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Determining the $^{14}O(\alpha,p)^{17}F$ astrophysical rate from Measurements at *TwinSol*

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Abstract

The $^{14}O(\alpha,p)^{17}F$ reaction is an important trigger reaction to the α-p process in X-ray bursts. The most stringent experimental constraints on its astrophysical rate come from measurements of the time-inverse reaction, $^{17}F(p,\alpha)^{14}O$. Previous studies of this inverse reaction have sufficiently characterized the high-energy dependence of the cross section but there are still significant uncertainties at lower energies. A new measurement of the $^{17}F(p,\alpha)^{14}O$ cross section is underway at the Twin Solenoid (*TwinSol)* facility at the University of Notre Dame using an in-flight secondary ^{17}F beam. The initial results are promising but improvements are needed to complete the measurement. The initial data and plans for an improved measurement are presented in this manuscript.

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1. Introduction

Type I X-ray bursts are the most frequently observed thermonuclear explosions in nature (Cyburt et al. 2016). They occur in accreting binaries and emit X-rays with light curves lasting 10-100s and recurring with periods of hours to days. The peak of the burst is initiated with the α-p process [$^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\alpha,p)^{21}Na(p,\gamma)^{22}Mg$…], which eventually transitions to the rapid-proton (rp) capture process leading to heavy element production. Recent sensitivity studies have shown that a number of these (α,p) reactions along with a handful of others can have dramatic effects on the observed X-ray burst light curve (Cyburt et al. 2016, Parikh et al. 2008). Of particular importance is understanding the trigger reaction, $^{14}O(\alpha,p)^{17}F$, since its rate determines, in part, the astrophysical conditions under which the α-p process is initiated.

The astrophysical $^{14}O(\alpha,p)^{17}F$ rate is dominated by the contribution of resonances arising from ^{18}Ne levels above 6 MeV in excitation energy and a direct reaction component (Hahn et al. 1996). Studies (Harss et al. 1999, Blackmon et al. 2001) of the reaction have focused upon measurements of the time-inverse reaction, $^{17}F(p,\alpha)^{14}O$, since high-quality beams of ^{17}F have been available and targets of CH_2 are much easier to implement than the helium targets that are required to measure $^{14}O(\alpha,p)^{17}F$ directly. The data from these studies are plotted in Fig. 1. While these data seem adequate above ^{17}F beam energies of 55 MeV, below this energy the measurements are sparse and suffer from large uncertainties, making it difficult to assess any possible resonance structure. Particularly important is determining the properties of potential resonances near $E(^{17}F)$=40 MeV that could correspond to a known ^{18}Ne state at E=6.15 MeV (Hahn et al. 1996). A new study of the $^{17}F(p,\alpha)^{14}O$ reaction was recently initiated at the University of Notre Dame Nuclear Science Laboratory (NSL) to address these uncertainties.

