Nuclear Astrophysics at the Holifield Radioactive Ion Beam Facility

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The potential for understanding spectacular stellar explosions such as novae, supernovae, and X-ray bursts will be greatly enhanced by the availability of the low-energy, high-intensity, accelerated beams of proton-rich radioactive nuclei currently being developed at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory. These beams will be utilized in absolute cross section measurements of crucial (p, γ) capture reactions in efforts to resolve the substantial qualitative uncertainties in current models of explosive stellar hydrogen burning outbursts. Details of the nuclear astrophysics research program with the unique HRIBF radioactive beams and a dedicated experimental endstation – centered on the Daresbury Recoil Separator – will be presented.

1. Introduction

Nuclear reactions synthesize heavy elements and produce energy in numerous astrophysical environments – ranging from the big bang to the interstellar medium to the hydrostatic and the explosive periods of a star's lifecycle. For this reason, accelerator-based measurements of nuclear reactions form a crucial foundation for models of astrophysical phenomenon. Critical comparisons of astrophysical models with observations, especially those from new devices such as the Compton Gamma Ray Observatory and the Hubble Space Telescope, require more accurate nuclear reaction rates than currently available. This is especially true for nova and supernova explosions – considered the primary sources of heavy elements in the Universe and the most energetic explosions (~10^{40-50} ergs) known. These explosions are characterized by extremely high temperatures (>10^8 K) and densities (10^{3-4} g/cm^3), conditions which cause hydrogen burning [i.e., (p, γ)] nuclear reactions to rapidly (on timescales of ns - min) produce nuclei on the proton-rich side of the valley of stability. Any such nuclei (which decay via e^+ - emission or e^- - capture) produced with half-lives longer than, or comparable to, the stellar burning timescales will become targets for subsequent nuclear reactions; therefore, sequences and cycles involving (p, γ) reactions on *proton-rich radioactive nuclei* will occur during these explosions.

Direct measurements of these crucial reactions have been, until recently, impossible because of the lack of intense radioactive nuclear beams. Current explosion models therefore employ reaction rate estimates based on systematic properties of nuclear states (i.e., information on analogue nuclei) and on partial resonance information from stable beam transfer reaction studies. Since these rate estimates can be incorrect by *orders of magnitude*, we are currently unable to determine whether, for example, the nucleosynthetic products of novae are limited to fairly low masses ($A < 20$) or can reach $A = 56$ and beyond [1]. Hence we cannot currently claim even a *qualitative* agreement between explosion models and observations.

The recent development of a ^{13}N radioactive beam at Louvain-la-Neuve and its use in measuring the important $^{13}N(p, \gamma)^{14}O$ reaction [2] has initiated a new era in laboratory nuclear astrophysics – one in which crucial, previously unattainable nuclear reaction rates can be directly determined (from absolute cross section measurements) and subsequently incorporated into an emerging generation of sophisticated, computationally intensive models of stellar explosions. The potential of this era to make fundamental advances in our understanding of explosive stellar nucleosynthesis will be greatly enhanced by the beams from the Holifield Radioactive Ion Beam Facility (HRIBF) at ORNL.

2. The Holifield Radioactive Ion Beam Facility

21. Radioactive Beam Production

When completed in 1995, the Holifield Radioactive Ion Beam facility [3, 4] will be the only US facility able to produce and accelerate beams of proton-rich radioactive heavy ions. A high-temperature (2000^{o} C), thin, refractory target [5] will be bombarded by a light ion (p, d, ^{3}He, or ^{4}He) beam from the K=105 Oak Ridge Isochronous Cyclotron (ORIC), and radioactive nuclei will be produced by transfer or evaporation reactions. For example, a Al_2O_3 target may be used to produce ^{17}F via the $^{16}O(d, n)^{17}F$ reaction. The radioactive isotopes will then diffuse through a short (10 cm) transfer tube from the hot target to a modular secondary ion source for ionization and extraction. The ion source will be chosen to maximize the extracted radioactive beam; initially, a plasma sputter source and a negative surface ionization source will be used [6]. The radioactive ions will then undergo two stages of mass separation before their injection into the 25-MV tandem accelerator and their subsequent acceleration and delivery to the experimental areas.

