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Commissioning of the Daresbury Recoil Separator for Nuclear Astrophysics Measurements at the Holifield Radioactive Ion Beam Facility

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The Daresbury Recoil Separator (DRS) has been installed for nuclear astrophysics research at Oak Ridge National Laboratory's Holifield Radioactive Ion Beam Facility. It will be used for direct measurements of capture reactions on radioactive ions which occur in stellar explosions such as novae and X-ray bursts. The physics motivation and plans for the first measurements with radioactive beams are described, and details of the new DRS experimental equipment and preliminary results from the first commissioning experiments with stable beams are given.

DISCLAIMER

1. Introduction

There are a number of important astrophysical events during which hydrogen is burned as fuel for (p,γ) fusion reactions under non-hydrostatic equilibrium conditions. These explosive hydrogen burning events, which include novae and X-ray bursts, are among the most energetic explosions ($\sim 10^{40-51}$ ergs) known in the universe. Furthermore, stellar explosions are among the primary sources of the elements. For this reason, they have been the focus of intense scientific research including astrophysical observations using new devices such as the Compton Gamma Ray Observatory and the Hubble Space Telescope, theoretical modeling of explosions utilizing massively parallel supercomputers, and laboratory measurements of the nuclear reactions that occur in (and sometimes drive) the explosions. These catastrophic stellar events are characterized by extremely high temperatures (10^{8-9} K) and densities (10^3-10^6 g/cm^3), conditions which cause (p, γ) reactions to rapidly (on timescales of ns - min) produce nuclei on the proton-rich side of the valley of stability. Any such radioactive nuclei produced with half-lives longer than, or comparable to, the mean time between fusion events will become targets for subsequent nuclear reactions. Sequences of (p, γ) reactions on proton-rich radioactive nuclei can therefore occur during these explosions [1]. The observable ashes of such nuclear burning sequences are an important probe of the conditions of these events, such as the temperatures, densities, and timescales. Comparisons of astrophysical models with observations require measurements of these reactions involving radioactive isotopes. Such measurements have been, until recently, impossible because of the lack of intense radioactive nuclear beams. Explosion models therefore employ reaction rate estimates based on systematic properties of nuclear states, on information from analogue nuclei, on partial resonance information from stable beam transfer reaction studies, and on statistical model calculations. Such rate estimates can, however, be incorrect by orders of magnitude [2], and therefore the model predictions of isotope synthesis and energy generation are necessarily uncertain. The recent development of radioactive beams has initiated a new era in laboratory nuclear astrophysics – one in which previously unattainable nuclear cross sections for astrophysically important reactions can be measured and subsequently incorporated into an emerging generation of sophisticated, computationally intensive models of stellar explosions. For example, beams of ^{13}N, ^{19}Ne, and ^{18}F have been used at Louvain-la-Neuve to measure the astrophysically important reactions ^{13}N(p, γ)^{14}O [3], ^{19}Ne(p, γ)^{20}Na [4], and ^{18}F(p,α)^{15}O [5, 6], and beams of ^{18}F and ^{56}Ni have been used at Argonne National Laboratory for the measurement of ^{18}F(p,α)^{15}O [7] and ^{56}Ni(d,p)^{57}Ni [8].

At Oak Ridge National Laboratory's Holifield Radioactive Ion Beam Facility (HRIBF), development of beams of radioactive nuclei involved in explosive hydrogen burning reactions occurring in hot, dense stellar environments is in progress. Reactions accessible at HRIBF include those in the Hot CNO cycle [9], occurring at stellar temperatures $T_9 \approx 0.1 - 0.2$ [where $T_9 \equiv T\ (K)\ /\ 10^9$] in red giants, nova explosions, and supermassive stars. At higher temperatures characteristic both of the most energetic novae and of X-ray bursts – $T_9 \geq 0.4$ – hydrogen burning may occur through the through the rapid proton capture process (rp-process) on nuclei with mass A > 20, which are produced via helium burning or via the "breakout" reaction sequence ^{14}O(α,p)^{17}F(p, γ)^{18}Ne($e^+ \nu_e$)^{18}F(p, γ)^{19}Ne(p, γ)^{20}Na(p, γ)^{21}Mg....[1] This "breakout" reaction sequence can increase the energy generated through nuclear burning, and significantly alter the abundances produced during stellar explosions. The rp-process path involves (p,γ) reactions near the proton drip line competing with e^+ - decay and reaction cycles (e.g., the

