Using ^{19}F(^{3}He,t)^{19}Ne*(γ) to Study Astrophysically Important Levels Near the ^{18}F+p Threshold

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Abstract. A direct test of nova explosion models comes from the observation of γ rays created in the decay of radioactive isotopes produced in the nova. One such isotope, ^{18}F, is believed to be the main source of observable γ rays at and below 511 keV. The main destruction mechanism of ^{18}F is thought to be the ^{18}F(p,α)^{15}O reaction, and uncertainties in the reaction rate arise from uncertainties in the energies, spins, and parities of the nuclear levels in ^{19}Ne above the ^{18}F+p threshold. To measure the properties of these levels, the ^{19}F(^{3}He,t)^{19}Ne*(γ) reaction was studied at Argonne National Laboratory and the Nuclear Science Laboratory at the University of Notre Dame.

INTRODUCTION

Nova explosions are energetic astrophysical events that can be observed as a sudden brightening of a binary system followed by a slow dimming. The brightening of the system occurs when the temperature and pressure on the surface of a white dwarf, that has been accreting mass from a less-evolved companion star, reach the right conditions for a thermonuclear runaway (TNR) to occur. Nuclei up to ^{40}Ca are thought to be created in the TNR, with some of those nuclei being important γ-ray emitters, whose γ rays could be detected to test current nova model predictions. However, no detected nuclear-decay γ rays have been confirmed to be from novae [1].

Gamma rays created via e^+-e^- annihilation are expected to have the highest flux from the explosion [2]. These γ rays would be observed as a line at 511 keV, with a continuum at lower energies produced via Compton scattering and photoelectric absorption in the envelope of the explosion [3]. Positrons are produced during the TNR by β^+-unstable nuclei generated by the hot CNO cycle. One of these isotopes, ^{18}F, has a half-life long enough (109.77(5) min [4]) such that any γ rays produced when it decays will be able to escape through the formerly opaque explosion envelope. Therefore, ^{18}F is believed to be the main source of the annihilation radiation γ rays.

Prior to decay, ^{18}F is destroyed by the $^{18}F(p,\alpha)^{15}O$ and $^{18}F(p,\gamma)^{19}Ne$ reactions, of which the (p,α) reaction rate has been shown to be 1000 times faster [5]. Therefore, to understand the production of the annihilation radiation, the $^{18}F(p,\alpha)^{15}O$ reaction rate needs to be sufficiently known to determine how much ^{18}F is destroyed. To estimate the rate, the properties of the energy levels in the compound nucleus, ^{19}Ne, need to be characterized. Interference between a broad *s*-wave resonance at E_{cm} = 665 keV and two $3/2^+$ states near the $^{18}F+p$ threshold has been shown to make the rate uncertain in the temperature range of nova nucleosynthesis (0.1-0.25 GK) [6]. The unknown energies of the two near-threshold $3/2^+$ states exacerbate this uncertainty.

The near-threshold $3/2^+$ states are believed to exist based on the structure of the mirror nucleus, ^{19}F, which has two $3/2^+$ states located at 6497 and 6527 keV. Previous attempts to measure these levels using charged-particle spectroscopy have not been conclusive [6-9] due to their close excitation energy spacing. Therefore, since γ-ray spectroscopy has superior energy resolution, detecting γ-rays from the de-excitation of these ^{19}Ne states would allow their energies to be determined. To do this, the $^{19}F(^3He,t)^{19}Ne^*(\gamma)$ reaction was measured at Argonne National Laboratory using Gammasphere ORRUBA Dual Detectors for Experimental Structure Studies (GODDESS) [10] and at the Nuclear Science Laboratory of the University of Notre Dame using *TwinSol* [11] and Clovershare. The two experiments are complimentary, in that the GODDESS experiment provides very good γ-ray angular coverage, albeit with a lower beam intensity, whereas the Twinsol experiment has less γ-ray angular coverage but can use higher beam intensities due to the separation of the tritons from the other reaction products.

