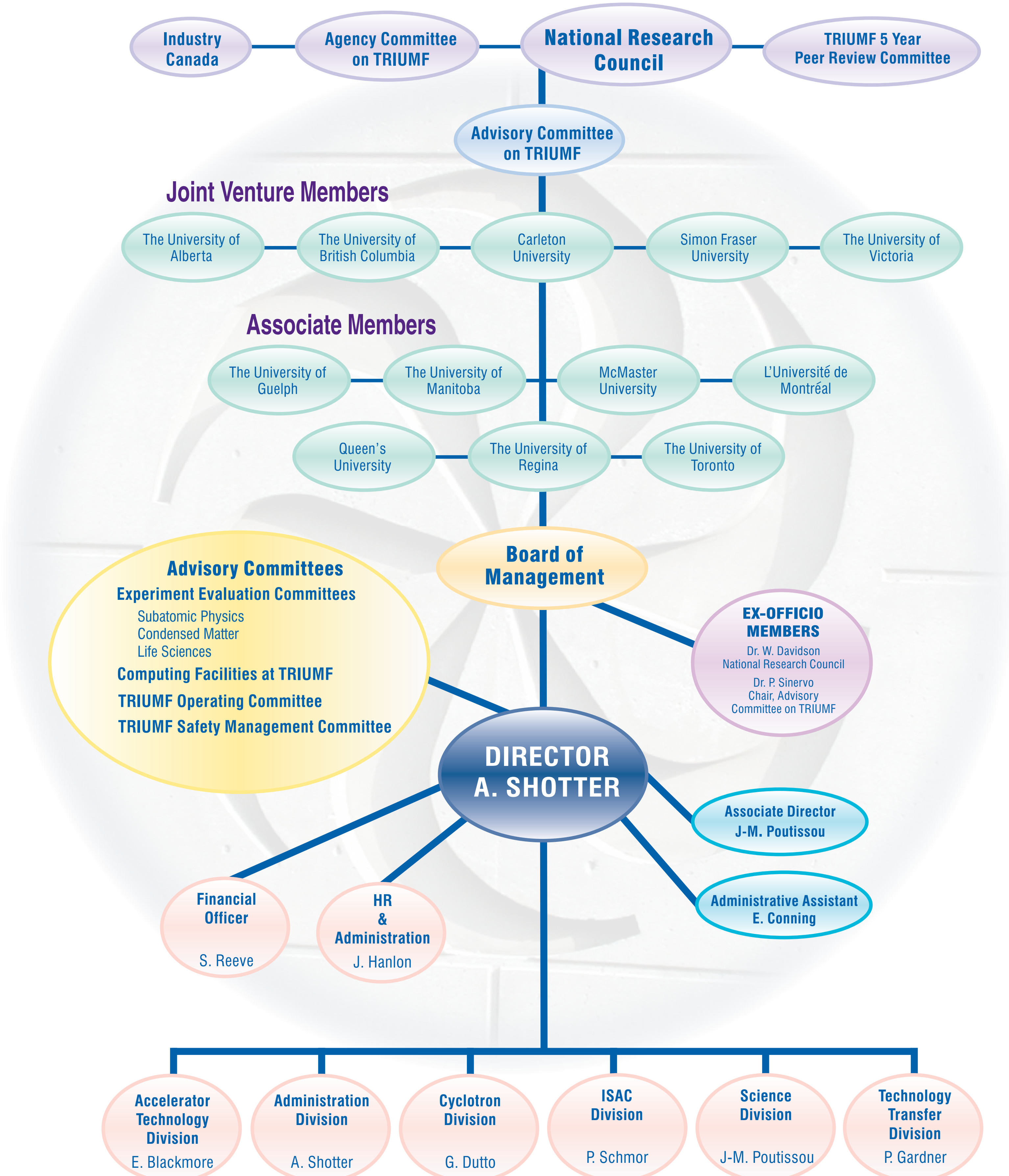
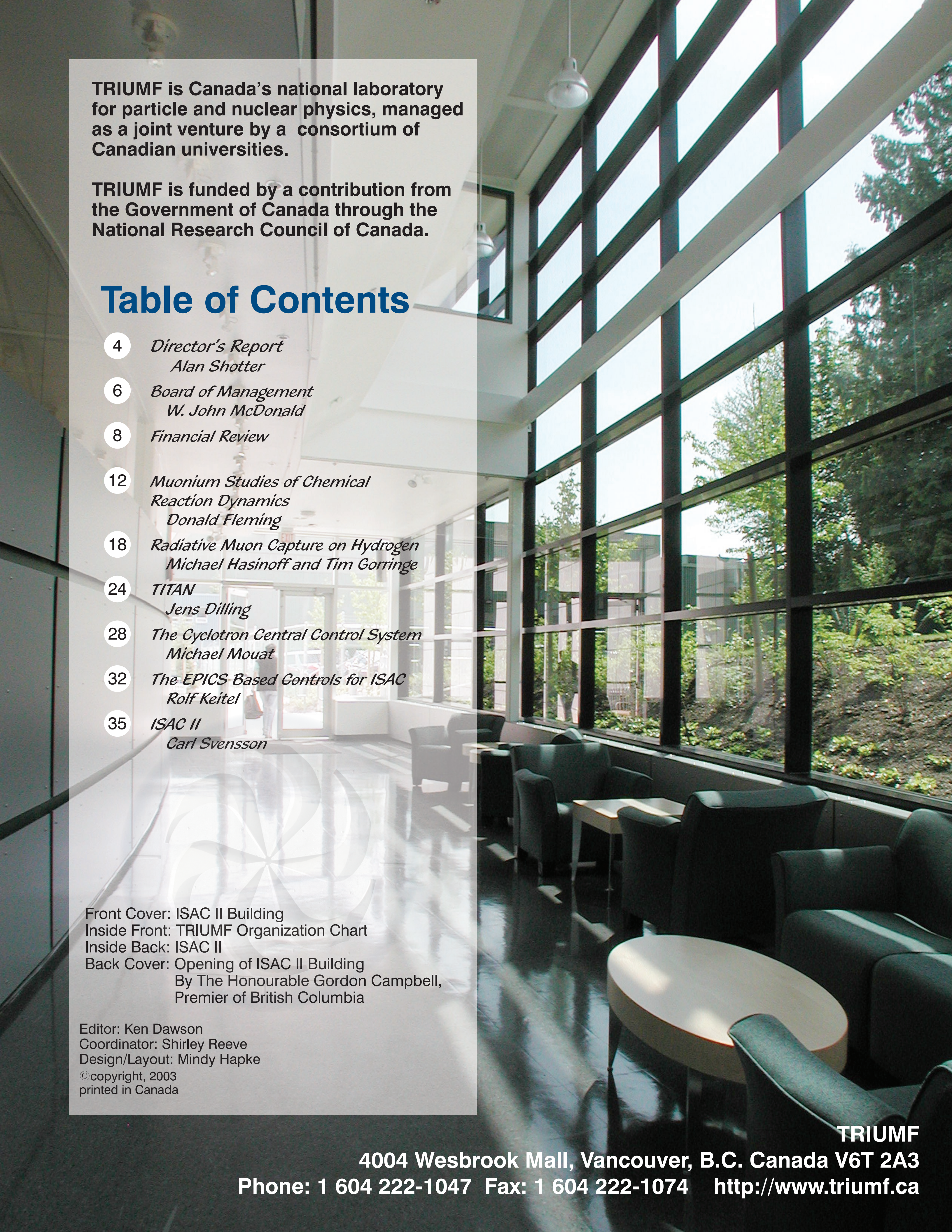
TRIUMF

Annual Financial & Administrative Report
2002-2003

Organization Chart





TRIUMF is Canada's national laboratory for particle and nuclear physics, managed as a joint venture by a consortium of Canadian universities.

TRIUMF is funded by a contribution from the Government of Canada through the National Research Council of Canada.

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By The Honourable Gordon Campbell, Premier of British Columbia

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Director's Report

Alan Shotter
TRIUMF Director

For several years the central theme for TRIUMF development has been the ISAC facilities. Major milestones for these facilities were successfully met during the year.

The first significant nuclear physics results from the DRAGON experiment were published as a *Physics Review Letter*. These results tied down the production rates of ^{22}Na from stellar hydrogen burning of the radioactive nucleus ^{21}Na. They are of great interest as ^{22}Na is a gamma ray marker for novae that the satellite INTEGRAL is searching for. This gamma ray satellite was launched by the European Space Agency in 2002 with a mission to search for radioactive species in different stellar environments.

Another milestone for ISAC was the completion, on time and on budget, of the new ISAC-II building. TRIUMF was honoured that Gordon Campbell, Premier of British Columbia, officially opened the new facility before an audience of over 400 invited guests and TRIUMF staff. The building contains an accelerator hall for the ISAC-II accelerator, an experimental hall for ISAC-II experiments, and general office and laboratory space. The TRIUMF staff who work in the new building all agree that the architects and the many companies involved in the construction process have designed and constructed a building that is architecturally pleasing as well as comfortable and efficient. TRIUMF's next challenge is to build the ISAC-II accelerator and construct new experimental equipment required to exploit the scientific opportunities presented by ISAC-II. Scientifically and technically, ISAC has evolved into the premier world facility for science involving radioactive beams. TRIUMF and several Canadian universities are appointing an increasing number of young scientists specifically to work with the ISAC facilities.

An important milestone was passed for the TRIUMF Life Sciences program with the purchase of two new PET tomographs. This will enable the very important human-based research to continue but will also enable a whole new research area involving small animals to be developed. The TRIUMF/UBC PET Group already has a considerable international reputation so these new facilities can only enhance this reputation further.

TRIUMF's other scientific programs are proceeding vigorously. The µSR program is attracting an increasing number of users from within Canada and around the world. New Canadian university faculty appointments are being made to exploit the fast-developing and intriguing science of µSR. The unique sensitivity of TRIUMF's µSR program to the internal force fields of materials is attracting the attention of material scientists worldwide.

The TWIST experiment aims to measure with unprecedented accuracy the decay characteristics of the muon. The first extensive experimental data collection run for TWIST occurred during the year and the success of this run demonstrated very clearly that the TWIST experiment has the potential to fulfill all its ambitious aims.

Director's Report

TRIUMF is a national facility and has as its goal the support of the entire Canadian particle and nuclear physics community. Facilities are provided at TRIUMF but TRIUMF also provides scientific and engineering support to mount front-line experiments at other international laboratories. Over the last few years a large part of this work has revolved around the specialized equipment being built by TRIUMF and Canadian industry as Canada's contribution to the LHC at CERN as well as vital contributions of equipment and expertise to the ATLAS detector, which will form part of the LHC experimental facility. Many of the milestones for this work have been successfully passed; Canada, through TRIUMF, has established a reputation in the international community for excellence in design, construction, and delivery of advanced technology, on time and on budget.

TRIUMF's outreach program involves both technology transfer and educational outreach. Technology transfer has many facets. One highlight is the collaboration between TRIUMF and MDS Nordion Inc which continues to be the best known of TRIUMF's successful technology transfers to Canadian industry. During the year MDS installed a third cyclotron at TRIUMF to produce more radioisotopes for medical therapy and diagnostic purposes. Because the demand for such isotopes is rapidly growing (currently enough isotopes are produced at the TRIUMF/MDS Nordion site for over 2 million medical procedures per year), this third cyclotron will only just meet the demand.

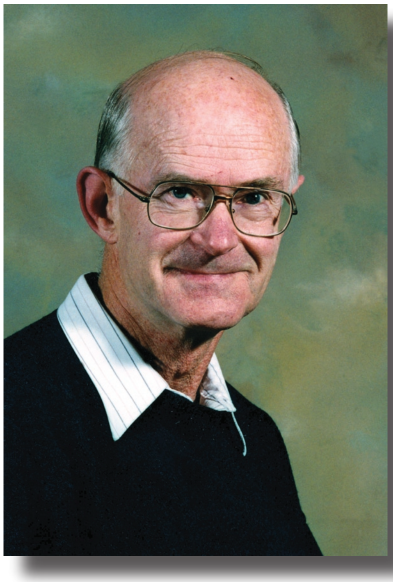
It is important that Canadians be aware of and understand TRIUMF's mission. For many years TRIUMF has had a successful program in this area. This year a new outreach program was started specially aimed at schoolteachers. The idea is to provide teachers interaction opportunities with TRIUMF staff and involvement in experimental programs to both inspire and inform them about advanced technical and scientific technology, methods and procedures. Teachers are then able to take this information and their experiences back to their students.

A major activity during the year was the preparation work for TRIUMF's 2005-10 Five-Year Plan. A series of workshops was held where different sections of the Canadian physics community were able to express their vision for the future. All these opinions were discussed in a town meeting at TRIUMF in September 2002. From this meeting, a planning group was set up to take forward the ideas and construct a coherent and comprehensive plan for presentation in 2003.

It has been a busy and exciting year at TRIUMF in terms of scientific output, interactions with society, and in establishing the foundation that will take TRIUMF, as a world-class laboratory, to 2010 and beyond.

Board of Management

On behalf of the TRIUMF Board of Management I am pleased to have the opportunity to comment on another very successful year for TRIUMF and to report on the activities of your Board.


W. John McDonald
Chair, Board of Management

Members of the Board are proud of the achievements of the many scientists from Canada and abroad who are making such good use of the facilities TRIUMF provides. These facilities support a truly exciting program of science in nuclear and astrophysics, precision tests of fundamental processes, medical physics, condensed matter physics, and nuclear chemistry. The scientific output of the lab is impressive for its breadth and scope, but especially for the high quality of the research that is accomplished. That quality has been recognized again by excellent support from the Natural Science and Engineering Research Council (NSERC). Of particular note was the NSERC award of two large grants for the TIGRESS and TITAN projects that will use the ISAC facility. TRIUMF was also a key participant in the successful proposal to build WESTGRID, a computing facility that will, among other things, provide vital support for Canada's particle physics program.

Quality programs in science, as in any other field, do not exist in a vacuum. TRIUMF has a tradition of building facilities that are unique and which push the frontiers of technology for acceleration, detection and use of subatomic particles for nuclear and particle research as well as medical and industrial applications. This year has seen the successful completion of the new ISAC II building and the commissioning of a second target station to support the increased demand for radioactive beams for ISAC research.

As part of their continuing support of the Canadian and International particle physics community, TRIUMF staff have continued to live up to their reputation for producing state of the art components as part of Canada's contribution to CERN. The ATLAS detector hadronic end-cap calorimeter components and the quadrupole magnets for the LHC were successfully completed on time and on budget. To the dedicated individuals that have brought these projects and others to completion on time and on budget, I extend congratulations and thanks on behalf of the Board.