Ne-Na and Mg-Al cycles); the process may produce nuclei up to mass 56 or, at temperatures $T_9 > 1$, even up to masses 70 - 100. Detailed calculations of the element synthesis and energy generation in the rp-process have recently been made. [10, 11] However, because most reactions in the Hot CNO breakout and in the rp-process are unmeasured, and because these sequences are sensitive to many of these rates, current calculations of these paths may be fundamentally altered with direct measurements of crucial reaction rates and other important nuclear parameters. Better reaction rates will also help determine the onset of the rp-process, the termination of the rp-process, and (in some cases) the temperatures of stellar explosions by comparison of model predictions to observed abundances. Nuclear masses (reaction Q-values) are also needed because they determine, with the reaction sequence, the energy generated by nuclear burning. Some of the first astrophysically important radioactive ion beams anticipated at the HRIBF include $^{17,18}F$ and ^{56}Ni, which will be used for measurements of the $^{17}F(p,\alpha)^{14}O$, $^{17}F(p,p)^{17}F$, $^{17}F(p,\gamma)^{18}Ne$, $^{18}F(p,\alpha)^{15}O$, $^{18}F(p,\gamma)^{19}Ne$, and $^{56}Ni(p, p)^{56}Ni$ reactions, respectively; additionally, a ^{7}Be beam will be developed for a measurement of the $^{7}Be(p,\gamma)^{8}B$ reaction, important for the solar neutrino problem. Details of plans for these measurements are given in ref. [12].

2. Experimental Techniques and Apparatus

2.1. *The Holifield Radioactive Ion Beam Facility*

The Holifield Radioactive Ion Beam Facility [13, 14] is the only U.S. facility able to produce and accelerate beams of proton-rich radioactive heavy ions. Radioactive ions are produced at HRIBF when a high-temperature (1100 - 2200° C), thin, refractory target [15, 16] is bombarded by a 0.5 kW light ion (p, d, ^{3}He, or ^{4}He) beam from the K=105 Oak Ridge Isochronous Cyclotron (ORIC). For example, fibrous Al_2O_3 targets [17] (with a high surface area to volume ratio and low density to enhance diffusion of radioactive isotopes) are being used to produce ^{17}F via the $^{16}O(d, n)^{17}F$ reaction at 30 MeV. A number of novel target configurations for high-efficiency release of radioactive isotopes are currently under design. [16] Once produced by transfer or evaporation reactions induced by ORIC beams, the radioactive isotopes diffuse out of the hot target material and through a short (10 cm) transfer tube to one of a variety of ion sources for ionization and extraction. Ion sources are also being developed to maximize the extracted radioactive beam [16, 18-20]. For example, a positive/negative surface ionization source has been developed for producing negative ions of radioactive fluorine. [18] Low-intensity radioactive $^{17,18}F$ beams have been produced in off-line tests; details of the radioactive ion beam development are given in ref. [21]. Once produced, the radioactive ions are then charge-exchanged (if they are positive ions) in a Cs vapor cell, then undergo two stages of mass separation (with $\Delta M / M \leq 0.5 - 1 \cdot 10^{-4}$) before their injection into the 25-MV tandem accelerator and their subsequent acceleration and delivery to the experimental areas. Radioactive beams produced at the HRIBF have high isobaric purity, good energy resolution, low emittance, low energies, and relatively high intensities, making them well suited for nuclear astrophysics studies.

2.2. *Direct Measurements of Capture Reactions*

One focus of nuclear astrophysics experiments at the HRIBF will be on absolute cross section measurements of astrophysically important capture reactions on radioactive nuclei in inverse kinematics – such as $p(^{17}F, ^{18}Ne)\gamma$, where a heavy radioactive ^{17}F beam will be incident on a hydrogen target. These measurements will utilize a recoil separator for direct recoil detection, which has a number of advantages over more traditional capture γ ray detection techniques. [22] The most important advantage is the high detection efficiency possible because all recoils are forward focused within a 0.5° opening angle of the beam direction. A necessary charge-state selection usually brings the total efficiency of such recoil detection down to approximately 40 %. Other advantages include a significant increase in the signal-to-noise ratio, because the detectors are placed far from the high background radiation near the target, and an increase in the detection schemes possible at the focal plane of a recoil separator – such as direct recoil detection, delayed-activity detection, and recoil-γ coincidences. The recoil detection approach is, however, very challenging because: (1) the recoils are emitted along the incident beam direction, so the separator must accept all of the beam particles; (2) the projectiles and recoils are "nearly" identical: they have approximately the same momentum, and differ in velocity by only a few percent and in mass by only one amu; and (3) the recoils are far less intense than the projectiles. The recoil separator must be optimized to collect one mass group (the recoils) at the final focus with the highest possible suppression of scattered projectiles. For proton capture reactions, this suppression must be on the order of 10^{-10} to 10^{-12}. It is also necessary to instrument the final focus of the separator with detectors designed to distinguish between the scattered projectiles and recoils, which is quite challenging in view of the low-energy (0.4 - 2 MeV/u) of the particles to be identified. The recoil detection technique for proton capture reactions was first proven viable with a measurement of the $p(^{12}C,^{13}N)\,\gamma$ reaction with a relatively small, non-optimized recoil separator at Caltech [22], where a 10^{-10} suppression of scattered beam particles was obtained.

