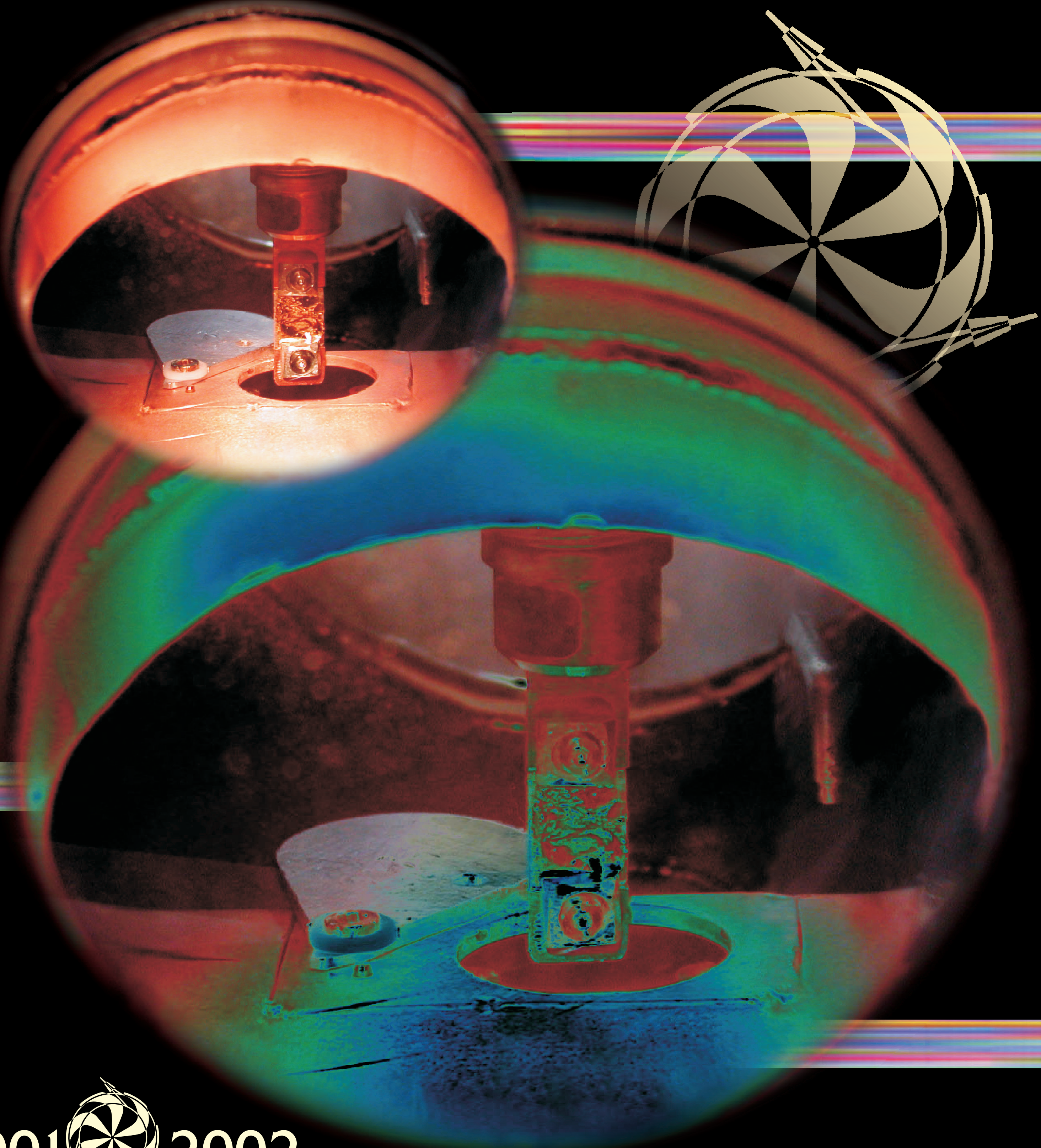
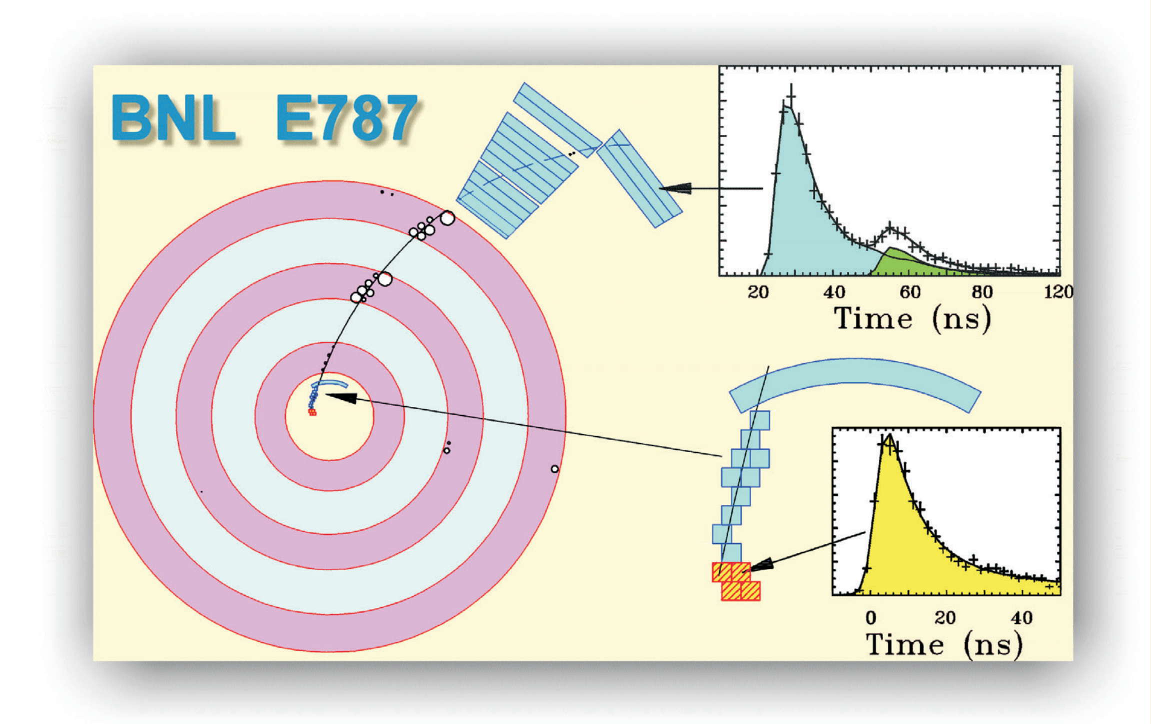
# TRIUMF

## ANNUAL FINANCIAL & ADMINISTRATIVE REPORT



2001 2002

# ONE IN THREE MILLION MILLION!



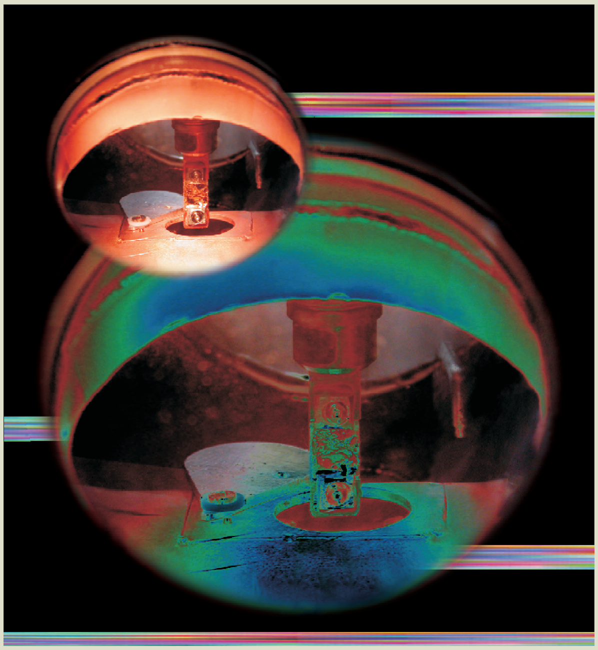

TRIUMF played a leading role in the Brookhaven 787 experiment, a search for the rarest decays of sub-atomic particles. The goal of the E787 detector, like many others, is to identify and measure the energy and direction of emission of all the observable subatomic particles resulting from a high-energy collision or decay. A combination of detector types aid in determining particle properties. Strong magnetic fields are used to curve the charged particles' trajectories in order to assist in energy measurement. For each event the detector system produces many thousands of electrical signals whose source, size and timing are all recorded by a complex computer-based data acquisition system. In E787, an advanced electronic filtering system reduced the number of candidate events which had to be saved for further consideration from 10 million per second to 10 per second.

The graphic shows a computer reconstruction of one of only two observations of the ultra-rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$ culled from an enormous sample of 6 million million decays. On the left is the end view of the E787 detector showing the reconstructed path of the $\pi^+$ in the target, drift chamber (indicated by drift-time circles), and range stack scintillation counters. The path is curved because there is a strong magnetic field applied. Only a small section of the range stack is shown and the lines there indicate the sections from which signals were recorded. At the lower right is an enlargement of the target region. Here the hatched boxes are kaon hits and the open ones pion hits. The size of the pulses generated by the stopped kaon in the scintillating target fibers is sampled every 2 nanoseconds. The results for this event are shown by the crosses while the solid curve is the expected shape. At the upper right is the signal observed when the $\pi$ meson decayed to a muon in the range stack scintillators where the pion stopped. The crosses are the pulse size data sampled every 2 nanoseconds and the curves are for the first second and combined pulses. The event clearly shows that a kaon decayed into a $\pi^+$ without the emission of any gamma rays, making it one of the rarest events ever observed.

**DOUGLAS BRYMAN**

*More details about this and other rare decay experiments appear in the article starting on page 10.*

2001 2002
TRIUMF FINANCIAL REPORT



## COVER PHOTO

$\beta$ NMR is a magnetic resonance technique being developed at TRIUMF/ISAC for the study of novel materials, particularly in thin film form. The technique probes only very close to the surface of the material under investigation. Therefore it is necessary that the experiment be performed in an extremely high vacuum to avoid condensation of residual gases on the sample. In the cover photograph a high purity gold foil sample is being installed in the spectrometer through an unseen vacuum lock above. Next the sample holder is threaded into the spectrometer through the open hatch. Finally the hatch is closed and the holder is driven horizontally into the bore of the magnet to place the sample in its experimental position.

*Andrew MacFarlane*

*Inside Front Cover: Rare Decay Event*
*Inside Back Cover: Next ISAC Step*
*Back Cover: Astrophysics With DRAGON*

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*Editor - Ken Dawson*
*Coordinator - Shirley Reeve*
*Design/Layout - Mindy Hapke*

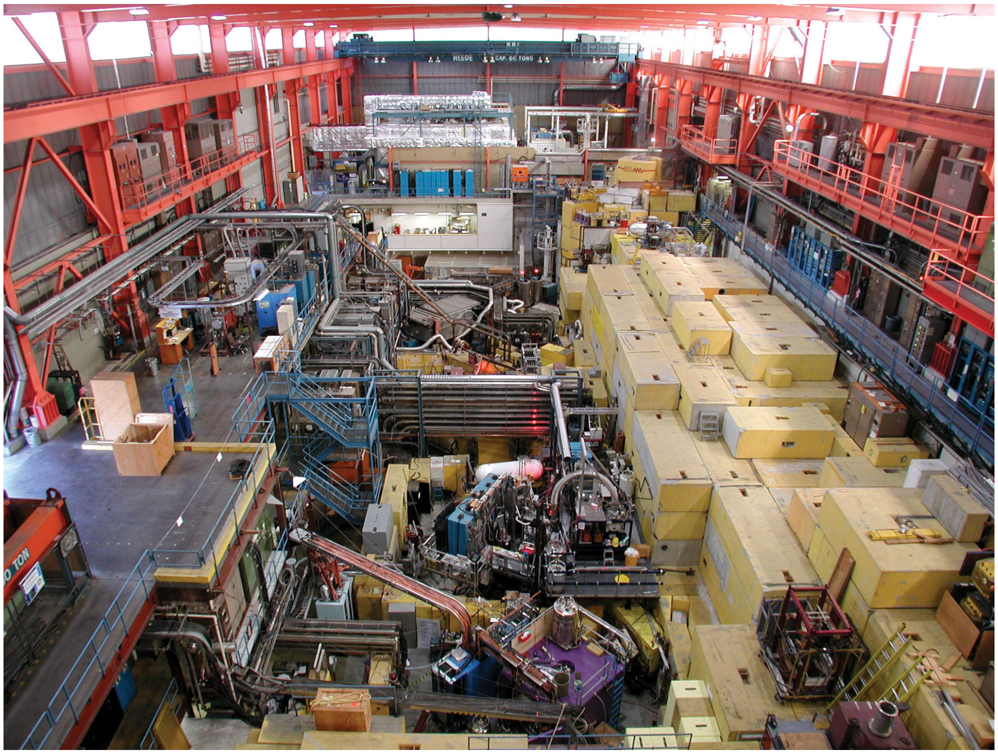
Alan Shotter

The TRIUMF laboratory is Canada's national laboratory for particle and nuclear physics. The mission of the laboratory is to provide in-house world class facilities for specialized areas, provide infrastructure support for Canadian scientists to participate in experiments outside Canada, and to encourage transfer of technology developed at the laboratory to the commercial sector.

