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Radioactive beams

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The interpretation of many astrophysical phenomena relies on an in depth understanding of different areas of physics. Nuclear physics has a particularly influential role in determining the energy and matter evolution at stellar sites. As more extensive observational data is gathered from earth and space observatories, an ever-greater demand is placed on our knowledge of the basic physical processes that underpin astrophysical phenomena. Reactions involving unstable nuclei are at the basis of our understanding of energy production and isotope evolution associated with explosive stellar events. These reactions can be studied with radioactive beams produced at ISOL facilities.

1. RADIOACTIVE BEAMS IN THE ASTROPHYSICAL SETTING

The interpretation of a particular astrophysical event generally emerges from a series of distinct activities. Following observation a physical model may be developed to aid the interpretation of the observation. Construction of such models invariably involves a series of assumptions and physics inputs from a variety of physics areas. Nuclear physics and atomic physics inputs are needed to describe the microscopic nuclear and atomic physics processes, but the understanding of macroscopic fluid flow, sometimes under the most extreme physical conditions, is also needed.

The nuclear physics inputs needed for such modeling problems may either come directly from laboratory-based experiments or from theoretical modeling of the nuclear problem. This paper will mostly deal with some of the challenges nuclear physicists face in providing the information needed to address different astrophysical situations. For example, the isotopic distribution of matter, the energy and matter evolution of main sequence stars, the physical processes behind novae, supernovae, and x-ray bursters, and the structure of neutron stars, all require for their interpretation detailed knowledge of nuclear processes.

Main sequence stars have lifetimes of several millions to several billions of years depending on their mass. The energy emitted from stars during their lifetime mainly originates from nuclear reactions within the stellar interior. These reactions mostly involve stable nuclei. For example, reactions such as $^{14}N + p \rightarrow {}^{15}O + \gamma$, $3\alpha \rightarrow {}^{12}C + \gamma$, $^{12}C + {}^{12}C \rightarrow {}^{24}Mg + \gamma$, $\alpha + {}^{12}C \rightarrow {}^{16}O + \gamma$, etc are all important but involve reactions between stable nuclei.[1)]

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Heavy stars come to the end of their life when material in the core of the star can no longer generate nuclear energy. This occurs when the core material that was initially hydrogen and helium is transformed to iron. At this critical point nuclear fusion reactions can no longer provide the energy needed to resist gravitational collapse. The rapid collapse of the core to nuclear densities, and the resulting rebound sends a massive shock wave through the star that results in a supernova explosion. The details of this explosive process are still not fully understood, but it is generally agreed that the explosive outburst is associated with nuclear processing involving a wide range of isotopes; in fact, the majority of these reacting isotopes are unstable.

It is interesting to note that the majority of stars are closely linked to other stars either as binary stars or higher cluster systems. Binary stars provide a fascinating spectrum of different stellar environments dependent on the masses of the stellar partners, their evolutionary state, and the separation between the partners. Phenomena such as dwarf nova, nova, x-ray bursters, supernova of Type 1a, and even some gamma-ray bursters have a natural explanation as being associated with a particular type of stellar binary system. So, for example, a nova explosion is thought to be associated with a binary system comprising of a white dwarf star and a main sequence star evolving towards the end of its life. As the main sequence star expands, material can pass over to the orbiting white dwarf forming a compressed layer of material on its surface. As the density and temperature of this layer increases, a point will be reached where a nuclear runaway situation can occur where the transferred hydrogen and helium explosively reacts with the heavier nuclei in the accumulated layers. Due to the explosive nature of this process, unstable nuclei as well as stable nuclei are involved. Another similar situation occurs with a binary system comprising a neutron star and evolving main sequence star. For this situation the explosive runaway leads to an intense burst of γ-rays – so called γ-ray bursters. Here the rapid nuclear processing occurs at a higher temperature and density than for a nova explosion, so the hydrogen and helium material transferred from the main sequence star can be explosively converted to nuclei up to, and maybe even beyond, mass 100.

