Studies in Nuclear Astrophysics Using Radioactive Beams at the HRIBF

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The availability of radioactive beams has produced great opportunities for advances in our understanding of the nucleosynthesis occurring in stellar explosions such as novae, X-ray bursts, and supernovae. At the HRIBF, we have used proton-rich beams such as ^{17,18}F and neutron-rich beams such as ^{82}Ge to study astrophysically-important reaction rates. Large-area detector arrays and kinematically-complete measurements have been used to overcome the challenges of low beam currents and beam impurities. The experimental methods and results are discussed.

1 Introduction

Nuclear astrophysics addresses some of the most compelling questions in nature: What are the origins of the elements that make life on earth possible? How did the sun, the solar system, the stars, and our galaxy form, and how did they evolve? What is the total density of matter in the universe, and will the universe eventually collapse or expand forever? Astrophysical models that address these crucial questions require a considerable amount of nuclear physics information as input. The majority of this required information, however, is currently based on extrapolations or theoretical models and does not have a firm experimental basis. Nuclear data is also an important ingredient in the interpretation of new observations made by ground-based observatories such as the Keck and European Southern Observatory (ESO) Very Large Telescopes, by space-borne observatories such as the Hubble Space Telescope and the Chandra X-Ray Observatory, and by large subterranean detectors such as the Sudbury Neutrino Observatory and Super-Kamiokande. More complete and precise nuclear physics measurements are therefore needed to improve astrophysical models and to decipher the latest observations [1].

Because radioactive nuclei play an influential, and in some cases the dominant, role in many cosmic phenomena, information on these nuclei is particularly important to improve our understanding of the processes that shape our universe. In the explosive environments of novae and X-ray bursts, hydrogen and helium react violently with heavier seed nuclei to produce extremely proton-rich nuclei via hot-CNO burning and the αp- and rp-processes. Neutron-induced nucleosynthesis may occur in the neutrino-wind driven shock front of supernova explosions initiating the r-process and producing extremely neutron-rich nuclei. These cataclysmic stellar explosions produce reaction flows through nuclei far from the valley of beta stability. To understand and interpret observations of these events we must understand the nuclear reactions, the nuclear structure, and the decay mechanisms for unstable nuclei. Because the lifetimes of most of the nuclei of interest are too short for use as targets in experiments, the required information can best be obtained by producing energetic beams of radioactive ions.

2 Experimental Details

At the ORNL Holifield Radioactive Ion Beam Facility (HRIBF), radioactive beams are produced by the ion source on-line (ISOL) method [2]. Light ion beams, accelerated by the Oak Ridge Isochronous Cyclotron (ORIC), bombard thick, hot, refractory targets to produce radioactive atoms. The atoms diffusing from the target material are ionized and extracted by a close-coupled ion source. After undergoing two stages of mass analysis, the radioactive ions are then injected into the 25 MV tandem accelerator, accelerated to the appropriate energy for the experiment, and delivered to the experimental station. At the HRIBF, a full suite of developed beams is available including 120 radioactive beams and 79 beams of stable species [3]. Available radioactive beams include proton-rich species such as ^{7}Be and ^{17,18}F and neutron-rich beams such as ^{82}Ge and doubly-magic ^{132}Sn. Energies up to $\sim$10 MeV/u are possible for low mass beams and up to $\sim$4 MeV/u for beams near ^{132}Sn.

The Nuclear Astrophysics group at the HRIBF has used these available beams to study 6 important astrophysical reactions. These studies were performed as part of the RIBENS collaboration [4] and involved 13 distinct measurements of nuclear properties or cross sections. The ^{17}F$(p,\gamma)^{18}$Ne [5,6] and ^{14}O$(\alpha,p)^{17}$F [7] reaction rates were studied with ^{17}F beams, while ^{18}F beams were used to determine the stellar rates of the ^{18}F$(p,\alpha)^{15}$O [8,9] and ^{18}F$(p,\gamma)^{19}$Ne [10] reactions. A radioactive $N = 50$ ^{82}Ge beam was used to study the ^{82}Ge$(n,\gamma)^{83}$Ge reaction [11], and the ^{25}Al$(p,\gamma)^{26}$Si rate was studied via a measurement of the ^{28}Si$(p,t)^{26}$Si reaction [12].