Equally important for TRIUMF's success is the professional and competent way the facilities are operated. Equipment has to be maintained and refurbished to meet ever-increasing demands for additional capability. This is particularly important in the case of the original H^- cyclotron that is the driver for multiple proton beams used for everything from medical treatment to the proton, meson, and radioactive beam programs. Staff members of the Cyclotron division are to be congratulated for their outstanding work in rebuilding and replacing key components of the cyclotron to ensure that it can continue to meet the demands placed on it. It is a tribute to their abilities that the cyclotron is operating at higher than ever efficiency despite the fact that it is now over 30 years old.

The preparation of a new TRIUMF 5-Year Plan for 2005 to 2010 has been largely completed this year as the result of an intensive amount of work by the whole Canadian subatomic physics community, led by Alan Shotter and his administrative team. This activity has been of great importance to the Board as it will set the stage for TRIUMF's future through this decade and beyond. The plan has been on the agenda of every meeting of the Board this year and the Board has been satisfied with the process and execution of this difficult exercise. Congratulations to all those who have worked so hard to balance their many competing demands so that TRIUMF can most effectively build on its success in the future.

As in the past, the Board has been regularly considering matters brought to it from its standing committees: Finance, Human Resources and Safety. In addition, technology transfer was the focus of much discussion this year and the Board decided to establish a fourth committee specifically to consider how to best enhance and promote TRIUMF's existing strengths and future potential in this area. While it is the excitement of the unknown that drives all scientists and the support of good science will continue to be the first priority at TRIUMF, it is also the case that good science frequently leads to developments that can benefit society. The Board recognizes the need to encourage the transfer of ideas developed through the science activity to the wider community. Another matter that received Board attention this year is the search for resources for the replacement of TRIUMF House. The Board is seeking support from the Universities to assist TRIUMF in maintaining this vital component to the success of the laboratory.

In closing, I would like to thank outgoing members of the Board, Indira Samarasekera, Peter Watson, Vern Petkau, Georges Michaud and Art MacDonald and welcome new members Don Brooks, Bob Carnegie, Richard Keeler, Claude Leroy and Aksel Hallin. I have appreciated the support of all members of the Board who give so generously of their time to assist TRIUMF in its important and exciting work. I would also like to acknowledge, on behalf of the Board, the core funding support of the Government of Canada through the National Research Council and the Government of British Columbia for its contribution to the ISAC-II building. Finally, I wish to personally thank President Arthur Carty of the National Research Council and his staff for their helpful advice and support.

The new TRIUMF House will open in the fall of 2004.

AUDITORS' REPORT

To the Joint Venturers of TRIUMF

The accompanying summarized statement of financial position and combined statement of funding/income and expenditures and changes in fund balances are derived from the complete financial statements of TRIUMF as at March 31, 2003 and for the year then ended on which we expressed an opinion without reservation in our report dated May 16, 2003. Those financial statements were prepared to comply with section 7 of the TRIUMF joint venture agreement and the contribution agreement with the National Research Council of Canada, and are prepared using the basis of accounting as referred to in note 2 to the accompanying financial statements. The fair summarization of the complete financial statements is the responsibility of management. Our responsibility, in accordance with the applicable Assurance Guideline of the Canadian Institute of Chartered Accountants, is to report on the summarized financial statements.

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

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

PricewaterhouseCoopers LLP

Chartered Accountants
Vancouver, B.C.
May 16, 2003

TRIUMF

Statement of Financial Position

As at March 31, 2003

	2003 $	2002 $
ASSETS		
Cash and temporary investments	3,844,414	4,399,885
Funding receivable	1,651,824	1,499,613
Total assets	5,496,238	5,899,498
LIABILITIES		
Accounts Payable	1,129,736	1,988,144
Funds received in advance	1,328,150	1,856,235
	2,457,886	3,844,379
Due to (from) joint venturers		
University of British Columbia	121,176	265,906
University of Alberta	(18,718)	(4,938)
Carleton University	(4,589)	213,816
University of Victoria	(22,094)	299
Simon Fraser University	(32,467)	4,743
	43,308	479,826
	2,501,194	4,324,205
Fund Balances		
Restricted		
Natural Sciences and Engineering Research Council Fund	1,789,374	888,008
MDS NORDION Fund	100,000	100,000
Affiliated Institutions Fund	143	143
	1,889,517	988,151
Other		
Commercial Revenue Fund	(31,383)	(239,706)
General Fund	98,534	12,462
Intramural Accounts Fund	1,038,376	814,386
	1,105,527	587,142
	2,995,044	1,575,293
Total liabilities and fund balances	5,496,238	5,899,498

Approved by the Board of Management

_____________________ Chair _____________________ Member

TRIUMF

Statement of Combined Funding/Income and Expenditures and Changes in Fund Balances
For the year ended March 31, 2003

	2003 $	2002 $
Funding/Income		
National Research Council Fund	41,000,000	40,000,000
Natural Sciences and Engineering Research Council Fund	6,078,010	4,783,305
MDS NORDION Fund	4,419,985	3,143,366
Province of British Columbia Building Fund	7,949,145	1,320,155
Affiliated Institutions Fund	2,148,275	1,658,482
Commercial Revenue Fund	804,885	455,189
General Fund	129,505	266,555
	62,529,805	51,627,052
Expenditures		
Buildings and improvements	8,912,172	1,855,596
Communications	163,419	123,011
Computer	1,420,213	1,200,886
Equipment	9,785,926	10,730,390
Power	1,943,129	1,771,945
Salaries and benefits	30,379,144	28,774,346
Supplies and other expenses	8,506,051	9,408,927
	61,110,054	53,865,101
Excess (deficiency) of funding/income over expenditures for the year	1,419,751	(2,238,049)
Fund balances – Beginning of year	1,575,293	3,813,342
Fund balances – End of year	2,995,044	1,575,293

TRIUMF
Notes to Financial Statements
March 31, 2003

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, through a contribution from the National Research Council of Canada.

Each university owns an undivided 20% interest in all the 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 of Canada, the Natural Sciences and Engineering Research Council, and governments; advances and reimbursements from other sources; royalty income; and investment income. TRIUMF has established a number of separate funds to account for the various funding sources. The sources and purposes of these funds are:

National Research Council Fund (NRC)
Funding and operations, improvements and development; expansion of technical facilities (excluding buildings) 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 Fund
Advances and reimbursements for expenditures undertaken at its TRIUMF site.

Provincial Government Building Fund
Funding from the Province of British Columbia and other sources 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.

2. Basis of Presentation
These summarized financial statements were derived from the complete financial statements of TRIUMF which were prepared in accordance with Section 7 of the TRIUMF joint venture agreement and the contribution agreement with the National Research Council of Canada, and follow Canadian generally accepted accounting principles for not-for-profit organizations as referred to in the Canadian Institute of Chartered Accountants Handbook except that all property, plant and equipment purchased or constructed for use at TRIUMF and related decommissioning costs (if any) are expensed in the period in which the costs are incurred.

Muonium Studies of Chemical Reaction Dynamics Muon Capture

Donald Fleming

TRIUMF's muon beams have played an important role in the elucidation of chemical reaction dynamics, complementing their roles in exploring particle physics and in studies of materials and superconductivity as described in earlier issues of this series of TRIUMF Annual Reports.

> ***"The intellectual framework for these studies encompasses as well the heroic ideas and events of a hundred years ago, which initiated the 20th century and made it into a century of science."***

The use of muons for studies of chemical reactions has its origins in early experiments in the 1960s and 70s at DUBNA in Russia, at Columbia University, at the Los Alamos Meson Facility, and at the old 184" cyclotron at Berkeley where the first definitive studies were carried out by a group of scientists from Berkeley, the University of Arizona and the University of British Columbia. However, over the past 25 years, it has been the TRIUMF program which has had the major impact on the field, giving justification to the title of this article. The intellectual framework for these studies encompasses as well the heroic ideas and events of a hundred years ago, which initiated the 20th century and made it into a century of science. We focus here on how TRIUMF was able to seize this special opportunity and on the fundamental results which emerged.

The simplest chemical reaction is between an atom (such as the hydrogen atom) and a diatomic molecule (such as the hydrogen molecule). The rate at which such a reaction proceeds depends upon the product of the concentrations of the two reacting species multiplied by a rate constant. Understanding the nature of the rate constant has been a goal since the first detailed studies were carried out at the end of the 19th century. It is determined experimentally by measuring the amount of reaction products when the reactants' concentrations and temperature are varied.

A framework for understanding reactivity was provided by the Swedish chemist Arrhenius before the advent of the theory of the atom or of quantum mechanics. In the fundamental equation of Arrhenius the temperature-dependent rate constant is given by the product of a so-called "frequency factor" (which depends on the size and speed of the reactants) and an exponential function whose negative exponent is the so-called "activation energy" divided by the product of the temperature and Boltzmann's universal constant. Initially both of the two parameters of the Arrhenius Law - the frequency factor and the activation energy - were regarded as empirical constants. The Law found widespread use in describing not only chemical reactions but also a wide range of natural phenomena including plastic flow, the creeping of ants and the flashing of fireflies, which surely would have been a surprise to Arrhenius. Quantum mechanics gave substance to the Arrhenius Law. Indeed, the success of quantum mechanics with chemical reactions helped to lay the foundation for the whole twentieth century of science.

> ***"Several fundamental principles of physics lie at the core of our understanding of chemical reactivity."***

The simplest atom in nature is the hydrogen atom and the simplest molecule is H_2, from which it follows that the simplest chemical reaction is the $H+H_2$ reaction. A theory of chemical reactivity for this most basic of reactions was first developed in the mid 1930s (by London, Eyring and Polanyi, the father of Canada's own Nobel laureate in chemistry, John Polanyi), not long after the advent of quantum mechanics. As well as laying the seeds for the modern, blossoming field of chemical reaction dynamics, this simplest of reactions still occupies a central position in the pantheon

Donald Fleming

Muonium Studies of Chemical Reaction Dynamics Muon Capture

of chemical dynamics because, in principle, it contains no adjustable parameters and can be calculated directly from first principles.

Several fundamental principles of physics lie at the core of our understanding of chemical reactivity. First, at a given temperature the molecules of a gas have a distribution of speeds which rises from zero at zero speed, goes through a maximum, and then falls to zero again for high speeds, with the average speed proportional to the square-root of the temperature. This fundamental speed distribution is due to Maxwell who, a hundred and fifty years ago, was also responsible for the foundations of electromagnetism. This Maxwellian velocity distribution lies at the heart of the Arrhenius rate equation and embodies the principles of both classical and quantum chemistry. Second, chemical reactions are governed entirely by an electromagnetic interaction, in particular the Coulomb interaction between the negatively-charged electrons and the positively-charged nuclei. Third, electrons are eighteen hundred times less massive than protons (or neutrons) and are therefore that much more mobile. (At room temperature, atoms or molecules have average speeds of several hundred meters per second, comparable to rifle bullets.) Thus when atoms or molecules approach each other, at each separation distance the electrons rapidly adjust their configuration, in response to the electric forces involved. Because of their mobility the electrons move as though the atoms were temporarily at rest.

As an atom and a diatomic molecule approach each other to engage in our generic chemical reaction there is, at first, a force of repulsion between the two systems due to the overlap of their electron "clouds". The like-charged electrons repel each other and this repulsion gives rise to an energy barrier that needs to be overcome before the reaction can take place. As the two systems get closer the electrons respond to the attraction of the atomic nuclei and form a "transition state" which lasts less than a trillionth of a second before breaking up to form the reaction products. The barrier involved in reaching the transition state can be compared to a familiar analogue. If we drive from Calgary to Vancouver we achieve a drop in potential energy equal to that for free fall from the elevation of Calgary to sea level at Vancouver. But, in the journey we had to surmount a gravitational barrier given by the height of the lowest pass through the Rockies.

Though the potential energy in a chemical reaction is dominated by what the mobile electrons do, the nuclei are not unimportant. In fact they give meaning to "dynamics" in the title of this article. Mass determines both the abundance of transition states and concomitantly how easily the potential barriers to reaction are surmounted. The effects of mass on chemical reaction rates are known

"... muonium acts chemically just like an ultra-light hydrogen atom."

as *Kinetic Isotope Effects*. The term "isotope" is well known, normally defined as atoms with the same number of protons but differing numbers of neutrons in their nucleus, classic examples being the familiar isotopes of Hydrogen (m_H=1), Deuterium (m_D=2) and Tritium (m_T=3). Perhaps its most well-known application is as "heavy water", D_2O, used as a moderator in the Canadian (CANDU) nuclear reactor and much in the physics news of late as key to the success of the Sudbury Neutrino Observatory (SNO) experiment, searching for flavor-changing electron neutrinos emitted from the sun. Prior to the TRIUMF work described herein, the most sensitive tests of mass on chemical reactivity were provided by comparisons of the reactivity of H and D atoms.

Muonium, first observed by Vernon Hughes in 1960 at Columbia University, is an atom whose

Muonium Studies of Chemical Reaction Dynamics Muon Capture

Donald Fleming

as an isotope of the hydrogen atom, but what a remarkable isotope it is! The muon mass is only $1/9^{th}$ the proton mass, but this is still 200 times the electron mass, so, effectively, from the point of view of electron mobility described above, muonium acts chemically just like an *ultra-light* H-atom. Thus, studying muonium reactivity extends the mass range at the most sensitive end of the isotopic mass scale, from a factor of two between H and D, to a factor of 18 between muonium and D, which has resulted in heretofore *unprecedented* tests of reaction rate theory by the gas-phase muonium chemistry program at TRIUMF. Before amplifying this theme though, a few words on the origin of muons and the basics of the Muon Spin Rotation technique that is employed in their study.

"It is as though Nature wanted the decay to cooperate with the experimenter."

When the TRIUMF cyclotron's intense beam of energetic (500 MeV) protons passes through targets of carbon or beryllium, a profusion of positively and negatively-charged pions are produced. These particles live for only a short time, 26 billionths of a second, though long enough to be used directly in many different nuclear physics experiments at TRIUMF, probing the details of the nuclear strong interaction. The breakup of the pions through the "weak interaction" produces muons and neutrinos. Again, the weak interaction causes the muon to break up spontaneously into electron and two neutrinos, with a half-life of 2 millionths of a second. Like its leptonic cousins, e^+ and e^-, the muon comes in two charge states, μ^+ and μ^-. The normal muon is negatively charged, like the electron and, indeed, can replace the electron in a "muonic atom", several interesting examples of which were studied in the early days of TRIUMF, including the recent RMC experiment discussed in this issue. Here, as noted, we are interested in the μ^+, the normal muon's antiparticle. There has long been interest as well in probing the weak interaction via the nuclear capture and decay properties of muons at TRIUMF, currently exemplified by the "TWIST" experiment described in last year's report, looking for rare events in the decay of the μ^+, the kernel of our muonium atom.