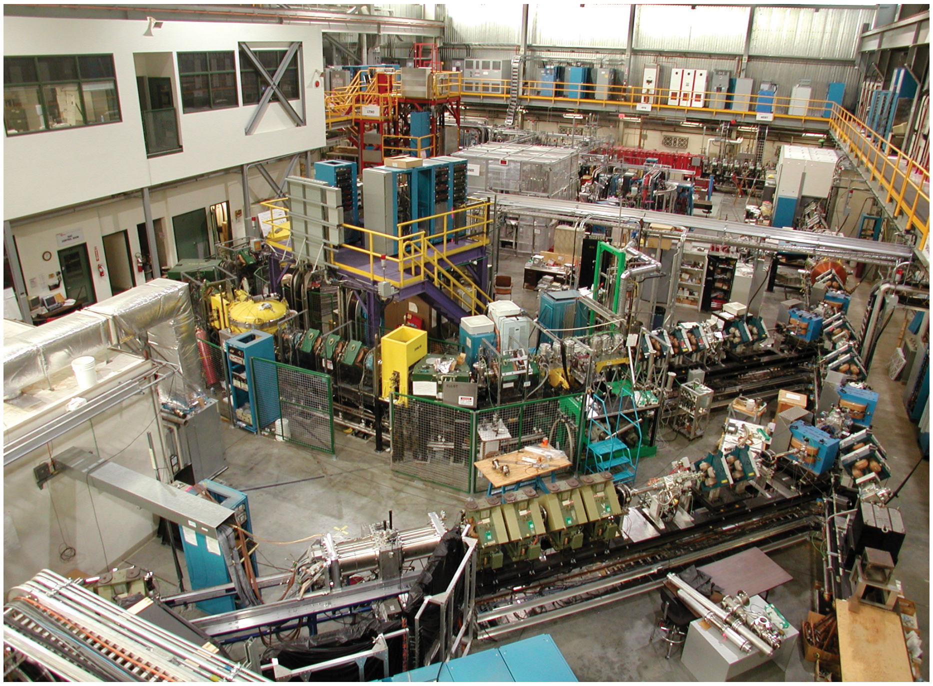
The facilities within the laboratory have been rapidly evolving over the past few years, so the laboratory is now one of the leading world facilities to provide high intensity radioactive beams for a variety of scientific fields. The radioactive ions are produced by spallation reactions using the 500 MeV protons from the main TRIUMF cyclotron. Isotopes are then selected by a mass separator before delivery to the experimenters. These ions of energy several keV/u are used for a variety of studies such as fundamental decay studies, nuclear structure studies, and material science studies. During this year a milestone was passed with the completion and commissioning of the RFQ and DTL accelerators that can accelerate both stable and unstable ions from 0.15 to 1.5 MeV/u. This energy range is ideal for investigating nuclear reactions of particular relevance to nuclear astrophysics. The accelerator system can accelerate $1^+$ ions of up to mass 30, but in the future this will be extended to heavier masses for higher charge states with a charge state booster now under construction. During the year another significant milestone was reached with the successful commissioning of the DRAGON and TUDA systems, special apparatus designed to investigate nuclear astrophysics reactions associated with radioactive beams. Both experimental systems undertook successful experimental investigations of the reaction $^{21}$Na (p, $\gamma$)$^{22}$Mg. This particular reaction is of great interest for the investigation of $^{22}$Na production in the galaxy since $^{22}$Na is produced from the decay of $^{22}$Mg.

Now that most of the main components of the first phase of ISAC are nearly all built, the laboratory began to turn its attention to the second phase. This phase will enhance the energy of radioactive ions to 6.5 MeV/u for ions of mass up to A = 150. The accelerator complex needed for this requires a new building, the funds for which have been generously provided by the BC provincial government. Construction of this building started in January 2002 and should take one year to complete. The accelerator structures associated with this second phase will be ready in the year 2005.

Over the past few years TRIUMF has made substantial contributions to the LHC accelerator at CERN. These contributions have been associated with several discrete projects, a major one in terms of resources has been the design and construction of 52 conventional double beam quadrupole magnets. These magnets are used for beam control in the cleaning sections of the main LHC accelerator. Due to the demanding accuracy needed for their function, they have been a challenge to produce. It is a tribute to all concerned at TRIUMF and to the manufacturing company, ALSTOM, that the fabrication problems have been



The Meson Hall



ISAC Experiment Hall

overcome and steady production started towards the end of the year. ATLAS Canada has the responsibility to produce the hadron endcap calorimeter, a component of the ATLAS detector. This project involving TRIUMF and several universities is nearing completion. TRIUMF provides for the management of the project and the clean rooms for the detector assembly before they are shipped to CERN for testing.

TRIUMF provides general infrastructure support for many Canadian physicists across Canada to enable them to participate in a meaningful way in many experiments outside Canada. By way of example, the inner tracking detector for the BaBar experiment at SLAC was made at TRIUMF; this experiment is now producing exciting new results concerning heavy quark physics, and the Canadian team members, through their responsibility for the operation of the inner detector, continues to be an essential part of this experiment.

Again TRIUMF is much involved in supporting the *K*-meson rare-decay experiment at Brookhaven. New results that provide better limits for the branching ratio are given in this report. However, the statistical errors are still too large for the results to challenge the standard model; more data to reduce the statistical errors are needed.

The main 500 MeV cyclotron, which can simultaneously deliver a variety of beams, has worked well during the year. It has mainly been used to provide the proton beam for ISAC while continuing muon production for the μSR program and TWIST. The TWIST experiment aims to measure the physical parameters associated with muon decay to an accuracy that will provide a stringent test of the standard model predictions. This last year saw the full commissioning of all components of the detector and a large superconducting magnet. The μSR program is an important part of the laboratory's activities since the modulation of μ decay characteristics in materials provides an excellent probe for a large variety of physical chemistry and materials science investigations. It continues to be a particularly important in the investigation of the magnetic properties of superconductors and is complemented by the new $^{8}$Li $\beta$NMR facility commissioned at ISAC.

The biological/medical program continues to be another important component of the laboratory's activities. Here the main project centres on the PET technique with TRIUMF providing the essential radioisotopes for this work. Successful grant applications during the year will mean new PET machines will be installed in the near future. In particular, a new micro-PET for small animal experiments will increase the importance and diversity of this research area. Proton irradiation both for cancer therapy treatment and for general irradiation work has continued to be an important activity during the year.

Technical knowledge transfer is an integral part of the mission of many scientific laboratories; TRIUMF is no exception. The highlight of this activity during the year was MDS Nordion's decision to build a new cyclotron on the TRIUMF site. This $20M commercial investment for radioisotope production gives testament to the excellent relationship TRIUMF has with MDS Nordion.

Within two pages it is difficult to give fully appropriate mention of all the relevant aspects of TRIUMF. However, it is certainly true that a laboratory is no better than the people within it. That the laboratory continues to run well is a tribute to all staff whether they are scientists, engineers, technicians, or administrative staff. Finally, but by no means least, on behalf of all staff I would also like to thank the previous director, Dr. Alan Astbury, who retired during the year, for his many years of hard work.

Alan Shotter

TRIUMF

## Joint Venture Members

- The University of Alberta
- The University of British Columbia
- Carleton University
- Simon Fraser University
- The University of Victoria

## TRIUMF BOARD OF MANAGEMENT

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- The University of Manitoba
- McMaster University
- L'Université de Montréal
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- The University of Regina
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National Research Council

Dr. P. Sinervo
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**J-M. Poutissou**

**Administrative Assistant**
**E. Conning**

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S. Reeve

**HR & Administration**
J. Hanlon

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**Experiment Evaluation Committees**

- Subatomic Physics
- Condensed Matter
- Life Sciences

**Computing Facilities at TRIUMF**

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**TRIUMF Safety Management Committee**

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**Administration Division**
A. Shotter

**Cyclotron Division**
G. Dutto

**ISAC Division**
P. Schmor

**Science Division**
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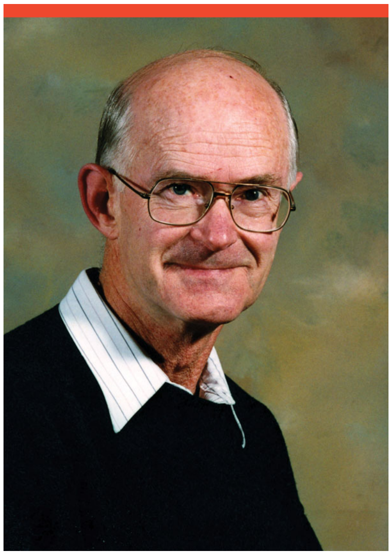
**Technology Transfer Division**
P. Gardner

W. John McDonald



It is with much pleasure that I take the opportunity to report on the activities of the TRIUMF Board of Management. I know that I speak for all of the members of the Board when I say that it is an honour to be associated with this fine organization. We are proud of the extraordinary way that TRIUMF staff have managed to succeed in building and operating new facilities such as ISAC–I, have carried out the program for building ISAC–II, contributed key components for the LHC and ATLAS at CERN, and all the while continuing an exciting program of science in nuclear and astrophysics, precision tests of fundamental processes, medical physics, condensed matter physics, and nuclear chemistry. The growth that has taken place in the transfer of TRIUMF technology to applications that benefit society and aid Canadian industries is an important indicator of the innovative skills and hard work of TRIUMF staff.

Like all successful organizations, TRIUMF relies on many individual contributions. I would be remiss if I did not also explicitly comment on the very able clerical and support staff that do so much to create the working environment that makes it possible for the technical, engineering and scientific staff to function at the high level of excellence they have demonstrated. For example, one cannot help but be struck by the positive comments one hears about a stay in TRIUMF House, the good food provided for a meeting by the cafeteria staff, or the efficient way the business office handles a variety of complex accounts and travel claims. It is clear that TRIUMF's successes have been achieved in large part because so many individual staff, including scientists, engineers, technicians, computer and management professionals as well as secretaries, clerks and other support staff have done their jobs well. I have only touched on a few of the many examples that could be given.

The Board's responsibilities include the appointment of Director, and I had the privilege of chairing the search committee which recommended that Alan Shotter be selected. With the support of the Board, the committee made an early decision to have as open a process as was possible. Accordingly, the community was invited to comment on the process and suggest candidates. Several helpful responses were received and the committee acquired a good list of potential candidates. Once a short list of three excellent candidates was formed the committee invited, and carefully considered, feedback from inside and outside the community. It then completed the difficult task of forming a recommendation for the Board. The Board, having considered the committee's recommendation, offered the position of Director to Dr. Alan Shotter. Dr. Shotter accepted and took up his duties as Director on September 1, 2001.

As in the past, the Board has been regularly considering matters brought to it from its standing committees: Finance, Personnel, and Safety. Other matters discussed in the past year include communications strategy, university relations, technology transfer and preparations for the next 5-year plan. In order to focus on particular issues the Board has decided that in the future, each of its meetings will have one extended discussion on a specific theme. The objective is to ensure that, over a period of 2 to 3 years, the Board would be able to review and make changes as appropriate to all of its key policies.

Before closing, I wish to acknowledge and thank Colin Jones and Alan Astbury. These two people provided wise and sure guidance to accomplish the successful shaping of a new future for TRIUMF following the Government's decision not to build KAON. Canada owes much to both of them for giving us the vision and the reality of a National Laboratory supporting the Canadian particle physics program abroad, and extending the in-house science program with the addition of a world leading radioactive beam facility. I am also personally grateful to Colin for the willing help and sage advice he gives to me as I attempt to follow his example as Board Chair and to Alan for his generosity in helping me during the search for a new Director and for making the transition to Alan Shotter's directorship go so smoothly.

W. John McDonald

PRICEWATERHOUSECOOPERS

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May 31, 2002

AUDITOR'S REPORT

To the Joint Venturers of TRIUMF

The accompanying condensed financial statements have been prepared from the statement of financial position of TRIUMF as at March 31, 2002 and the statement of combined funding/income and expenditures and changes in fund balances for the year then ended. We have audited those financial statements and reported thereon without reservation on May 31, 2002.

In our opinion, the accompanying condensed financial statements are fairly stated in all material respects in relation to the financial statements from which they have been derived.

PricewaterhouseCoopers LLP

**SUMMARY COMPARISON WITH PRIOR YEAR'S FUNDING**

| | 2001/2002 | | 2000/2001 | |
|---|---|---|---|---|
| **SOURCE OF FUNDS** | **$,000** | **%** | **$,000** | **%** |
| NATIONAL RESEARCH COUNCIL | 40,000 | 77.48% | 39,000 | 76.53% |
| NSERC | 4,783 | 9.26% | 6,793 | 13.33% |
| PROVINCE OF BRITISH COLUMBIA | 1,320 | 2.56% | | |
| MDS NORDION INC | 3,143 | 6.09% | 2,496 | 4.90% |
| AFFILIATED INSTITUTIONS | 1,659 | 3.21% | 1,812 | 3.56% |
| COMMERCIAL REVENUE | 455 | 0.88% | 445 | 0.87% |
| INVESTMENT AND OTHER INCOME | 267 | 0.52% | 413 | 0.81% |
| TOTAL | 51,627 | 100.00% | 50,959 | 100.00% |

## *TRIUMF*
### *Statement of Financial Position*
### *As at March 31, 2002*

| | 2002 $ | 2001 $ |
|---|---|---|
| **Assets** | | |
| Cash and temporary investments | 4,399,885 | 5,925,389 |
| Funding receivable | 1,499,613 | 970,925 |
| **Total assets** | 5,899,498 | 6,896,314 |
| **Liabilities** | | |
| Accounts payable | 1,988,144 | 2,038,561 |
| Funds received in advance | 1,856,235 | 1,109,104 |
| | 3,844,379 | 3,147,665 |
| **Due to (from) joint venturers** | | |
| The University of British Columbia | 265,906 | (33,390) |
| The University of Alberta | (4,938) | (1,345) |
| Carleton University | 213,816 | - |
| The University of Victoria | 299 | (12,520) |
| Simon Fraser University | 4,743 | (17,438) |
| | 479,826 | (64,693) |
| | 4,324,205 | 3,082,972 |
| **Fund Balances** | | |
| **Restricted** | | |
| Natural Sciences and Engineering Research Council Fund | 888,008 | 2,274,694 |
| MDS NORDION Inc. Fund | 100,000 | 100,000 |
| Affiliated Institutions Fund | 143 | 143 |
| | 988,151 | 2,374,837 |
| **Other** | | |
| Commercial Revenue Fund | (239,706) | 972 |
| General Fund | 12,462 | 767,067 |
| Intramural Accounts Fund | 814,386 | 670,466 |
| | 587,142 | 1,438,505 |
| | 1,575,293 | 3,813,342 |
| **Total liabilities and fund balances** | 5,899,498 | 6,896,314 |

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# TRIUMF
## *Statement of Combined Funding/Income and Expenditures and Changes in Fund Balances*
## *For the year ended March 31, 2002*

| | 2002<br>$ | 2001<br>$ |
|---|---|---|
| **Funding/income** | | |
| National Research Council Fund | 40,000,000 | 39,000,000 |
| Natural Sciences and Engineering Research Council Fund | 4,783,305 | 6,792,528 |
| MDS NORDION Inc. Fund | 3,143,366 | 2,495,762 |
| Province of British Columbia Building Fund | 1,320,155 | - |
| Affiliated Institutions Fund | 1,658,482 | 1,812,417 |
| Commercial Revenue Fund | 455,189 | 445,019 |
| General Fund | 266,555 | 413,393 |
| | 51,627,052 | 50,959,119 |
| **Expenditures** | | |
| Buildings and improvements | 1,855,596 | 229,594 |
| Communications | 123,011 | 200,707 |
| Computer | 1,200,886 | 1,265,353 |
| Equipment | 10,730,390 | 6,359,572 |
| Power | 1,771,945 | 1,712,516 |
| Salaries and benefits | 28,774,346 | 27,420,958 |
| Supplies and other expenses | 9,408,927 | 14,697,955 |
| | 53,865,101 | 51,886,655 |
| **Deficiency of funding/income over expenditures for the year** | (2,238,049) | (927,536) |
| **Fund balances - Beginning of year** | 3,813,342 | 4,740,878 |
| **Fund balances - End of year** | 1,575,293 | 3,813,342 |

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# *TRIUMF*
## *Notes to Financial Statements*
## *March 31, 2002*

**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 and the University of British Columbia, 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 20% interest in all assets and is responsible for 20% 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, 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 various funding sources. The sources and purposes of these funds are as follows:

**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 for expenditures undertaken at its TRIUMF site.

**Provincial Government Building Fund**

Funding from the Province of British Columbia for the construction of new facilities.