While the availability of radioactive beams provides great opportunities for the better understanding of nuclei and nuclear reactions far from stability, there are also great challenges that most be overcome to utilize such beams. Radioactive beams are generally available only at a much lower intensity than stable beams ($\sim 10^{4-7}$ ions/s compared to 10^{9-12} ions/sec for stable beams). High-efficiency large solid-angle detector arrays have been developed to deal with low beam intensity measurements. The Silicon Detector Array (SIDAR) [13] is a segmented array of silicon strip detectors that has been used for the majority of the nuclear astrophysics measurements at the HRIBF. Other detector arrays available at the HRIBF include the CLARION array of Clover germanium detectors and the HYBALL array of CsI detectors [14]. Another challenge is that radioactive beams are frequently contaminated with an unwanted isobar. While this contaminant can sometimes be removed with chemical techniques at the ion source or by fully stripping the beam, a general solution does not exist and many times an isobarically mixed beam will be delivered to the experimenter. A detector system with high selectivity is many times the best solution to the problem. Kinematically-complete measurements utilizing coincidence techniques is one method to identify the events of interest. We have frequently detected the beam-like recoil from a reaction in a gas-filled ionization counter, identifying the proton number (Z) of the recoil, and thus determining the reaction channel. Because the measurements of astrophysical interest are usually performed in inverse kinematics, the beam-like recoils are forward focused and can be efficiently detected in an ionization counter covering relatively small laboratory angles ($< 10°$).

While direct measurements of the reaction of interest are extremely important, it is not generally possible (or even desirable) to measure the reaction cross section at all of the energies required to completely determine the stellar reaction rate. It is important to have complimentary measurements which may not directly determine the reaction rate but do help to elucidate the structure of the nuclei involved. A good understanding of the properties of states in the compound nuclei can be used to calculate the stellar reaction rate over a large range of astrophysical temperatures. Direct measurements of reaction cross sections should thus be complimented with other studies such as single-nucleon transfer reactions populating states of interest or particle-decay branching ratio studies from stable beam measurements. These points are discussed further in the next section discussing the ^{18}F$(p,\alpha)^{15}$O reaction.

3 The ^{18}F$(p,\alpha)^{15}$O Reaction Rate

The decay of ^{18}F is thought to provide the most prolific source of gamma rays during the first several hours after a nova explosion. Orbital gamma-ray telescopes are probing and will continue to probe nova remnants searching for this signature of radioisotope decay [15]. To interpret these expected observations, we must understand the destruction rate of ^{18}F in the nova environment and, in particular, we must know the rate of the ^{18}F$(p,\alpha)^{15}$O reaction as it is the main destruction path for ^{18}F at high temperatures. Unfortunately, recent evaluations found that the amount of ^{18}F that is produced in nova models in uncertain by a factor of 300 just due to uncertainties in the ^{18}F$(p,\alpha)^{15}$O reaction rate [16]. It was critical that more and better studies of the reaction rate be performed.

A radioactive ^{18}F beam was produced at the HRIBF via the ^{16}O$(\alpha,pn)^{18}$F reaction. The beam had an average intensity of 2×10^5 ^{18}F/s and was contaminated by the stable isobar ^{18}O at a ratio of ^{18}O/^{18}F ~ 8. The mixed beam was used to bombard a polypropylene CH_2 target as shown in Fig. 1. Recoil α and ^{15}O ions were detected in coincidence in the SIDAR array. By plotting the α energy versus the heavy recoil energy, the ^{1}H(^{18}F,α)^{15}O events were cleanly distinguished from the contaminant ^{1}H(^{18}O,α)^{15}N events. The yield of the ^{1}H(^{18}F,p)^{18}F reaction was measured simultaneously. Protons elastically scattered from ^{18}F were detected in the SIDAR and distinguished from ^{18}O induced events by requiring coincidence with recoil ^{18}F ions detected in a gas ionization counter. Excitation functions for the ^{1}H(^{18}F,α)^{15}O and ^{1}H(^{18}F,p)^{18}F reactions were produced by measuring the yields of these reactions as a function of beam energy (Fig. 2). Precise resonance parameters were obtained from a simultaneous fit of the data sets [9]. Use of this method allowed the strengths of two important ^{18}F$(p,\alpha)^{15}$O resonances at $E_{c.m.}$ = 330 and 665 keV to be determined [8].