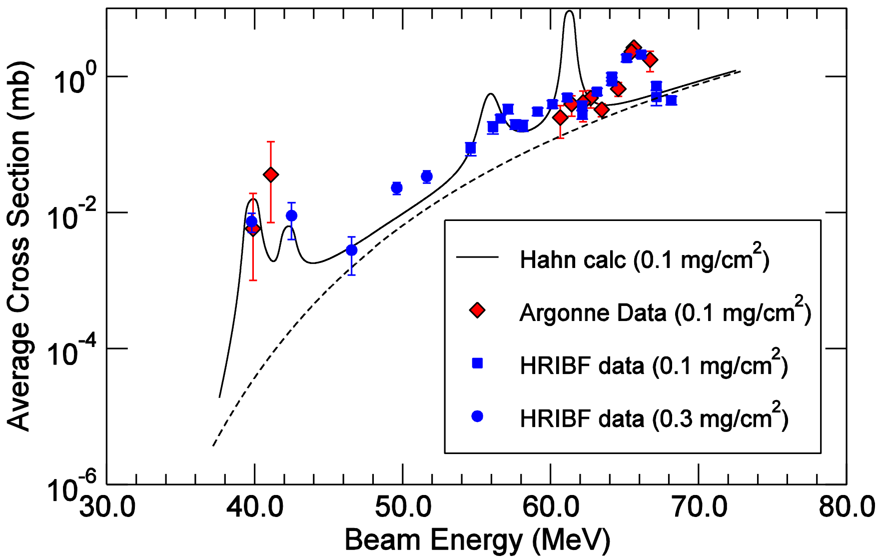

Figure 1: (color online) Previous $^{17}F(p,\alpha)^{14}O$ measurements. The HRIBF data are from Blackmon et al. 2001, and the Argonne data are from Harss et al. 1999. The target thickness is indicated in the legend. The solid curve is a prediction based upon resonance parameters from Hahn et al. 1996 averaged over the energy loss in the target.

2. ^{17}F(p,α)^{14}O Measurements

Beams of ^{17}F were produced using the Twin Solenoid (*TwinSol*) magnetic separator (Lee et al. 1997). Energetic (60-80 MeV) beams of ^{16}O were accelerated by the NSL FN tandem and delivered to the *TwinSol* production target consisting of 4 gas cells containing approximately 1 atm of D_2 gas enclosed by 5 μm thick Ti windows (O'Malley et al. 2016). The 4 cells were attached to a single vacuum feedthrough in order to allow rapid changing of production targets in the event of window rupture. The ^{17}F ions were produced in the gas cells by the ^{2}H(^{16}O,n)^{17}F reaction, which, owing to the inverse kinematics, were produced at very forward angles of less than 5 degrees. The primary ^{16}O beam was stopped in a water-cooled Faraday cup directly after the production target, while the produced ^{17}F ions were collected and transmitted by *TwinSol*. Using primary beams of 50 pnA of ^{16}O resulted in ^{17}F secondary beam intensities of ~10^5 ^{17}F/s at roughly 50% purity with ^{17}F/^{16}O ~ 1. A spectrum of the secondary beam as sampled by a silicon telescope is shown in Fig. 2. Multiple energies of the beam constituents (primarily ^{16}O and ^{17}F) were observed as a result of multiple charge states being transmitted with similar magnetic rigidities. These lower energy components and contaminants in the beam were not expected to produce background since (p,α) reactions were energetically forbidden for these constituents.

To study the ^{17}F(p,α)^{14}O reaction, this beam bombarded 400 μg/cm^2 CH_2 targets. Both the heavy and light reaction products were detected simultaneously in two annular arrays of silicon detectors. The larger detector array covered 8˚-25˚ in the laboratory while the smaller detector covered 3˚-6˚. The time between coincident events was measured by triggering a time to amplitude converter (TAC) on any hit in the larger detector and stopping the clock on delayed coincident events from the smaller detector. True coincident events were evident from their very tight time correlation. The unreacted beam was attenuated and detected downstream from the silicon detectors with a fast ionization counter in order to monitor the purity and intensity of the secondary beam. The (p,α) events of interest were identified by plotting the energy of coincident events in the large and smaller detector arrays. Proof of principle data were taken with an ^{17}O beam and are plotted in Fig. 3. The ^{1}H(^{17}O,α)^{14}N events were cleanly separated from elastic scattering and other background events.