**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.

**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.

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# RARE DECAYS - INVESTIGATIONS INTO THE HEART OF MATTER

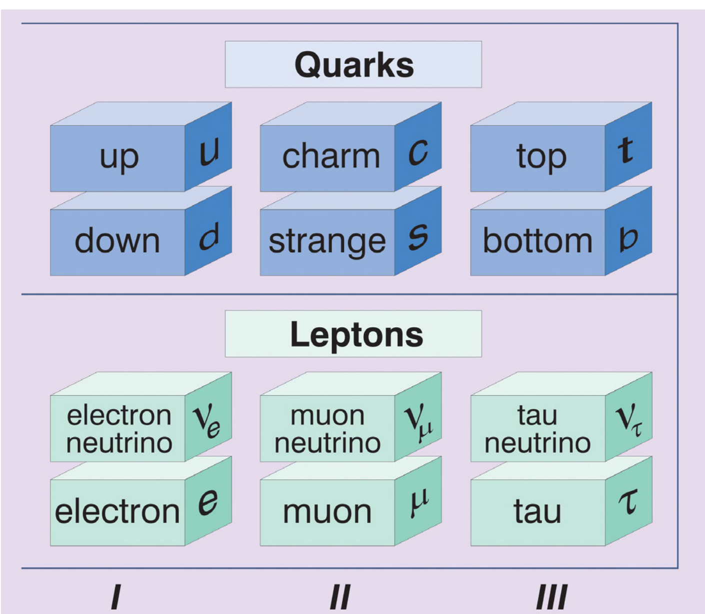
Douglas Bryman, Christopher Hearty and John Ng

The innermost secrets of matter and energy are to be discovered in the world of fundamental particles. These particles compose all normal matter and the laws they obey apparently apply at all times and at all places in the universe. The goal of particle physics is to map out this world and discover the rules that govern its behavior. This knowledge has far-reaching consequences for our understanding of what the universe is and how it came to be.

Physics, astronomy and mathematics have had phenomenal success in discovering simple laws and symmetry principles which govern matter at its most fundamental level. These triumphs have unraveled the behavior of matter at the smallest scales, have had immense consequences in our being able to understand the history of the universe, and have led to the development of the basic mathematical models needed for such understanding.

Thanks to new experimental findings made accessible by particle accelerators worldwide, the last few decades have brought a radically new and simple picture of nature on the most fundamental level. Matter is assembled from a few basic building blocks called quarks and leptons. This synthesis of knowledge is called the Standard Model of Particle Physics.

In the Standard Model quarks are classified into three families or generations. Each generation consists of a pair of quarks with different masses and electric charges. Names, seemingly arbitrary - but not quite, have been assigned to each of the six quarks. The first generation is composed of the up (*u*) and down (*d*) quark. The second generation consists of the charm (*c*) and the strange quark (*s*) while the members of the third generation are known as the top (*t*) and bottom (*b*) quark. In addition to their mass and charge, each quark has a number of other properties such as spin (angular momentum) that can only have discrete values. All these quantities play an important role in limiting the way quarks can interact.




Three Generations of Matter

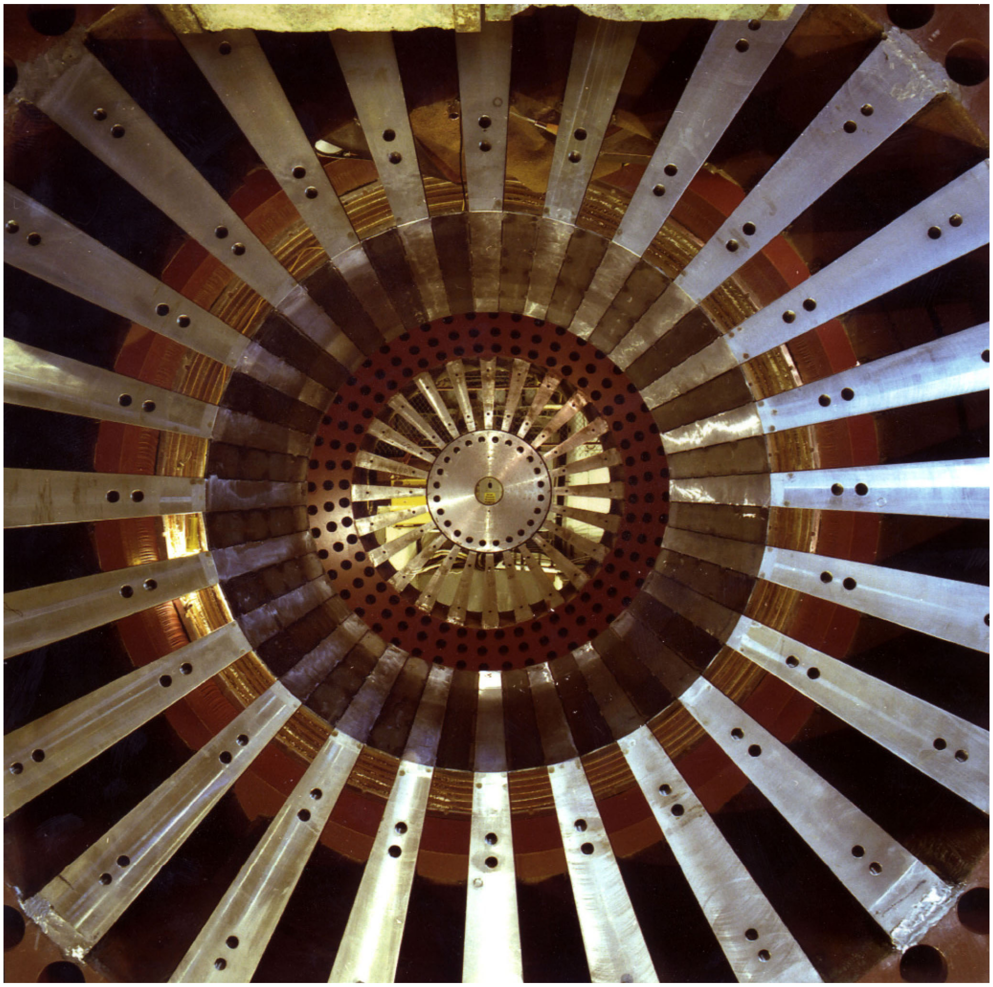
The leptons also appear in three generations. Like the quarks each generation contains two particles, one an electron-like particle, the other an (almost) massless, chargeless one that only interacts very weakly with matter. All leptons appear to be point-like particles without any known internal structure.

In 1928 Dirac predicted that for every particle there exists an antiparticle of exactly the same mass and spin. If a particle also carries an electric charge then the antiparticle will carry an equal but opposite charge. Thus, for each quark and each lepton there is a corresponding antiquark and antilepton. (An anti-particle is indicated by a bar over its symbol.)

The properties of quarks are such that they can exist, even if only for a short time, only in combinations of two or three quarks known as hadrons. A single quark cannot be isolated nor can groups of four ever be created. The groups of three are called baryons. They include the proton (*uud*) and neutron (*udd*). The groups of two, consisting of a quark and an antiquark, are called mesons. They include the $\pi$ meson ($u\bar{d}$), the kaon ($u\bar{s}$), and the $B^0$ meson ($d\bar{b}$). With the exception of the proton all hadrons are known to be unstable. It is believed that the proton, too, is unstable. Experiments are underway attempting to observe this. However, due to the very long life-time, over $10^{33}$ years, they are extremely difficult.

One of the most useful and fruitful concepts of physics is that of the conservation law and its associated symmetry. A conservation law simply states that during a process a certain measurable quantity remains constant. This can usually be shown to be a result of an underlying symmetry. All symmetries lead to conservation laws and vice versa. For example momentum conservation can be shown to result from the symmetry (equivalence) of all systems moving at constant speed with respect to one another, and energy conservation from the independence of the laws of physics from the choice of the start of the time variable.

This situation continues to hold true for the symmetries in the subatomic world except that, because of the special properties of the fundamental particles, many more processes, and hence symmetries are possible. A very important symmetry is associated with changing a particle into its antiparticle or vice versa. It is known as charge conjugation, **C**. Many laws of physics do not change their forms (are invariant) when this change takes place. In a **C**-invariant world one would not be able to tell whether it is made up of matter or antimatter. Similarly the operation of reversing the direction of all spatial coordinates, known as the parity transformation, **P**, is also respected by many laws of physics. Such a world cannot be distinguished from its mirror image. The classical laws of physics and Maxwell's equations of electromagnetism are all invariant under **P**.



The E787 magnet.

Before 1957 it was believed that the laws governing elementary particle interactions were invariant under the symmetries **C**, charge conjugation or reversal, and **P**, parity or spacial inversion. In that year, Lee and Yang proposed that the weak interactions, those responsible for the decay of the neutron into a proton, electron, and an anti-neutrino do not obey either **C** or **P**. However, they appeared to respect the combined symmetry of **CP** taken together. In 1964 an historic experiment by Christensen, Cronin, Fitch and Turlay found that the product of symmetries **CP** is violated approximately one out of 500 times in the decay of neutral kaons.

The discovery of such occasional violations of a symmetry lead us to a more profound understanding of the universe. The Big Bang should have produced equal amounts of matter and antimatter, which would subsequently mutually annihilate, producing a universe filled with photons and nothing else. This is close to what actually happened: almost all matter did annihilate with antimatter, producing the flood of photons that form the 2.7 $^0$K cosmic microwave background. But a tiny excess of matter over antimatter - one part in ten billion - ensured that some matter survived to form the stars, planets and us. In 1967 Sakharov, taking his lead from the measured symmetry violation in kaon decay, showed that a matter-dominated universe could occur if a set of simple principles which involve **CP** symmetry violation were obeyed. However, in the context of the Standard Model, these effects fail to explain the matter dominance effect by about ten orders of magnitude, leading physicists to search for entirely new effects which could have far-reaching implications for our view of the universe.

In 1973, when only three types of quarks were known to exist, theoretical studies showed that in order for **CP** violation to occur at least three more types of quarks had to exist. This spurred searches for the missing types. One, the charm quark, was quickly found in 1974, while the bottom quark was identified in 1977. It took a long time, till 1995, for particle accelerators to reach high enough energies for the top quark to be discovered. It is by far the most massive quark of all, weighing in at a bit less than an entire gold atom.

**CP** symmetry violation is one of the most important outstanding issues in the study of elementary particle physics with profound implications on the relationship

# RARE DECAYS - INVESTIGATIONS INTO THE HEART OF MATTER

TRIUMF

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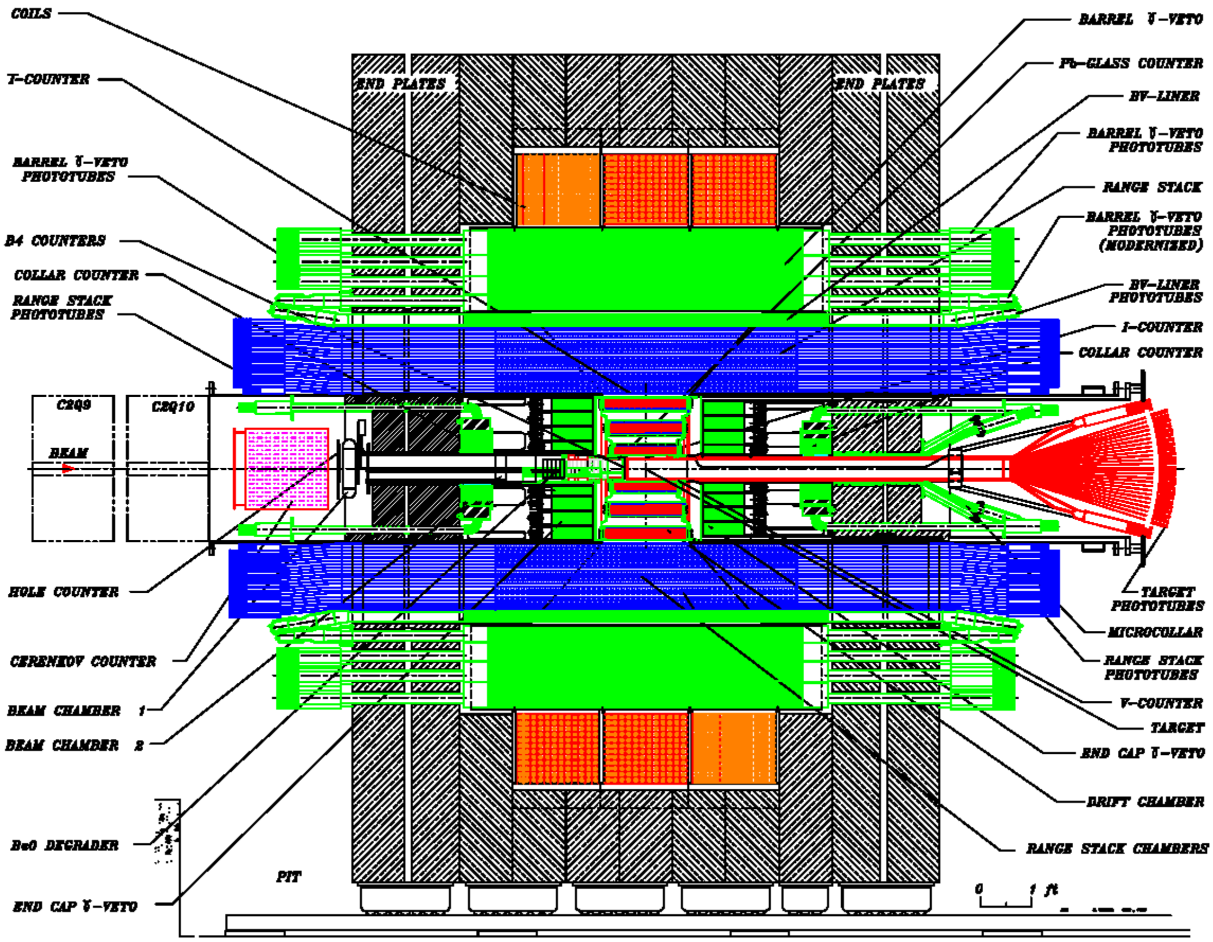



Cross section of the upgraded E787 apparatus to be used for the E949 experiment.

between the quarks, and possibly also on the origin of matter in the universe. Seeking an understanding of this is one of the main areas of worldwide activity in particle physics. The experiments described below, studying the rarest known examples of particle decays, are among a new generation of international collaborative projects conceived to explore the interactions of elementary particles at mass and energy scales not achieved since the time of the Big Bang.