$^{19}F(^3He,t)^{19}Ne^*(\gamma)$ USING GODDESS

Experiment Overview

The $^{19}F(^3He,t\gamma)^{19}Ne$ reaction was studied using a 30-MeV ^3He beam delivered by ATLAS at Argonne National Laboratory. Beam intensities of approximately 2.5 pnA impinged on a 995 μg/cm^2 CaF_2 target supported on a thin carbon backing (0.12-μm thick). Reaction tritons were detected in the Oak Ridge Rutgers University Barrel Array (ORRUBA) [12], which was augmented with QQQ5 detector telescopes on the endcaps [10], whereas γ rays from the de-excitation of the ^{19}Ne nuclei were detected using the high-purity germanium (HPGe) detector array Gammasphere [13]. The combination of these two detection systems is known as GODDESS; a schematic is given in Fig. 1.

Charged-Particle Detection

ORRUBA consists of up to 12 ΔE-E telescopes in the downstream half of the barrel; some of these were removed to make room for the target ladder. These telescopes each consist of a 65-μm thick BB10 detector, which is segmented into eight strips along the length of the barrel, and a 1000-μm thick Super X3 (SX3) detector, which consists of four electronically-segmented resistive strips along the length of the barrel. The resistive strips of the SX3 detectors allow for precise angular reconstruction of the detected particles with a resolution of approximately 1°.

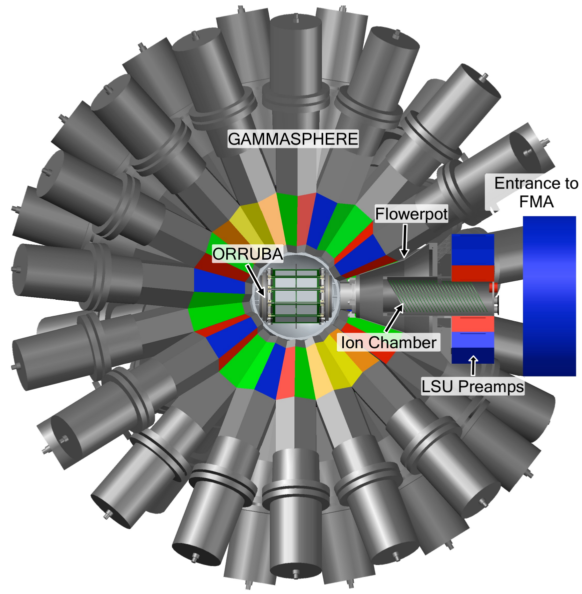

FIGURE 1. Drawing [14] of GODDESS showing the individual components. The ion chamber was not used in this experiment.

For this experiment, the downstream endcap of the ORRUBA barrel consisted of two ΔE-E telescopes created using QQQ5 detectors with thicknesses of 100 and 1000 μm. The QQQ5 detectors are electronically segmented into 32 annular strips whose pitch decrease at larger angles, thereby also providing an angular resolution of approximately 1°. To stop the scattered ^{3}He beam, an aluminum degrader plate (0.5-mm thick) was mounted in front of the QQQ5 detectors. The degrader reduced the triton energies by about 1/3, allowing the tritons generated via population of the ^{19}Ne ground state to be stopped in the telescope.

Figure 2 shows the particle identification (PID) spectrum obtained in the QQQ5 detectors at 20°. In this spectrum, protons and deuterons from (^{3}He,p) and (^{3}He,d) reactions with the target nuclei can also be seen. However, no helium nuclei are seen since they were stopped in the aluminum plate. The plate reduced the charged-particle energy resolution to approximately 500 keV, but this was not an issue since the level energies were to be identified via their γ-ray decays in the Gammasphere spectra. The charged-particle spectra were used to provide a reaction-channel gate on the Gammasphere spectra such that the higher-lying states could be cleanly identified via triton-γ-γ coincidences.