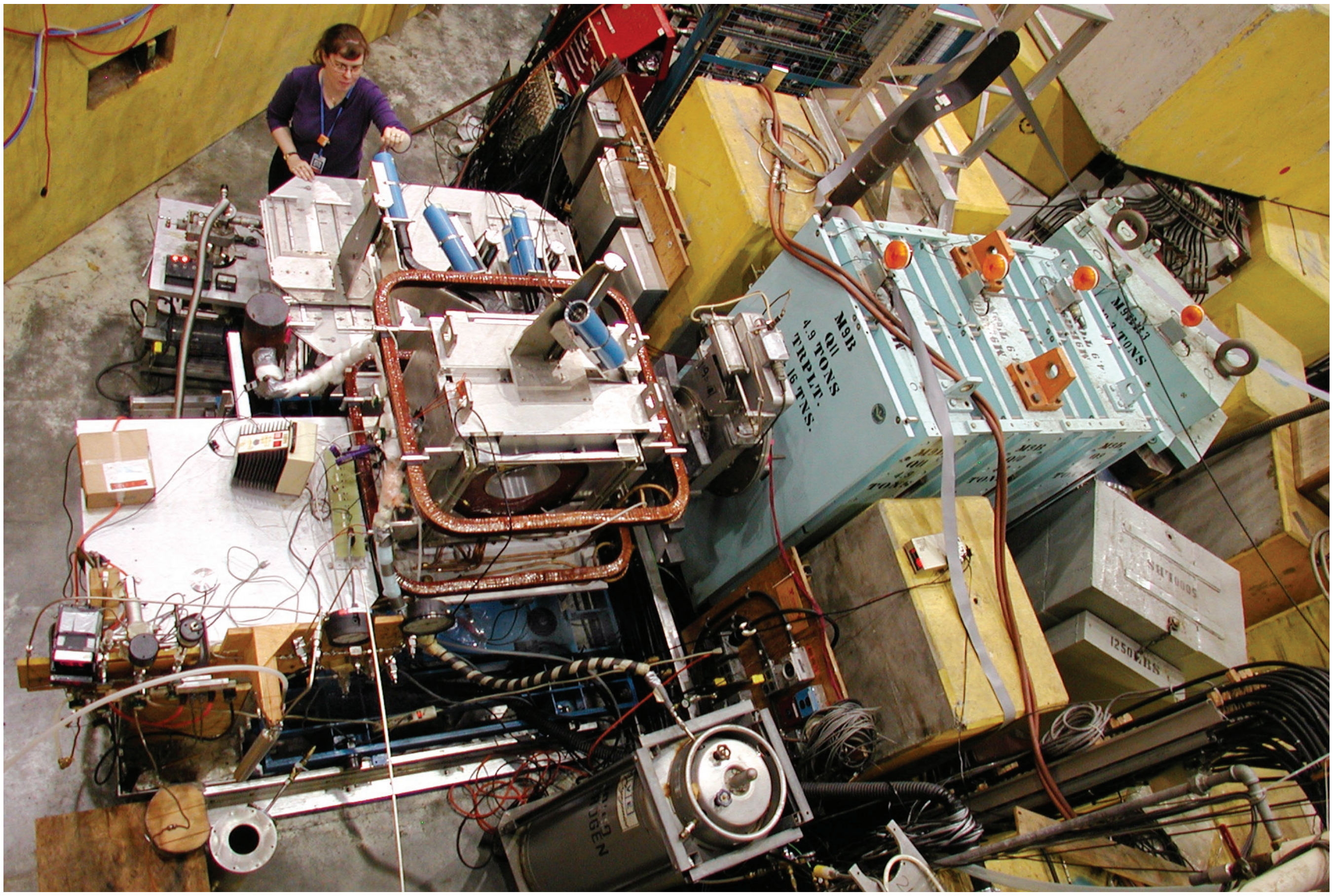
When the μ^+ decays into a positron and neutrino the weak interaction, which causes the decay, gives it a very useful property. All of the muons have their spins pointing in the same direction and the positron is emitted preferentially along this direction. It is as though Nature wanted the decay to cooperate with the experimenter! If the spinning muon is placed in a magnetic field perpendicular to its spin axis the axis precesses around the field direction much like a spinning top. In the experiments a detector, in a fixed direction, catches the emitted positrons and the precessing muons act much like a lighthouse beam. Whenever the precessing muons happen to point in the direction of the detector the number of positrons caught increases dramatically. This is the essence of what is called Muon Spin Rotation (μSR) experiments. The precession is rapid compared to the muon lifetime and the oscillating counting rate of the detector is a beautiful signal which tells us much about the muon's decay and about the magnetic field in which it precesses.

Here we are interested not in the precession of the bare muon but rather in the precession of the muonium atom. The muon and the electron of the muonium atom interact in such a way as to "lock" the precession of the muon to that of the much more rapidly precessing electron. The net effect is to have a μSR oscillation rate which is about a hundred times faster. The "lighthouse" effect, as seen by the positron detector still applies.

As an example of an experiment with precessing muonium atoms we take a secondary beam of fast muons from TRIUMF and pass it through nitrogen gas. The nitrogen gas slows the muons down and also allows them to each steal an electron from the

Donald Fleming

Muonium Studies of Chemical Reaction Dynamics Muon Capture



are then observed by a positron detector in a fixed direction. If the perpendicular magnetic field causing the precession is about 8 gauss (about 30 times the earth's magnetic field in Vancouver) the observed μSR oscillations occur about 8 times per microsecond.

The science of chemical reaction dynamics focuses not on the μSR oscillation itself but rather on the damping of this oscillation because of the loss of muonium atoms through chemical reactions. In the experiments the beautiful μSR signal drops off exponentially. The rate of exponential fall off, typically with a half-life of a fraction of a microsecond, informs us about the reaction rate. Of course, even in the absence of a chemical reaction the μSR signal falls off because of gas impurities and magnetic field inhomogenieties and also the finite lifetime of the muons, but such "background" damping is easily disentangled from the sought for damping due to chemical reactions. We discuss below the results for the reaction rates, as a function of temperature, for muonium in hydrogen gas and fluorine gas.

Before describing these results we provide a perspective for the importance of such experiments to the reaction dynamics community. The transition states of a specific chemical reaction are discrete energy levels corresponding to the vibrations of the participating atoms of the whole system. For all except the simplest atoms (such as hydrogen with only one electron) enormous computing power may be required for the transition state: it involves the bonds between all of the atoms.

Muonium Studies of Chemical Reaction Dynamics Muon Capture

Donald Fleming

Quantum theory tells us that the vibrational transition states are discrete and have spacings inversely proportional to the square root of the mass of the vibrating atoms. Thus when muonium reacts with a diatomic molecule the transition states are much farther apart, by a factor of three,

> *"Quantum mechanics provides some magic for the surmounting of the barriers which impede the formation of the transition states."*

and harder to reach than for similar reactions of hydrogen with the same molecule. The activation energy of the Arrhenius Law is therefore strongly impacted by both the spacing of the transition states and by the barriers associated with the formation of the transition states. Quantum mechanics can give us parameter-free estimates of both effects. We expect that muonium will have much slower reaction rates than hydrogen because of the larger spacing of transition states.

Quantum mechanics provides some magic for the surmounting of the barriers which impede the formation of the transition states. In quantum mechanics atoms can be regarded as either waves or particles. Their wave nature allows them to tunnel through barriers not only to go over the top. We cannot burrow through the Rockies on our way from Calgary to Vancouver but the atoms have significant probability of burrowing through their barriers. Quantum barrier tunneling depends dramatically on the mass of the tunneling particles. It is the most facile for electrons and accounts for an important tool in materials science, the Scanning Tunneling Microscope. It also accounts for spontaneous alpha-particle decay of heavy atoms in which the alpha particles, in leaving the nucleus, tunnel through an electric barrier.

Since muonium is so much lighter than hydrogen we can expect muonium tunneling to be much faster than that of hydrogen. This gives the opposite effect to that of the transition state spacing which slowed the muonium rate. Effectively the ease of tunneling lowers the activation energy. Both quantum effects on the dynamics of chemical reactions have been shown definitively by the TRIUMF experiments.

The relative importance of vibrational energy and quantum tunneling effects in muonium and hydrogen reactivity depends on the nature of each reaction. For exoergic reactions which involve a net energy gain (so that the product molecule is more tightly bound than the initial molecule) as exemplified by the reactions of muonium and hydrogen with fluorine molecules, the dominant quantum effect is the enhanced barrier tunneling of muonium. Conversely for endoergic reactions which involve a net energy loss, exemplified by the reaction of muonium and hydrogen with deuterium molecules, the enhanced spacing of the vibrational transition states dominates and the lighter isotope has lower rates.

The reactivity comparison of muonium and hydrogen (or deuterium) atoms with both fluorine and deuterium (or hydrogen) molecules were

> *"...In a series of difficult but epoch-making experiments which are essential for a fundamental understanding of chemical reaction dynamics."*

accomplished first at TRIUMF, by the present author and his colleagues, in a series of difficult but epoch-making experiments which are essential for a fundamental understanding of chemical reaction dynamics. Over most of the temperature range the experiments clearly obey the temperature dependence of the Arrhenius law and yield constant frequency factors and activation energies. For the simplest of these reactions, those with deuterium, both the frequency factors and the activation

Donald Fleming

Muonium Studies of Chemical Reaction Dynamics Muon Capture

energies can be rigourosly calculated with quantum mechanics. These calculations, originally by George Schatz of Northwestern University, are almost indistinguishable from the experimental results of our TRIUMF experiments. Recent more complete calculations continue to verify this agreement between theory and experiment. These reactions remain the most definitive test of chemical reaction theories and therefore constitute the foundation of chemical reaction dynamics. The activation energies for muonium and deuterium interacting with hydrogen molecules are (in units of electron volts) 0.58 eV and 0.37 eV, respectively, a substantial difference almost entirely due to the difference in the spacing of the corresponding transition states.

Conversely the reactions of hydrogen-like isotopes with fluorine molecules dramatically illustrate the effect of barrier tunneling. Again there is excellent agreement of our experimental results with theory, as calculated by Kurosaki and Takayanagi in Japan. The observed reaction rates for muonium greatly exceed those for hydrogen as one would expect when barrier tunneling predominates.

The observed reaction rates also illustrate some quantum effects which go beyond the Arrhenius Law. At the lowest temperatures, where the atoms move most slowly and tunneling is more extreme, the experimental rates deviate from the exponential behaviour of the Arrhenius Law. This deviation was first predicted many years ago by Eugene Wigner and his predictions agree with our experiments. These experiments were the first experimental confirmation of Wigner tunneling. It is a stunning example of the facility with which muonium tunnels through barriers and therefore is such a magnificent tool for the study of chemical reaction rates.

The experimental results at TRIUMF for muonium and hydrogen interacting with hydrogen and fluorine are representative of the TRIUMF gas-phase muonium chemistry program. It has produced many other results. This program had its genesis in the dying days of the old 184” cyclotron at Berkeley, which occurred in 1976 when the TRIUMF cyclotron delivered its first beam. Then, waiting at TRIUMF, was the M20 secondary beamline for muons largely built with components borrowed from Berkeley by David Garner, a UBC graduate student and by Jess Brewer, a UBC Killam fellow who was associated with Professor Kenneth Crowe of Berkeley. The participation of Professors Yamazaki and Nagamine of Tokyo University was also essential. Thus was born the TRIUMF μSR facility which has now evolved into the Center for Molecular and Materials Sciences at TRIUMF. It encompasses a very wide program, including studies with TRIUMF’s new ISAC Facility.

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The subject of Muonium Chemistry at TRIUMF is also much broader than the field of chemical reaction dynamics discussed herein, and includes as well the major field of muoniated free radicals (a recent IUPAC-sanctioned nomenclature) which are invariably formed by muonium addition reactions to unsaturated bond systems. These kinds of reactions are also currently under study in the gas-phase, notably in the realm of atmospheric chemistry, but have also facilitated an interesting and wide range of novel studies of polyatomic organic free radicals, extensively investigated by Dr. Paul Percival and his group in the Chemistry Deptartment at SFU. But that’s another story!

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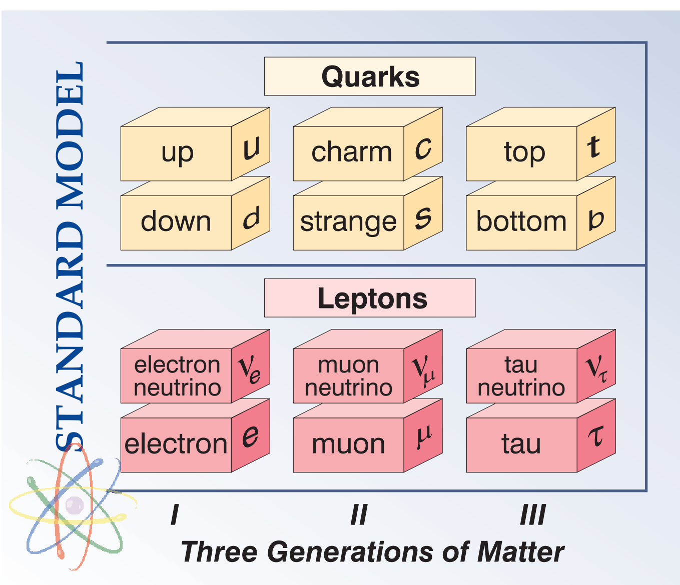
Radiative Muon Capture on Hydrogen

Michael Hasinoff
Tim Gorringe

Symmetries, Conservation Laws and Particle Physics

Most people are well aware of the fact that symmetries are very powerful tools of famous artists. Perhaps the most famous examples are the beautiful mosaic patterns on the walls of the Alhambra in Granada and Michelangelo's "Creation" painting on the ceiling of the Sistine Chapel in the Vatican in which the right hand of God is reflected as the left hand of Adam.

Symmetries are also very important to the physicist because they are each the result of an underlying conservation law. After many years of observation physicists have now come up with a Standard Model (SM) to describe both the elementary particles and the fundamental forces in nature. Within this Standard Model, the elementary particles consist of six leptons and six quarks which form three families each comprising one lepton pair and one quark pair. These elementary particles interact via only two forces: the strong force which is felt only by the quarks and the electroweak force which is felt by all particles. (The gravitational force has yet to be incorporated into the Standard Model.) The Standard Model has been amazingly successful in its description of the electroweak force. However, our basic model of the strong interaction, Quantum



ChromoDynamics (QCD) is somewhat more complicated and our knowledge about the origins of the quark masses as well as the masses of the proton and neutron is still rather limited. Encoded in QCD are various symmetries which yield conserved currents that constrain both the fundamental interactions of the quarks and gluons and the resulting interactions of the nucleons and mesons. Thus, despite the complicated quark-gluon substructure of the nucleons, it is possible to make some precise predictions about their elementary properties.