At the Brookhaven National Laboratory an international team is measuring rare decays of the kaon into a pion and a pair of neutrinos to get a more precise handle on **CP** violation. Another approach to **CP** violation is being carried out at Stanford. The BaBar experiment involves measurements of the decay of the $\mathbf{B^0}$ meson. If the Standard Model is correct, these experiments are two very different approaches to measuring the same fundamental quantities. A disagreement between their results would be a dead giveaway that the Standard Model is wrong and might give an indication of what to do to fix it.

### Symmetry Violation and Rare *K* Decay Experiments

Detailed theoretical studies have shown that very rare *K* meson decays can get to the heart of the **CP**-violation issue. These long sought-after processes involve both charged and neutral varieties of the *K* meson through its decay to a $\pi$ meson, a neutrino ($\nu$), and an antineutrino ($\bar{\nu}$): $K^+\to\pi^+\nu\bar{\nu}$ and $K_L^0\to\pi^0\nu\bar{\nu}$. These reactions are so rare that theory predicts they will only happen several times in every hundred billion *K* decays. This "dynamic duo" of rare decays is being pursued in experiments at Brookhaven National Laboratory (BNL) in New York by an international team of 50 scientists from Canada, Japan, Russia and the United

States. The Canadian contingent is from the University of Alberta, the University of British Columbia, and TRIUMF.

### $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ Experiments at BNL

After careful study of six trillion subatomic particle decays, the collaboration known as E787 (for its experiment number) recently announced spotting one of the rarest occurrences in the subatomic world – the decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ – for a second time. The researchers have spent 12 years searching for this rare decay at BNL. In this time, they have processed enough data to fill 50 million CD-ROMs.

E787 reported the first ever example of this rare decay four years ago. The second observation, reported in the January 28, 2002 issue of Physical Review Letters, represents an important confirmation of that discovery.

To search through 6 trillion decays, the E787 collaboration first needed to get a hold of 6 trillion *K* mesons. For this they chose BNL's Alternating Gradient Synchrotron, a particle accelerator capable of producing the world's most intense beam of *K* mesons. Since *K* mesons only exist for about 12 billionths of a second, the E787 collaboration had to build a state-of-the-art particle detector the size of a small house in order to capture these fleeting decays in detail. This machine is capable of examining one million decays every second.

Those decays that the machine decided were promising were short-listed to magnetic tape. This "short" list, which was thousands of gigabytes in size, was pored over in detail by the physicists as they reconstructed what really happened inside the detector. Out of all that data, they've now found two events explicable only by the rare *K* decay which is one of the keys to understanding the universe's most elemental forces and building blocks. This is a decay that physicists have been looking for since the 1960s, but nobody knew for sure if it could be measured.

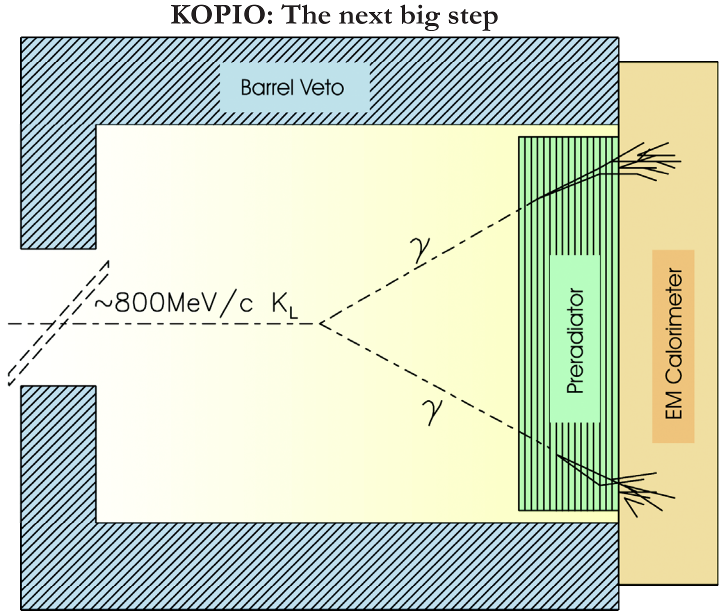
The reason $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is worth so much careful study is that it involves some of the more exotic aspects of the Standard Model. *K* decays in general have proved a rich and often surprising source of information on fundamental questions in particle physics, largely due to the *K*'s "strange" quark, a heavy relative of the quarks that comprise ordinary matter such as atomic nuclei.

When a $K^+$, the lightest particle to contain a strange quark, decays to a $\pi^+$, which is comprised of ordinary quarks only, the strange quark is converted into a "down" quark. This is forbidden in any direct process by the Standard Model. However $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ still has a small chance of occurring by means of an indirect two-step process involving other quarks – in particular, the massive "top" quark. Understanding such complex forms of decay is especially important to physicists attempting to learn how matter behaves at the most fundamental level.

Over the course of the 12-year experiment, the E787 team led by TRIUMF/UBC, BNL and Princeton University scientists, upgraded its detector shown on the previous page with new instruments and components to track particles and observe them decay in nanosecond detail. For E787, TRIUMF produced state-of-the-art high tech particle detection equipment and high speed electronics which was shipped to BNL for incorporation in the experiment. The new observations were made in data analyzed by the group working at TRIUMF and UBC.

Now that it has proven to have the sensitivity to see the rare *K* decay, a follow-up experiment (E949) will attempt to gather ten times as much data again, so that the decay can be studied in greater detail. This new data set will also test the possibility that the events seen might instead involve entirely new particles or forces.

**KOPIO: The next big step**

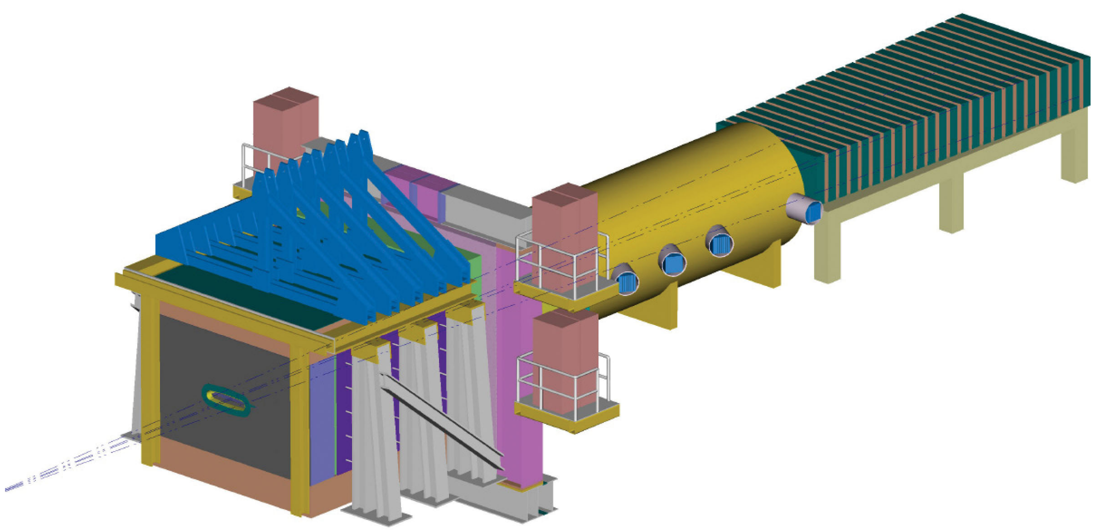



Concept for the KOPIO experiment.

The neutral K meson version of E787/E949 is the new KOPIO project designed to discover and study the process $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$. This reaction is unique because it is directly dominated by **CP** violation. Theoretical uncertainties are extremely small, so measurement of the fraction of decays which result in this mode of decay will

# RARE DECAYS - INVESTIGATIONS INTO THE HEART OF MATTER

Douglas Bryman, Christopher Hearty and John Ng



Artist's conception of the KOPIO detector.

provide the standard against which all other measures of CP violation will be compared, and even small deviations from the expectation derived from Standard Model predictions or from other measurements, e.g., from the *B* meson measurements discussed below, will unambiguously signal the presence of new physics. Using current estimates of Standard Model parameters this decay mode is expected to occur in only three out of every 100 billion decays.

In order to measure this extremely rare reaction, a new experiment, KOPIO, with unprecedented sensitivity has been proposed and accepted at the Alternating Gradient Synchrotron (AGS) accelerator of BNL. The new technologies proposed for the KOPIO detector represent an improvement in resolution by a factor of more than 100,000 over previous instruments. This great improvement will open a vast window of discovery that could transform our picture of nature. Such a new picture could occur if KOPIO discovers entirely unanticipated phenomena or if a discrepancy is found between the experiments using *B* mesons and those using *K* mesons.

The experimental aspects of measuring $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ are quite challenging. It is a three body decay where only a neutral pi meson, $\pi^0$, is observed. There are competing decays which also yield $\pi^0$s but with probabilities that are millions of times larger. Thus, a detection technique must be developed that provides maximum possible redundancy for this kinematically unconstrained decay, that has an optimum system for insuring that the observed $\pi^0$ is the only observable particle emanating from the $K_L^0$ decay, and that has multiple handles for identifying possible small backgrounds that might simulate the desired mode. It is with these issues in mind that the KOPIO experiment has been designed.

The concept for KOPIO is shown schematically on the previous page and in an artist's conception in the figure to the left. KOPIO employs a low energy, time structured neutral *K* meson ( $K_L^0$) beam to allow determination of the incident *K* momentum. This intense beam, with its special characteristics, can be provided only by the BNL AGS which is available for use during the operation of the Relativistic Heavy Ion Collider (RHIC). The goal of KOPIO is to obtain about 50 events with a signal to background ratio of 2:1. This will yield a statistical uncertainty in the measurement of the **CP** violation parameter of the Standard Model to less than 10%. While $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ is clearly the focus of KOPIO, many other radiative-type *K* decays of significant interest for study of low-energy interactions of quarks and numerous searches for non-Standard Model processes will also be accessed simultaneously.

The KOPIO apparatus includes a gamma ray imaging detector which is the responsibility of the Canadian group. It is a new type of high resolution, high efficiency gamma ray imaging device. In applications detecting medium energy gamma rays (from particle physics to medical imaging diagnostics) it is often desirable to measure as many kinematic properties as possible, such as energy, position, time of interaction, and angle, with high resolution and high efficiency. However, in previous detectors, it was generally necessary to choose at most two among high efficiency, high energy resolution, and good position resolution. Very few detector configurations can also measure photon angles (e.g. pair spectrometers) but at the cost of low efficiency and complexity. Some segmented crystal detector configurations have been used to simultaneously obtain good energy resolution, efficiency and modest position measurements but these are extremely costly making them unsuitable for very large area coverage.

Elements of the KOPIO preradiator design for imaging gamma rays have already been shown to be potentially useful for several other applications and generated a patent. In the late 1990s, TRIUMF developed an imaging scheme based on 9 MeV gamma rays for the detection of plastic and other explosives that was the basis for a $20 million development funded by the U.S. government. The original design included a conventional crystal imaging gamma camera system. In 2000, a patent was granted to D. Bryman for a gamma ray imaging system applicable to the explosives imaging problem, which is based on an array of gas tracking chambers and plastic scintillators similar to the arrangement invented for the KOPIO preradiator detector described above. The cost-effective KOPIO-type approach, which provides 3-dimensional position measurements with high resolution and faster timing, may also have applications to other gamma ray imaging problems.

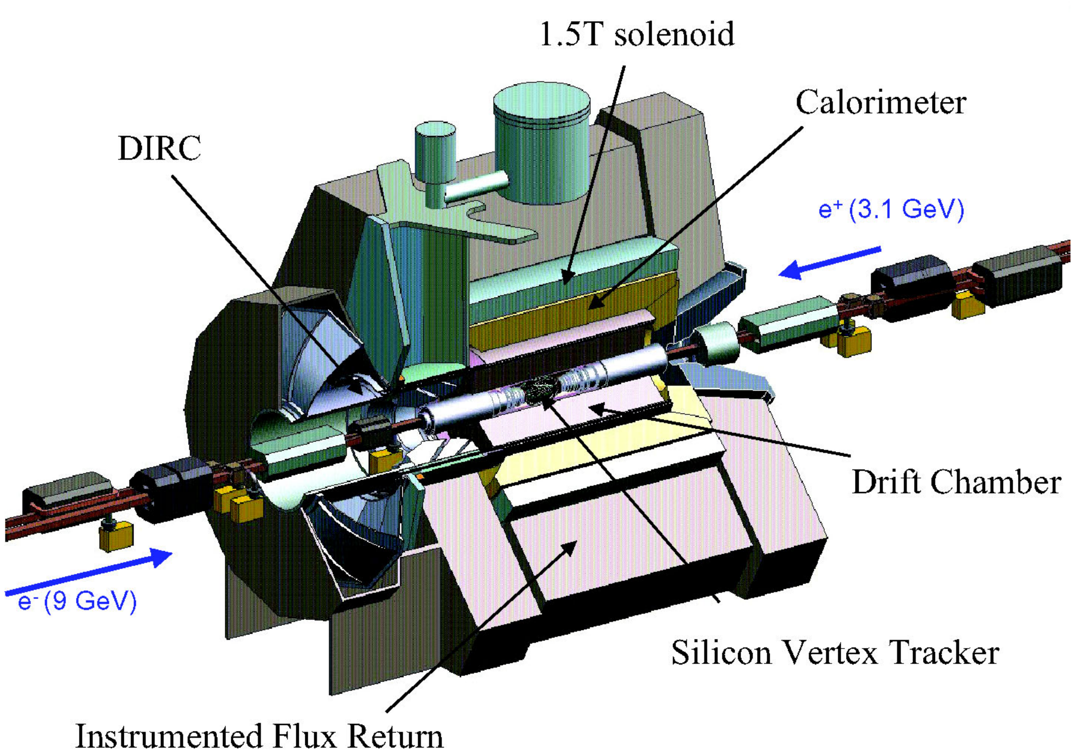
The international KOPIO collaboration consists of 65 scientists from 6 countries. UBC, BNL, INFN (Italy), Kyoto, Moscow (INR), TRIUMF, Virginia, Virginia Polytechnic, Yale, and Zurich, are among the significant participants. The experiment is currently in the design and prototyping stage and is expected to begin operation in 2005.

