Recent Nuclear Astrophysics Measurements using the *TwinSol* Separator

D W Bardayan¹, T Ahn¹, J Allen¹, F D Becchetti², J C Blackmon¹, M Brodeur¹, B Frentz¹, Y K Gupta¹,⁴, M R Hall¹, O Hall¹,⁵, S Henderson¹, J Hu¹,⁶, J M Kelly¹, J J Kolata¹, A Long¹, J Long¹, K Macon³, C Nicoloff¹,⁷, P D O’Malley¹, K Ostdiek¹, S D Pain⁸, J Riggins², B E Schultz¹, M Smith¹, S Strauss¹, R O Torres-Isea²

¹Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA
²Physics Department, University of Michigan, Ann Arbor, MI 48109, USA
³Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA
⁴Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai, 400085, India
⁵Department of Physics, University of Surrey, Guildford, GU2 7XH, United Kingdom
⁶Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
⁷Department of Physics, Wellesley College, Wellesley, MA 02481, USA
⁸Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

E-mail: danbardayan@nd.edu

**Abstract.** Many astrophysical events, such as novae and X-ray bursts, are powered by reactions with radioactive nuclei. Studying the properties of these nuclei in the laboratory can therefore further our understanding of these astrophysical explosions. The *TwinSol* separator at the University of Notre Dame has recently been used to produce intense (~10⁶ pps) beams of ¹⁷F. In this article, some of the first measurements with these beams are discussed.

### 1. Introduction

Nova explosions and X-ray bursts are brilliant astrophysical events resulting from the rapid accretion of hydrogen-rich material onto a degenerate star from a binary companion [1]. Convection mixes underlying material with this layer of hydrogen, and thermonuclear reactions are initiated as the temperatures and densities rise. These reactions produce radioactive proton-rich nuclei, which can be involved in further nuclear processing owing to the short reaction times in such environments. The explosion dynamics and nucleosynthesis in such explosions are therefore strongly dependent upon the reaction rates and the properties of the proton-rich, exotic nuclei produced.
2. Production of Radioactive Beams

At the Notre Dame Nuclear Science Laboratory (NSL), studies of proton-rich nuclei are enabled via the use of the TwinSol magnetic separator [2]. Intense (~1 µA) stable beams are accelerated up to ~5 MeV/u by the NSL 11-MV FN tandem accelerator for bombardment of light-ion gas targets to produce exotic nuclei. The use of inverse-kinematical production reactions results in higher-energy, forward-moving radioactive beams and higher-efficiency capture of the exotic products by the TwinSol solenoids. The production target consists of 4 independent gas cells that typically contain ~1 atmosphere of hydrogen or helium gas held by 5-µm-thick Ti windows. A picture of the production target assembly is shown in Fig. 1. The use of multiple gas cells on a single motorized feedthrough allows for fast and efficient changeovers in the event of window deterioration and rupture. The primary beam is subsequently stopped and monitored by a Faraday cup directly behind the target while the exotic reaction products produced at angles between 2-5 degrees are transmitted through the TwinSol device. Within the past year, a primary focus of the TwinSol nuclear astrophysics program has been the production and use of intense $^{17}$F beams, the discussion of which comprises the remainder of this article.

$^{17}$F beams between 40-52 MeV are produced by bombarding deuterium gas with $^{16}$O beams between 64-74 MeV. The energy range of exotic beam products is determined by the reaction kinematics of the $^2$H($^{16}$O,$^{17}$F)n reaction and by the energy loss in the gas-cell and windows. The secondary $^{17}$F beam is subsequently purified by separation and focusing with the TwinSol solenoids onto a secondary target ~2 m downstream from the second solenoid. The beam composition is assayed at the secondary target position via use of a silicon surface barrier detector telescope and a position-sensitive ionization counter (see Fig. 2). The secondary beam is primarily composed of $^{17}$F and $^{16}$O with ratios varying between $^{17}$F/$^{16}$O ~ 0.5-1.5 depending upon the particular tune. In general the $^{16}$O contaminants are not well focused at the secondary target positions, and thus the beam purity can be improved by appropriate beam collimation. Typical collimation size is between 0.5-2.5 cm depending upon the type of measurement being performed. Trace amounts of $^{17}$O, $^{15}$O, $^{14}$N, and $^{12}$C are also observed in the beam. Secondary beam intensities of up to $2 \times 10^6$ $^{17}$F/s are observed for primary beam intensities of 1 µA of q=+7 $^{16}$O.

Fig. 1: The new NSL multi-cell gas production target is shown in the initial vacuum testing stage with blank flanges (left) along with the windows installed (right).
3. $^{17}\text{F}$ half-life measurement

In astrophysical explosions, one of the primary determinants of the nucleosynthesis is the lifetimes of the nuclei involved. Whether a synthesized radioactive nucleus is subject to further nuclear reactions or simply decays back towards stability is largely determined by its half-life. $^{17}\text{F}$ is produced in large amounts in novae, but despite years of study, there was not good agreement for the half-life of $^{17}\text{F}$ (as shown in Table 1), and thus a new measurement was warranted.