The Daresbury Recoil Separator (DRS), built for a nuclear structure research program at Daresbury Laboratory in the U.K. [23], was transferred to the HRIBF where it forms the core of an endstation dedicated for nuclear astrophysics capture reaction measurements [24]. The DRS is currently being commissioned with stable beams, described in Section 3. The device (Figure 1) is a large-acceptance (6.5 msr, ± 2.5 % in velocity), high-mass resolution (300), 90-ton, 13 meter-long mass separator designed to detect weak channels in fusion evaporation reactions — where there is typically a large velocity difference between the beam particles and the recoils of interest. The DRS features two long (1.2 meter), crossed electric and magnetic field velocity filters, followed by a 50° dipole magnet that gives a mass/charge final focus. There are 14 magnets in total: two velocity filter dipoles, 9 quadrupoles, two sextupoles, and the 50° dipole. The velocity filters have maximum electric and magnetic field strengths of approximately 4 MV/m and 0.5 Tesla, respectively. To increase the projectile suppression of the DRS for inverse-kinematics proton capture reactions at the HRIBF, the system has been reconfigured to have an ion-optic focus and adjustable slits between the two velocity filters. This rearrangement decouples the two velocity filters – they are now operated as separate spectrometers. The majority of the projectiles are stopped in the new slits between the two velocity filters. In another change, the velocity filters now have opposite field orientations (and therefore give opposite deflections to the beam particles), a configuration estimated by ion - optics calculations to give better projectile suppression. Monte Carlo simulations have been performed to determine the placement of slits to minimize the scattered beam that is estimated to reach the focal plane. Detailed focusing adjustments in the form of linear combinations of field strengths of the 14 DRS magnets have been determined for some of the most common aberrations and incorporated into the DRS magnet control system. [25] In another modification, the distance between the final DRS quadrupole and the focal plane has been increased to accommodate the future installation of additional focal plane detectors. For example, a second timing detector can be used to obtain the time-of-flight difference between projectiles and recoils to improve projectile suppression. A new compact target chamber has been constructed for the DRS, designed to accommodate the close placement of a highly-segmented BaF_2 array for capture γ ray detection. A second target chamber has been built for measurements of transfer and capture reactions with a large Si strip detector array. Initial experiments will be run with CH_2 foil targets because of their ease of fabrication, whereas later experiments will use a gas target (described below). The DRS transmission of capture-reaction recoils is limited primarily by the charge-state selectivity of the 50° dipole magnet to be approximately 40 % for many of the recoils of interest; the dipole is needed to give a mass/charge final focus. This high efficiency enables measurements of resonant (p, γ) cross sections as low as ~1 μb (corresponding to resonance strengths ~1 meV [9]) with 3 % statistics to be made in approximately 3 weeks with radioactive beam intensities of 0.1 pnA ($6 \cdot 10^8$ s^{-1}) and thick (25 μg/cm^2) targets.

There are two detectors currently operating at the DRS focal plane: a carbon-foil microchannel plate detector (providing timing and position information) and a gas ionization counter (providing particle identification). The first detector has an intrinsic horizontal position resolution of 1 mm, as tested with radioactive sources and slits at the HRIBF. This is sufficient because the target beam spot width of ≈ 1 mm combined with the target-to-detector DRS horizontal magnification of ≈ 3 gives focal plane groups of ≈ 3 mm width. The ion counter has three separate anodes for particle identification – two energy loss signals and one residual energy signal – and is typically operated with 5 - 30 torr of isobutane gas. Details of the detectors can be found in ref. [23]. The performance of the ion counter for the low-mass, low-energy ions of interest is discussed in Section 3.