**BaBar**

The goal of BaBar is to precisely understand **CP** violation in a second venue, the decays of the *B* meson. The detector and the PEP-II electron-positron particle collider, make up the B-Factory located at the Stanford Linear Accelerator Center. The collaboration consists of more than 500 scientists and engineers from Canada, the United States and Europe. Canadian faculty members, located at UBC, University of Victoria, L'Université de Montréal and McGill, collaborate on BaBar and make use of the facilities provided by TRIUMF.

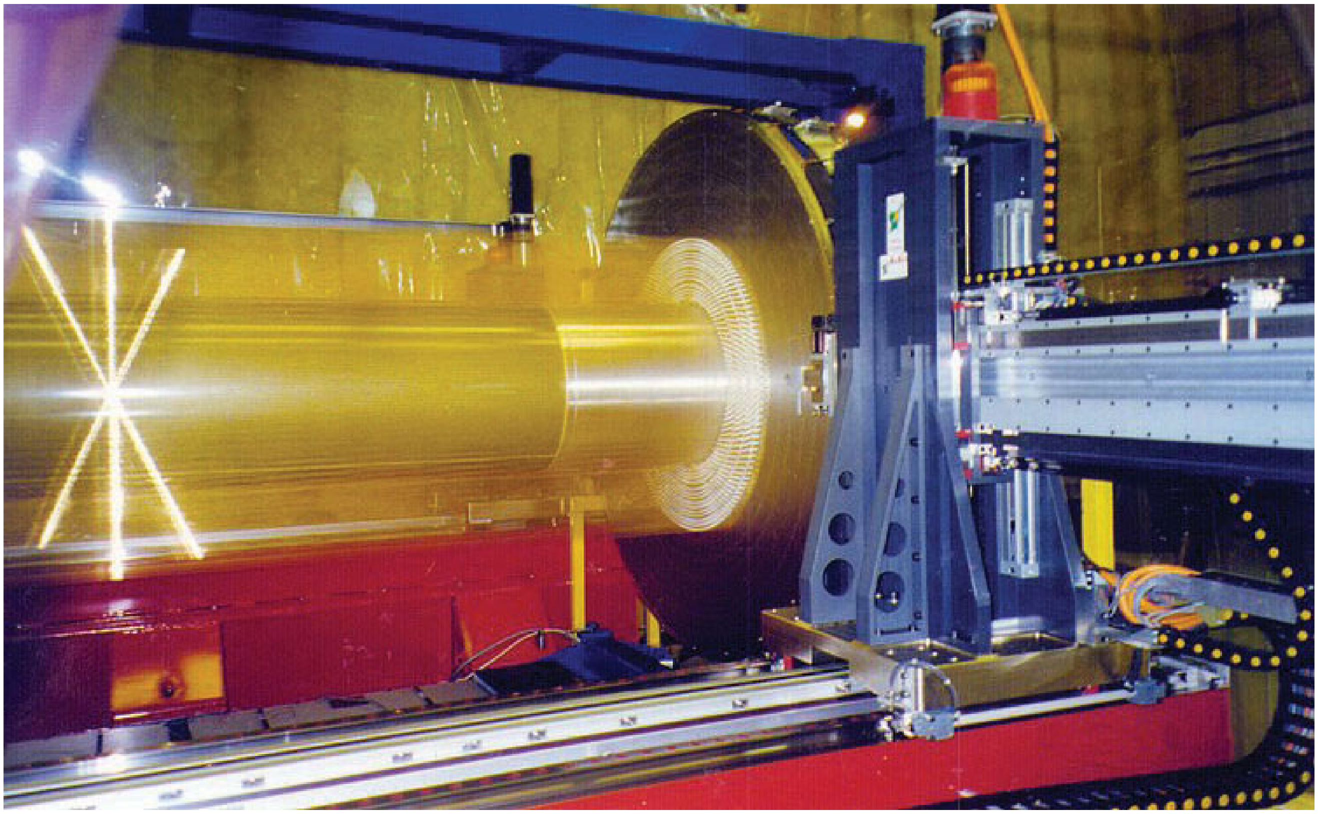
PEP-II is a new facility built specifically for this measurement. It collides bunches of electrons at 9.0 GeV with their antimatter equivalent, positrons, at 3.1 GeV. The collisions occur approximately 100 million times per second. Of these about 30 result in an electron and a positron annihilating to create a pair of leptons or quarks. A *B* meson is produced together with its antimatter equivalent, an anti-*B*, an average of only three times per second.

The energies of the colliding electron and positron are such that the *B* mesons produced are moving in the




Artist's conception of the BaBar detector. TRIUMF constructed the Drift Chambers.

Douglas Bryman, Christopher Hearty and John Ng



Drift chamber wires were installed using robotic tools.

direction of the incoming electrons at approximately one-half the speed of light. The distance a *B* meson travels before decaying (0.25 mm on average) is therefore directly related to its lifetime. **CP** violation will reveal itself as subtle differences between the lifetimes of the *B* and anti-*B* mesons when decaying to certain selected final states. The *B* meson can decay in many different ways, but less than 0.01% of all decays are of the type useful for the study of **CP** violation. This low fraction required that PEP-II be designed to produce huge numbers of *B* mesons.

B mesons decay to stable leptons and photons through a complicated, cascading chains of events. Intermediate products include other mesons leading to a multitude of particles, most having very high energies, and many existing for only very short periods of time. All these particles must have their identities, energies and trajectories determined in order to fully reconstruct the sequence of decay events. The high energy of the decay products makes them capable of penetrating large amounts of matter. Because of this and the need to determine trajectories the apparatus used must be large and consist of a variety of different devices to enable all the needed parameters to be measured. This information allows only the rare **CP**-violating decay chain to be selected. It, of course, also allows other decay modes to be selected for different studies.

The 1,000-ton BaBar detector surrounds the PEP-II collision point. Because of their short lifetime, the *B* mesons themselves do not enter the detector, so BaBar reconstructs their properties by examining their decay products. To do this, BaBar is assembled from five subsystems, each optimized to measure a different property of the decay particles.

The silicon vertex tracker at the heart of the detector, in conjunction with the surrounding drift chamber, measures the trajectories of electrically charged particles. Since the drift chamber is immersed in a strong, 1.5 Tesla, magnetic field all moving charged particles are forced to move along arcs of circles. The radius of each arc is a measure of the particle's momentum. The information from these two parts of the detector can be extrapolated backwards to locate the decay point of each of the two *B* mesons and hence their lifetimes.

The remaining systems - the detector of internally reflected Cherenkov light, the calorimeter, and the muon detector - measure the speed of charged particles and the energy of photons and electrons. These systems distinguish muons (heavy cousins of the electron) from other charged particles.

Douglas Bryman, Christopher Hearty and John Ng

All information from the detector is acquired by computers and stored in a database for later analysis by members of the collaboration. This database is currently the largest one in the world, over 500,000 gigabytes, and is expected to double within the year.

The drift chamber was constructed at TRIUMF, with the assistance of American and Italian collaborators, as the Canadian contribution to the BaBar detector. It consists of 28,768 fine wires strung between two endplates that precisely locate the wires. Inner and outer cylinders support the wire tension, align the endplates, and contain the helium-based gas used in the chamber.

The wires were installed with the assistance of two robots supplied by Italian collaborators. The work took place in a large clean room originally built for the Hermes experiment, and now used by the ATLAS collaboration. Construction took one year and was followed by the shipment of the chamber to SLAC and its integration with the rest of BaBar. The drift chamber is performing to specifications and is expected to do so for the life of the project. Its construction has been a tremendous success for TRIUMF's program that provides infrastructure support for Canadian particle physicists.

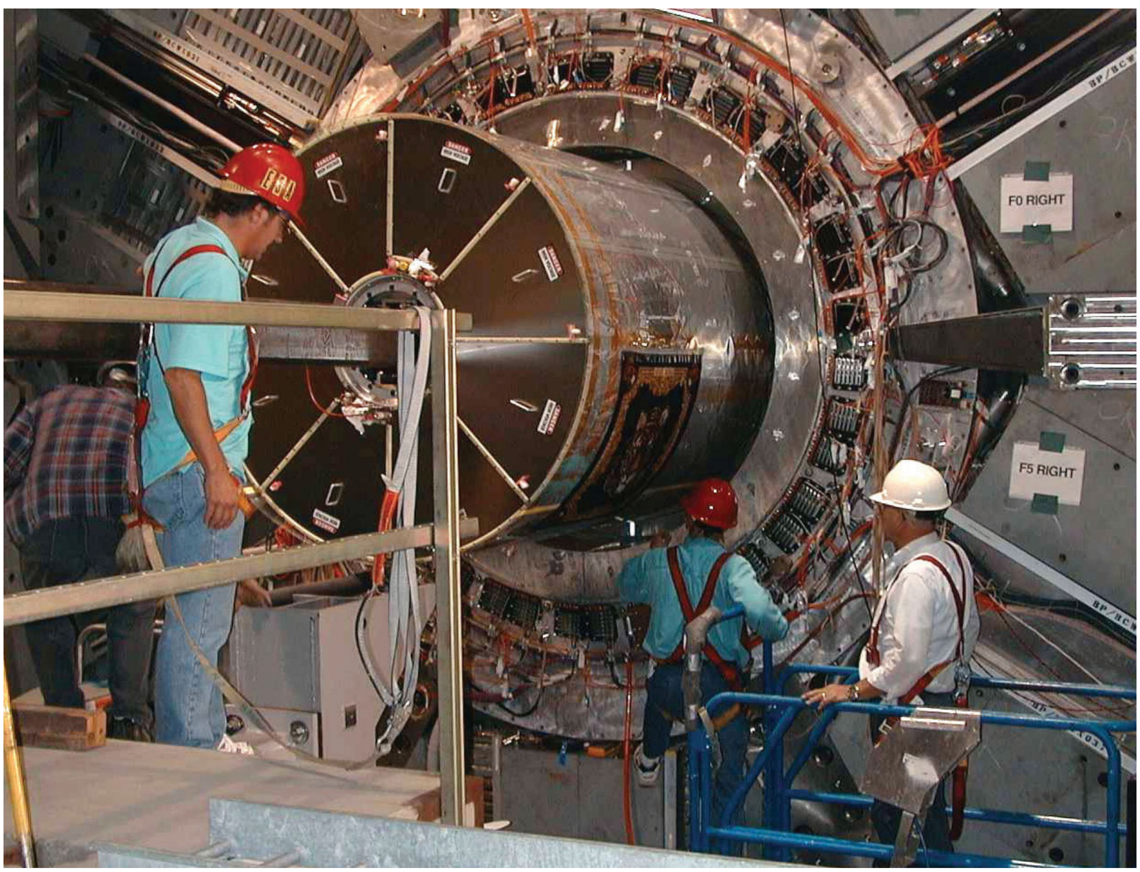
PEP-II has been operating very well, producing 30% more data per year than designed. The degree of **CP** violation is characterized by a non-zero value for a parameter called $\sin(2\beta)$. BaBar has unambiguously measured CP violation in B decay with the value $\sin(2\beta) = 0.72 \pm 0.09$.

BaBar has produced many other exciting results as well. One analysis, led by the Canadian group, has studied the production in the decay of *B* mesons of charmonium mesons, which consist of a c quark paired with an anti-c quark. The momentum distribution of the charmonium mesons is surprising, and may indicate that the *B* meson has a different internal structure than suspected.

The next steps for BaBar are to study **CP** violation in other decay modes, where the results should be predictable from current measurements. The huge data set that BaBar is accumulating will allow the Canadian group to undertake sensitive searches for rare *B* decays that could indirectly point the way to new physics.

Despite all these measurements the issue of **CP** violation is not closed. Often the devil is in the details. The current Brookhaven $K^+$ experiment will provide more of these needed details. KOPIO will provide another test of the current theory as the quantity it will measure is predicted with considerable accuracy. BaBar has shown conclusively that **CP** violation occurs in a second system and is refining this measurement as well as carrying out tests of other aspects of the Standard Model. It is in experiments such as these that our fundamental understanding of our universe, its origin, and our possible fate lie.

*Douglas Bryman holds the J.B. Warren Chair in the Department of Physics at the University of British Columbia. He is the co-spokesperson (co-leader) of the experiments at Brookhaven. Christopher Hearty, of the Department of Physics at UBC, is a member of the BaBar collaboration. John Ng is a research scientist in the Theory Group at TRIUMF.*




Inserting the drift chamber into the BaBar detector.

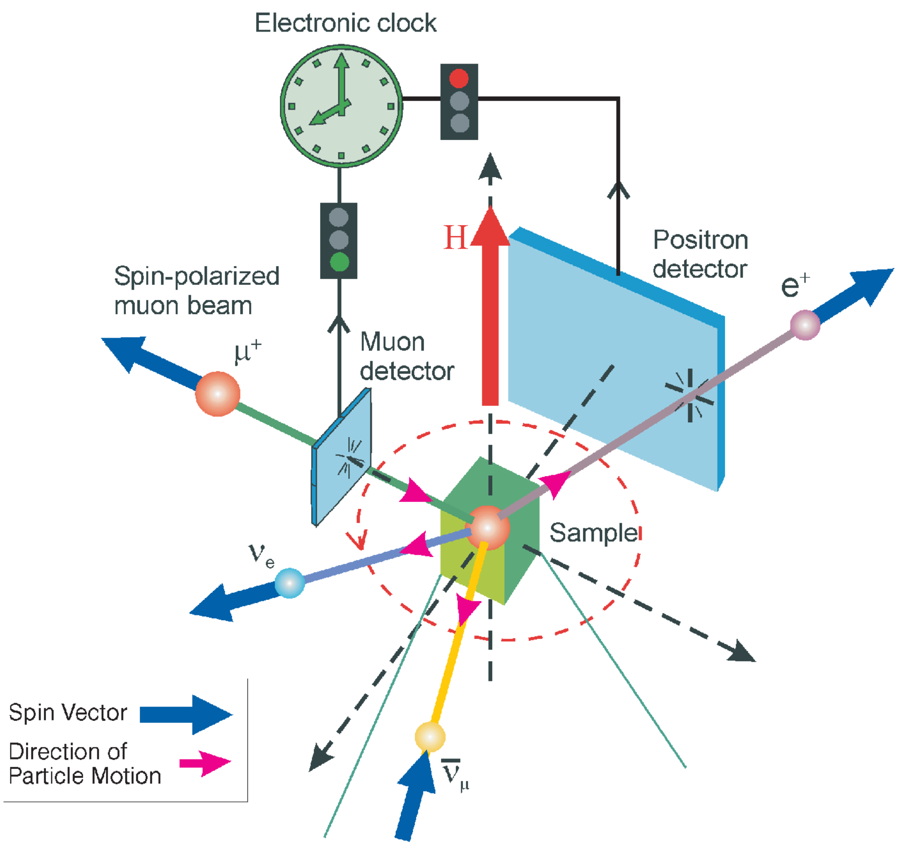
# SUPERCONDUCTIVITY STUDIES USING MUONS

Jeff Sonier

The TRIUMF μSR facility currently supports a diverse range of experimental programs. Almost one-third of this research is concentrated in the area of superconductivity – the complete loss of electrical resistance below a critical temperature, $T_c$. The highest values of $T_c$ (the maximum is currently 160 K) are in compounds composed of copper-oxygen planes separated by charge reservoirs. These are the *high-temperature superconductors* (HTSCs).