Gamma-Ray Detection

Gamma rays from the de-excitation of the ^{19}Ne nuclei were detected in the Compton-suppressed HPGe detector array Gammasphere, which can have up to 110 detectors. For this experiment, Gammasphere consisted of 92 detectors. To cleanly identify weak gamma branches from the levels of interest, additional coincidence requirements needed to be included. Placing constraints on the timing between ORRUBA and Gammasphere greatly reduced the random background and increased the signal-to-noise ratio, allowing ^{19}Ne gamma rays to be initially observed (see Fig. 3). For further analysis, the spectrum then needs to be gated on an energy range of the detected tritons shown in Fig. 2. Doing so allows constraints to be placed on energy of the ^{19}Ne level that the detected γ ray originated from. Gating on a well-known low-energy γ ray (i.e. the 238- or 275-keV γ rays from the first and second excited states, respectively) is also necessary to correctly identify the transitions. The analysis of these data using these techniques is ongoing.

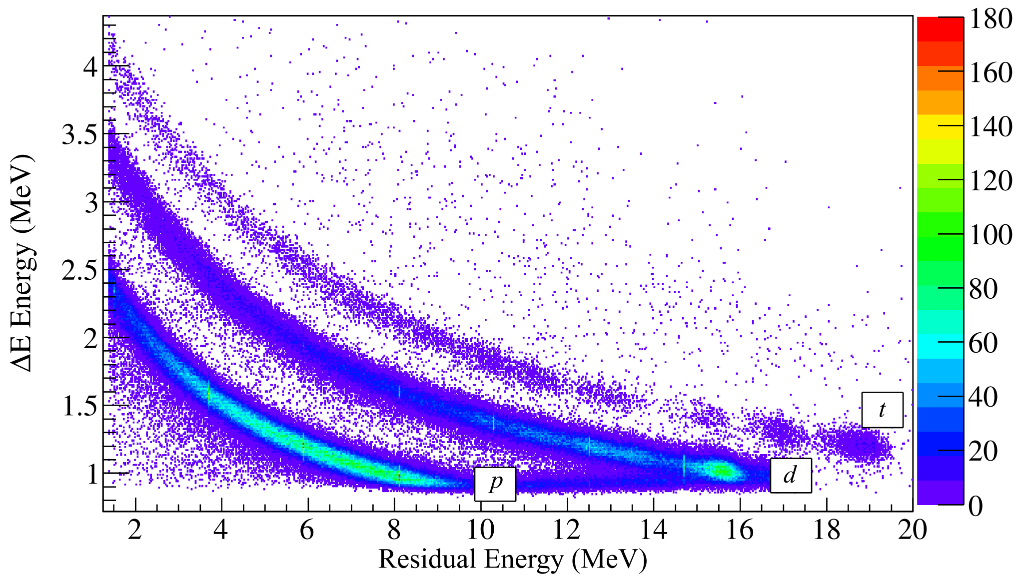

FIGURE 2. Particle identification spectrum detected in the QQQ5 telescopes at 20°. The tritons from the reaction of interest can be easily separated from the protons and deuterons from (^{3}He,p) and (^{3}He,d) reactions in the target.

