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Direct measurements of (p,γ) cross sections at astrophysical energies using radioactive beams and the Daresbury Recoil Separator

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There are a number of astrophysical environments in which the path of nucleosynthesis proceeds through proton-rich nuclei. Radioactive nuclei have traditionally not been available as beams, and thus proton-capture reactions on these nuclei could only be studied indirectly. At the Holifield Radioactive Ion Beam Facility (HRIBF), some of the first direct measurements of (p,γ) cross sections on radioactive beams have been made. The Daresbury Recoil Separator (DRS) has been used to separate the recoils of interest from the unreacted primary beam and identify them in an isobutane-filled ionization counter. Data from ^{17}F$(p,\gamma)^{18}$Ne and ^{7}Be$(p,\gamma)^{8}$B measurements are presented.

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1. Introduction

In novae and x-ray bursts, hydrogen fuel is burned through a series of proton-capture reactions on stable and radioactive nuclei followed by subsequent β decays [1]. The nucleosynthesis can lead to proton-rich nuclei, many of which have scarcely been studied in the laboratory. Now, however, with the development of intense reaccelerated beams of radioactive nuclei, it is possible to make direct measurements of proton-capture cross sections far from stability and thus calibrate this flow to heavier elements. At the HRIBF [2], some of the first measurements with radioactive beams have been made.

Proton-capture reactions are studied at the HRIBF by bombarding a windowless hydrogen gas target [3] with intense radioactive beams. The recoil products from (p,γ) reactions are separated from the primary beam with the DRS [4]. The DRS has two large 1.5-m-long Wien Filters with adjustable slits that are used to intercept the primary beam after it has been steered off axis (see Fig. 1). A final A/q focus is obtained at the focal plane of the DRS where a segmented, isobutane-filled gas ionization counter is located. Comparison of the differential energy loss with the total energy allows for the atomic number to be determined for the detected ions. Scattered primary beam that “leaks” through the DRS can therefore be distinguished from the (p,γ) reaction products, which are counted to determine the cross sections for proton capture.

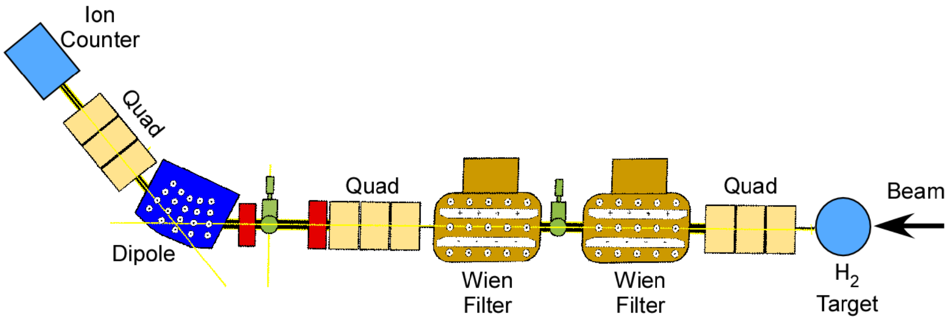

Figure 1: The Daresbury Recoil Separator is used for studying proton-capture reactions on exotic nuclei. When tuned for capture recoils, the primary beam is intercepted by moveable slits after the first Wien filter. The recoils of interest are identified and counted by an ionization counter at the DRS focal plane.

2. The ^{17}F$(p,\gamma)^{18}$Ne Reaction

The ^{17}F$(p,\gamma)^{18}$Ne reaction is important in a number of astrophysical environments. In novae, the ^{17}F$(p,\gamma)^{18}$Ne reaction controls the flow through the sequence ^{16}O$(p,\gamma)^{17}$F$(p,\gamma)^{18}$Ne$(\beta^+)^{18}$F leading to the production of the radioisotope ^{18}F, which is a target of γ-ray astronomy [5]. If, however, the β-decay of ^{17}F is faster than the proton-capture rate, the production of odd-mass isotopes ^{15}N and ^{17}O is increased. These isotopes are thought to be primarily made in novae and thus their abundances are good indicators of the conditions present in the explosion [6]. In x-ray bursts, it was found [7] that the energy generation rate during the preburst phase is strongly affected by the rate of this reaction. Heavy element production is later initiated by the αp chain ^{14}O$(\alpha,p)^{17}$F$(p,\gamma)^{18}$Ne$(\alpha,p)^{21}$Na..., which, in turn, depends on the rates of reactions involved.