While it has been over 15 years since the thrilling discovery of the first HTSC, there remains an extraordinary worldwide scientific interest in this subject. With no established theoretical model, high-$T_c$ superconductivity is today's major open problem in condensed matter physics. Motivating the effort to solve this puzzle is the potential for large-scale applications that exploit the unique properties of HTSCs, accessible at temperatures warmer than liquid nitrogen (77 K). Such applications include electric power transmission cables, energy-efficient motors, wireless communications systems and hospital magnetic resonance imaging scanners.

However, HTSCs are not without their limitations. There is a severe reduction of their current-carrying capabilities in strong magnetic fields. In addition, they are difficult and costly to fabricate. The announcement in January 2001 of superconductivity at 39 K in magnesium diboride ($MgB_2$) generated a frenzy of excitement as researchers around the world raced to understand why this material superconducts at temperatures well above those of similar alloys. While $MgB_2$ wires and films are less expensive and easier to fabricate than their HTSC counterparts, applications are limited to modest magnetic field environments and require the use of expensive liquid helium as a coolant.

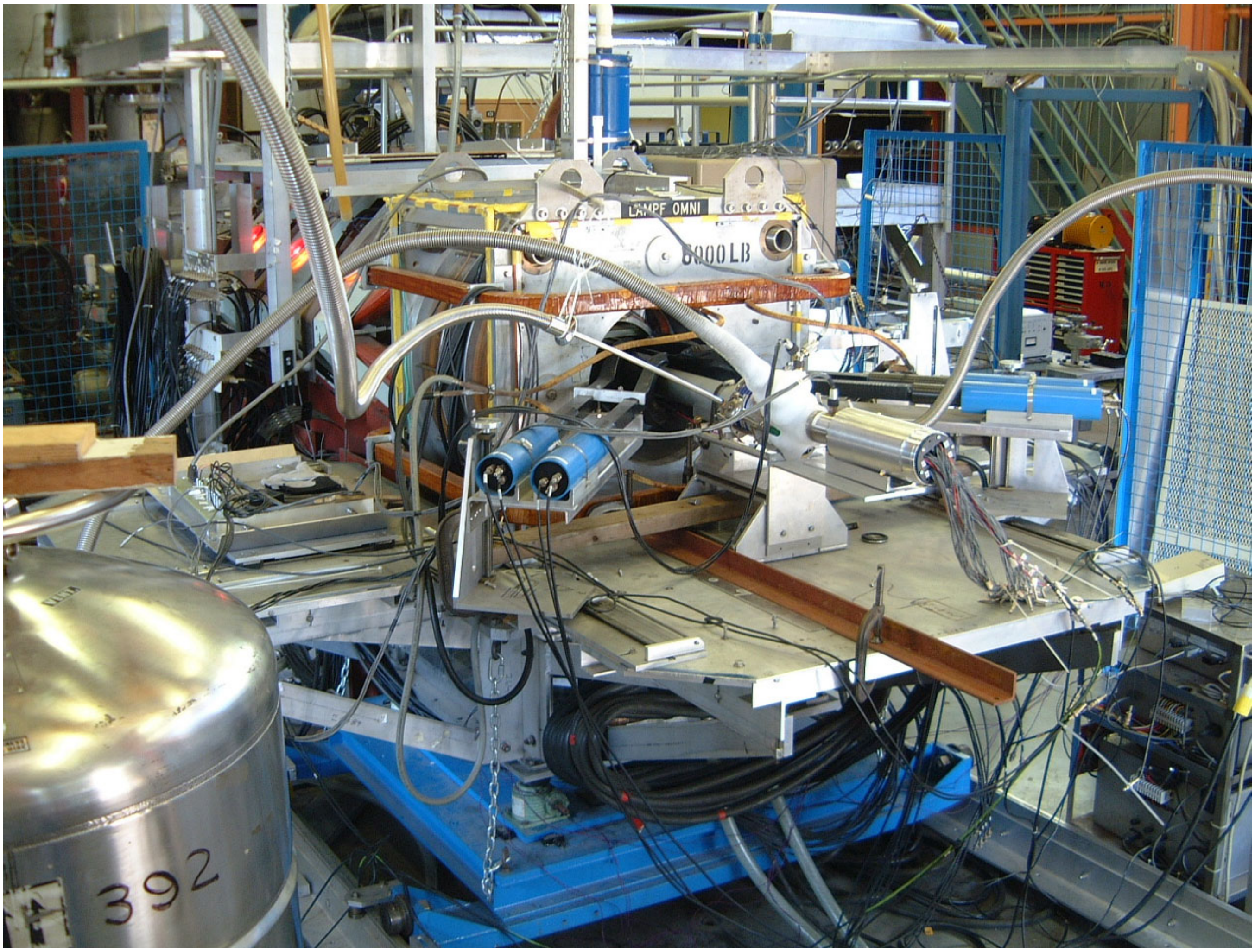



Positive muons ($\mu^+$) can be used to measure the magnetic field distribution of the vortex state in the bulk of a superconducting material. After implantation into the superconductor, the spin of a $\mu^+$ precesses at a frequency that is directly proportional to the local magnetic field at its stopping site. The $\mu^+$ lives for only about two millionths of a second, after which it decays into a positron (e+) and a neutrino, anti-neutrino pair. The time evolution of the muon-spin polarization is monitored by detecting the decay positrons from millions of implanted muons. Because muons stopping at different places in the vortex lattice experience different local magnetic fields, the measured muon-spin precession signal contains a continuous distribution of precession frequencies.

Understanding how HTSCs and other classes of unconventional superconductors work is likely to lead to the design of higher performance, lower cost materials for an increased number of technological applications – perhaps eventually to the development of a *room-temperature* superconductor! Yet the fascination with HTSCs extends well beyond their direct practical applications. Strong correlations between charge carriers is a common thread linking high-$T_c$ superconductivity with a range of other interesting physical phenomena, such as colossal magnetoresistance, the quantum Hall effect, heavy fermion behaviour and the Coulomb blockade in single-electron transistors. The new physics that HTSCs hold thus has far reaching implications for modern condensed matter physics – knowledge of which helps form the basis of materials science that is central to the design of many new high technology products.

One of the most interesting properties of so-called *type-II superconductors*, such as the HTSCs, is that they permit normal and superconducting regions to coexist in the same sample. When placed in a sizeable magnetic field, quantized magnetic flux lines known as *vortices*, extend through the bulk of the superconductor. Currents comprised of paired electrons, called *Cooper pairs*, swirl around the normal vortex cores, screening the

Jeff Sonier

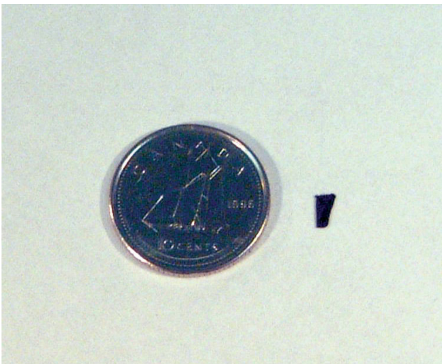



A typical μSR experimental setup for measuring the vortex state of a superconductor. The superconductor is cooled below $T_c$ using a helium gas-flow cryostat, and a pair of Helmholtz coils creates the magnetic field that forms a vortex lattice inside the sample. An arrangement of counters inside and outside of the cryostat is used to detect the incoming muons and the decay positrons.

rest of the sample from the penetrating field and producing magnetic fields inside the cores that are parallel to the applied field. One of the keys to theoretical progress in high-$T_c$ superconductivity is determining the fundamental physical properties of the normal vortex cores and the surrounding superconducting regions.

The experimental techniques available for probing the magnetic structure of the vortex state in the bulk of a sample are rather limited. Conventional NMR (and $\beta$-NMR) measurements are often complicated by additional sensitivity to local electric field gradients, while neutron scattering requires large defect-free samples. On the other hand, the internal magnetic field distribution of the vortex state can be measured very accurately with μSR in small homogeneous samples. The positive muon ($\mu^+$) has a magnetic moment that is larger than any nuclear magnetic moment, and hence when implanted in matter it becomes an *extremely sensitive local probe of magnetism*. Information on the local static or dynamic magnetic environment of the muons, is passed on to us by positrons emitted from the decay of the muons inside the sample (see figure on preceding page). Because muon beams possess a natural spin polarization of nearly 100%, μSR is far more sensitive than any NMR method.

For several reasons the μSR facilities at TRIUMF are particularly well suited for investigating the vortex state in a superconductor. First, TRIUMF is one of only two facilities in the world that provides nearly *continuous* beams of muons with the intensity required for μSR. The great advantage over other μSR facilities utilizing *pulsed* muon beams is that the time resolution of the μSR signal can be made two orders of magnitude smaller. This property enables studies of the vortex state at much higher magnetic fields. Currently, TRIUMF is home to the world's only μSR high-field/high-timing resolution spectrometer (Hi-Time), which has a maximum operating field strength of 7 Tesla (*i.e.*, a field nearly 200 times larger than what is measurable at a pulsed muon beam facility). Second, innovative design has produced a new generation of sample holders at TRIUMF that allow samples as small as 2-3 mm in diameter to be studied with μSR. Comprised of scintillation detectors, these holders are designed to reject the many muons that miss or pass through small samples, accepting only those that stop in the sample – greatly reducing or eliminating what would normally be an overwhelming background signal. Although simple in their function, the development of *low-background* sample holders has been technically challenging, because the samples and hence the detectors must be contained within a cryogenic environment.



μSR at TRIUMF has been used to study the vortex lattice in this electron-doped superconducting $Pr_{2-x}Ce_xCuO_4$ single crystal. Only recently has it become possible to measure such small-sized samples with μSR. This superconducting crystal is far too small to measure with neutron scattering and is not appropriate for conventional NMR studies, which require polycrystalline samples.

From μSR measurements of superconductors in the vortex state one obtains information on two very important length scales in superconductivity theory, the *magnetic penetration depth*, $\lambda$, and the *coherence length*, $\xi$. The penetration depth is the characteristic length scale for the falloff of magnetic field from a vortex, which is directly related to the density of the Cooper pairs. The coherence length is related to the size of a vortex core and is a measure of the shortest distance over which superconductivity may be established. Early measurements of $\lambda$ in a HTSC at TRIUMF provided some of the first evidence for unconventional pairing of the superconducting carriers. Today, local and visiting scientists routinely carry out such measurements on a wide variety of superconductors. In the past year alone, μSR at TRIUMF has been used to measure $\lambda$ in several newly discovered superconductors: $MgB_2$, the pyrochlore oxide $Cd_2Re_2O_7$ and the heavy-fermion systems $CeMIn_5$ (M ≡ Ir, Rh, Co) and $PrOs_4Sb_{12}$. The results of these studies have provided some of the first clues on the nature of the superconducting state in these compounds.

A crucial prediction of some theoretical models is that HTSCs can have antiferromagnetic vortex cores. However, there are very few experimental techniques that have access to the internal magnetic structure of vortices and hence the capability of addressing this very important fundamental issue. Recently, μSR measurements carried out at TRIUMF have provided strong evidence for antiferromagnetic vortex cores in the HTSC $YBa_2Cu_3O_{6.50}$. Combined with the results of experimental techniques that probe electronic structure, a new picture of the dependence of the ground state of HTSCs on charge carrier concentration is emerging.

Most of what we know about HTSCs comes from studying compounds whose charge carriers are holes. The ability to carry out μSR experiments on small samples is providing the first opportunity to study the vortex structure in *electron-doped* HTSCs. Symmetry, or the lack thereof, between electron- and hole-doped HTSCs has important theoretical implications. Thus far the challenge has been to grow quality single crystals for experimental study. Electron-doped HTSC crystals are more difficult to make than their hole-doped cousins and are usually inhomogeneous with poor surfaces. As a *bulk probe* of matter, μSR avoids the latter complication. Because sample homogeneity generally improves with decreasing sample size, TRIUMF's arsenal of uniquely developed *low-background* sample holders is an invaluable asset. μSR studies of small (see Fig. 3) *electron-doped* HTSC single crystals are now underway.

In the last five years, TRIUMF's μSR facility has advanced tremendously through the development of new instrumentation and automation capabilities. This has opened up new applications of μSR for characterizing and understanding the fundamental properties and interactions of a wide range of important materials. It is anticipated that μSR at TRIUMF will continue to evolve as a powerful experimental tool, becoming more accessible to a larger community of condensed matter physicists, materials scientists and chemists.