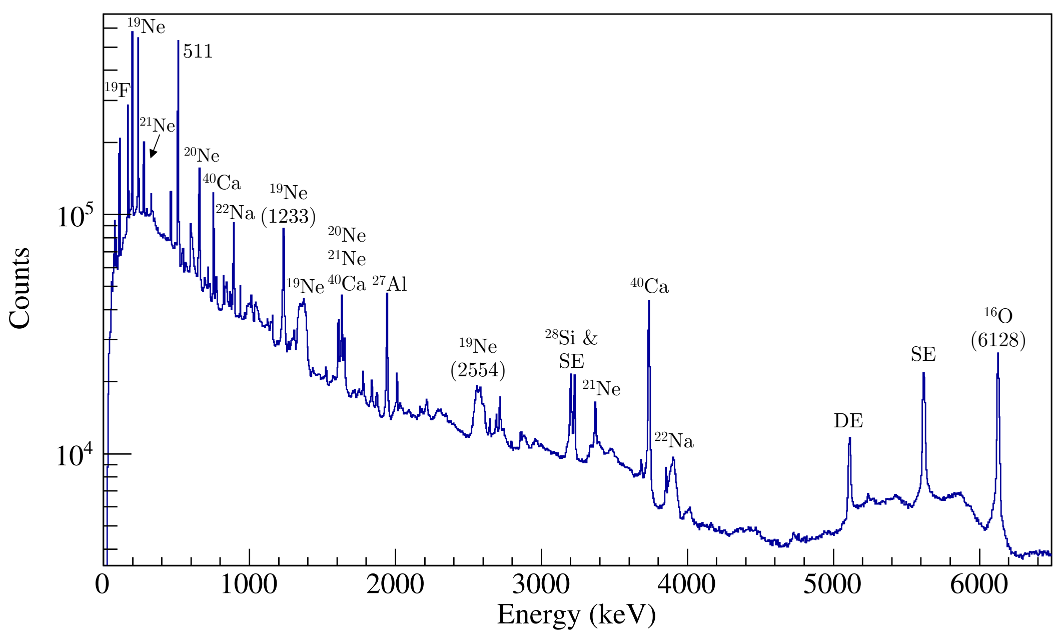

FIGURE 3. Summed timing gated γ-ray spectrum from all 92 Gammasphere detectors. Large peaks in the spectrum are labeled with their most likely source. Single-escape (SE) and double-escape (DE) peaks in the spectrum are also marked.

^{19}F(^{3}He,t)^{19}Ne*(γ) USING *TWINSOL* AND CLOVERSHARE

Experiment Overview

To complement the GODDESS experiment, the ^{19}F(^{3}He,t)^{19}Ne*(γ) reaction was also measured at the Nuclear Science Laboratory at the University of Notre Dame. The 10-MV FN Tandem accelerator was used to deliver ^{3}He beams with energies of 25.5 and 21 MeV to the target position with beam currents of 30 and 50 nA, respectively. In this case, a 1.13 mg/cm^2 CaF_2 target was used. Like the GODDESS experiment, tritons were to be measured in coincidence with de-excitation γ rays. To measure the γ rays, four HPGe clover detectors from the Clovershare collaboration were mounted over the target position. A recessed flange was used on the target chamber to ensure that the detectors could be mounted as close to the target as possible.

The *TwinSol* [11] separator, consisting of a pair of 6-T superconducting solenoids, was used to collect the reaction tritons between 2° and 5° in the laboratory frame and separate them from the other reaction products. The majority of the ^{3}He beam was stopped in a Faraday cup just upstream from the entrance to the first solenoid. The tritons were focused at the crossover between the two solenoids, where any elastically scattered $^{3}He^{1+}$ contaminants were stripped to $^{3}He^{2+}$ by a 0.38 mg/cm^2 Mylar foil, and a collimator stopped any unfocused contaminants. The reaction tritons were then focused by the second solenoid onto a ΔE-E telescope. A schematic of the entire setup can be seen in Fig. 4.

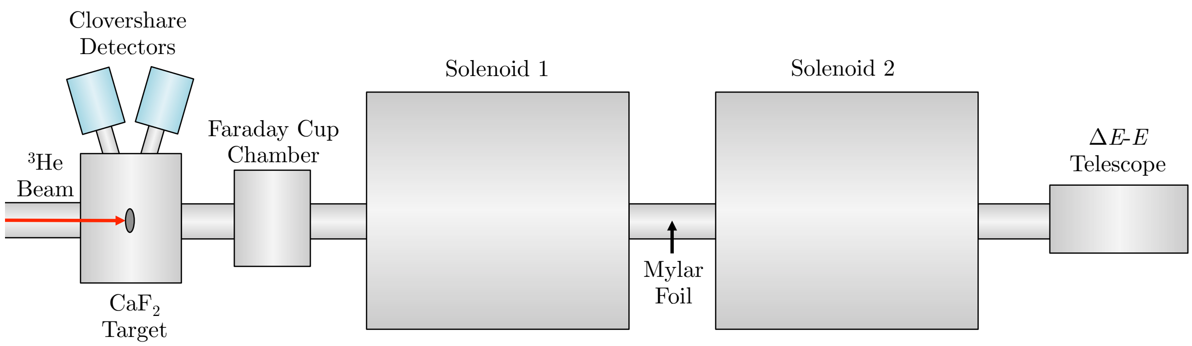

FIGURE 4. Schematic of the *TwinSol* experimental setup. Reaction tritons were collected by the two solenoids and focused onto the silicon detector telescope. De-excitation γ rays were measured in coincidence with the tritons using four clover detectors mounted over the target position.