It was found, however, that other low energy resonances may also make important contributions to the ^{18}F$(p,\alpha)^{15}$O rate especially at low temperatures [16]. The cross sections populating these state were too low to be measured in the laboratory so other methods were necessary to constrain their strengths. An alternative measurement involved populating the mirrors of the ^{19}Ne levels of interest via the ^{18}F$(d,p)^{19}$F reaction. The idea was that by measuring the single-particle neutron spectroscopic factors of states in ^{19}F, one could then use isospin symmetry to constrain the proton partial widths (and thus the strengths) of the mirror levels in ^{19}Ne. This experiment was recently performed at the HRIBF, and while the analysis is still preliminary, it looks likely that important constraints will be placed on the strengths of several resonances in ^{19}Ne [17].

4 Studies of r-Process Nuclei

The r-process produces roughly half of the elements heavier than iron via a series of neutron captures and beta decays flowing through extremely neutron-rich nuclei. The path and abundances produced are uncertain, however, because of the lack of information on the properties and structure of extremely neutron-rich nuclei. Recently accelerated beams of many neutron-rich nuclei have become available at the HRIBF opening some of the first studies of many nuclei thought to be on the r-process path.

The most critical piece of information that is needed to understand r-process nucleosynthesis is the masses of nuclei along the path. The masses used in calculations are currently based almost entirely upon extrapolations. It is critical that mass models be benchmarked in this mass region with actual measurements.