From the above, in summary, stellar evolution is strongly associated with nuclear processing of isotopes. Reactions involving stable nuclei drive the evolutionary stages of main sequence stars, while reactions with unstable nuclei dominate the outcome of explosive events. For an understanding of stellar evolution in general, both types of reactions need to be studied in the laboratory. For reactions involving stable isotopes, in principle it is reasonably straightforward to study these reactions in the laboratory. However, the problem is the need to study the reactions at low energies corresponding to the interior temperatures of main sequence stars; this can present the experimenter with extreme challenges due to the low experimental yields associated with very low cross sections. For reactions involving unstable nuclei, due to much higher stellar temperatures, the cross sections needing to be measured are significantly higher, but the real challenge here is to produce in the laboratory the radioactive ions on which to measure the cross sections.

There are two basic methods to produce such radioactive beams – in-flight fragmentation of high energy heavy ion projectiles and the ISOL method. For the in-flight method, projectiles at several hundred MeV per nucleon are fragmented by target nuclei. The high energy fragments are then separated into isotope mass and charge by a magnetic spectrometer. For the ISOL method, a charged particle beam is stopped inside a thick target. Nuclear reactions induced by the slowing down of the beam produce a variety of unstable isotopes. With the target being at high temperature, these isotopes diffuse out of the target, where they are ionized, accelerated, and then mass analyzed to separate out the isotopes of interest. The ISOL method is better suited to measure stellar nuclear reaction rates since the corresponding radioactive beams are generally more intense than for the fragmentation method for isotopes not too far removed from stability, and good beam quality can be achieved at the energies corresponding to stellar temperatures.

2. THE ISOL METHOD FOR RIB PRODUCTION

There are various facilities around the world producing accelerated radioactive beams. To illustrate progress in this field, reference will be made to the first pioneering facility and then to one of the most high-powered ISOL facilities currently working.

The cyclotron facility at Louvain-la-Neuve, Belgium (http://www.cyc.ucl.ac.be/RIB.html) is a University facility and has been successfully producing accelerated radioactive ion beams for a variety of isotopes for about 15 years. These beams mainly have been used to address nuclear astrophysics problems. The driver accelerator that produces the radioactive isotopes is a K = 30 cyclotron which delivers intense beams of protons up to 200 μA. Post-acceleration of specific radioactive ions either uses a K = 110 cyclotron, or a newly designed K = 44 cyclotron specially optimized for the high acceleration efficiency that is so important for radioactive beams. Recently this accelerator has delivered a beam of ^{19}Ne of intensity 5 x 10^9 particles/sec in an energy range of 7.5 to 9.5 MeV/u.

The TRIUMF laboratory facilities are based on a suite of five cyclotrons. These cyclotrons are used to service a range of activities ranging from pure particle and nuclear physics research to medical applications. The ISAC facility uses one of the proton beams from the main 500 MeV cyclotron. This cyclotron accelerates H^- ions and simultaneously can provide several beams of different intensities and energies to a variety of target stations. The ISAC facility is based on the ISOL method and uses a beam of up to 100 micro-amps, 500 MeV protons from this cyclotron. The beam is transported into a purpose-built target area where it is directed onto specially constructed targets. The resulting spallation reaction produces a variety of radioactive isotopes. The trick then is to extract these isotopes from the target, ionize them, mass separate them, select the appropriate isotope and then deliver this isotope beam to the experimenter. Since this is an online system, isotopes can be delivered to the experimenter with lifetimes as low as tens of milliseconds.

Due to the high radioactivity produced in the target, handling of the targets and its associated ancillary equipment has to be done remotely. The need to do this in a highly shielded area is one of the main costs associated with the ISAC facility, as indeed it will be for any high-powered ISOL facility. To increase the flexibility of the facility there are two target stations, one in use, and the other in waiting for use or in maintenance mode. Fig. 1 gives a present layout of the ISAC facility.