Future DRS detector systems include a second carbon-foil microchannel plate detector (for timing, as mentioned above) and a moving tape system with associated NaI detectors for delayed activity measurements. A windowless, differentially-pumped extended gas target, and a gas jet target, are currently being designed for the DRS. The design of the extended gas target will be similar to that used in Naples. [26] Gas targets are preferred over CH_2 foil targets for a number of reasons. Higher yields are obtained for the same target (energy loss) thickness, since there is no energy loss to carbon atoms in the gas target. Also, alpha-induced reactions [(α, γ) and (α, p)] are measurable with gaseous helium targets. Finally, the background from carbon-induced reactions is greatly reduced when pure gas targets are used, and gas targets have no physical degradation or hydrogen-depletion problems common to CH_2 foils.

2.3. *Other Nuclear Astrophysics Measurements*

In addition to (p, γ) capture reaction studies, other types of nuclear astrophysics measurements are planned with HRIBF's accelerated beams of proton-rich radioactive heavy ions. Reactions such as (p, p) and (p, α) with radioactive beams in inverse-kinematics (e.g., p(^{17}F, ^{17}F)p) will be used to precisely determine resonance energies, total widths, limits on spins and parities, and cross sections. Once a He gas target is available, (α, p) reactions will be measured with the same techniques. Light-ion products of these reactions will be detected in a silicon detector array (SIDAR), an annular array of 128 silicon strip detectors similar to the array in ref. [27]. Another class of experiments planned at the HRIBF are transfer [e.g., (d, p)] and charge-exchange [e.g., (^{3}He, t)] reactions with radioactive beams. Such reactions have been extensively used with stable