Symmetries or patterns are central to both the construction and the realization of the Standard Model. For example, the so called gauge symmetries are believed to be responsible for the form of the interactions and for enforcing related conservation laws. The exact conservation of electric charge is a familiar example of an underlying gauge symmetry. In addition the Standard Model contains a very rich variety of approximate symmetries. Of special importance are the symmetries associated with the two lightest quarks, the so-called "up" and "down" quarks. The strong force between quarks is understood to be independent of the type or "flavour" of the quark. Consequently the two most familiar bound states of up and down quarks, the proton *(uud)* and the neutron *(udd)* have almost identical masses. This flavour symmetry of the u and d quarks is called "isospin" symmetry.

Quarks also have spin. Physicists view quarks as spinning tops rotating either clockwise or counterclockwise about their direction of motion. This "handedness" leads to two copies of isospin symmetry-one for left handed quarks and another for right handed quarks. This dual isospin symmetry is called "chiral" symmetry.

Chiral symmetry is realized in nature in an intriguing manner. Whereas isospin symmetry is immediately discernable from the masses of the particles that are made of up and down quarks -- this is not the case for chiral symmetry. Rather, physicists

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believe that the chiral symmetry of up/down quarks is a so-called hidden symmetry-a fact that delayed its discovery for many years.

While hidden, this symmetry does predict the existence of an associated, approximate conservation law. This underlying conservation law acts somewhat like electrical charge conservation -- i.e., by constraining or dictating the form of the interactions between neutrons and protons and other particles. Interestingly, this symmetry predicts that the characteristic strengths of two parts of the proton's electroweak interaction are related. More specifically the strengths of the two parts are characterized by two numbers which we denote as g_a and g_p and chiral symmetry makes the prediction that g_p should equal exactly 6.7 g_a.

The RMC cylindrical gold target with its flattened hemispherical dome. Both pieces have a thickness of only 0.25 mm. They were welded together in the TRIUMF workshop.

The muon capture studies at TRIUMF were aimed at directly testing this "golden" prediction of chiral symmetry thereby exploring one of the most fascinating and elusive symmetries of the Standard Model of Particle Physics.

Muons, Muonic Atoms and Muonic Molecules

Detailed studies of the weak interaction over the past 50 years have established the property of "Lepton Universality" which indicates that the interactions of the 3 charged leptons (electron, muon, and Tau) are all the same except for terms which are mass dependent. As a consequence of this fact we can utilize the muon or the Tau as a heavy electron and thus obtain more details about the weak interaction beyond those which can be obtained from β (electron) decay studies of radioactive nuclei. The muon was discovered in cosmic rays in 1937; it is absolutely identical to the electron in all aspects except its mass. It was originally thought to be the particle responsible for the strong interaction between nucleons but its very high penetrating power in matter quickly convinced physicists that it was a weakly interacting particle just like the electron. In the Standard Model the muon is the second generation partner of the electron with a mass 207 times greater than the electron mass. The third charged lepton, the Tau (τ), is even heavier, about 3500 times the electron mass. It is too massive to be produced at TRIUMF.

When a negative muon enters into a target material it quickly slows down and is captured into one of the Bohr orbits surrounding the nucleus. The energy released is transferred to the atomic electrons as the muon cascades down to the lowest allowed orbit which has a radius 207 times smaller than the corresponding electron orbit. As a result, some of these orbiting muons can interact with a proton inside the nucleus, rather than decaying. This muon capture process can provide us with new information on both the weak and the strong interactions.

The chiral symmetry of QCD is a spontaneously broken symmetry so a massless pseudoscalar goldstone boson (the pion) must exist and the underlying conserved currents are related to g_p. The fact

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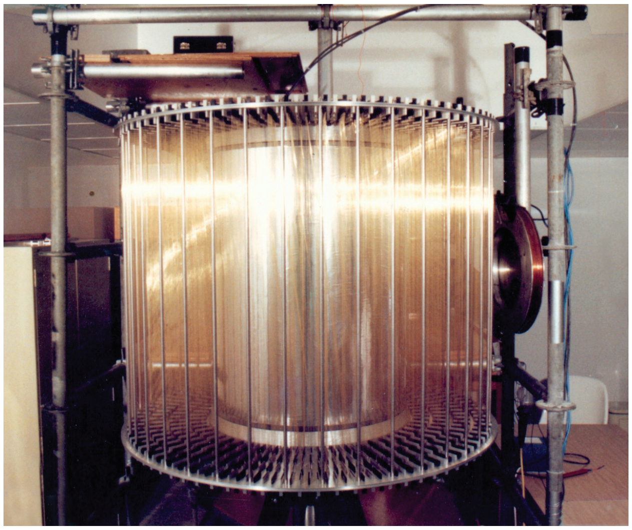
that the quarks are not exactly massless means that these hadronic currents are not exactly conserved and this leads to a relationship between the probability of pion emission by a proton and the value of the axial and pseudoscalar coupling constants ($g_a$and g_p) of the proton.

The determination of this very important parameter of the weak interaction (g_p/g_a) was the primary goal of the TRIUMF Radiative Muon Capture experiment. Since the detailed structure of all but the lightest nuclei is still the subject of intense research we must study muon capture in the lightest nuclei in order to learn about the weak interaction. The muon capture rate increases roughly as the 4th power of the number of atomic electrons. Hence very few muons are captured in the lightest and best understood muonic atom, muonic hydrogen, μp. However, creative physicists have managed to measure the muon capture process in both gaseous and liquid hydrogen targets. Because of the rather small size of the μp atom only about 1 in 1000 muons are captured; the rest decay with a characteristic lifetime almost equal to that of the free muon. Also, since the μp atom is electrically neutral and quite chemically reactive, it can readily combine with hydrogen, deuterium or tritium atoms in the target forming muonic molecules. Most of these molecules then undergo a strong reaction, known as muon catalyzed fusion, which fuses the nuclei in the molecule producing gammas and neutrons thereby preventing the observation of the muon capture reaction. Consequently the deuterium content of normal hydrogen, 150 parts per million (ppm), is a major problem. Pure protium gas, less than 2 ppm deuterium, must be employed in such experiments.



The cylindrical drift chamber during its construction and testing phase.

Looking for a Needle in a Haystack

Radiative Muon Capture (RMC) is similar to Ordinary Muon Capture (OMC) except that the final state contains an additional high-energy gamma ray. This is a doubly rare process. Only about 1 in 10,000 capture events will contain a gamma-ray and, since only 1 in 1000 muons are themselves captured in muonic hydrogen, the overall RMC probability is only about 1 in 10,000,000. In addition the reaction products of RMC, a neutron, a neutrino, and a gamma ray, are uncharged particles, all notoriously difficult to detect cleanly. Nevertheless RMC is very sensitive to g_p/g_a and so we decided to attempt such a measurement at TRIUMF. One might say that we were looking for the proverbial "Needle in a Haystack". The extremely low rate for RMC meant that the experiment had to be designed very carefully.

Firstly, the pion contamination in the beam had to be greatly reduced since every pion stopping in liquid hydrogen produces either a 129 MeV gammaray or 2 gamma rays of energy between 55 and 85 MeV from π^0 decay. To accomplish this task we used an RF separator to deflect the e^- and π^- onto vertical slits while allowing the muon beam to pass straight through into the liquid hydrogen target. This RF separator reduced the pion flux by a factor of 10,000. We then used measurements of the time-of-flight along the 10 m beamline and the energy deposited in a thin plastic scintillator placed just in front of the liquid hydrogen target to reject any

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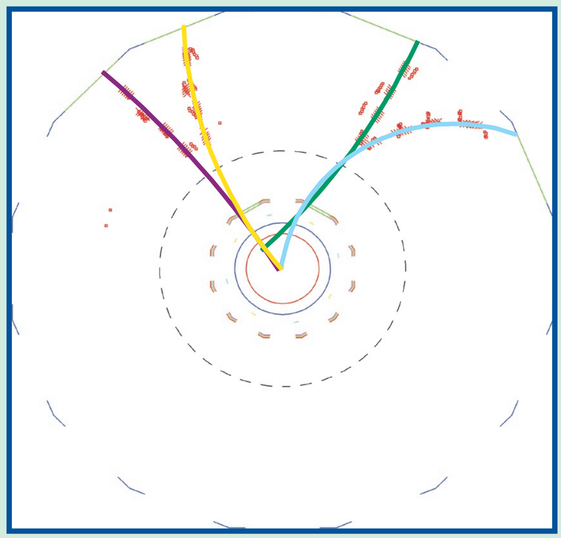
remaining pions in the beam. Since the pion energy spectrum is rather distinctive the effectiveness of all these pion rejection techniques could be readily demonstrated to be greater than 1 in a billion.

Secondly, before liquefaction the hydrogen target gas had to be completely free of any heavier gasses (e.g., N_2, O_2, Ar) or else all the stopped muons would be transferred from the neutral μp atoms to the heavier contaminants before the capture process could occur. For this purpose we passed the protium gas through a palladium filter each time it was transferred into the target vessel. In addition, the entire inner section of the target was baked at a temperature of more than 200°C for several hours in order expel any adsorbed gases from the walls.

Thirdly, the deuterium concentration of normal hydrogen (150 ppm) would produce an RMC signal from ^{3}H due to the pμd molecular fusion process about 3 times greater than the signal expected for hydrogen RMC. In order to obtain such ultra-pure protium gas we purchased "zero water" from AECL in Chalk River, and then electrolyzed this water and collected the pure H_2 gas. In this way we were able to liquefy H_2 gas containing less than 1.4 ppm deuterium in our first experimental test run and less than 0.1 ppm in all our subsequent data collection periods, thereby reducing the ^{3}He background to about one percent of the RMC signal.

As mentioned above, the μp atom rapidly transfers its muon to any heavier nucleus for which the capture process is highly probable (rate $\sim Z^4$). Since we needed to have a high density liquid target it was impossible to avoid muon captures in the front face and side walls of the target vessel. We therefore decided to utilize a heavy metal in which the μ^- lifetime would be as short as possible (τ_H = 2195 nsec, τ_{Pb} = 72 nsec). Initially we selected tantalum as a heavy tough metal but inquiries into its price in thin sheets quickly convinced us that a gold or silver container would be much better since these metals could easily be rolled and welded into the correct shape in the TRIUMF workshop. They could also be resold once the experiment was completed. The total cost of the gold used for our target container was only about $7000.

Finally, the very low probability for RMC required a high beam rate and a high efficiency, large-area detector with good energy resolution. Moreover, the unavoidable backgrounds required a visual detector which could cleanly identify gamma ray events. After extensive computer simulations we decided to construct a large cylindrical pair-spectrometer (length = 1.0 m, diameter = 1.2 m) with



The high energy gamma rays produced are detected in the Radiative Muon Capture (RMC) Spectrometer.Their energy is such that when they interact with matter they easily produce an electron pair, one with a positive charge (a positron) and one with a negative charge.

The space inside the spectrometer is filled with a magnetic field which causes the electrons to follow curved paths. In the spectrometer we "see" snapshots of segments of these electrons' paths. We look for sets of four segments that appear to be caused by the same electron. A set of four connected segments allows the radius of curvature of the path and hence the electron's energy to be determined. The direction in which the path bends allows us to distinguish between electrons and positrons. The sum of the energies of the electron and positron plus the energy required to create their mass (1 MeV) is the energy of the gamma ray.

In this snapshot we see two different gamma rays. They are converted to electron pairs at two different locations near the center of the chamber. We also see two small noise events which are unrelated to the two gamma ray tracks.

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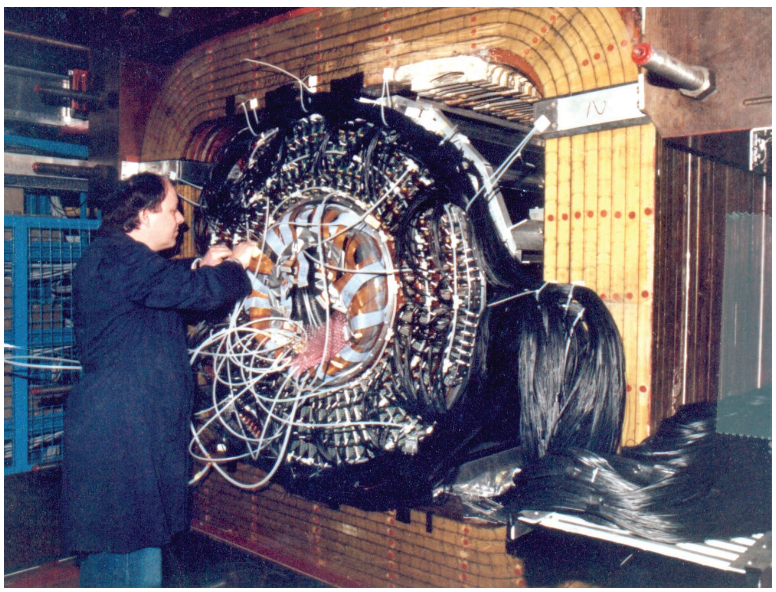
1632 anode sense wires and 5320 cathode field shaping wires. The chamber was designed and constructed mostly at TRIUMF, but the large area aluminum endplates, the thin carbon fibre/epoxy inner and outer chamber walls and the plastic wire feed-throughs were all fabricated by local companies. It took nearly 2 months with 4 people working 16 hours/day to string all the thin wires in the chamber. Each sense wire was connected to a time-to-digital converter so that we could determine the position of a track from the drift time onto the anode wires to a precision of about 0.15 mm. The orginal high-energy gamma ray is converted into an e^+e^- pair after passing through a thin (1.1 mm) cylindrical lead sheet. An additional inner wire chamber is placed inside the drift chamber in order for us to obtain a second longitudinal point and thereby measure the longitudinal momentum as well as the radial momentum of the two curved tracks. The requirement of both an e^+ and e^- track in every event was accomplished within 1μsec by using a special hardware box designed and constructed at TRIUMF to examine the hits on the drift chamber wires.



The cylindrical drift chamber with all its associated cabling mounted in the solenoidal magnet.

The energy spectrum of the RMC gamma rays extends up to about 100 MeV. However, the region of interest is restricted to energies above 55 MeV due to the bremsstrahlung radiation emitted by the much more copious decay electrons. In this high energy region we can also detect background gammas from cosmic rays as well as from high energy neutrons produced by the proton beam on the beryllium meson production target. We were able to reduce the cosmic ray background somewhat by placing an array of large scintillators and wire chambers on the top and sides of our large solenoidal magnet. The residual background spectrum was measured during beam-off periods as well as when the proton beam was delivered onto the production target but our beamline magnets were turned off (i.e., when the other beamline sharing the front end of our channel was performing a different experiment). In this way we were able to determine our two major sources of background which amounted to about 10% of our RMC signal. The normalization of the background spectrum was carefully checked using both the exposure lifetime as well as by the number of gamma events observed between 100 and 200 MeV where no real RMC events were expected.