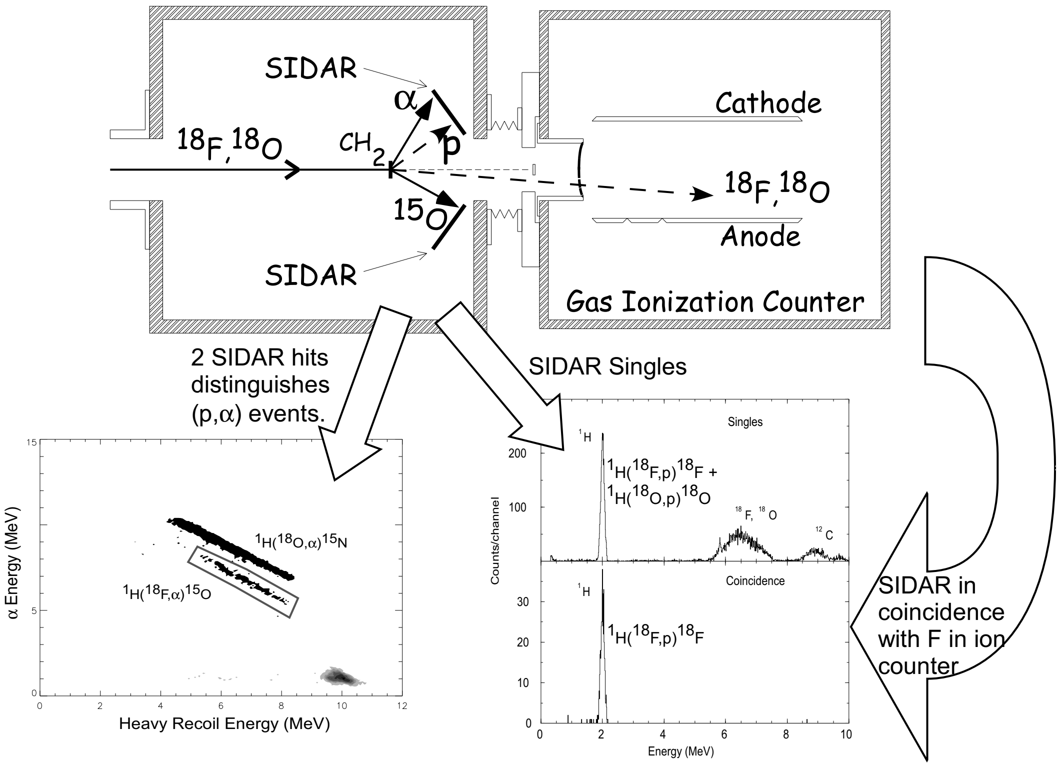

Figure 1. A mixed ^{18}F/^{18}O beam bombarded a polypropylene target. Recoil α and ^{15}O ions were detected in coincidence in SIDAR, while beam-like ^{18}F recoils were detected in an ionization counter and in coincidence with scattered protons.

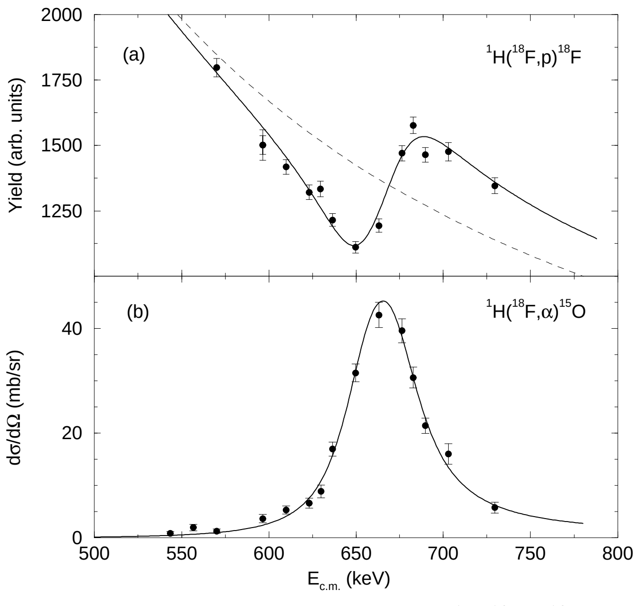

Figure 2. Excitation functions for the ^{1}H(^{18}F,p)^{18}F and ^{1}H(^{18}F,α)^{15}O reactions were produced by measuring the yields of these reactions as a function of beam energy.

To better constrain these mass models, mass measurements were performed on a number of short-lived neutron-rich fission products at the HRIBF. The measurements were performed using a simple setup consisting of a position-sensitive microchannel plate and an ion counter mounted near the focus of the energy-analyzing magnet of the 25-MV tandem accelerator [18]. The idea of the measurements was that two isobars of different mass passing through the tandem simultaneously will have the same energy but different momenta, and thus will be bent to different locations at the focus of the energy-analyzing magnet. By measuring an unknown mass difference relative to a known mass difference, it is not necessary to known the magnet radius. Measurements of mass differences were performed by measuring the position and Z of each ion in a mixed beam composed of unknown- and known-mass isobars. Using this technique, the masses of $^{77-79}$Cu, $^{83-86}$Ge, and $^{84-86}$As have been measured for the first time. It is expected that in the final analysis, the masses will be determined with roughly a 200-keV uncertainty.

In addition to knowing the masses, it is also important to understand the structure of r-process nuclei and how shell structure evolves away from stability. It is especially important to understand nuclei near neutron-closed shells where the r-process abundances peak as a result of the small neutron-capture cross sections of these nuclei. We have performed the first neutron-transfer experiment on an r-process nucleus by studying the ^{2}H(^{82}Ge,p)^{83}Ge reaction in inverse kinematics [11]. The (d,p) reaction provides a great deal of information on the compound nucleus. The energies of the detected protons yield the excitation energies of single-particle neutron states. The angular distributions elucidate the spins, and the relative populations of states determine neutron-spectroscopic factors. Knowledge of these spectroscopic factors is critical for calculating the neutron-capture rates. A beam of 4 MeV/u ^{82}Ge was used to bombard a deuterated-polypropylene (CD_2) target. Protons from the