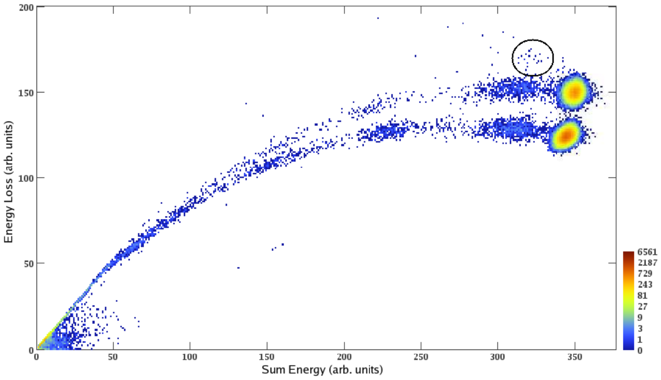

Figure 2: The ion counter ΔE vs. E spectrum obtained for the 3^+ ^{17}F$(p,\gamma)^{18}$Ne resonance. Recoil ^{18}Ne ions are circled.

The ^{17}F$(p,\gamma)^{18}$Ne reaction rate is thought to be dominated by direct capture below 0.3 GK and a single 3^+ resonance at $E_{c.m.} = 600$ keV at higher temperatures. The resonance energy and and proton width have been precisely measured in a ^{1}H(^{17}F,p)^{17}F study [8], but the strength of this important resonance had never been directly measured. Since the γ width is much smaller than the proton width for this resonance, the resonance strength is directly proportional to the γ width. As only estimates existed for the strength of the 3^+ resonance, the rate of the ^{17}F$(p,\gamma)^{18}$Ne reaction has been uncertain by orders of magnitude [9]. The goal of the HRIBF study was to make the first direct measurement of the strength of the 3^+ ^{17}F$(p,\gamma)^{18}$Ne resonance.

A mixed ^{17}F/^{17}O beam (^{17}F was typically 35-70 % of the total beam) bombarded the windowless hydrogen gas target operated at 4 Torr. Beam currents up to 2×10^{7} ^{17}F/s were obtained. Since charge state distributions of ^{18}Ne recoils were not known, the DRS was tuned in succession for the three strongest charge states and the yields integrated to determine the total reaction rate. A ^{17}F bombarding energy of 10.83 MeV was used which, after energy loss in the target, corresponded to a center-of-mass energy range coverage from 590 - 606 keV. Data obtained on resonance are shown in Fig. 2. Data were also taken off resonance to estimate the background that was present in Fig. 2. The resonance strength was extracted from the observed yield by integrating the Breit-Wigner resonance cross section weighted by the stopping cross section over the energy range covered by the target [10]. The resonance strength obtained in this work is $\omega\gamma = 33\pm14(stat)\pm17(sys)$ meV [11]. The calculated ^{17}F$(p,\gamma)^{18}$Ne reaction rate is larger than previous estimates by a factor of ~ 1.8 at 1.0 GK.

3. The ^{7}Be$(p,\gamma)^{8}$B Reaction

The ^{7}Be$(p,\gamma)^{8}$B reaction is important for understanding the observed flux of solar neutrinos from the sun. There have been several studies of the ^{7}Be$(p,\gamma)^{8}$B reaction by both direct and indirect techniques. Unfortunately, the required precision has not yet been reached as the direct measurements and the indirect techniques (e.g., Coulomb dissociation) have converged at different values for the astrophysical S-factor at 0 keV, $S_{17}(0)$ [12]. As described in a review article [13], “It is essential to have additional ^{7}Be$(p,\gamma)^{8}$B measurements, to establish a secure basis for assessing