One might say that this enormous amount of work by the team of TRIUMF engineers and technical staff working alongside the International team of 20 physicists from Canada, Australia, China, Switzerland and the USA did finally result in the eventual discovery of our “Needle in the Haystack”. In total we observed 397 “good” events which provides a statistical uncertainty of ± 20. However, this number also contains some unavoidable backgrounds which we must subtract before we obtain our final result. The largest background comes from the high energy tail of bremsstrahlung from the much more copious decay electrons of energy less than 55 MeV which extends up to almost 65 MeV. Extensive computer simulations as well as mea-

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surements with a μ^+ beam indicate that this background contribution is 48 ± 7 events. Gamma ray backgrounds from cosmic rays and beam neutrons each contribute 29 ± 10 events. The remaining background contributions from beam pions and target impurities result in 9 and 3 events, respectively. Thus our final published spectrum contained 279 ± 26 RMC events above 60 MeV for times longer than 365 nsec after a beam muon stopped in the LH_2 target. The time cut was necessary to remove RMC events from those muons stopping in the gold target walls or silver heat shields. These events were collected in about 90 days of running time over a period of 3 calendar years. This long data collection period was somewhat unfortunate for our Montreal graduate student, Guy Jonkmans. It was caused by two catastrophes entirely beyond our control. First, the silver heat shields kept at 77 K started to weaken and bent enough to touch the gold target wall so that we could no longer liquefy the hydrogen gas in the target. This required a complete refabrication of the silver heat shields by the TRIUMF machine shop and a re-assembly and bake-out of the target by the targets group under the expert leadership of Dr. Dennis Healey. Secondly, the RF separator, developed in 1979 for the muon-electron conversion experiment, developed an internal water leak over the long Christmas break in December 1992. Unfortunately this leak was not discovered until New Year's eve when the water started leaking out of the beam line onto the floor. The subsequent cleanup and pumpdown of the beam line and repaired RF separator took nearly 6 months.

Intriguing Results

The comparison of our final spectrum with the theoretical prediction lead to a surprise. Our measured value for g_p/g_a was 9.7 ± 0.8 whereas the theoretical prediction was 6.7 ± 0.2, a difference of nearly 50%. Many theoretical attempts have been made to explain this surprising result, but, to date, none has succeeded. One possible explanation could involve the molecular levels of the $p\mu p$ system formed prior to the muon capture. In liquid hydrogen the μp atom quickly forms a $p\mu p$ molecule (within 400 nsec). Since both the muon and the proton are spin ½ particles there are 2 allowed final states (both protons having parallel spins $\uparrow\uparrow$ and both protons having opposite spins $\uparrow\downarrow$), called ORTHO and PARA, respectively. The RMC rates from these 2 different $p\mu p$ molecular states have different time dependencies and the absolute capture rates differ by a factor of about 2.5. In addition, there can also be transitions from the higher energy ORTHO state to the lower energy PARA state and the probability for such a transition is not well-known. The most recent theoretical prediction for the mean lifetime of this transition is τ_{op} = 14.5 ± 2.0 μsec while the only experimental measurement of τ_{op} yields 24 ± 6 μsec - a discrepancy of almost 100%. The value for g_p/g_a determined from the RMC experiment depends only rather weakly on this ortho-para conversion whereas the g_p/g_a value determined from the Saclay OMC experiment decreases from 11.1 to 6.6 to 1.98 as $\lambda_{op} = 1/\tau_{op}$ varies from 0 to 41,000 to 71,000 sec^{-1}.

Thus we decided to repeat the ortho-para conversion experiment at TRIUMF. Five liquid scintillator detectors were placed around our protium target and the time spectrum of the 5.2 MeV neutrons emitted in Ordinary Muon Capture were observed after rejection of the more copious gamma-ray flux by using the differences in the time development of the output voltage pulse for a neutron and a gamma ray event. The analysis of these data is nearly complete and the results are eagerly awaited by the entire QCD community. The present indications are that the result will be sufficiently precise to have a major impact on resolving this discrepancy in our knowledge of the proton's axial coupling.

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TITAN

Jens Dilling

Nuclear and particle physicists study matter at the very smallest scale, exploring the structure and interactions of the most fundamental particles that make up everything in the universe, from stars to starfish. Over the past few decades many experiments have confirmed the picture of all matter as being made up of quarks and leptons. The coupling of these particles is described by the Standard Model of fundamental particles and interactions, which accounts remarkably well for the world we live in. Thus, it explains the forces that hold both atoms and nuclei together.

> ***"An important problem we want to address at ISAC is whether the Standard Model is complete with only three families of quarks and leptons."***

However, the Standard Model leaves many important questions unanswered. Why do three families of quarks and leptons exist? Can we understand the source and pattern of their masses? Will we discover more types of particles and forces at yet higher-energy accelerators? Are quarks and leptons really fundamental, or do they, too, have substructure? What is the nature of dark matter? Questions such as these provide the stimulus for ongoing research in nuclear and particle physics. At TRIUMF a large amount of this research is now centered at ISAC.

ISAC is one of the leading facilities world-wide for the production of exotic nuclei. Exotic or radioactive nuclei are made up of protons and neutrons, just as their stable brothers, but have an unbalanced ratio of these. As a result, they undergo radioactive decay in order to change this ratio to a more stable configuration. The decay that transforms a neutron into a proton or a proton into a neutron is called beta-decay. At the quark level, the proton consists of 2 *up* quarks and a *down* quark while the neutron consists of an *up* quark and 2 *down* quarks. In order for a proton to convert into a neutron one of its *up* quarks must change into a *down* quark. This change is brought about by the weak force. In addition to the quark transformation, the positive charge carried by the proton must be removed, since the neutron is electrically neutral. This is done by emitting a positively charged beta-particle, which gives this form of transformation its name: beta-decay. Similarly for the conversion of a neutron, consisting of 2 *down* quarks and an *up* one, into a proton, one of its *down* quarks must change into an *up* quark and a negative beta-particle is emitted.

An important problem we want to address at ISAC is whether the Standard Model is complete with only three families of quarks and leptons. We attack this problem through the observation of the beta-decay of exotic nuclei containing an excess of neutrons. The measurable quantities are the half-life of the radioactive nuclei and the energy available for their decay. A simple relationship between these quantities which should be the same for all nuclei is predicted by the Standard Model since, in each case, we have the same change between *up* and *down* quarks. However, depending on the particular nucleus undergoing decay there will be different environments of other protons and neutrons, which lead to small corrections to the relationship predicted by the Standard Model. At present there appear to be slight discrepancies between the data and model predictions, but these might be accounted for by inadequacies in the calculation of the theoretical corrections. Measurements with **TITAN** (**T**RIUMF's **I**on **T**rap facility for **A**tomic and **N**uclear science) will provide more precise experimental data, which will check this possibility.

Precision half-life measurements are already under way at ISAC and some results have been reported. The other experimental quantity, the available decay energy, can be determined from a precise measurement of the masses of the initial and final nuclei involved in the decay. The available decay energy, E, is then given by Einstein's mass-energy relationship, $E=\Delta m\, c^2$, where Δm is the mass difference between the two nuclei, before and after the decay.

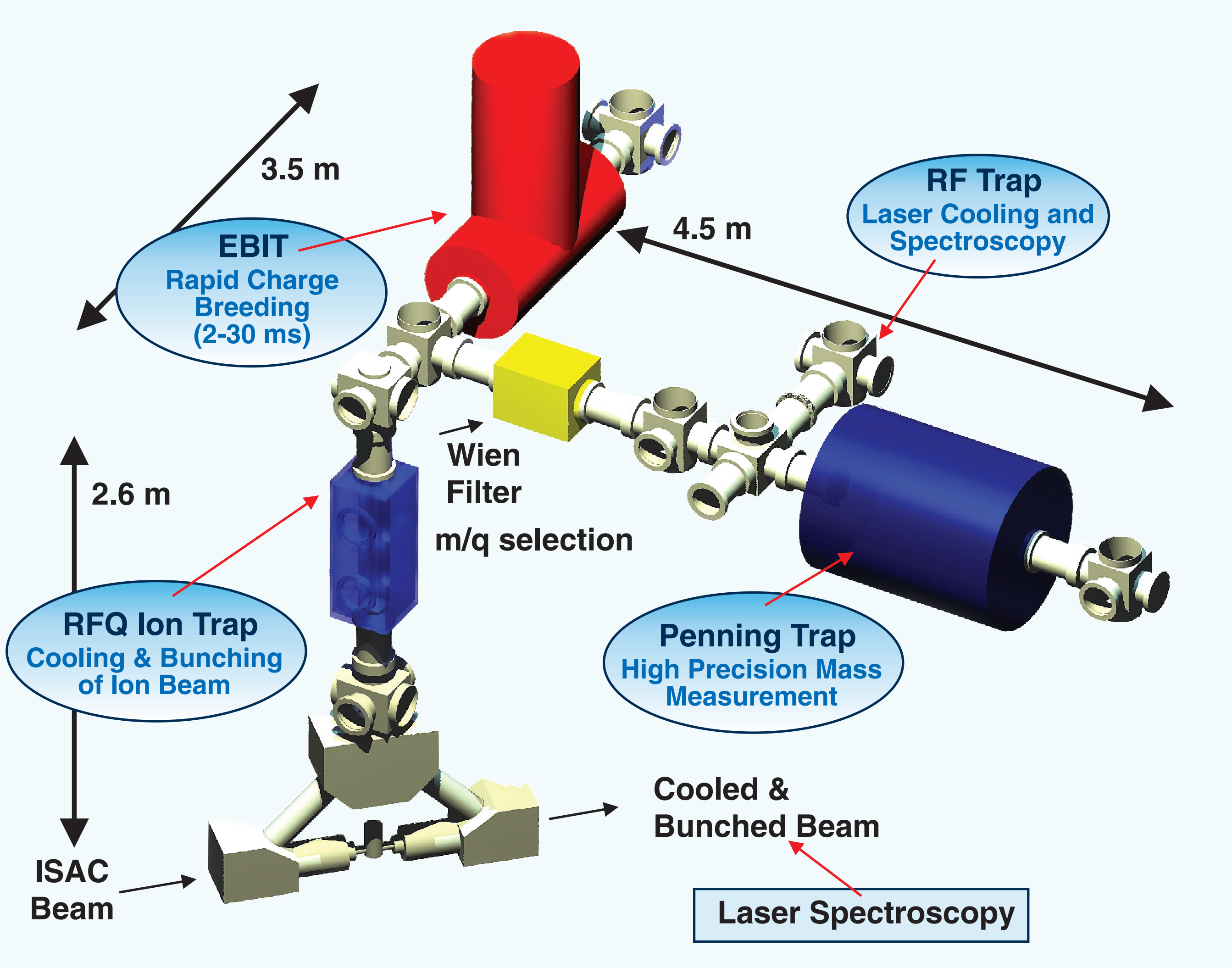
Jens Dilling

TITAN

TITAN's task at ISAC is to measure very precisely the masses of short-lived exotic nuclei, which will provide information necessary to allow calculation of the detailed corrections needed for a critical test of the Standard Model. The precision needed in the mass measurement is about one part in 100,000,000 corresponding to determining the mass of a car with a precision of about 10 milligrams.The fact that the nuclei of interest have an average half-life of only about one-tenth of a second makes this an extremely difficult task. The TITAN approach to the problem involves two important features: an extremely well-controlled environment, and a measurement of frequency as the primary mass-related experimental observable.

The environment is generated by a Penning ion trap. Such a trap uses a combination of magnetic and electric fields to provide a region in space where ions are trapped. Since this region is at an extremely low pressure the ions do not interact with any material. The magnetic and electric fields are shaped with a precision that makes it possible to understand the motion of the ion extremely well,

TITAN: TRIUMF's Ion Trap for Atomic and Nuclear Science



The proposed TITAN facility at TRIUMF/ISAC; located 2.6 m above the present beam line level. The multi-component system will allow for a wide variety of fundamental and applied physics experiments.

and allows control, once the ion is trapped, with almost arbitrary accuracy. At CERN, for example, single anti-protons (stable, non-radioactive anti-matter) could be trapped and kept from interacting and annihilating with normal matter for several months at a time. The pressure, hence, the number of residual gas-atoms or molecules per cubic millimeter, in the trap was less than in outer space between stars.

"The precision needed in the mass measurement is about one part in 100,000,000, corresponding to determining the mass of a car with a precision of about 10 milligrams in one tenth of a second."

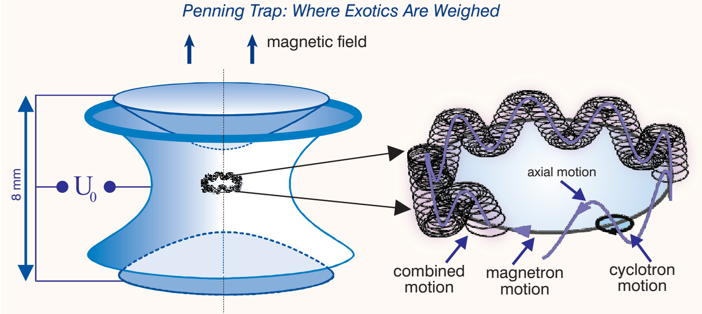
If an alternating electric field is applied to the static electric and magnetic fields used to confine the ions in the Penning trap, the ions can be made to act as though they were in a (very!) small cyclotron. The exact frequency at which this happens is inversely related to the mass of ion. Thus the mass measurement is changed to a frequency measurement. (Of all physical quantities frequency measurements are capable of the highest precision.) Besides the measurement of this frequency, one needs to know the charge state of the ions and the magnetic field strength, both of which are straightforward measurements. Once the mass is measured the available energy for the beta-decay process can be determined.

Before entering the TITAN Penning Trap, the exotic nuclei, which come from the ISAC facility in the form of an ion beam, need to undergo a series of preparatory steps as illustrated in the figure on the previous page. The first step takes place in an **RFQ** (**R**adio-**F**requency **Q**uadrupole) ion trap. This trap consists of four rods to which an alternating high-frequency voltage is applied. By proper choice of the frequency and the voltage, the ions can be confined between the rods, being alternately attracted and repelled by, but never touching, the rods. In addition the device is filled with a cold gas and the interactions with it leads to a cooling of the ions. This device accomplishes two things: a large number of ions is accumulated and their energy (temperature) is reduced to a value better suited for our precision mass measurements.