2.2. Radioactive Beam Species

There is a strong overlap between anticipated HRIBF beams and those radioactive nuclei involved in hydrostatic and, especially, explosive hydrogen burning reactions occurring in hot, dense stellar environments. Reactions that will be studied with HRIBF beams include those in the Hot CNO cycle [7], occurring at temperatures $T_9 \approx 0.1 - 0.2$ [where $T_9 \equiv T(K) / 10^9$] in red giants, nova explosions, and supermassive stars. Also accessible at HRIBF will be reaction sequences such as $^{14}O(\alpha, p)^{17}F(p, \gamma)^{18}Ne(e^+ \nu_e)^{18}F(p, \gamma)^{19}Ne(p, \gamma)^{20}Na(p, \gamma)^{21}Mg$... and $^{15}O(\alpha, \gamma)^{19}Ne(p, \gamma)^{20}Na(p, \gamma)^{21}Mg$..., which may (at $T_9 \approx 0.2$, characteristic of nova explosions) process C, N, and O nuclei to masses $A > 20$, therefore leading to hydrogen burning through the rapid proton capture process (rp-process) [8]. These "breakout" reaction sequences offer a promising explanation of observations of Ne, Na, Mg, Al, and heavier nuclei in material ejected from novae [9] - explosions which are thought to be purely nuclear events initiated solely by (p, γ) reactions on C and O nuclei on the surface of a white dwarf star.

HRIBF beams will also enable studies of hydrogen burning through the rp-process and extended rp-process [10], thought to occur at the very high ($T_9 \approx 0.3 - 0.4$) temperatures characteristic both of the most energetic novae and of X-ray bursts and supernovae. 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 reach mass 56 or (for the extended rp-process) mass 70 - 100. Because almost all relevant reactions in the Hot CNO breakout and in the rp-process are *unmeasured*, and because these sequences are extremely sensitive to the stellar temperature and density, current calculations of these paths [1] must be considered tentative. Accurate nuclear reaction rates will allow us to begin to delineate the transition to and the path followed in the rp-process, and in some cases will allow us to determine explosion temperatures by comparison to abundance observations (e.g., for Mg and Al isotopes [11]). Our studies at HRIBF will also address the tantalizing prospect that hydrogen burning through the Hot CNO cycle and rp-process may proceed *hydrostatically* (i.e., non-explosively) in high temperature, low density Thorne-Zytkow objects [12].

Some of the first astrophysically important beams anticipated at HRIBF include $^{17,18}F$, $^{33,34}Cl$, ^{31}S, ^{27}Si, and $^{14,15}O$. The choice of F and Cl for initial beams was made because of the importance of the $^{17,18}F(p, \gamma)^{18,19}Ne$ and $^{33,34}Cl(p, \gamma)^{34,35}Ar$ reactions, and because it is expected that these beams will be produced with high ($>10^9$ s^{-1}) intensities. More information on the astrophysically important reactions at HRIBF may be found in [1] and [13].

2.3. Suitability for Nuclear Astrophysics Studies

In addition to being astrophysically important isotopes, radioactive ion beams from HRIBF will have a number of important characteristics (some detailed in [14]) which make them well suited for nuclear astrophysics studies: high isobaric purity, good energy resolution, low emittance, low energies, and high intensities. First, the two-stage mass analysis system on the tandem injector line will give a very high isobaric purity ($\Delta M / M \leq 0.5$ - $1 \bullet 10^{-4}$), substantially reducing backgrounds from capture reactions on stable isobars. Next, the 25 MV tandem accelerator has excellent energy resolution ($\Delta E / E \leq 10^{-4}$) and emittance (0.5 π mm mrad), important for high precision, low background absolute cross section measurements. Furthermore, the tandem efficiency at astrophysically important energies (E / A = 0.2 - 2 MeV/amu) has recently been improved by replacing the spark gaps by a resistor chain. Finally, the radioactive beam intensities will vary greatly with the species, but the anticipated values are 10^8 - 10^{10} s^{-1}, sufficient for a variety of nuclear astrophysics measurements described in the next section.

3. HRIBF Nuclear Astrophysics Measurements and Apparatus

3.1. Direct Measurements of Capture Reactions

The HRIBF nuclear astrophysics program will primarily emphasize making absolute cross section measurements of astrophysically important (p, γ) capture reactions on radioactive nuclei with the Daresbury Recoil Separator (DRS) [15]. This device, currently being transferred from Daresbury Laboratory to ORNL, will form the core of a dedicated nuclear astrophysics endstation. Capture reactions will be measured in inverse kinematics [e.g., p(^{17}F, ^{18}Ne)γ] with the DRS, utilizing direct recoil detection techniques as well as delayed-activity recoil detection and recoil–γ coincidences. These studies will employ the following equipment: a focal plane detector system [15] consisting of a carbon-foil multichannel plate detector (timing and position information) and gas ionization counter (energy loss and total energy information); a second carbon-foil multichannel plate detector (timing information) allowing time of flight measurements; a moving tape system and associated NaI detectors for delayed activity measurements at the DRS focal plane; and a highly-segmented array of BaF_2 detectors for the detection of capture γ rays at the target chamber. We plan to construct a gas-jet He target for the DRS for the direct measurement of (α, γ) reactions; however, we will initially concentrate on (p, γ) reactions using CH_2 foil targets. With radioactive beam intensities of 10^9 s^{-1}, we will be able to measure resonant (p, γ) cross sections as low as ~1 μb (corresponding to resonance strengths ~1 meV [7]) with thick targets in approximately 3 weeks with 4 % statistics.