(d,p) reaction were detected at backward laboratory (forward center-of-mass) angles in the SIDAR. The ^{82}Ge beam was contaminated with ^{82}Se at a ratio of ^{82}Se/^{82}Ge $\sim 6/1$. After passing through the target, the beam ($\sim\ 10^5$ pps) entered the gas ionization counter allowing the identification of ^{2}H(^{82}Ge,p)^{83}Ge events and rejecting ^{2}H(^{82}Se,p)^{83}Se events. The detector configuration was the same as in Fig. 1 except SIDAR was placed at backward laboratory angles and the entire beam (not just scattered beam) was detected in the ion counter. The spectrum of SIDAR events in coincidence with recoil ^{83}Ge ions is shown in Fig. 3 and clearly shows the presence of protons from the (d,p) reaction. Preliminary analysis indicates that the $\frac{1}{2}^+$ excited state is only about 260 keV above the $\frac{5}{2}^+$ ground state [18]. This excitation energy is lower than predicted by shell-model calculations and is being further investigated.

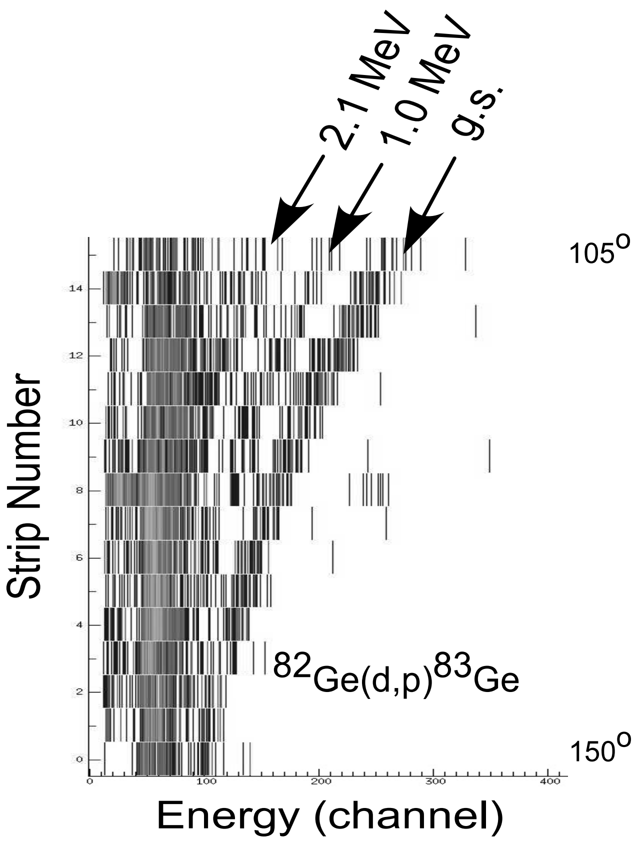

Figure 3. The energy of ions detected in SIDAR in coincidence with Ge recoils. Transitions populating states in ^{83}Ge are labeled with their approximate excitation energy.

5 Conclusions

The availability of radioactive beams has opened new vistas for studies in nuclear astrophysics. At the Holifield Radioactive Beam Facility, we have used beams of ^{17,18}F to study nova and X-ray burst nucleosynthesis. We are also using neutron-rich beams to study nuclei near or on the r-process path. We have made the first neutron-transfer measurement on an r-process nucleus via a ^{82}Ge$(d,p)^{83}$Ge study. We are planning to continue our studies using beams of ^{7}Be, ^{84}Se, and ^{132}Sn.

Most of the experiments mentioned here were performed by the Radioactive Ion Beams for Explosive Nucleosynthesis Studies (RIBENS) collaboration which is a collaboration of approximately 30 scientists from 11 institutions including ORNL, Yale University, University of North Carolina at Chapel Hill, Tennessee Technological University, Colorado School of Mines, Rutgers University, and the University of Edinburgh. The author thanks P. A. Hausladen for permission to discuss the mass measurements.

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