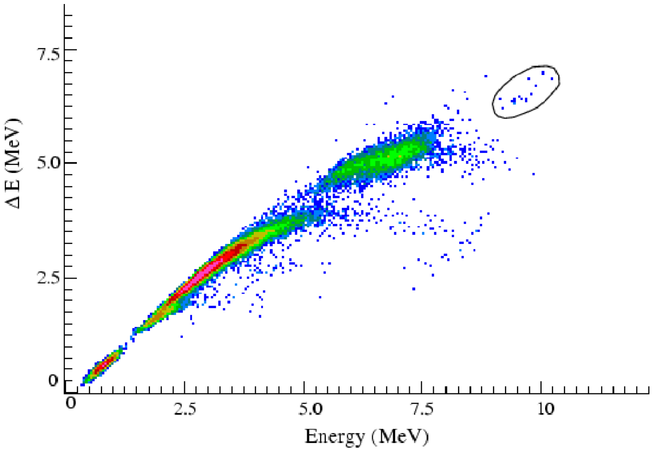

Figure 3: The ion counter ΔE vs. E spectrum obtained for the ^{1}H(^{7}Be,γ)^{8}B reaction. Twenty-two events from ^{8}B recoils were observed.

the best estimate and the systematic errors for $S_{17}(0)$.” “Experiments with ^{7}Be ion beams would be valuable. Such experiments would avoid many of the systematic uncertainties that are important in interpreting measurements of proton capture on a ^{7}Be target.”

To address these issues, we are beginning a study of the ^{7}Be$(p,\gamma)^{8}$B cross section at the HRIBF [14]. The goal of our initial measurement was to make the first statistically-significant measurement of the cross section using a radioactive ^{7}Be beam. The measurement was made at a single energy since the energy dependence has been well characterized by previous studies but the absolute value of the cross section is still uncertain. The radioactive ^{7}Be material accelerated to make the ^{7}Be beam was produced at the Triangle Universities Nuclear Laboratory (TUNL). A 10-MeV proton beam bombarded a series of Li metal targets producing ^{7}Be via the ^{7}Li$(p,n)^{7}$Be reaction. The material was then loaded into sputter cathodes to be used in a multi-sample sputter ion source [15] at ORNL. Beam currents peaked at about 2×10^{7} ^{7}Be/s with typical beam compositions of ^{7}Li/^{7}Be $\sim$ 7/1 [14].

The 12-MeV beam was used to bombard the windowless hydrogen gas target run at a pressure of 5 Torr. The DRS was tuned for ^{8}B recoils of charge state q=+5 ($>$ 90% charge state fraction) and data were accumulated for approximately 4 days. The resulting ion counter spectrum is shown in Fig. 3. Twenty-two ^{8}B events were observed during this time as shown encircled in Fig. 3. The amount of beam that bombarded the gas target was determined from the number of scattered protons observed in the $\pm45^{\circ}$ silicon detectors. The ratio of scattered protons to impinged beam particles was measured by implanting the beam into metal plates while counting scattered protons with the detectors. The plate was then removed and the amount of ^{7}Be determined from a γ-ray spectrum taken with a calibrated Ge detector. These samplings were performed at regular intervals to account for long-term changes in the beam purity, none of which were observed.

Putting this information together, the cross section of the ^{7}Be$(p,\gamma)^{8}$B reaction was determined to be $(1.12\pm0.27)\mu$b at $E_{c.m.}$=1.5 MeV [14]. This agrees with the values measured in Ref. [16] with a ^{7}Be target. From Ref. [16], the extrapolated value of the cross section from the 1.4 - 1.6 MeV data points is $(0.91\pm0.03)\mu$b at 1.5 MeV. Using the extrapolation from [16] of our cross section to stellar energies yields an S-factor of $S_{17}(0) = (26.8\pm6.5)$ eV-b [14]. The uncertainty in our result is dominated by statistics. To address this, future runs will make use of higher amounts of activity initially loaded into the sputter cathode to produce higher intensity ^{7}Be beams. Arrangements have been made for future ^{7}Be production to occur at the Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI) in Debrecen, Hungary. It is hoped that with increased beam intensity, measurements at several energies can be made.

4. Conclusions

The availability of intense radioactive beams is providing opportunities to directly measure proton-capture rates on astrophysically-important nuclei. The Daresbury Recoil Separator has been installed at the HRIBF and complemented with a windowless hydrogen gas target to perform such measurements. The first direct measurement of the ^{17}F$(p,\gamma)^{18}$Ne reaction has been made, along with the first statistically-significant measurement with a ^{7}Be beam of the ^{7}Be$(p,\gamma)^{8}$B cross section. This measurement, however, is not yet statistically competitive with ^{7}Be target experiments and thus work is ongoing to improve the intensity of the ^{7}Be beam at HRIBF.

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