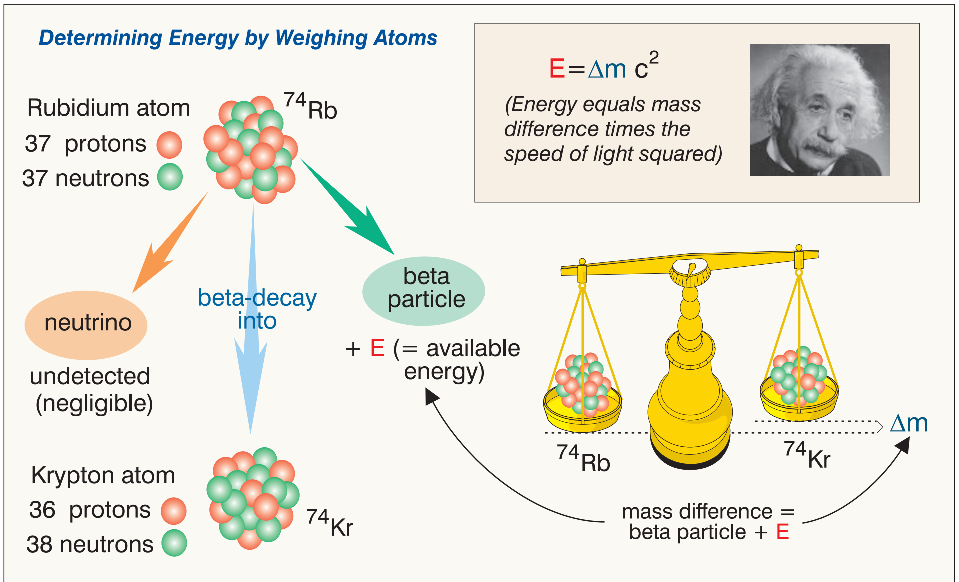
The next step in the TITAN system is an **E**lectron **B**eam **I**on **T**rap (EBIT). The purpose of this device is to reach higher charge states, by removing more and more electrons from the atom or ion. This is done by bombarding the trapped particles with an electron beam, which collides with the electrons of the atoms, and kicks them out. This process works, as long as the binding energy of the electron (a measure of how tightly the electron is attached to the nucleus) is smaller than the energy of the incoming beam. The process is a dynamic rather than a well controlled one, since the kicked out electrons may attach to other ions. As a result the ions that are extracted from this trap are a cocktail of ions in various charge states.

The Penning trap mass measurement requires, however, the exact knowledge of the charge state of the trapped ion. In the next step, a Wien filter, the ions travel through a region in which electric and magnetic fields are at right angles to one another and the direction of the incident ions. With such a configuration only ions of one specified charge

Penning Trap: Where Exotics Are Weighed



Schematic Penning trap with magnetic field pointing upwards, and motion of stored ions there in. The complicated combined motion of the ions is composed of the axial, the slow magnetron, and the fast cyclotron motion. The total behavior of the ions has been investigated and is now understood extremely well.



Schematic beta-decay of a radioactive Rubidium atom (composed of 37 protons + 37 neutrons = 74 nucleons, therefore called ^{74}Rb) into a Krypton atom (36 protons + 38 neutrons = 74 nucleons, called ^{74}Kr). By weighing the two different atoms, the available energy, E, for the beta-decay is determined.

will be able to go straight through and into the Penning trap.

The need for high charge states comes from the requirement to perform the Penning trap mass measurement quickly, since the nuclei of interest are radioactive and decay. In the quantum world there are pairs of variables both of which cannot be simultaneously measured to high accuracy. This is Heisenberg's uncertainty principle which says, for example, that the better the position of a particle is determined, the less precise its momentum is known. Another pair of such variables is energy and time. Longer observation times lead to higher precision mass (energy) measurements. The radioactive ions in the Penning trap, however, only allow a short observation time before they decay.

The way out of this apparent dilemma, is to use highly charges ions because the frequency at which they absorb energy is directly related to their charge. Note that time and frequency measurements are very closely related. Since we are stuck with a frequency uncertainty due to Heisenberg's principle, we still can reach a better value for the relative precision of our measurement by boosting the absolute value of the frequency. This is done by using highly charged ions. By comparing the frequency so measured to that for a trapped stable ion, whose measurement can take place over a much longer time, we reach the necessary absolute precision for mass measurements of exotic nuclei.

"Longer observations time lead to higher precision mass (energy) measurements. The radioactive ion in the Penning trap, however, only allow a short observation time before they decay. But we found a way out of this apparent dilemma ."

TITAN is the first system that will use this combination of various ion traps and techniques. It will provide the crucial data required to evaluate the validity of the theoretical corrections needed for a test of the Standard Model. The uniqueness of the system allows for other fundamentally important experiments in the fields of, for example, atomic physics, where laser spectroscopy measurements are foreseen.

The TITAN system was proposed to NSERC and has received funding to be built over the next three years. The main investigators are based at TRIUMF and eight other Canadian universities, but the collaboration is truly international, with parts of TITAN (the EBIT) being built at the Max-Planck Institute for Nuclear Physics in Heidelberg, Germany. Precision mass measurements are planned to begin in 2006.

Jens Dilling is a research scientist at TRIUMF and leader of the TITAN Ion Trap Group.

The Cyclotron Central Control System

Michael Mouat

The Basics

In many, large industrial and research facilities, from pulp mills to particle accelerators, there is a need for a computerized process control system. The 500 MeV cyclotron facilities at TRIUMF are no exception. Multiple high-energy protons beams are simultaneously extracted from the cyclotron and delivered for pure and applied science programs. The cyclotron comprises thousands of devices that need to be monitored and controlled and a specialized control system exists to provide the required supervision.

> ***"The cyclotron comprises thousands of devices that need to be monitored and controlled and a specialized control system exists to provide the required supervision."***

Associated with these devices are many different types of signals, including items such as beam currents, voltages, temperatures, water flows, laser frequencies, vacuum levels and probe positions. From the perspective of the control system, each device is organized into one of more than 30 functional groups or systems such as the magnet system, the beamline 1A vacuum system and the radio frequency (RF) system. Integrating these systems and acting like a central nervous system is a configuration of computers and control system components called the Central Control System (CCS). The CCS has a variety of duties which fall into two classes: monitoring and control.

"Monitoring" usually involves reading cyclotron device values and using those data in one or more ways. Displaying the values on computer screens is perhaps the most common and visible application of monitoring. Other activities run continuously in the background such as periodically comparing the values being read to predetermined warning and trip levels, and issuing a message to the cyclotron operators or taking appropriate "control" actions if the condition occurs.

"Control" allows the characteristics of a device to be changed, such as turning "on" a power supply or changing its voltage. Controlling devices can take on many forms. A closed loop control is an example of controlling a device where one or more signals are monitored and then a value, such as a voltage level, is automatically changed. An example of closed loop control is where an experimenter wants to keep the proton beam precisely on a target and has the beam position measured and automatically steered by the control system to prevent the beam from wandering off the target.

The CCS must handle other responsibilities beyond monitoring and control. Requests for new functionality come from a wide variety of control system users. Cyclotron operators are the primary users but scientists, engineers, technologists and others also use the CCS and generate requests for new features.

CCS Evolution

The CCS was first configured in the early 1970s, at about the same time as the implementation of the other TRIUMF cyclotron systems.The control system has evolved on a continuous basis from that time to meet the needs of a growing and technologically evolving research facility and to fulfill the requirements of machine protection, reliability and efficiency.

When the CCS was installed in 1973 computers were in their early stages of development and were often seen as unreliable and unnecessary. The staff who were responsible for the CCS felt that a system that included computers would be needed and designed a computer based control system. Although the first computers did not work well and were returned to the supplier, the next manufacturer's attempt did eventually run

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The Cyclotron Central Control System

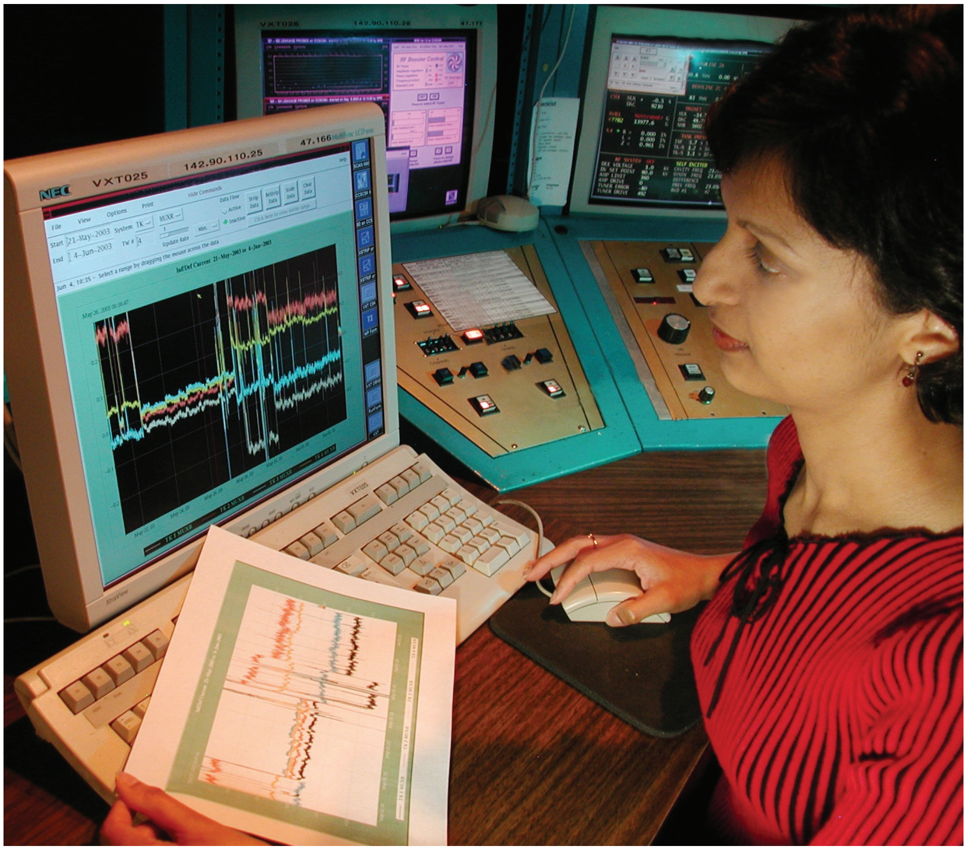
better and those original 16 bit computers and the supervisory system they were connected to became required for cyclotron operation. Although the computers and other components have been updated over the years, the original control system design continues to function well.

Cyclotron operation is a 24 hour-a-day, 7 day-a-week production process. To maintain this ambitious level of operation, the reliability of the production of particle beams must be equivalent to the reliability of a modern industrial complex. In many ways this goal of reliability runs against the intrinsic “unknowns” of pursuing new science and new accelerator technology. It is a significant challenge to maintain reliability as the accelerator technology and science rapidly advance and equipment must be updated. Introducing new equipment can introduce new bugs. As in the other cyclotron systems such as magnets, vacuum and RF, the CCS must deal with these two competing requirements of reliable beam production and new developments.

Operational Issues

But unlike the other systems, the CCS has a primary “diagnostic” duty to aid in detecting, characterizing, and annunciating problems in other systems. In many cases problems can be detected by the CCS before they affect beam production, effectively enhancing the reliability of those systems. The CCS even diagnoses many of the problems that happen to itself. This diagnostic responsibility involves gathering data for analysis, analyzing and reporting problems, taking protective actions, and allowing operators and others to perform experiments on the accelerator as a whole and on the individual sub-systems. To aid in providing these diagnostic and machine protection duties, many sensors and devices have been added. Further aid is provided via the display of parameter values as trends on a graph or as vectors, and as messages when a notable event occurs.

The CCS handles a variety of other functions beyond the simple monitoring and device control. Complex actions can be performed. Whether it is quickly setting dozens of devices to a known state, providing closed loop control, or running numerous devices simultaneously according to a given formula, the CCS has the flexibility to adapt to new requirements.



Data acquisition, analysis and display are important functions of the control system.

The Cyclotron Central Control System

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To provide the day-to-day operational duties and allow new developments in parallel, the CCS has been configured with two clusters of computers, one for production and one for development. These computers are connected to the cyclotron's large system of data acquisition hardware and thus have access to thousands of input and output signals. Connections from the computers to the acquisition systems, disk systems, and network are done in parallel. Typically each computer in each cluster has similar capabilities. If one computer is shutdown other computers can see all of the same equipment because the data acquisition equipment is not directly attached to just one computer. This type of configuration provides redundancy, improved performance, and better fault diagnosis. The architecture also provides a reliable platform for development.

"Providing the required new functionalities is also a high priority and because the 500 MeV cyclotron is a one-of-a-kind, the approach to providing solutions reflects this uniqueness.

The present setup uses the X Window protocol for producing colour graphics and a single computer can run displays on a dozen monitors or more. The topic of colour displays was once seen as a technical issue in the cyclotron's main control room because the control room is within the fringe field of the cyclotron's main magnet. When colour monitors were initially introduced the picture quality was poor. This was the result of the monitor's electrons having their flight path to the screen surface altered by the non-uniform magnetic field. The electrons would be aimed at perhaps a green dot but be deflected to a different colour providing a washed-out appearance. Better quality monitors and proper degaussing techniques have permitted the use of colour monitors but they still have to be degaussed each time the main magnet power goes on or off. The advent of LCD monitors has been a revelation for use in magnet fields such as those found in TRIUMF's cyclotron control room.

The issue of colour monitors is just one example of the many challenges in operating a large control system. A team of TRIUMF staff with training and experience in electronics, computer science, and engineering are responsible for maintaining the existing central control system and meeting new needs as they arise. Because TRIUMF operates around the clock and faults can happen at any time, the duties for the CCS Group members include being on call. Most problems are not so serious that they prevent scheduled beam production but downtime does occur and minimizing it is one of the highest priorities. Providing the required new functionalities is also a high priority and because the 500 MeV cyclotron is a one-of-a-kind, the approach to providing solutions reflects this uniqueness.

Developments

Many of the control system requirements are not solved with commercial off-the-shelf solutions. As a result, software and hardware development are ongoing activities. There is a continuous stream of requests for new features in the CCS and support for new devices in the other systems. Clearly there is no lack of imagination or good ideas driving the requests for new functionality.

Because the CCS has been operational for 30 years and many applications were developed years ago, it is not uncommon to replace an old application with newer technology. An example of this evolution is the software and hardware configuration that handles wirescanners in the ion source injection beam line. Wirescanners are motorized devices that pass a wire through the beam of particles perpendicularly to the beam's longitudinal motion. The position of the wire and the current on the wire are read out, the data is analyzed, and a display is produced. Years ago a system was set up to do wire scans. It has run successfully but there were limitations and some

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A newly designed electronics board is thoroughly tested.

spare parts were no longer available. Recently a new system has been implemented and it meets all of the old requirements and provides several new features.