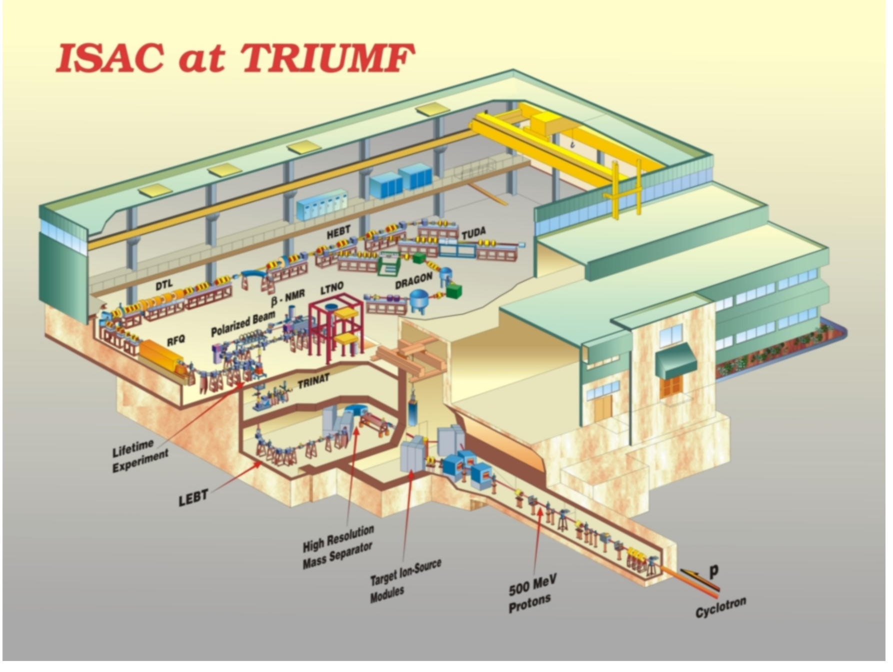

Figure 1 The ISAC facility at TRIUMF

The ISAC facility has been operating up to the present time using a surface ion source. However an ECR source has now been installed, and there is progress towards the development of a laser ion source. This will ensure a wide variety of unstable isotopes of different elements can be produced as pure isotope beams.

The most important factor in any ISOL facility is the composition, construction and mode of operation of the isotope production target. The ISAC target is designed to take up to 100 micro-amps of a 500 MeV proton beam. The target material may come as a powder, pellets or compressed composite discs. The target is 1.8 cm in diameter and can be up to 19 cm long. Control of the target temperature is very important for efficient release of spallation produced isotopes. Generally for low intensity proton beams, the target must be externally heated, while for higher intensity proton beams, the target must be cooled. Different target materials are used depending on the particular isotope that needs to be produced. In this way a whole variety of R.I.B. isotopes ranging in mass from 8 to 160 have been produced for a range of experiments with an intensity over the range of 10^3 to 10^{11} particles per second. More details can be found on the TRIUMF web site: http://www.triumf.ca/people/marik/homepage.html.

3. EXPERIMENTAL REQUIREMENTS FOR AN ISOL ASTROPHYSICS PROGRAM.

Explosive stellar events can process material rapidly sometimes on time scales much shorter than a second. For this situation, reactions involving unstable nuclei completely dominate not only the energy output but also the chemical evolution of the star's material. The reaction rates for most of the relevant reactions are unknown. Hence the motivation to produce intense radioactive beams is obvious. However using such beams to measure cross sections presents the experimenter with some unique problems. Firstly, the beams are generally much lower in intensity than for normal measurements with stable beams, and since the beam is radioactive its decay can produce unwanted background in detectors. In order to minimize these problems, detectors measuring reaction products must be made efficient and cover as much of the reaction solid angle as possible. As illustrations of some experimental apparatus specially designed to address theses problems, the situation at ISAC will be discussed.

The isotopes produced by the ISAC target are first ionized in an appropriate ion source and then mass selected by a high resolution mass spectrometer. The ions leaving this spectrometer will have an energy of 2 keV per mass unit. These ions may then either be delivered to the experimenter as is, or be further accelerated. Generally, for nuclear astrophysics purposes, the ions are accelerated; this is undertaken by the use of an RFQ accelerator section, followed by possible electronic stripping before further acceleration through a DTL accelerator. The final ion energy can be between 0.15 to 1.8 MeV/u.

Many of the reactions of interest in explosive stellar burning involve (p, γ), (α,γ), and (α, p) reactions. To study these reactions with unstable ions requires the use of inverse kinematics. Two experimental facilities have been constructed specially to study these types of reactions. The DRAGON[2)] (Figure 2) recoil spectrometer is designed to measure radiative capture reactions. The radioactive beam of interest is directed onto a windowless gas target of either hydrogen or helium. The beam particles together with the few forward peaked radiative captive ions are then directed into the spectrometer, the main purpose of which is to cleanly separate the radioactive beam ions from the few reaction product ions.