Charged-Particle Detection

For the measurement at higher beam energies, the telescope consisted of three large-area silicon strip detectors, each with a thickness of 500 µm. For the measurement at lower energy, the telescope was modified, with the first strip detector being replaced with a 100-µm surface-barrier silicon detector. *TwinSol* was used to select tritons corresponding to excitation energies ranging from 4.2 to 5.5 MeV and 5.5 to 6.6 MeV for the higher and lower beam energies, respectively. Since the de-excitation γ rays from ^{19}Ne have been well-studied below 5.0 MeV, selecting the tritons between 4.2 and 5.5 MeV allowed the data to be compared to previous measurements. Figure 5 shows the PID detected by the telescope for the lower of the two beam energies. Good separation between the tritons and deuterons that made it through *TwinSol* can be seen. Preliminary analysis on the γ-ray data is still ongoing.

CONCLUSION

The $^{19}F(^{3}He,t)^{19}Ne^{*}(\gamma)$ reaction was studied at Argonne National Laboratory and the University of Notre Dame using GODDESS and *TwinSol* with Clovershare, respectively. GODDESS was used to detect reaction tritons in coincidence with γ rays from the decay of ^{19}Ne. Similarly, reaction tritons collected and separated by *TwinSol* were detected in coincidence with γ rays in four HPGe detectors. Analysis of the γ-ray spectra is ongoing to determine the level structure of ^{19}Ne near the $^{18}F+p$ threshold.

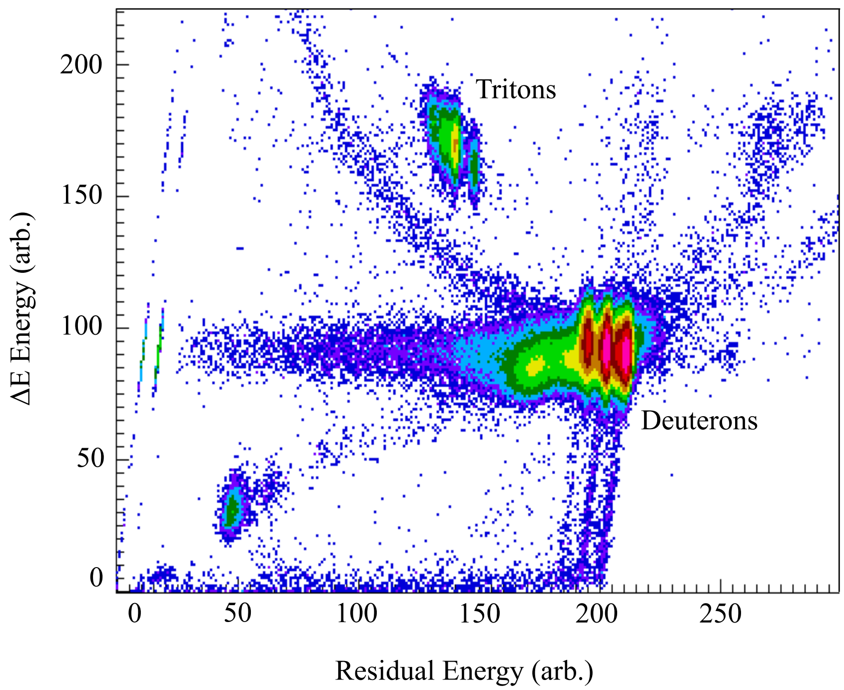

FIGURE 5. Preliminary particle identification spectrum for the lower of the two beam energies. The tritons are clearly separated from the deuterons by their energies. The detected tritons were from the population of the ^{19}Ne excitation energy levels between approximately 5.5 and 6.6 MeV.

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