RADIOACTIVE BEAMS

A world-class Canadian facility offers exciting new tools for research.

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ISAC at TRIUMF

There is a world-class facility in Vancouver, BC, that is doing state-of-the-art research in the area of nuclear science. The research uses a probe previously unavailable, namely, accelerated radioactive beams. While most of the research in progress may appear to be in the domain of physics, there is a rich overlap between disciplines with chemists contributing a major part. The roles of the federal and provincial governments are also important in the success of the TRIUMF-ISAC facility, which can be used as a model of how such major science facilities can be organized.

Radioactive beams

Approximately 115 elements are known. While some are radioactive only, most have a range of stable and unstable (radioactive) isotopes. For about 50 years, nuclear scientists had only stable isotopes available as projectiles for acceleration to the high velocities required for probing the nature of the nucleus and its many dynamic interactions. A great deal has been learned, but many important questions remain. Can we predict the limits of nuclear stability? What are the heaviest nuclei possible? What constitutes a stable nucleus, especially at the extreme limits of stability? Within the past decade, we have learned how to produce energetic beams of most isotopes, stable or radioactive. These advances have opened up new avenues of research as the ratio of protons to neutrons can be varied and studied in a controlled fashion. A great deal is being learned as these new techniques are improved.

Radioactive beams are usually produced by one of two different methods—the isotope separation on-line (ISOL) method and the projectile fragmentation approach. In the ISOL approach, energetic protons, neutrons, heavy ions, or even electrons can be used to produce radioactive species. Following extraction from the target and then ionization in an ion source, the radioactive species as an ion beam is mass analyzed and either stopped (for studies of its properties) or accelerated using an appropriate accelerator. In the fragmentation approach, a very energetic heavy-ion beam is allowed to pass through a thin foil in which the beam fragments into a number of species, many of which are radioactive. Electromagnetic devices are then used to select a desired fragment, which is usually the radioactive species of interest. This species, which moves essentially as fast as the particles in the original beam, is used in various ways. At the Isotope Separation and ACcelerator (ISAC) facility in Vancouver, the ISOL method is used, and we will focus on this.

Using a variety of different targets and ion sources (e.g. heated surface ionization for alkali elements, electron cyclotron resonance ionization for volatile elements, laser ionization for metals), a wide range of radioisotopic beams can be and have been produced. Based upon years of experience in Canada and elsewhere, beams from about 80 elements and their associated isotopes can be extracted (refer to the Web sites listed at the end of this article for specific elements).

Radioactive beam facilities worldwide

Over the last 15 years, there has been a gradual transition from accelerators of stable heavy ions to radioactive beam facilities. At present, there are four major fragmentation facilities in the world—the NSCL at Michigan State University in the U.S.; GSI in Germany; the GANIL in France; and RIKEN in Japan.

In addition to the TRIUMF-ISAC facility in Canada, radioactive beam facilities based upon the ISOL approach exist at HRIBF in Oak Ridge, TN, in the U.S., ISOLDE at CERN in Switzerland, SPIRAL at the GANIL in France, and at Louvain-la-Neuve in Belgium. There are other facilities based upon different production approaches at Texas A&M University, ATLAS at the Argonne National Laboratory in the U.S., Jyväskylä in Finland, the Tokai facility in Japan, and Catania in Italy. The next generation radioactive beam facilities are being planned in the U.S. with the RIA project and in Europe with the EURISOL project. At present, ISAC has the highest radioactive beam intensities in the world due to the high intensity of energetic protons, which are used in beam production.

The TRIUMF-ISAC facility

TRIUMF is Canada's National Laboratory for Particle and Nuclear Physics. It was built in the early 1970s and was operated by collaboration between four universities—The University of British Columbia, Simon Fraser University, the University of Victoria, and the University of Alberta. The full membership collaboration has grown over the years to include the University of Toronto and Carleton University and there are now seven associate member