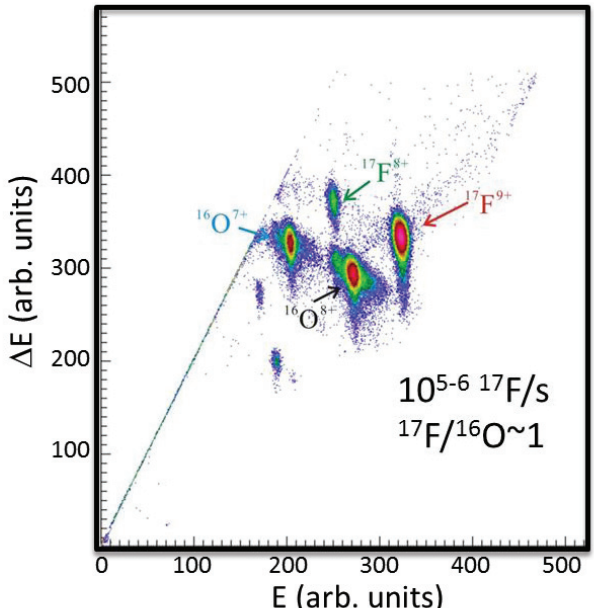

Figure 2: (color online) A particle identification spectrum taken to assay the secondary beam. Multiple charge states with the same magnetic rigidity and transported by *TwinSol* to the secondary target. A small amount of N and C was also observed.

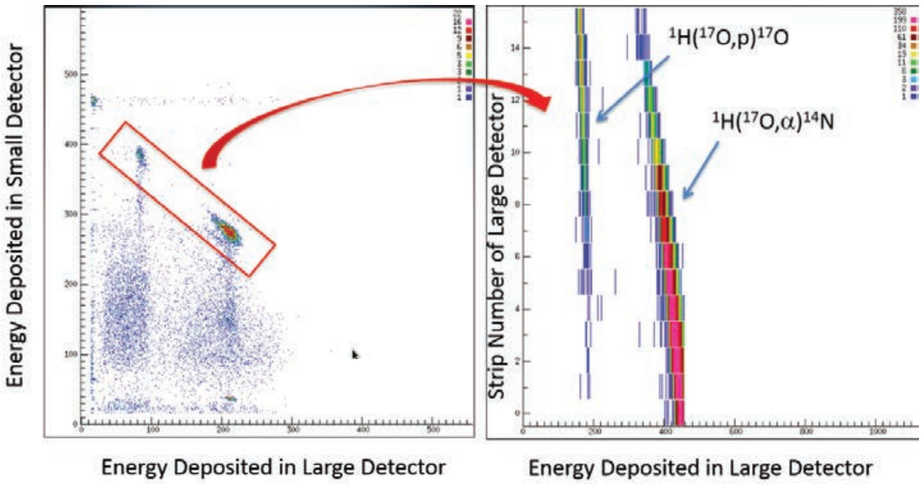

Figure 3: (color online) Data taken with an ^{17}O beam on a CH_2 target. Events from the ^{1}H(^{17}O,p)^{17}O and ^{1}H(^{17}O,α)^{14}N reactions are cleanly identified.

Encouraged by the results from the ^{1}H(^{17}O,α)^{14}N runs, a first attempt was made to study the ^{1}H(^{17}F,α)^{14}O reaction. It was clear that this measurement would be more challenging, owing to the fragmented nature of the secondary beam and the lower cross section for the ^{17}F(p,α)^{14}O reaction. Data were taken for ~62 hours with a 51.5-MeV ^{17}F beam on target. A plot similar to Fig. 3 is shown in Fig. 4 for the ^{17}F data along with a simulation (Pain 2017) for the expected energies (not intensities) of detected events. While elastic scattering (p,p) events were evident from the four primary constituents of the beam, there was not a clear signature of the ^{17}F(p,α)^{14}O events even though on the order of 20-30 events were expected during this time period. The random coincidence background was too large to cleanly identify the events of interest.