In general, there are a number of advantages of recoil detection over capture γ ray detection for our inverse kinematics absolute cross section measurements [16]. These include: a significant increase in the signal to noise ratio, because the detectors are place far from the high radiation area near the target; an increase in efficiency, because of the forward focussing of the recoils in inverse kinematics reactions; and an increase in flexibility, because many detection options (direct recoil detection, delayed activity detection, and recoil-γ coincidences) may be utilized at the focal plane. The recoil detection approach for our measurements was proven viable with p(^{12}C,^{13}N) γ excitation function measurements with a relatively small recoil separator at

Caltech [16]; with a non-optimized setup, a factor of 10^{10} rejection of scattered beam particles was achieved. The DRS is expected to obtain a factor of 10-100 better projectile suppression because of its two very long (1.2 meter), high field strength (3 MV/m and 0.5 Tesla) velocity filters. We anticipate increasing this suppression further by using an ion-optical DRS configuration featuring a horizontal crossover and an aperture between the two velocity filters [17].

3.2. Other Nuclear Astrophysics Measurements

In addition to capture reaction studies, we are planning four other types of nuclear astrophysics measurements with HRIBF's unique, intense, accelerated beams of proton-rich radioactive heavy ions. First, we plan to measure elastic scattering reactions with the high-quality HRIBF radioactive beams in inverse-kinematics (e.g., p(^{17}F, ^{17}F)p') to precisely determine resonance energies and total widths before measuring the corresponding (p, γ) capture reaction (with its much lower cross section). We will detect the heavy recoils in the DRS and the scattered protons in an annular array of double-sided silicon strip detectors, similar to the array described in [18]. Because the scattering cross sections are ~1 b, much lower beam intensities (~10^5 s^{-1}) are required: with very thin targets (10^{16} cm^{-2}) and a 25 % detector solid angle efficiency, 4% statistics will be easily obtained in one day.

Next, we plan to measure astrophysically important (p, α) reactions, because the ratio of certain (p, γ) / (p, α) reactions (e.g., on ^{18}F) can crucially determine whether nuclei are processed to higher masses [(p, γ)] or recycled back to lower masses [(p, α)] in stellar hydrogen burning. We will measure such reactions in inverse-kinematics [e.g., p(^{18}F, ^{15}O)α] with recoil detection, light-ion detection, and coincidence techniques. The cross sections and yields for these reactions will be ~ 10^2 - 10^3 larger than those for the (p, γ) reactions. (α, p) reactions will be measured with the same techniques once a He target is available.

Another class of experiments planned at HRIBF are transfer [e.g., (p, d)] and charge-exchange [e.g., (^{3}He, t)] reactions with radioactive beams. Such reactions have been extensively used with stable beams (e.g., [19]) 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, we greatly expand the number of resonances that can be investigated, and hence the number of rates that may be indirectly determined, with this technique. These measurements will require higher energies(> 5 - 10 MeV/amu) to ensure that the direct reaction component dominates the compound nuclear component. Such measurements can be carried out with the DRS or the Recoil Mass Spectrometer [20], a new mass separator at HRIBF designed for nuclear structure studies. With a beam intensity of 10^9 s^{-1} and a thin target (10^{17} cm^{-2}), 4% statistics can be obtained in a few days for these studies.

Additionally, we plan on making mass and lifetime measurements and level density determinations at HRIBF for proton-rich radioactive nuclei important for explosive nucleosynthesis. 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.

4. Summary

HRIBF presents an exciting, unique, and long-awaited opportunity for the nuclear astrophysics community, in which fundamental advances in our understanding of explosive stellar nucleosynthesis may be made by utilizing proton rich radioactive beams to determine crucial reaction rates. The RIBENS collaboration (Radioactive Ion Beams for Explosive Nucleosynthesis Studies), involving ≈15 members from 10 institutions, has been formed to design and implement this experimental nuclear astrophysics program. Furthermore, this work at HRIBF will be coupled to other ORNL nuclear astrophysics efforts, specifically in stellar explosion modeling – which will exploit the laboratory's massively parallel computational facilities – and in heavy-element neutron-rich nucleosynthesis studies – via (n, γ) measurements in progress at the ORELA (Oak Ridge Electron Linear Accelerator) white neutron source [21].

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