop and were contracted out to a Canadian company for fabrication. In the construction of the ISAC radio frequency quadrupole, there was a need to put a conducting copper layer on steel plate. Superior Electro Plating of Surrey, British Columbia expressed interest in developing this technology, and TRIUMF personnel worked with them to establish the procedure for successfully accomplishing the job. Since then, copper plating on steel has been used in many of the ISAC target modules, saving money by using mild steel rather than stainless steel in certain applications where the copper layer is needed to resist corrosion. PR Manufacturing Inc. of Toronto, Ontario, fabricated some of the very large structures required by TRIUMF for assembling the Canadian-made components for the ATLAS detector at CERN. Brandt Industries, of Regina, Saskatchewan constructed some of the large vacuum tanks for the ISAC target station, as well as tanks for the pulse-forming networks used in the CERN LHC injection kickers developed at TRIUMF.

In summary, the challenges of fabricating the state-of-the-art components required for the TRIUMF scientific programme are being met by a group of skilled technologists in the TRIUMF Machine Shop. In turn, these craftsmen get the benefit of interesting and varied work to perform and the knowledge they are contributing to the success of TRIUMF.

TRIUMF is Canada's national laboratory for particle and nuclear physics, managed as a joint venture by a consortium of Canadian universities. It is operated under a contribution from the Government of Canada through the National Research Council of Canada.





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