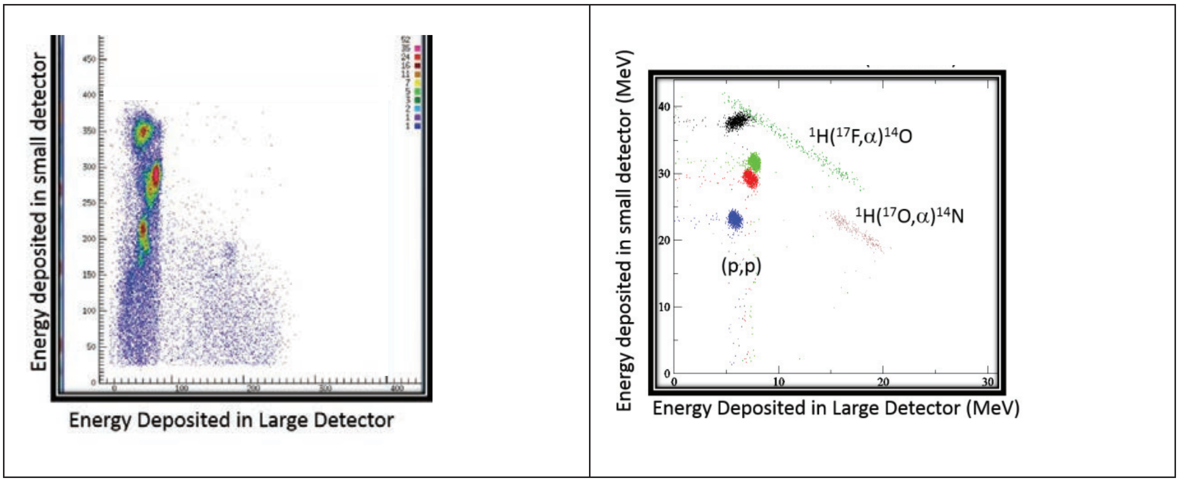

Figure 4: (color online) Left: Data similar to Fig. 3 taken with the secondary ^{17}F beam on a CH_2 target. Right: A simulation of the expected energies of groups produced by various reactions.

3. Outlook

While the first attempt to study the ^{17}F(p,α)^{14}O reaction was not successful, there are a number of improvements that will be implemented for upcoming measurements. One improvement aimed at increasing the clarity of the obtained spectra will be to image electron emission induced by the incident beam from the CH_2 target with a position-sensitive microchannel plate detector. This offers a number of advantages such as measuring the position of incident ions on an event by event basis and establishing an event time reference. Imaging the ion positions will allow for a better determination of the reaction products' angles of emergence. The timing measurements can be used to distinguish protons from α particles hitting the silicon detectors via their time of flight and identifying the beam constituents by measuring their time of flight through the separator. Detector telescopes may also be implemented by adding an additional layer of silicon detectors (65-100 μm thick) to distinguish α particles emitted from the reactions.

Improvements will also be made to the beam intensity and quality. The production targets have been redesigned by increasing the length a factor of two and reducing the entrance/exit windows by 20% in thickness. Since most of the energy that is lost by the primary beam as it traverses the target occurs in the window, doubling the length of the cell should result in a factor of two increase in the beam intensity without any further degradation of beam quality. By a similar argument, reducing the entrance/exit foil thicknesses should result in better beam quality with no loss in intensity. A secondary benefit is that a lower-energy primary beam can be used (since the energy loss is less), and higher primary beam intensities will be available since the FN tandem would be running well below its instability limit. Depositing less energy in the windows should also result in increased window lifetimes during bombardment. Already, the original 5 μm thick Ti windows have been replaced with 4 μm foils with no obvious decrease in performance. These windows have been used in several subsequent *TwinSol* measurements and should result in greatly improved beam characteristics. Further tests are currently being performed with 3 μm Ti windows that were rolled from thicker foils. Finally, additional improvements will come from relocating the second *TwinSol* solenoid further downstream. Simulations indicate moving the second solenoid 1 m downstream should result in beam spots roughly one-half of the current size (0.5" compare to 1"). Work is currently underway to implement this change.

In conclusion, determining the rate of the ^{14}O(α,p)^{17}F reaction is critical to understanding the initiation of the αp process in X-ray burst nucleosynthesis. The best constraints on the rate so far have come from measuring the inverse reaction, ^{17}F(p,α)^{14}O. At the Notre Dame NSL, a new experiment is under development to measure the ^{17}F(p,α)^{14}O cross section over the entire energy range needed for X-ray burst models. Initial tests have indicated that further improvements and developments are needed and those are currently underway. New measurements will begin once the FN tandem upgrade is complete in 2017.

Acknowledgements

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