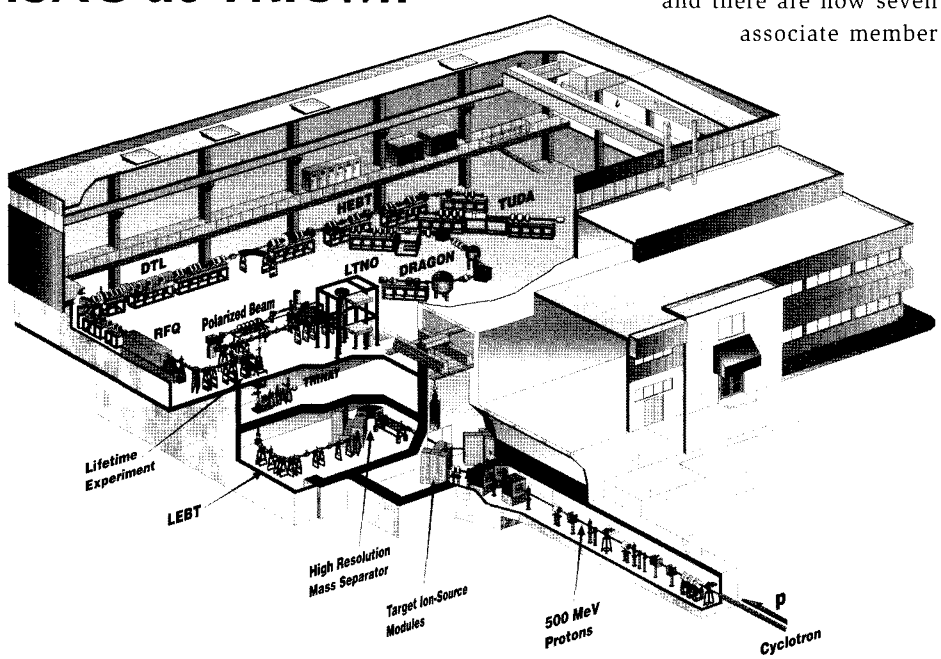

Figure 1. Illustration of the ISAC-I facility at TRIUMF. The 500 MeV protons from the cyclotron strike a thick target producing the radioisotopes. Extraction with the ion source and mass analysis through the separator allow radioisotopic beams to be delivered to any of the experimental facilities. The RFQ and DTL accelerators allow beams to be accelerated up to 1.8 MeV/u.

universities. For many years, the main science at TRIUMF was intermediate-energy physics along with condensed matter physics using muons but, in the last ten years, the ISAC Radioactive Beam facility was constructed and now the focus of the science is more directed onto low-energy subatomic physics along with studies of material science. In addition, there is strong interest in high-energy physics and further, TRIUMF houses one part of the MDS Nordion organization, the largest producer of radiopharmaceutical isotopes in the world. Related to these is the extensive program in the life sciences for which radiotracers are produced and utilized in a wide range of disciplines including botany, chemical engineering, earth sciences, medicine, and chemistry.

Radioactive beams are produced at ISAC by target fragmentation using the intense beam of energetic (up to 520 MeV) protons from the largest cyclotron in the world. As many as five beams of such protons can be extracted from the cyclotron simultaneously and can be used in different experimental systems. The proton beam for ISAC then intercepts a thick (approximately 19 cm in length) target leading to the production of the isotope of interest followed by on-line extraction, mass separation, and acceleration. The diffusion of an isotope/element in a thick target matrix, typically heated up to 2200°C is basically high-temperature chemistry, and the successful development of a good target can take years of testing. ISAC-I was built to perform studies in elemental synthesis by measuring nuclear astrophysical cross sections and rates, nuclear structure, fundamental symmetries, and material science. An upgrade to ISAC-II to give higher accelerated radioactive beam energies to get above the coulomb barrier for reactions is in progress and will be ready in 2006 for the first experiments.

Experimental program

There is an extensive research program at ISAC that ranges from measuring the distribution of protons within the very neutron-rich Li nucleus, magneto-optical trapping to allow the study of the helicity of neutrino emission in β decay in a search for the new physics grail, surveying and analyzing the very weird shapes the nucleus can take, and exploring possible approaches to produce new superheavy elements using radioactive beams. However, for brevity, two studies will be used to illustrate the unique, world-class research in progress.

The first involves using a low-velocity, polarized beam of ^{8}Li ions to examine the properties of thin films and interfaces. Andrew MacFarlane and Rob Kiefl from The University of British Columbia, Kim Chow from the University of Alberta, and their collaborators have recently shown it is possible to perform β-detected NMR on a nanometre-length scale by adjusting the energy of implantation of the polarized beam. The method was first demonstrated with a thin (19 nm) Ag film deposited on a $SrTiO_3$ substrate.[1,2] These studies revealed two sharp resonances attributed to Li at the interstitial and substitutional sites in the ultra thin Ag film. Since Ag is relatively inert, one can use this technique to measure magnetic field distributions with a resolution of roughly 0.5 G near any surface or interface. In essence the polarized Li acts like a local magnetometer, which can be used to characterize the local magnetic field at the depth of implantation. This has many possible applications, e.g. studies of the vortex lattice near the surface of a superconductor or the magnetic properties of a monolayer of magnetic molecules. Depth-resolved β-NMR is an extension of a very successful program at TRIUMF using muons to probe the magnetic properties of bulk materials. The spectrometer coupled with the polarized ^{8}Li beam is unmatched in the world.