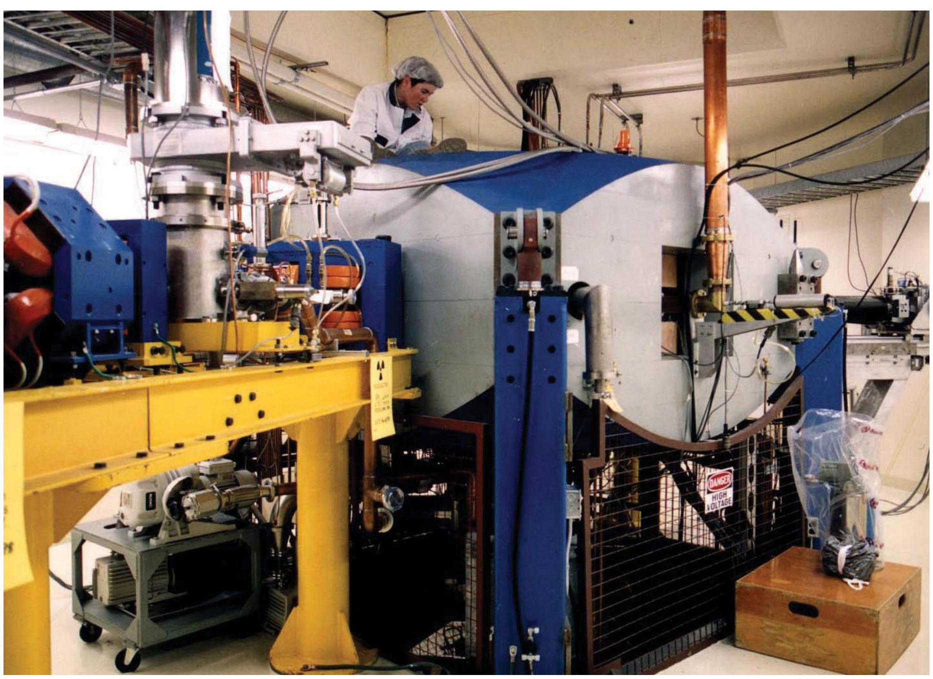
*Jeff Sonier is a member of the Physics Department at Simon Fraser University.*

# MDS NORDION AND TRIUMF

Philip Gardner and Ann Fong

## OVER 20 YEARS OF SUCCESSFUL COLLABORATION

Twenty-five years ago, the innovative management team at Atomic Energy of Canada Ltd. (AECL) recognized the potential of cyclotron-produced radioisotopes for medical science advancement. From that vision emerged the remarkably successful alliance between TRIUMF and AECL. Since the 1950s, AECL has been producing isotopes using nuclear reactors. In 1978, AECL's Commercial Products Division approached TRIUMF about using its 500 MeV cyclotron to produce other radioisotopes. The result was the flourishing collaborative research and production site located at TRIUMF on the University of British Columbia's campus. Since its inception it has created benefits for both medical science and economic growth. In 1979 AECL's Commercial Products Division was renamed the Radiochemical Company, and 3 years later began exporting cyclotron-produced isotopes from the TRIUMF site. Two smaller cyclotrons were subsequently purchased and used exclusively by the AECL for the commercial production of isotopes. One of these was designed and commissioned by TRIUMF staff. In 1991, AECL privatized its operations under the name Nordion International Inc., which was later acquired by MDS Inc., a Canadian-based international health and life sciences company, and renamed MDS Nordion Inc.



The TR30 cyclotron, owned and operated by MDS Nordion, for the production of radioisotopes.

MDS Nordion's headquarters are in Kanata, Ontario. In addition to the TRIUMF site, it has operations running in Belgium (reactor and cyclotron isotope production, radiopharmaceuticals), Laval, Quebec (research, training and testing of cobalt-60 irradiators), Germany (brachytherapy systems and radiography cameras), Sweden (development of computer products and software, and accessories for radiation therapy), as well as offices in Japan and Hong Kong which serve the Pacific Rim. Total corporate annual sales are approximately $350 million, over 95% of which are exported to some 80 different countries.

**WORLDWIDE, IT IS ESTIMATED THAT UP TO 20 MILLION NUCLEAR MEDICINE IMAGING AND THERAPEUTIC PROCEDURES ARE PERFORMED EACH YEAR.**

MDS Nordion's Vancouver operation on the TRIUMF site currently employs 50 full-time permanent staff and 22 contract staff. These 22 contract staff are TRIUMF employees, supported by Nordion on a full-time, cost-recovery basis and they are responsible for the operation of Nordion's two compact commercial cyclotrons. To date, the cumulative sales of MDS Nordion in Vancouver have exceeded $200 million. The licensing agreements between TRIUMF and MDS Nordion have resulted in royalties of several million dollars that TRIUMF has utilized as supplementary funding for further research, as well as related technological activities that support the transfer of TRIUMF technologies to Canadian industry.

Nordion's operation at TRIUMF is unique in Canada. In fact, it is one of only a few sites worldwide that produces cyclotron-based isotopes. According to the U.S. Institute of Medicine, there are over 36,000 diagnostic medical procedures employing radioisotopes performed in the United States each day. About 100 million laboratory tests using radioisotopes are performed there each year.

MDS Nordion produces

Philip Gardner and Ann Fong

the following radioisotopes under license from TRIUMF for sale worldwide:

- *palladium-103*, used for prostate cancer therapy;
- *strontium-82*, used for high resolution heart imaging to detect coronary artery disease and for diagnosing bone lesions;
- *thallium-201*, widely used as a heart imaging agent;
- *indium-111*, used in blood cell labeling, as a heart imaging agent and to locate tumours;
- *gallium-67*, used to detect such conditions as Hodgkin's disease;
- *cobalt-57*, used as a marker to estimate organ size/location, and for diagnosis of anaemia related to vitamin B12 deficiency;
- *iodine-123*, used traditionally for thyroid imaging, also currently made into a radiopharmaceutical for neurological diagnosis of Parkinson's disease, schizophrenia and Alzheimer's disease, in oncology for cancer imaging (e.g. breast cancer), and in cardiology for imaging cardiac tissue.

Since the 1950s, nuclear medicine has become an increasingly important and utilized part of patient care. The procedures are generally safe and painless. Only very small amounts of the radioisotope or radiopharmaceutical are needed to diagnose and treat disease. When introduced into the body these substances are attracted to specific bones, tissues or organs. Because these substances are radioactive they decay emitting radiation that can be detected using special types of cameras that show the distribution of the isotope in the body. Both reactor- and cyclotron-produced radioisotopes emit gamma rays but only the cyclotron produced ones also emit the positrons that are essential for PET scans. The images so obtained provide physicians with critical information on how the body is functioning. This in turn helps them to diagnose disease, determine the best course of treatment, and monitor the progress of the treatment. Current studies at TRIUMF are showing the promise of using radioisotopes to treat cancerous growths, resulting in significantly less trauma to the patient than caused by the traditional methods.

**IN THE UNITED STATES ONE OUT OF EVERY THREE MEDICAL PATIENTS UNDERGOES AT LEAST ONE NUCLEAR MEDICINE TEST.**

A MDS Nordion technologist preparing radioisotopes at TRIUMF for shipment

MDS Nordion is the only Canadian supplier of many of these crucial radioisotopes. Through its licensing agreements with TRIUMF, Nordion has first rights to the cutting-edge isotope technology originating from TRIUMF research. This ensures timely dissemination of the technology, while delivering the maximum benefit to the Canadian economy.

The demand for radioisotopes has grown each year as diagnostic techniques and screening capabilities have increased. To help satisfy the growing demand, Nordion is investing $20 million to build a new commercial cyclotron facility at its TRIUMF site. This new facility will increase MDS Nordion's radioisotope production capacity in Vancouver in order to help meet the

Philip Gardner and Ann Fong

ever-growing demand for iodine-123 and palladium-103. The new cyclotron will bring with it an extension to the current building that houses the Vancouver MDS Nordion team. Construction began in 2001 and production is expected to begin in January, 2003. In addition to meeting global demands for medical isotopes, the new facility will create additional opportunities for high quality employment. By the year 2006, it is projected that there will be 53 employees and 31 contract employees, all of them in highly skilled positions.

State of the Nordion facility addition as of May, 2002

MDS Nordion is now working at full capacity to ensure that the demand for high-priority isotopes is met. The new cyclotron will be capable of meeting additional demands for these and other existing products. The increase in production and export will also assist TRIUMF and Nordion in continuing their research and development of new cyclotron-produced isotopes, which will further advance the Canadian nuclear medicine industry. The improved radioisotope production capability of Nordion at the TRIUMF site is estimated to provide products for 1,000,000 nuclear medicine procedures around the world each year.

**THERE ARE CURRENTLY OVER 100 DIFFERENT MEDICAL IMAGING PROCEDURES IN USE.**

The synergistic benefits flowing from the long-term relationship between the TRIUMF universities and MDS Nordion are manifold and well recognized by Nordion's customers. TRIUMF has provided and continues to provide leading-edge research skills to MDS Nordion. At the same time, MDS Nordion has introduced the concept of the marketplace to TRIUMF staff, as well as the potential social and economic benefits that can flow from the practical application of scientific skills and knowledge.

The success of the TRIUMF-Nordion partnership has not been based on any one strategy or set of strategies. It started with a sharing of knowledge and has succeeded because of the level of mutual trust and respect the two parties have established. Both parties recognise that, while working together, each must respect the fact that they are two discrete entities and must remain independent; that the synergy from the relationship lies in the strength of the other's difference; and that the collaboration is a joint effort, where either success or failure affects both parties equally. Further developments are under way, with TRIUMF working on new types of targets, new calibration sources, and cyclotron improvements, and with Nordion expanding its radioisotope product line. These developments are aimed at making still further advances into the cost-effective production and delivery of short-lived radioisotopes to the health care system.

Looking back, the TRIUMF-Nordion co-operation of the past 25 years has been a major Canadian success story. As a result of this success, Canada is now one of the world's major suppliers of cyclotron-produced radioisotopes, and the future holds even greater promise.

*Philip Gardner is the head of TRIUMF's Technology Transfer Division. Ann Fong is a Technology Transfer Officer.*

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When visitors come to TRIUMF for the first time they are often surprised that the facility gives the impression of a busy factory rather than the picture of a research laboratory typically portrayed in the popular media. Their impression is not far off the mark and in fact for many years TRIUMF was referred to as a 'meson factory'. Most of the safety hazards associated with the activities carried out at TRIUMF are also those one would find in a typical light industrial setting. However, an inevitable consequence of the operation of particle accelerators such as the cyclotrons at TRIUMF is the production of radiation. This introduces a hazard that is unfamiliar to many people and hence perceived as more threatening than the other more familiar hazards. The popular impression that the effects of radiation are somehow mysterious and poorly understood is not entirely justified as there exists a vast body of research on radiation effects going back more than 100 years. Also there are available relatively simple and inexpensive devices with sufficient sensitivity to measure radiation and radioactivity at levels far below where they constitute a significant hazard.

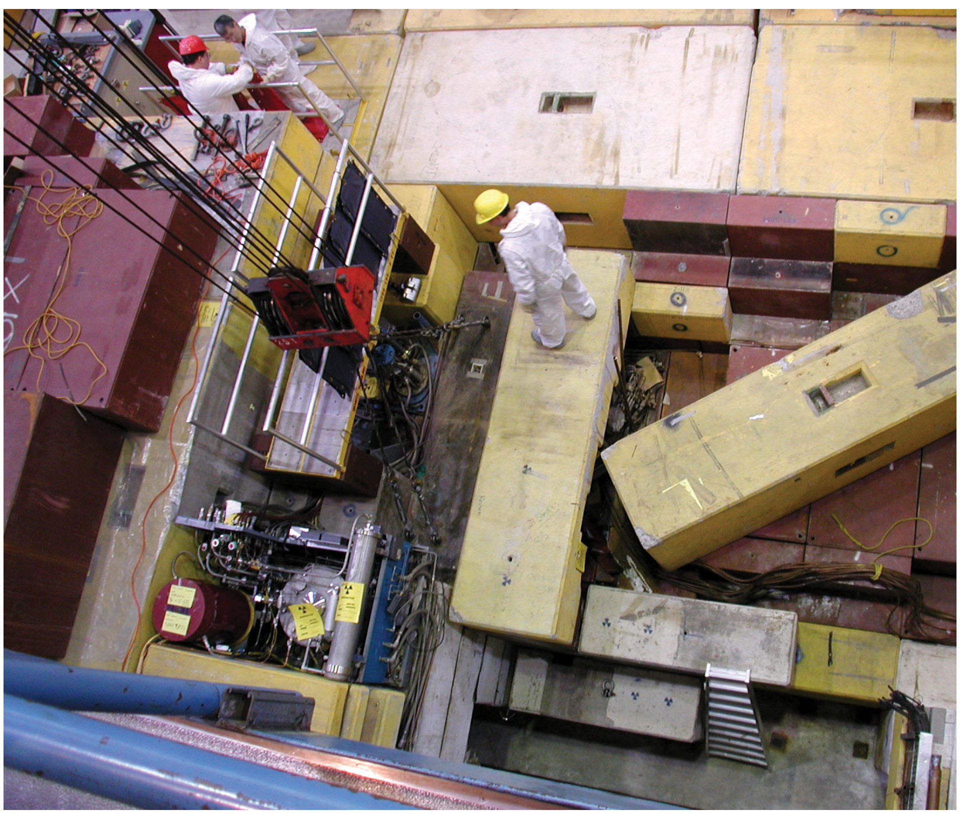
The activities that take place at TRIUMF are very diverse. They include clerical administration duties, operation of heavy machinery, welding, machining new parts for experiments and the fabrication of delicate electronic components. The most obvious industrial hazards are probably those encountered in servicing the equipment that handles the more than 8 Megawatts of electrical power required to energize the cyclotrons and other apparatus. There are also those associated with using overhead cranes to move concrete shielding blocks weighing up to 100 tons.

## OCCUPATIONAL HEALTH AND SAFETY

While radiological safety receives a great deal of TRIUMF's attention, occupational health and safety consumes an equal amount of time and resources.

TRIUMF management and staff have developed a safety culture that strives for an awareness of safety issues and a recognition of responsibility for performing all work in a safe manner. To do this, TRIUMF works closely with all federal, provincial and regional health and safety organizations.

The federally mandated "Workplace Hazardous Material Information System" (WHMIS) is a North American wide standard that provides workers involved with controlled products or hazardous materials with safety information. TRIUMF provides in-house WHMIS training for that all those scientists, engineers, technicians and students involved with controlled products. They must complete and pass an examination with an 80% or better mark. Ongoing training ensures that the WHMIS policies and procedures are not neglected or forgotten with time.



Maintenance work on one of the target areas along the high-intensity beam line from the 500 MeV cyclotron shows a combination of the industrial and radiation environments at TRIUMF

The Workers Compensation Board of B.C. (WCB) regulations apply to TRIUMF and the WCB regularly inspects the laboratory to verify compliance with their regulations. TRIUMF has achieved the same premium rate classification as the B.C. universities discounted by an additional 15% because of our low claim rate.

Even in the best run facilities, accidents can happen and TRIUMF has six designated

Level II and 18 Level I first aid attendants on staff to ensure that appropriate first aid is available on the TRIUMF site 24 hours a day, 52 weeks a year. TRIUMF also works closely with the Vancouver Fire and Rescue Services who monitor the TRIUMF site on a regular basis for fire and other related safety hazards. Most of the TRIUMF staff has received training in fire and safety procedures and emergency preparedness programs through an approved in-house training program or directly from courses offered by the Vancouver Fire and Rescue Services.

The federal, provincial, regional and city organizations that provide occupational health and safety information and monitoring provide a valuable resource for TRIUMF. They, along with the universities and colleges that train health and safety officers, make themselves constantly available to TRIUMF to answer questions and offer suggestions. Because of its size and complexity, TRIUMF is also a resource for all these organizations and for the community at large, providing information, training and assistance.


The fabrication of special mechanical components for experiments and experimental facilities shows one of the industrial aspects of work at TRIUMF.