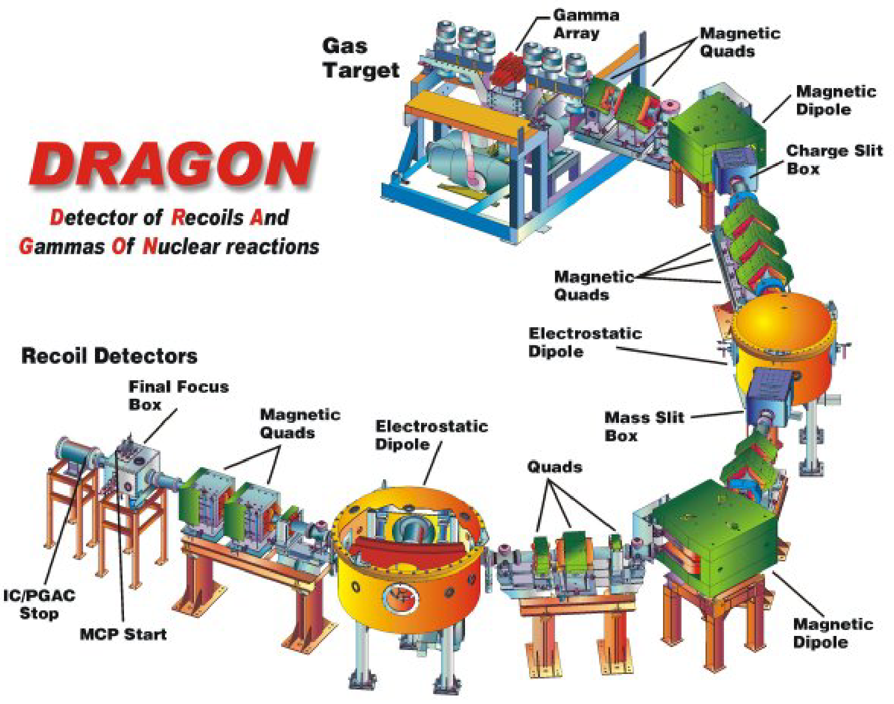

Figure 2 The DRAGON facility.

For the DRAGON spectrometer this separation can be up to 1 in 10^{15} (i.e., for the passage of 10^{15} beam particles, only one of these particles will find its way in error to the end detector). This is achieved by a succession of ion charge and mass selection systems, together with detection of the radiative capture γ-rays by a BGO array surrounding the gas target. Recently this spectrometer has been used to measure the reaction ^{21}Na (p, γ)^{22}Mg at energies corresponding to nova astrophysical temperatures.[3)] Measurements such as this will be of crucial importance for the interpretation of the new gamma ray satellite data as this becomes available.[4)]

The TUDA facility (Figure 3) is a large general purpose scattering chamber specifically designed to accommodate a variety of charge particle solid state detector arrays.[5)] These arrays are capable of detecting emitted particles with a solid angle approaching 4π. So even with low intensity radioactive beams, it is possible to study a variety of reactions. Currently the system has been used to complement reactions studied by the DRAGON spectrometer. In particular elastic scattering can be an excellent guide to identify study regions for investigating radiative capture reactions.[6)] As another example, explosive stellar burning often involves (α, p) reactions. The TUDA facility is ideally suited to study such reactions.