The second study is in the area of elemental synthesis in the universe. While a good deal is now known on the production of elements in stellar factories, it is clear that elemental production also occurs in explosive scenario such as novae, X-ray bursts, and supernovae. The problem has been that it was impossible to measure the rates when one of the reactants was short lived, e.g. a half-life of seconds. Such studies can now be done when the short-lived reactant is accelerated onto a gas target. ISAC is one of the few places in the world where such studies can be done and uses the unique DRAGON facility.[3] While full details can be found elsewhere,[4,5] a beam of ^{21}Na ions with energy

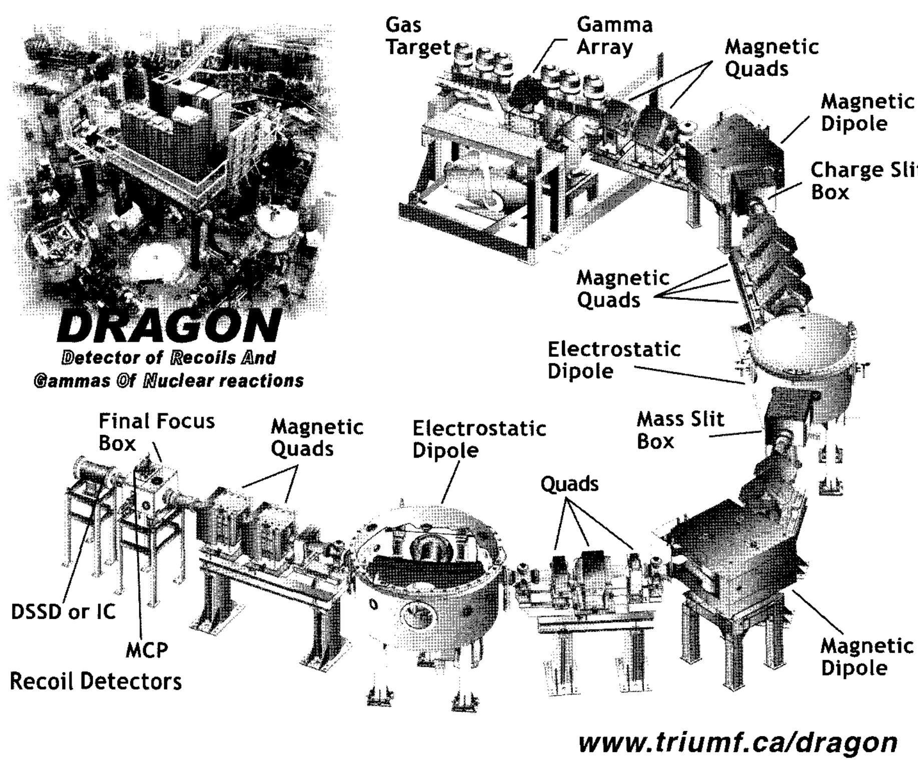

Figure 2. Illustration of the main components of the DRAGON recoil mass spectrometer; the inset shows a photo of the actual device. The unique DRAGON facility allows the measurement of reaction strengths important to understanding elemental synthesis in the universe. DRAGON filters out the interesting product nuclei from these weak reactions with suppression factors of 10^9 to 10^{13} possible, depending on the detector configuration and the specific reaction under study.

matching that of inside an exploding star was directed onto a H_2 gas target, the resultant recoiling ^{22}Mg products are separated from the beam ions and detected at the end of DRAGON in conjunction with emitted γ rays. The rate of the $^{21}Na(p,\gamma)\ ^{22}Mg$ reaction was measured and it is now understood why the accompanying isotope ^{22}Na, produced in such explosions, has not yet been observed as predicted with orbiting γ-ray telescopes.

The role of government and the universities

For such a facility as ISAC, support from both the provincial and federal governments is essential. All of the buildings at TRIUMF were constructed with funds from the Government of British Columbia and the federal Government of Canada through the National Research Council Canada-supplied operational funds. Funds for all experimental programs are supplied through peer-reviewed agencies such as the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canadian Foundation for Innovation (CFI), and the Canadian Institutes of Health Research (CIHR). The unique aspect of TRIUMF has been the role of the universities, who have successfully managed (financially and safely) the laboratory together since its initial funding in 1968. At present, TRIUMF is on a five-year funding cycle, which allows for proper planning and the building of the complex facilities needed at a world-class laboratory. A thorough review of the laboratory is performed several times a year by a federally appointed committee, Advisory Committee On TRIUMF (ACOT), and a detailed evaluation is performed prior to funding every five years. Only experiments approved by a committee of international scientists are allowed to be pursued at TRIUMF.

Conclusion

There exists in Vancouver a world-class experimental facility performing state-of-the-art studies in subatomic and condensed matter science using radioactive beams. The ISAC facility is open to any good experiment and the role of the government has been basically a hands-off approach to the micromanaging of the facility with careful, periodic reviews of the facility's status. It is useful to point out that research at TRIUMF underwent a major revision from intermediate-energy science using energetic protons to low-energy science using accelerated radioactive beams, successfully. Simultaneously, TRIUMF has maintained a strong connection to high-energy physics by providing the infrastructure for required experimental apparatus used in laboratories around the world. The TRIUMF site is also the location of a MDS Nordion facility, the largest producer of radiopharmaceutical isotopes in the world, and a successful example of technology transfer. TRIUMF is a useful model for big science projects being considered for development in Canada.

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For further information visit:

TRIUMF
www.triumf.info

Simon Fraser University
www.sfu.ca/triumf/

Radioactive Beam Availability
www.triumf.ca/people/marik/Yields.html
http://isolde.web.cern.ch/ISOLDE/

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