Table 1: Previous $^{17}\text{F}$ half-life measurements are shown.

| $^{17}\text{F}$ Half-life (s) | Reference |
|-------------------------------|-----------|
| 66.0±0.2                      | [3]       |
| 65.2±0.2                      | [4]       |
| 64.50±0.25                    | [5]       |
| 64.8±0.12                     | [6]       |
| 64.31±0.09                    | [7]       |

The secondary $^{17}\text{F}$ beam from TwinSol was implanted into thick tantalum foils on the end of a rotating arm. After a fixed implantation time, the foil was rotated 180 degrees to face a 25-mm-thick plastic scintillator coupled to a photomultiplier tube. While one foil was being counted by the plastic scintillator, a second foil would be subject to further implantation. After the same fixed amount of time, the rotation and counting sequence would begin again. The number of counts observed in the plastic scintillator were referenced to an accurate 100 Hz clock that only deviated by approximately 3s in 10 h during a calibration test. The data collected by this procedure is plotted in Fig. 3 along with a decay-curve fit taking into account the small amount of $^{15}\text{O}/^{17}\text{F}~10^{-3}$ in the beam and letting the background detector count rate ($\sim$2 Hz from room $\gamma$ background) vary as a parameter of the fit. The half-life resulting from this fit was 64.402 ± 0.042 s [8], which agrees well with another recent measurement, 64.347 ± 0.035 s [9] but not several earlier measurements (Table 1).
Fig 3: The number of decay events observed as a function of time in 5-second bins from several cycles of $^{17}$F implantation into Ta foils, rotation in front of a plastic scintillator, and counting $\beta$ particles from the decay.

4. Study of the $^{17}$F(p,α)$^{14}$O reaction

A second thrust of the work with $^{17}$F beams is to better understand the $^{14}$O(α,p)$^{17}$F reaction rate in X-ray bursts. Owing to the difficulty in studying the reaction rate directly, the time-inverse reaction, $^{17}$F(p,α)$^{14}$O, will be studied instead. States in $^{18}$Ne from $E_\gamma=6-7.5$ MeV provide important resonances in the $^{14}$O(α,p)$^{17}$F reaction rate at X-ray burst temperatures, and determining their properties is a top priority [10]. A number of studies have been performed of the $^{17}$F(p,α)$^{14}$O reaction [10-12] and the existing cross section data is plotted in Fig. 4. 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 $E_\gamma=6.15$ MeV [10].

Fig 4: Previous $^{17}$F(p,α)$^{14}$O data sets are shown with the legend indicating the CH$_2$ target thickness that was used in each case. The calculation uses resonance parameters from Hahn et al. [10] to estimate the expected cross section averaged over the energy loss for a 0.1 mg/cm$^2$ target.
To measure the $^{17}$F(p,α)$^{14}$O cross section below 55 MeV, polyethylene (CH$_2$)$_n$ foils will be bombarded with intense $^{17}$F beams produced by TwinSol. The reaction products, $^{14}$O ions and α particles, will be detected in coincidence in annular arrays of silicon strip detectors. Events from the $^{17}$F(p,α)$^{14}$O reaction can be distinguished from other reactions products by their distinctive reaction kinematics and by requiring a tight time-correlation between the detected $^{14}$O ions and α particles. It is envisioned that further clarification of the data can be accomplished via pulsing the beam in short (1-2 ns) bunches and measuring the time-of-flight of ions through the TwinSol separator. This should help reduce background events from the contamination of other ions in the secondary beam.

As a test of the procedure and setup, a measurement of the $^{17}$O(p,α)$^{14}$N reaction was performed at TwinSol. In this case, the production target and Faraday cup were removed so that the $^{17}$O beam could be directly tuned through the separator. The beam then bombarded a 400 µg/cm$^2$ polyethylene foil and reaction α particles were detected at angles between 8-24 degrees in coincidence with recoil $^{14}$N ions. By requiring a proper time coincidence and Q-value for the reaction, the events in Fig. 5 were selected. The events from the $^1$H($^{17}$O,α)$^{14}$N and $^1$H($^{17}$O,p)$^{17}$O reactions were clearly visible and separated. After this successful test run, future studies will focus on measuring the $^{17}$F(p,α)$^{14}$O cross section directly.

5. Conclusions

In conclusion, the availability of exotic beams is opening new and unprecedented opportunities to study astrophysical explosions such as novae and X-ray bursts. TwinSol at the University of Notre Dame was the first such device in the U.S. dedicated to the production of radioactive beams. Recent upgrades to TwinSol have improved its ability to study nuclei and reactions of astrophysical interest. The uncertainty in the $^{17}$F half-life has been greatly reduced, and preparations are on-going for a new study of the $^{14}$O(α,p)$^{17}$F reaction.
This research was supported by the Department of Energy Office of Nuclear Physics, the National Nuclear Security Agency, and the National Science Foundation.

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