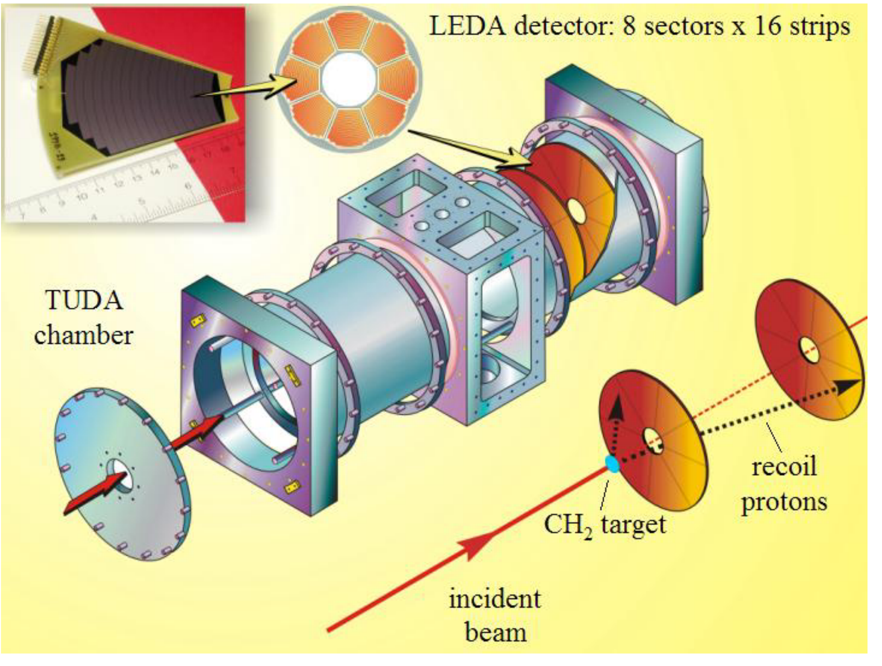

Figure 3 The TUDA facility.

The DRAGON and TUDA facilities are designed to study a wide range of reactions of astrophysical interest. However, the current configuration of the accelerators at ISAC restricts the acceleration of ions to A < 30. However in this mass range there are various reactions of special interest involving the hot CNO cycle, the CNO cycle, Ne-Na cycle, and the Mg-Al cycle. Currently, reactions involving radioactive aluminum isotopes are under investigation.

The present ISAC facility, designated ISAC-I, although capable of producing a wide range of isotopes in the keV/u range, can presently only accelerate ions to the MeV/u range for A< 30. To increase the range of ions that can be accelerated and to increase the acceleration energy, a new post-accelerator is under construction. The new accelerator complex, designated ISAC-II, will be capable of acceleration of radioactive ions up to A = 160 and to an energy of 6.5 MeV/u. The type of post accelerator will be a superconducting linear accelerator. In addition to the accelerator, a charge state booster is being developed so that higher ion masses can be accelerated through the initial RFQ accelerator that has a restriction of A/q < 30. The current plans are to have first beams accelerated through this new accelerator in 2005.

When ISAC-II is operational it can be used to address a range of astrophysical problems associated with heavy unstable isotopes. This will be particularly relevant for the astrophysical p and r process and also the higher reaches of the rp process. For these studies, a variety of well-established experimental techniques will be used, but they will need to be specially adapted for radioactive beam experiments. For ISAC-II there will be a need to build new particle and neutron detection arrays; high efficiency γ-ray detector arrays and magnetic spectrometers will also be needed.

4. LOOKING TO THE FUTURE

As ISOL facilities like TRIUMF come on line it is clear that there needs to be a continuing beam development program to produce a variety of RIBs. Different radioisotopes may require different targets and ion sources and these have to be developed to work in high-powered environments. A two-stage target with fast neutrons from a primary target producing fission isotopes in a secondary target is an attractive method to produce intense beams of some neutron rich radioisotopes. These ideas, however, still have to be proved in practice.

Intense RIB are difficult to produce and so an attractive idea could be re-circulation of these beams. The idea would be to capture the beams in a ring that would then make multiple passes through a thin target. Some initial studies suggest this may be practical in the 10-20 MeV/u range but unfortunately may be difficult for short-lived isotopes in the astrophysical range of ~ 1MeV/u.[7)]

Where a direct observation of a particular reaction is very difficult with a radioactive beam, it may be possible to make progress by using indirect methods such as Coulomb breakup or quasi-elastic transfer reactions. Such methods seem to offer attractive alternatives especially for the low energy regions for charge particle reactions. All indirect methods, however, rely on some theoretical model to extract the reaction strengths. Therefore the accuracy of these methods rests with theoretical understanding of the details of the reaction mechanism; so the accuracy will always remain an open question to some extent. Due to this uncertainty, direct measurements are always preferable and should be the driving force to develop intense radioactive beams.

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