## RADIATION HAZARDS

Because the operation of TRIUMF involves the production and use of radiation, the laboratory is classified as a "nuclear facility" under the federal Nuclear Safety and Control Regulations. These regulations, administered by the Canadian Nuclear Safety Commission (CNSC), require TRIUMF to be licenced by the CNSC to operate its accelerators. This licence specifies that the facility must be operated in accordance with the parameters assumed in the safety analysis that was submitted by TRIUMF to the CNSC before the licence was issued. The CNSC also requires frequent reporting of the results of all radiation safety measurements and the radiation dose received by all workers at TRIUMF. CNSC inspectors visit the laboratory several times each year to verify that TRIUMF is complying with all the conditions set out by the operating licence. In the spring of 2001 the CNSC performed a detailed review of the safety program at TRIUMF that required all employees to answer a detailed questionnaire. This was followed by in-depth interviews with approximately 60 employees as well as several days of observation of work practices. The review found that *"employees interviewed and surveyed across the TRIUMF Facility described the organization as a safe place to work and one that places a high priority on environment, safety, and health issues"*. The CNSC also found that *"employees indicated that management places a high level of emphasis on environment, safety, and health issues and that employees are generally aware of these issues"*.

## RADIATION SOURCES AT TRIUMF

It is the interaction of the accelerated protons with matter that leads to the radiological hazard associated with proton accelerators such as those at TRIUMF. These interactions produce both 'prompt' radiation, which persists only while the accelerator is in operation, and 'induced' radioactivity, which continues after the accelerator is shut down.

Prompt radiation consists of a mixture of many different particles produced when high-energy protons bombard any kind of material. The most copious and penetrating components of this radiation are gamma rays and neutrons. Gamma rays are best absorbed by heavy materials. On the other hand light materials are the ones most effective in slowing down and absorbing neutrons. At TRIUMF much of the shielding material is

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A view of the radiation badge room and the two personnel radiation monitors that everybody who enters or leaves the experimental areas at TRIUMF has to pass through

a combination of steel and concrete. It's the hydrogen in the water in concrete that makes it so effective in the attenuation of neutrons of lower energy.

Visitors to TRIUMF are usually impressed by the great amount of concrete shielding, both permanently installed and also in the form of movable concrete blocks. Up to 2 metres of steel followed by 5 metres of concrete is required to reduce the gamma ray and neutron radiation field to safe levels near those points where the full high-intensity proton beams are stopped. Some of this shielding is evident in the picture on page 24. The exact amount of shielding required in each case is calculated using powerful computer simulations that can estimate the required thickness for very complicated shielding arrangements.

Two highly reliable, completely independent sets of radiation monitors continuously measure the prompt radiation generated by the 500 MeV cyclotron at TRIUMF both inside and immediately outside the shielding. The readings from more than one hundred monitors are displayed in the control room and are continuously recorded by a dedicated computer. If the radiation field at any place even momentarily exceeds a very low, safe threshold, these radiation monitors are programmed to immediately stop the operation of the cyclotron. Unlike nuclear power reactors, accelerators do not generate but rather consume great amounts of electrical power. Their successful operation depends on the orchestration of the precise value of a great number of parameters such as the magnetic fields that confine the particle orbits, the radiofrequency power that produces the accelerating fields and the vacuum in the chambers and beam pipes that confine and guide the particle beams. Any deviation of these parameters from their required value will result in the particle beam striking the walls of a chamber or a beam pipe. This causes unwanted radiation to be produced and, as a result, the radiation safety system stops the accelerator from producing any more beam. This can be reliably done in a fraction of a second by interrupting any of the sources of power that contribute to the acceleration process. There is no stored nuclear energy that must be dissipated nor is there any possibility of a run-away reaction. As a result, the cyclotrons at TRIUMF have operated safely for almost 30 years with negligible exposure due to prompt radiation of any of the staff. Radiation levels at and beyond the TRIUMF site boundary are monitored continuously and have always been too low to be measurable.

The prompt radiation near the accelerator and proton beam lines is so intense that personnel have to be excluded from the immediate vicinity. An access control interlock system prevents access to any area inside the shielding during operation. Any violation of this system would result in the immediate shutdown of the accelerator. In order to enter any of the rooms in which the accelerators or proton beam lines are housed, the accelerator or the particular beam line must be turned off using three different, independent methods.

A by-product of proton accelerator operation is the radioactivity induced in the accelerator components and beam lines as well as some of the surrounding structural materials. This radioactivity, which remains after the accelerator is turned off, is produced by the small fraction of protons that are lost during the acceleration process and during transport of the proton beams to the experiments. Because of the very high intensity of the proton beams at TRIUMF, even a small loss can result in significant production of radioactivity in the various components. The radiation that is emitted by these radioactive components after the cyclotrons are turned off complicates their repair and maintenance. Major maintenance activities are usually only carried out after a 'cooling off' period lasting several weeks. Because many of the radioactive atoms produced by the proton bombardment are short-lived such delays greatly reduce the radiation intensity to levels that allow maintenance work to be carried out safely.

While every effort is made to keep the radioactivity induced in accelerator components to a minimum there are three small cyclotrons at TRIUMF whose aim is to produce radioactivity in certain materials. These machines are run by TRIUMF for MDS Nordion and are used to produce radiopharmaceuticals. This facility is described in the previous article.

### RADIATION SAFETY PROGRAM

In order to minimize the effect of the radiation generated by the accelerators, TRIUMF has from its inception implemented an effective radiation safety program. This program consists of two parts: the optimization of protection for workers and the public and the control of releases of radioactive material to the environment.

The optimization of protection refers to the internationally established principle that radiation exposure should always be kept "as low as reasonably achievable" (ALARA). As a starting point, TRIUMF has developed a policy that requires worker radiation dose to be kept at less than 50% of the regulatory limit for radiation exposure. In addition, much effort has gone into designing safety features into the equipment and developing special techniques for remotely handling some of the more radioactive components. Through the use of these techniques and careful planning of maintenance activities, worker dose is kept to a minimum. Four radiation protection technicians monitor the radiation fields and take samples of the radioactive materials for analysis before any maintenance work is performed on radioactive equipment. As a result of these efforts the radiation exposure of the laboratory workers at TRIUMF has actually gone down over the years despite the fact that the number of installed cyclotrons and the intensity of the proton beams that they produce has continued to rise.

Canadian regulations require that radioactive emissions from nuclear facilities must be kept low enough so that the public is not exposed to more radiation than about half that due to natural 'background' radiation. This ubiquitous 'background' radiation is primarily due to the natural radioactivity that is found in all soils, the radon gas that is emitted from most soils, and the cosmic radiation that constantly bombards the earth.

The neutrons that are generated by proton bombardment produce some very low levels of very short-lived radioactivity in the air of the accelerator rooms. Some of this radioactivity, which is similar to that used in the medical scanning technique known as positron emission tomography (PET), is exhausted to the atmosphere. Also, inevitably some small fraction of the radioactivity generated for medical uses is lost during preparation. All emissions from TRIUMF are continuously monitored and samples of vegetation and ground water from the surrounding environment are periodically analysed to verify that the emissions do not lead to any significant exposure of any member of the public. The emissions from TRIUMF are indeed so low that the effect on the public cannot be measured. TRIUMF has used internationally accepted environmental modeling techniques to demonstrate that the dose to the public from all emissions are less than about 1% of that due to the typical background radiation. The background radiation can in fact vary from place to place by more than a factor of two. In Vancouver the background radiation is particularly low because of the low levels of radon emitted from the local soils. (The natural radiation level is much higher in some parts of the Okanagan where the soil often contains relatively high levels of natural uranium.)

Air quality monitors are associated with each main target area. They are checked and adjusted regularly.

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Checking for radiation around a fume hood in which radiochemical work is carried out.

## SAFETY OF EXPERIMENTS

Experiments are carried out at TRIUMF by teams of scientists whose members come from many countries around the world. The experiments may, for example, involve the use of powerful lasers, flammable gases at high pressures or temperatures, or toxic and radioactive substances. To ensure a high standard of safety during the execution of these experiments, every experiment that is to be performed at TRIUMF, no matter how apparently innocuous, must first pass a safety review. In this review the experiment leader must demonstrate that all possible radiological and industrial hazards likely to be encountered have been identified and measures put in place to ensure that these hazards cannot result in harm to either personnel on site or to the public off site. Only once all safety measures have been approved and put in place is the experiment allowed to proceed. As a result there has not been a serious accident involving an experiment at TRIUMF in all the years of operation.

## SAFETY ORGANIZATION

The TRIUMF Office of Environment, Health and Safety, staffed with several physicists and their supporting technical personnel, administers the safety program at TRIUMF. They have oversight responsibility for monitoring all safety aspects of the laboratory. Rather more emphasis is put on radiation safety because of the greater level of public and regulatory concern about this hazard.

Either through a *Fault Report* or a *Safety Deficiency Report* any person at TRIUMF can bring a workplace hazard to the attention of those in a position to rectify it. The TRIUMF Accident Prevention Committee (TAPC) helps identify these hazards by doing monthly inspections and in some instances finding safety deficiencies unnoticed by that area's supervisor and workers. The TRIUMF First Aid Team reviews injuries every 3 months looking for possible trends and contributing factors and forwards that information on to OH&S for possible action. Fire Safety Wardens keep an eye out for potential fire hazards and if found report them to the Fire Safety Director.

Each of the six TRIUMF division heads chairs a safety committee that reviews all safety concerns within that division on a regular basis. The director of TRIUMF meets four times a year with the division heads and the heads of the operations staff as well as the chair of the TRIUMF Accident Prevention Committee to receive status reports on all safety matters and to address any outstanding issues. This assures that all safety issues are promptly identified and resolved.

In order to keep abreast of the latest developments in their field, the safety staff keeps in close contact with similar groups at other accelerator laboratories in the US, Europe, Japan and Russia. A number of collaborative efforts and reciprocal visits have resulted from these contacts. The staff also participates in international meetings on accelerator safety and in efforts at standardization of policies and practices.

Management, visiting scientists and all employees at TRIUMF are highly cognizant of the special concerns that arise out of the laboratory's status as a nuclear facility. They work continuously to ensure that the risk due to the unique hazards associated with the operation of the laboratory is reduced to a minimum. This positive safety culture has resulted in an exemplary safety record, both industrial and radiological, and in continued reduction of the radiation exposure to laboratory personnel.

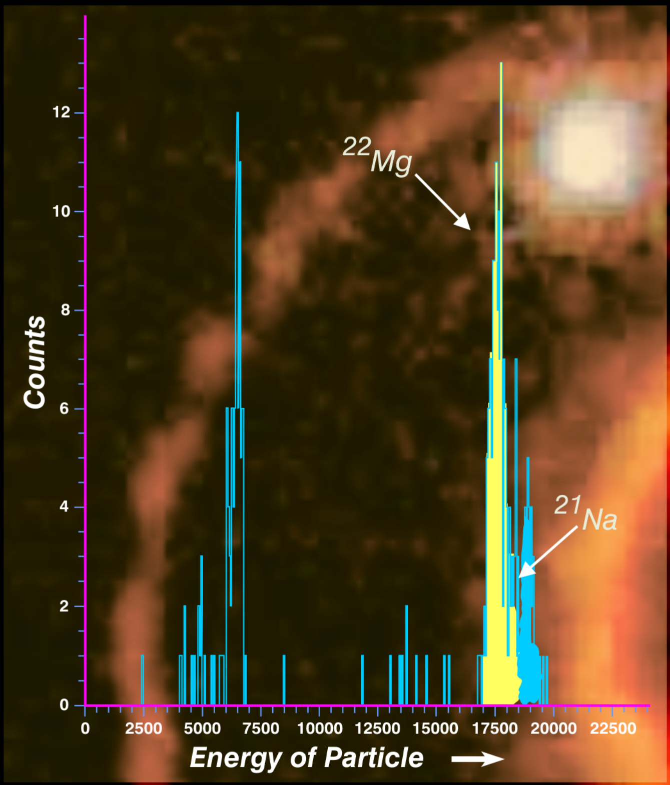
*Lutz Moritz is the manager of Environment, Health and Safety. Gordon Wood is responsible for OH&S at TRIUMF.*

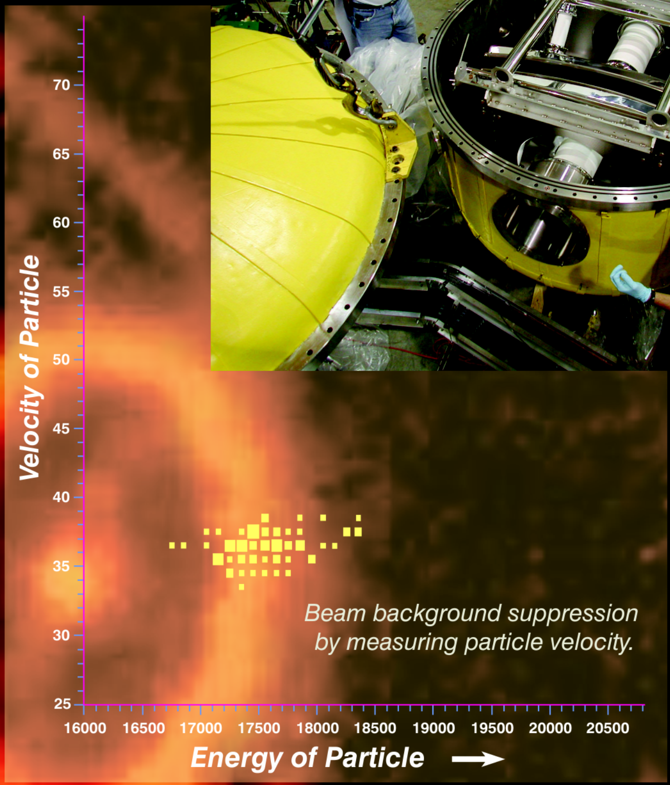
# The Future
# TRIUMF - ISAC-II

**See next year's report!**

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

*One of DRAGON's Electrostatic Dipoles*




*Beam background suppression by measuring particle velocity.*

Nova and supernova explosions of stars are the "cauldrons of the cosmos" producing most of the matter out of which we are made. Temperatures and pressures in them are so high that unstable isotopes can undergo nuclear reactions before they have had time to decay. These reactions can affect the rate of energy production during the explosion, as well as the amounts of different elements to be found in the "ashes" from the explosion. DRAGON's first experiment was to measure the probability for unstable Sodium-21 to produce Magnesium-22 in nova or supernova explosions. The results should help astrophysicists explain observations from orbiting gamma-ray telescopes, and the ratios of Neon isotopes in gas trapped in meteoritic grains.

*David Hutcheon*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