An interesting aspect to working with the CCS is that you get introduced to many technologies. In assisting other groups you must learn about their systems and requirements. These learning occasions occur at a variety of times but especially when there are new developments and when problems occur. Examples of developments and problems, and the control system's ability to provide assistance, vary widely.

In one case, the top half of the main magnet structure, about two thousand tons of steel and equipment, is periodically jacked up to provide access to the internals of the cyclotron. The lifting system includes 12 jacks that take a large, mechanical load. Over time the jack mechanisms wear and start to bind. It has been found that by using the CCS to read all of the jack motor currents 50 times a second while under load, the locations where the lifting mechanism is binding can be determined. When a jack binds its motor works harder and draws more current. Those jacks that are binding are rebuilt earlier, before serious problems arise.

A recent example of a new development, the weekly testing of parts of the Safety System was made more efficient. Previously, two people equipped with walkie-talkies were needed to conduct tests in various parts of the buildings. Now one person with a handheld Palm Pilot-like PDA and the appropriate software and hardware infrastructure can do the job. That person can view the safety system signals via the CCS on their PDA screen as they perform the tests and do the job in less time than it previously took two people.

When looking at the future for TRIUMF we can see a variety of new developments and with them the accompanying challenges for the control systems. The cyclotron beam intensity will be increased twofold, a new ion source for the cyclotron is being discussed and a new primary proton beam line is being considered. With the recent completion of the ISAC II building and the ongoing science programs in other parts of TRIUMF, it is clear that the facilities exist here for exciting research in the future. For the Central Control System, its evolution will continue as long as new science is to be pursued.

Mikael Mouat is the Controls Group Leader, Cyclotron Division at TRIUMF.

The EPICS Based Control System for ISAC

Rolf Keitel

A New Control System - Why?

The ISAC Radioactive Beam Facility, although fed by the TRIUMF proton beam, is only very loosely coupled to the TRIUMF cyclotron. The TRIUMF beam hits a hot target, short-lived radioisotopes emerge from it, and ISAC accelerates and guides these radioisotopes as beams to experiments. Control of the cyclotron proton beam is independent of the control of the ISAC radioactive beam; even the vacuum spaces for the proton beam lines and the ISAC machine are separated by a thin metal window. This loose coupling made it possible to start the design of the ISAC control system with a clean slate.

In a modern particle accelerator, the control system is the "hands, eyes and ears" of the machine operators, who work with accelerator devices at a

ISAC operations control console.

distance from the control room and 24 hours a day. There are many devices, approximately 3000 in the case of ISAC-I, and that number will probably double once the second phase of ISAC is complete. The control system "unclutters" the vast amount of machine information and presents it to the operator tailored for the task at hand. It supports complex operations, which involve measuring and adjusting hundreds of devices at a time, such as switching between different beam types and performing automatic measurement sequences at the press of a button. In contrast to control systems for industrial plants, the ISAC control system must be flexible enough to accommodate the constantly evolving nature of the experimental facility.

Two decisions had a major influence on the control system design. First, all machine and device protection functions of the ISAC accelerator were to be handled by the control software. This led to the need for a flexible implementation of a complex set of interlocks and their visualization for the operators. Second, many ISAC devices have no local control capability. The control system must therefore be able to present complete detailed information on every device for diagnostic and maintenance purposes. This also requires the control system to be operational during maintenance and shutdown periods.

Outside the scope of the ISAC control system is personnel protection against radiation and high voltage hazards, which are looked after by independent systems.

Software Decisions

At the time when the conceptual design for the ISAC control system started, we learned about the EPICS system. The acronym stands for **E**xperimental **P**hysics and **I**ndustrial **C**ontrol **S**ystem and covers several different aspects:

- *A control system architecture, which is described later in this article;*
- *A control system software toolkit, which provides an extensible, scalable infrastructure and framework for building a control system together with a set of generic tool applications;*

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The EPICS Based Control System for ISAC

- *A collaboration of controls groups in more than 100 laboratories all over the world, who use and co-develop EPICS, with the core development work centred at the Los Alamos and Argonne National Laboratories in the US. This group stays in touch by using the e-mail list server at Argonne and with regular collaboration meetings.*

In 1996, after a short, intensive evaluation of EPICS, we developed a small prototype of the ISAC control system for an Ion Source Test Facility. This validated the concept and the green light for using EPICS for the ISAC control system was given.

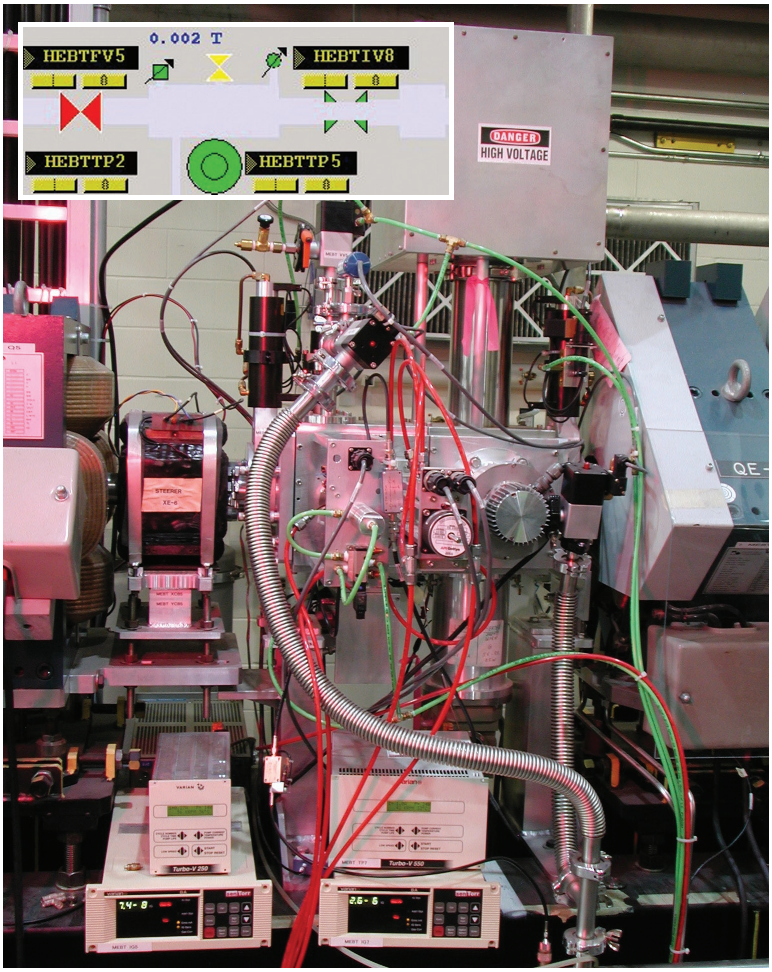
Hardware Decisions

ISAC accelerator devices fall into four groups with slightly different control requirements: vacuum, beam optics, beam diagnostics, and RF devices.

The vacuum systems operate all the time and use many interlocks. We selected a commercially available Programmable Logic Controller (PLC) system for the control of the vacuum devices, and also for the heavily interlocked ion sources. PLCs are widely used in industrial controls, B.C. pulp mills being a good example. These systems are robust and reliable, and the program logic is easily visualized. They are on-line programmable, i.e., the software can be modified without shutting down the system. PLC systems come, however, with a fairly high price tag and some limitations, which precludes their use for the whole accelerator control system.

Beam optics devices guide or accelerate the beams using electric and magnetic fields. From the controls point of view, they consist of one or more power supplies, each of which is controlled by a dedicated small microprocessor card located at the supply. Up to 100 controllers are connected on a CAN-bus loop. CAN is a highly reliable field bus, which was developed by the automotive industry to simplify the wiring and reduce associated costs in modern cars. We reaped the same benefits in our control system and achieved a very economical solution for the beam optics system with this distributed system of TRIUMF designed controller cards.

Beam diagnostic devices measure the total current or profiles of the beam in space or time. We chose to control these devices with VME modules located with the front-end computers. VME, Versa Module Eurocard, is an international electronic instrumentation standard, in which both mechanical and electrical aspects are specified. We started buying commercially available modules, but switched to designing our own at TRIUMF for better features and economy.



"Real world" view and control system display of some ISAC equipment.

The EPICS Based Control System for ISAC

Rolf Keitel

Finally there are the RF devices, which drive the accelerating structures of the RFQ and the Linac (see Financial Reports 1999/2000 and 2000/2001) and need closed-loop feedback at speeds which can only be realized in dedicated hardware. These systems are in the realm of the RF group and beyond the scope of this article. The ISAC control system provides the supervisory control of these systems.

Software Implementation

Software for the ISAC control system is spread over 35 computers connected via the ISAC controls Ethernet. (This does not count the more than 600 microprocessors in the CAN controllers). The majority of the computers run EPICS software and belong to one of two categories:

- *Front end computers, in EPICS lingo called Input-Output-Controllers (IOC), which have hardware connections to devices. Each IOC "owns" the devices it controls;*
- *Application servers and console workstations, which provide services to operators and experimenters.*

The EPICS toolkit software provides a powerful infrastructure for communications between all EPICS computers, the "Channel Access" protocol. Each IOC serves its information via Channel Access based on Channel, i.e. process variable, names. For constructing the IOC software, which determines the details of device control and readout, EPICS uses a framework which is built around the extremely powerful concept of function blocks, often called EPICS "records". Tools exist to configure these records to achieve the desired software functionality. This system is extensible: we can easily add new record types. It is also well-layered so that existing record types can be easily adapted to new hardware.

In addition, EPICS provides tools for interactive building of operator screens, for alarm handling, for high volume data archiving, for activity logging, and for interactive access to all process variables.

By using the EPICS control system model and infrastructure, we could concentrate on working on ISAC-specific problems. Compared to conventional control system development, there is a marked shift of effort from programming to tool-based configuration. This is very similar to commercial control system software packages used in industry, but EPICS has more built-in flexibility for the quirks of the accelerator and experimental physics requirements - and it is free!

We supplemented the EPICS system with tools to alleviate repetitive interactive configuration tasks, making use of a relational database, which contains all control-related ISAC device data. As part of the control system quality assurance, software tools also verify the implementation and the display of interlocks against specifications.

What comes next?

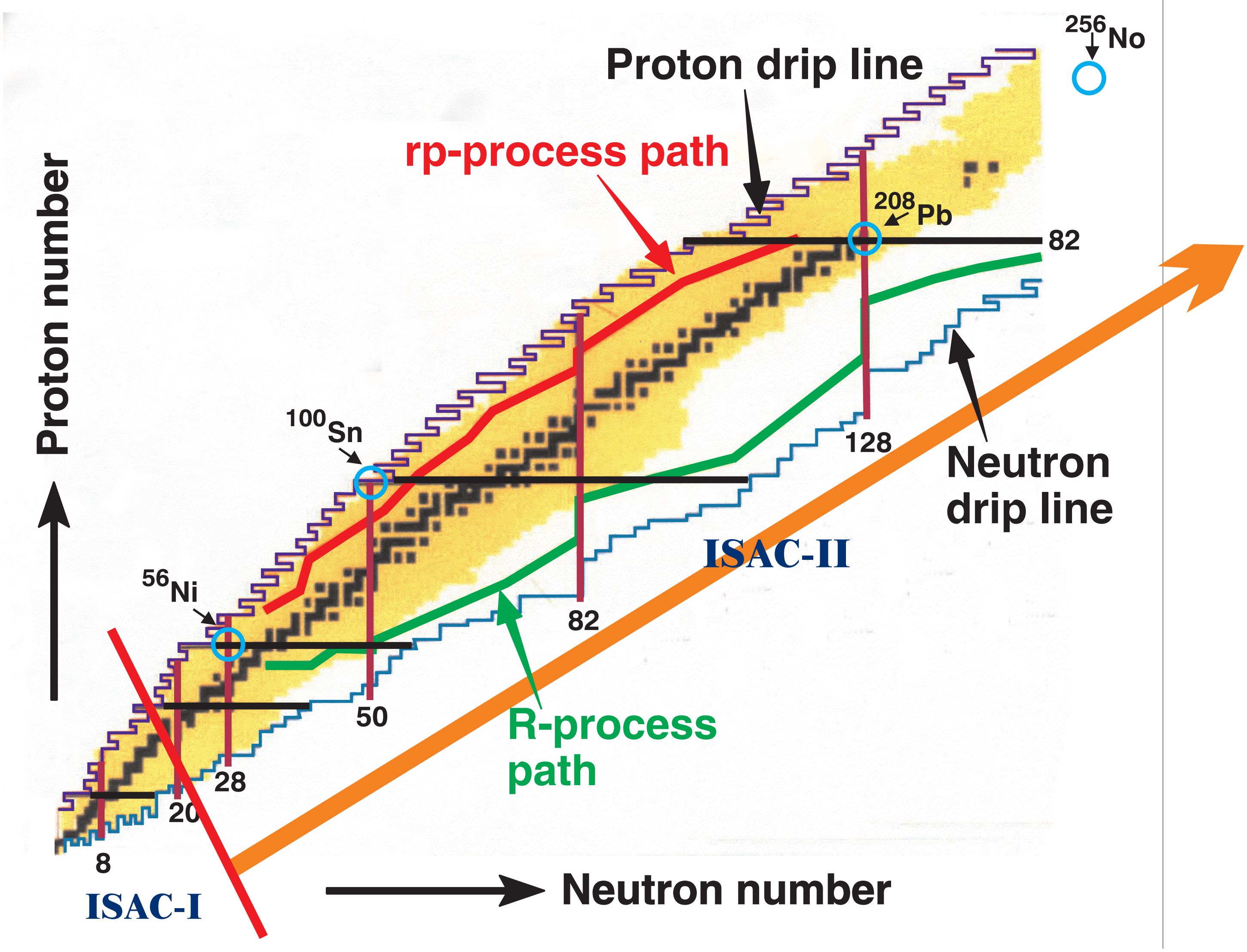
Now that ISAC phase one is complete and fully operational, it is clear that using EPICS for the ISAC control system was an excellent choice. In fact, it would have been impossible to provide the required functionality with the existing manpower in any other way given the tight schedules.

For controlling ISAC-II, the road-map is clear as the EPICS architecture is inherently extensible. We will do "more of the same", with a look at staying current with modern equipment. The well-layered EPICS software architecture allows this creeping modernization, which, in the long run, will allow economical upgrades of the control system in small sections.

Rolf Keitel is Group Leader of Electronics Development and ISAC Controls at TRIUMF.