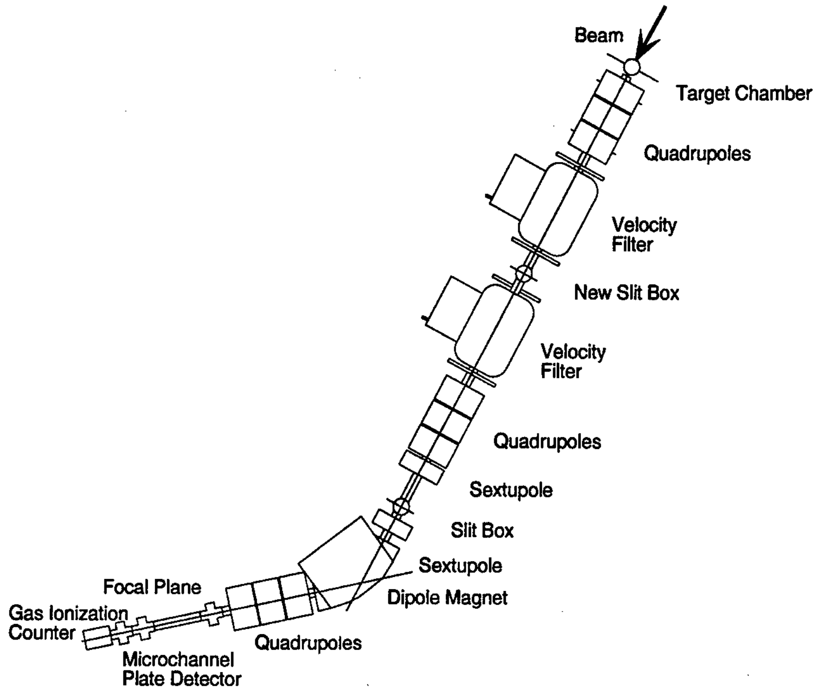

Figure 1. The Daresbury Recoil Separator

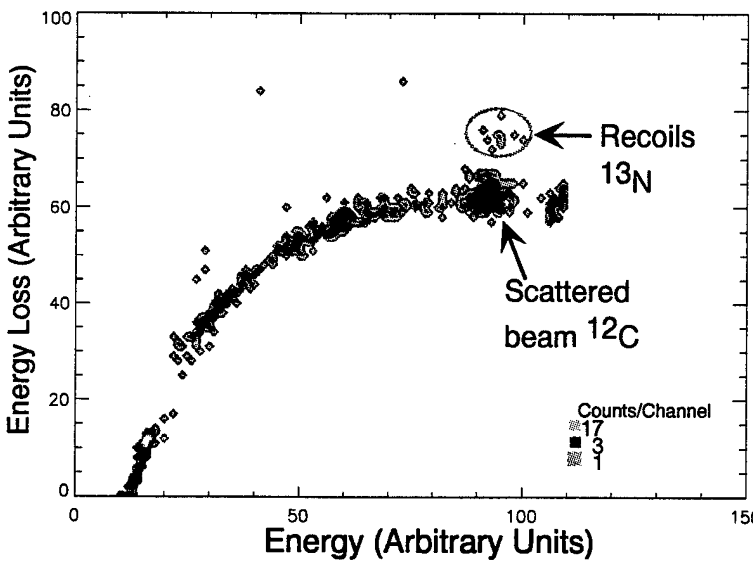

Figure 2. Measurement of the ^{13}N recoils and ^{12}C scattered beam particles from the ^{12}C (p, γ)^{13}N Capture Reaction in the DRS Focal Plane Gas Ionization Counter.

beams (e.g., [28]) to indirectly determine stellar reaction rates by populating low energy, near-threshold (p, γ) resonances and measuring resonance energies, spins, and widths. By using radioactive beams, the number of reactions that can be investigated with this technique is greatly expanded. Mass measurements, lifetime measurements, and level density determinations will also be made at the HRIBF for nuclei near the proton drip-line that are important for explosive nucleosynthesis processes. Measuring these properties for a few crucial nuclei will help verify the Hauser-Feshbach statistical model programs currently used to estimate many reaction rates involving high-mass (A > 50) stable and unstable nuclei. [29]

3. Commissioning Experiments

Commissioning of the DRS with radioactive sources and with stable beams is in progress. The p(^{12}C,^{13}N) γ reaction was recently measured with a 0.666 MeV/u ^{12}C beam and a CH_2 target to determine the DRS projectile suppression and the recoil transmission for inverse kinematics capture reactions. The ionization counter spectrum for this capture reaction measurement is shown in Figure 2. The preliminary determination of the suppression of scattered beam particles – defined by the ratio of beam particles incident on target to those reaching the focal plane – was $3 \bullet 10^{-11}$, which is within the 10^{-10} to 10^{-12} range needed. Furthermore, the gas ionization counter cleanly separated (i.e., with no overlap) the energy-loss (i.e., Bragg) curve of the low-mass, low-energy ^{13}N recoils from that of the scattered ^{12}C projectiles above 0.4 MeV/u. The *combined* projectile rejection of the DRS and the focal plane detector was, therefore, well beyond that needed for the planned radioactive ion beam experiments. However, the DRS transmission for the recoils was 7 %, approximately a factor of 7 lower than expected. Since CH_2 targets could withstand only approximately 0.5 pnA of beam current before breaking, the count rate of this measurement was limited to a few counts per hour, and therefore the settings of the DRS could not be optimized for recoil transmission and projectile suppression. However, the ^{14}N + ^{12}C elastic scattering reaction, with a cross section a factor of 10^6 larger than the capture reaction (and therefore suitable for parameter optimization), was measured with a 1 MeV/u ^{14}N beam and a carbon target. The DRS was tuned for the ^{12}C particles knocked out of the target by the beam particles, and the suppression of the scattered beam particles, was measured to be $5 \bullet 10^{-11}$, consistent with the result from the capture measurement. Additionally, the gas ionization counter cleanly separated the carbon recoils and the nitrogen scattered beam particles above 0.4 MeV/u, again consistent with the capture reaction measurement. For these reasons, parameters optimized with elastic scattering reactions should give similar performance when used for capture reactions. Further commissioning tests with both elastic scattering and stable-beam capture measurements are planned to optimize these results and to improve the DRS recoil transmission.

4. Summary

Measurements of capture reactions on proton-rich radioactive isotopes are crucial to the understanding of the isotope synthesis and energy generation occurring in spectacular stellar explosions such as novae and X-ray bursts. The Daresbury Recoil Separator has been installed at ORNL's Holifield Radioactive Ion Beam Facility for these measurements. The DRS is currently being commissioned with stable beams, and measurements with proton-rich radioactive beams will begin soon. Initial tests have shown that the DRS can give an excellent suppression of scattered beam particles in inverse kinematics capture reactions. Additionally, development will soon begin on neutron-rich radioactive isotopes relevant for studies of heavy element nucleosynthesis. In addition to the HRIBF measurements, there are astrophysics research efforts at ORNL in theoretical astrophysics and nuclear astrophysics data evaluation which are closely coupled to the HRIBF work, as well as research in heavy element nucleosynthesis, theoretical atomic astrophysics, and atomic astrophysics data.

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