Carl Svensson

The TRIUMF Isotope Separator and Accelerator (ISAC) produces radioactive ion beams of unprecedented intensities by the on-line isotope separation technique. The high-quality beams of separated isotopes can be delivered directly to a variety of experimental facilities, or can be accelerated to energies typical of explosive astrophysical events. These unique beams currently support a diverse program of research spanning the fields of nuclear astrophysics, nuclear structure, fundamental interactions, and condensed matter physics, much of which cannot be carried out anywhere else in the world. ISAC-II represents a major upgrade to the ISAC facility that will extend the range of radioactive nuclei that can be accelerated from mass number A = 30 to A = 150, and the maximum energy of the accelerated beams from the present 1.5 MeV/A to 6.5 MeV/A for the



The reaction paths of heavy elements synthesis. The dark squares indicate the position of stable nuclei, the yellow the known unstable nuclei and the drip lines enclose the region beyond which it is thought that no nuclei can exist. The vertical (horizontal) lines indicate the neutron (proton) shell gaps called magic numbers. The ISAC-II facility provides the opportunity to extend studies of exotic nuclei far from the valley of stability.

ISAC-II

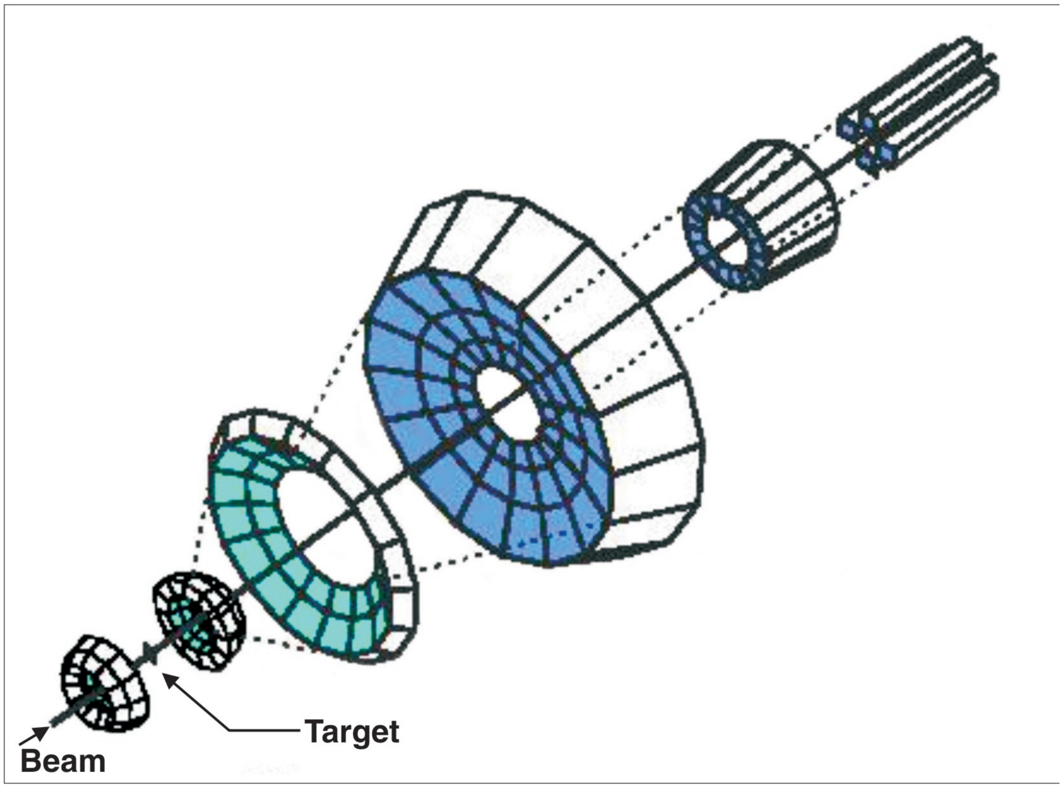
Carl Svensson

entire mass range, and as high as 15MeV/A for light nuclei. The greatly expanded range of isotopes and energies available at ISAC-II will create vast new opportunities for experimental nuclear astrophysics, nuclear structure, and nuclear reactions research at TRIUMF.

"The greatly expanded range of isotopes and energies available at ISAC-II will create vast new opportunities for experimental nuclear astrophysics, nuclear structure, and nuclear reactions research at TRIUMF."

Nuclear astrophysics experiments aimed at understanding the origins of the heavy elements and the associated timescales and energy release in explosive astrophysical events were a major motivator for the construction of the ISAC facility at TRIUMF. Radiative capture cross section measurements and nuclear structure studies with the DRAGON and TUDA facilities at ISAC-I have, for example, already made major contributions to our understanding of the break-out from the carbon-nitrogen-oxygen (CNO) nuclear reaction cycles in novae and X-ray bursts (see 2000-2001 report in this series). This breakout leads into the rp-process, a long sequence of proton captures and beta decays among proton-rich nuclei that are the key source of energy in the explosive X-ray bursts that follow the accretion of hydrogen-rich material onto the surface of a neutron star. The rp-process quickly synthesizes nuclei up to ^{56}Ni (Nickel 56), but its progress beyond this region, perhaps as far as nuclei of mass near ^{100}Sn (Tin 100), is an important topic of current research. With the range of accelerated isotopes expanded from A = 30 up to A= 150 by the ISAC-II upgrade, the opportunity will be presented to extend studies from the break-out region to the entire rp-process pathway.

The higher beam energies available at ISAC-II will also open the door to a broad range of experimental techniques such as Coulomb excitation, fusion-evaporation reactions, and direct proton (d,nγ) transfer reactions that will complement the radiative proton capture experiments at astrophysical energies. As one example, planned studies of ^{58}Zn (Zinc 58) in Coulomb excitation and fusion-evaporation experiments at ISAC-II will provide crucial nuclear structure input to determine the radiative proton capture rate for Copper 57 (^{57}Cu(p,γ)^{58}Zn), a key step in allowing the rp-process to proceed beyond the ^{56}Ni region.



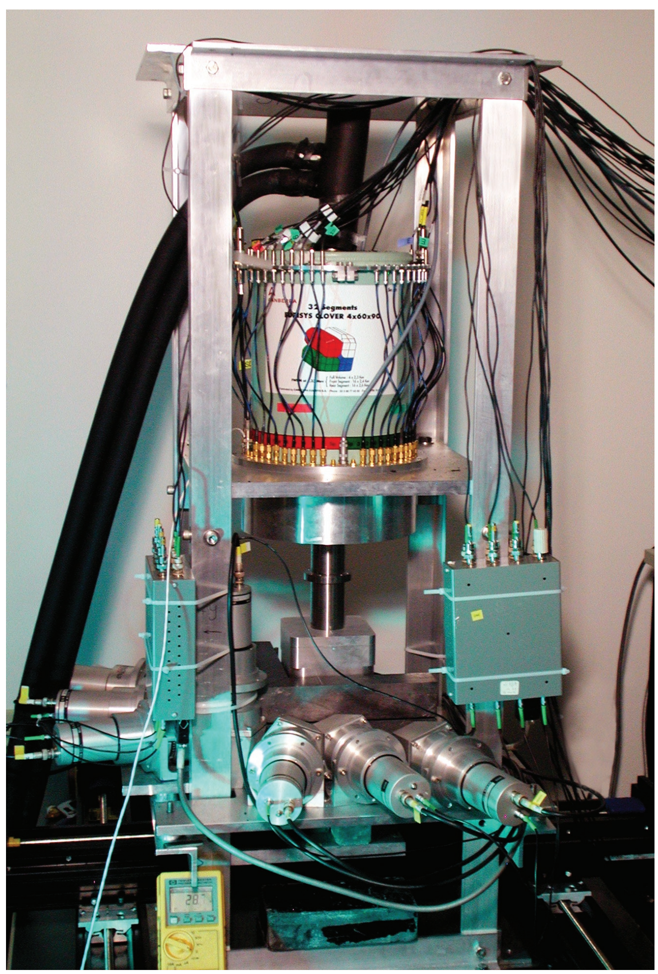
A sketch of the heracles detector array now being set up at TRIUMF by the Laval
University group. It is designed to identify and measure nuclear fragments

Carl Svensson

On the other side of stability, the rapid-neutron capture process (r-process) is believed to be responsible for the synthesis of about half the elements heavier than iron. Starting from a light nucleus, the rapid capture of neutrons leads to heavier isotopes until the capture rate is balanced by photodisintegration. Beta decay must then occur before neutron capture can resume. The stellar environment associated with the r-process and its detailed pathway are, however, still uncertain. Indeed, a whole variety of scenarios may apply and nuclear reactions through excited states may be of great importance. While direct study of much of the expected r-process region lies beyond the reach of current and planned radioactive beam facilities, many important questions associated with nuclear behaviour far from stability have direct bearing on the predictive power of r-process calculations. For example, changes in nuclear shell structure are crucial for determining the r-process path. In the absence of direct radiative capture measurements on the r-process nuclei, it is essential to gain as much knowledge as possible of nuclear structure in neutron-rich nuclei. Studies of neutron-rich nuclei by Coulomb excitation and direct neutron (d,pγ) transfer reactions will thus form a major component of the ISAC-II nuclear astrophysics program.

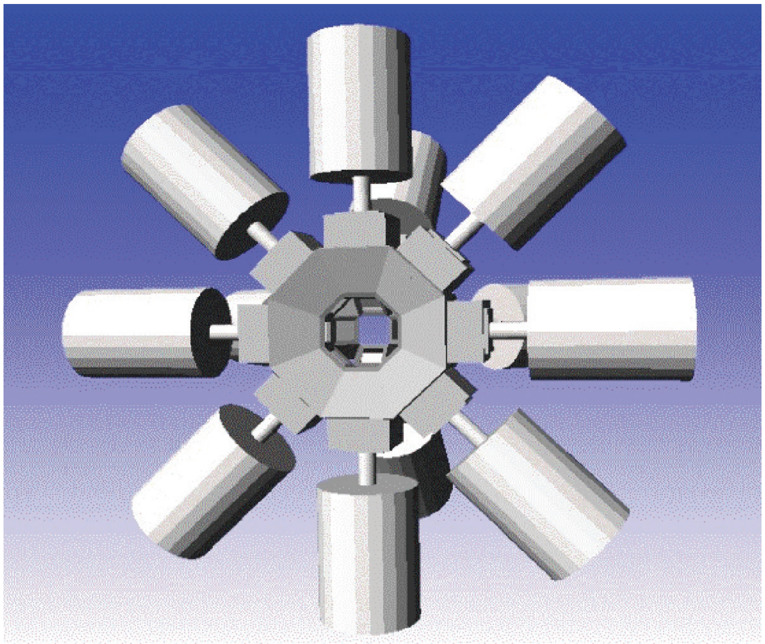
> ***"The wealth of far-from-stability nuclear structure information to be uncovered at ISAC-II will have direct impact on the theoretical models required to calculate nucleosynthesis pathways in astrophysical environments."***

The above examples illustrate the close connection between the nuclear astrophysics and nuclear structure programs at ISAC-II. The wealth of far-from-stablity nuclear structure information to be uncovered at ISAC-II will have direct impact on the theoretical models required to calculate nucleosynthesis pathways in astrophysical environments. Research into nuclear shell structure is a particularly elegant example of this synergy. Far from the valley of nuclear stability, valence nucleons become weakly bound, implying extended wave functions and density profiles that will modify the shell gaps, changing their size, the magic numbers, and potentially even eliminating significant shell gaps altogether. Understanding this evolution of shell structure is of fundamental nuclear structure importance. At the same time, it is also of major importance in nuclear astrophysics as it is these shell gaps that, to a large extent, determine the pathways, endpoints, and final abundances in explosive nucleosynthesis. Whether it is investigating the existence of predicted new shell closures in



TIGRESS 32-fold segmented HPGe prototype detector on the test stand at TRIUMF.

Carl Svensson



The full 12-detector TIGRESS array for ISAC-II in close-packed configuration.

neutron-rich nuclei such as ^{54}Ca, (Calcium 54) studying neutron-proton correlations around the doubly-magic N=Z (neutrons = protons) nuclei ^{56}Ni and ^{100}Sn, probing the exotic high-K isomers predicted to result from shell structure in the neutron-rich nuclei in the mass 180 region, or investigating the deformed shell structure responsible for the stability of "super-heavy" elements like ^{256}No (Nobelium 256), studies of nuclear shell structure will form a central theme in the ISAC-II nuclear structure and nuclear astrophysics programs.

The ambitious science program at ISAC-II will, of course, require the development of a number of state-of-the art spectrometers in addition to ion source and accelerator facility developments. The past year has witnessed tremendous progress on the ISAC-II instrumentation front. The Laval group, for example, have moved the HERACLES CsI(Tl) multi-detector array to TRIUMF and is reconfiguring it for reaction mechanism studies with the highest energy (15MeV/A) radioactive beams from ISAC-II. A next-generation recoil spectrometer is a high-priority experimental facility for ISAC-II, and a workshop held at TRIUMF in July, 2002 to begin the conceptual design phase for this spectrometer drew more than 35 interested scientists from Canada and abroad. The TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) is a state-of-the-art gamma-ray spectrometer for ISAC-II. TIGRESS will be based on a new 32-fold segmented HPGe clover detector design. A prototype of the TIGRESS detector was received at TRIUMF in December, 2002, and subsequent testing has confirmed that it meets or exceeds all TIGRESS design specifications. The TIGRESS collaboration, which includes scientists from TRIUMF and six Canadian Universities (Guelph, Laval, McMaster, Montreal, Simon Fraser, and Toronto), received an $8.06M equipment grant from the Natural Sciences and Engineering Research Council in the 2003 competition to construct the 12-detector TIGRESS array at ISAC-II over the next six years. An early implementation of TIGRESS, comprised of four of the new HPGe detectors, will be ready to accept the first accelerated beams from the new superconducting linear accelerator in 2005, ensuring that the Canadian community can immediately reap the scientific benefits of the world-leading investments in the ISAC-II facility.

"TIGRESS will be ready to accept the first accelerated beams from the new superconducting linear accelerator in 2005, ensuring that the Canadian community can immediately reap the benefits of the world leading investments in the ISAC-II facility."

Carl Svensson is Assistant Professor of Physics at the University of Guelph.

ISAC-II

"ISAC-I and now ISAC-II, when it comes on line in 2005, are and will be for the remainder of this decade the premier facilities worldwide for the production and subsequent acceleration of exotic beams using the Isotope Separator On-Line (ISOL) technique. The intensities available from the facility exceed those available elsewhere by one to two orders of magnitude".

Natural Sciences and Engineering Research Council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ON THE 11TH DAY OF JUNE 2003
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