Direct measurement of the E_r = 457 keV resonance in the astrophysical ^{19}Ne(p, γ)^{20}Na reaction

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Classical novae occur in binary systems consisting of a compact white dwarf and a main-sequence companion. The white dwarf accretes hydrogen-rich material onto its surface, resulting in thermonuclear runaway. Two broad types of novae exist depending on the underlying composition of the white dwarf: carbon-oxygen (CO), and oxygen-neon (ONe). The more massive ONe novae reach significantly higher peak temperatures (T ~ 0.4 GK), resulting in synthesis of nuclei up to the Si – Ca mass region [1, 2]. In a detailed study of different nova models [3], it was found that the significant detection of ^{19}F in nova ejecta was one of only four isotopic signatures of an underlying ONe white dwarf. Hence it is crucial that both the production and destruction of ^{19}F in classical novae be fully understood. The production of ^{19}F in ONe novae occurs through the reaction chain ^{17}O(p, γ)^{18}F(p, γ)^{19}Ne(β^+)^{19}F. However, this may be bypassed at higher temperatures through the alternative reaction path ^{19}Ne(p, γ)^{20}Na(β^+)^{20}Ne. As a result, a precise determination of the ^{19}Ne(p, γ)^{20}Na reaction rate is important for understanding ^{19}F generation in ONe classical novae.

At nova temperatures, the ^{19}Ne(p, γ)^{20}Na reaction rate is thought to be dominated by a single resonance at $E_r \sim$ 450 keV, populating an excited state in ^{20}Na with $E_x \sim$ 2640 keV. The strength of this resonance has been investigated in multiple experiments over the past 20 years, and it still subject to debate. Early (^{3}He, t) measurements [4, 5] generated conflicting 1^+ and 3^+ assignments for the ^{20}Na excited state corresponding to the $E_r \sim$ 450 keV resonance. A later attempt at a direct measurement of the ^{19}Ne(p, γ)^{20}Na reaction [6] established an upper limit on the resonance strength of 15 meV, suggesting a 1^+ spin-parity for the corresponding ^{20}Na state but not ruling out a 3^+ assignment. Most recently, a detailed ^{20}Mg β-decay study at the Texas A&M Cyclotron Institute established a log ft lower limit of 6.9 on the branch to the $E_x \sim$ 2640 keV state in ^{20}Na, firmly establishing the state as 3^+. Additionally, high-resolution measurements of the ^{20}Na proton separation threshold [8] and the excitation energy of the resonance in question [9] established a resonance energy of 457(3) keV, around 10 keV higher than previously thought. This suggests that the direct measurement of Ref. [6] failed to observe the resonance as a consequence of running on the wrong beam energy.

In order to resolve this situation, we have undertaken another direct measurement of the E_r = 457(3) keV resonance in ^{19}Ne(p, γ)^{20}Na, armed with updated knowledge of the resonance energy. This measurement was performed at the TRIUMF radioactive beam facility in Vancouver, Canada. We produced a beam of ^{19}Ne ions using the ISOL technique, impinging 500 MeV protons onto a high-power SiC production target. The ^{19}Ne ions were then post-accelerated to a laboratory energy of ~490 AkeV before impinging onto a windowless, recirculating gas target filled with ~8 torr of H_2. The beam energy was chosen to place the 457 keV resonance approximately in the center of the gas target. The overall ^{19}Ne beam current was $\sim 5\times10^6$ particles/second.

The ^{20}Na recoils resulting from ^{19}Ne(p, γ)^{20}Na were sent through the DRAGON recoil mass separator [10], where they were separated from unreacted beam and other reaction products by means of two successive pairs of magnetic and electric dipoles. Since it acts as both a charge and mass filter, only ions in the 6^+ charge state were transmitted through DRAGON. Particles reaching the DRAGON focal plane were detected in a pair of microchannel plates (MCPs) and an ionization chamber segmented into four anode regions. In coincidence, the γ rays resulting from ^{19}Ne(p, γ)^{20}Na were detected in an array of bismuth-germinate (BGO) scintillators surrounding the target. Recoil/γ-ray coincidences were separated from a background of "leaky" ^{19}Ne beam arriving at the focal plane in random coincidence with room γ rays by analyzing the time of flight between the two MCPs ("MCP TOF") and between the γ ray signal and the upstream MCP ("separator TOF"), as well as the ionization chamber energy loss signals.

Figure 1 shows a plot of total energy loss in the ionization chamber vs. energy lost in the first (upstream) anode. The events denoted by red stars also appear clustered in plots of separator vs. MCP TOF. They are clearly well separated from the other loci in the ion chamber E-ΔE, giving conclusive

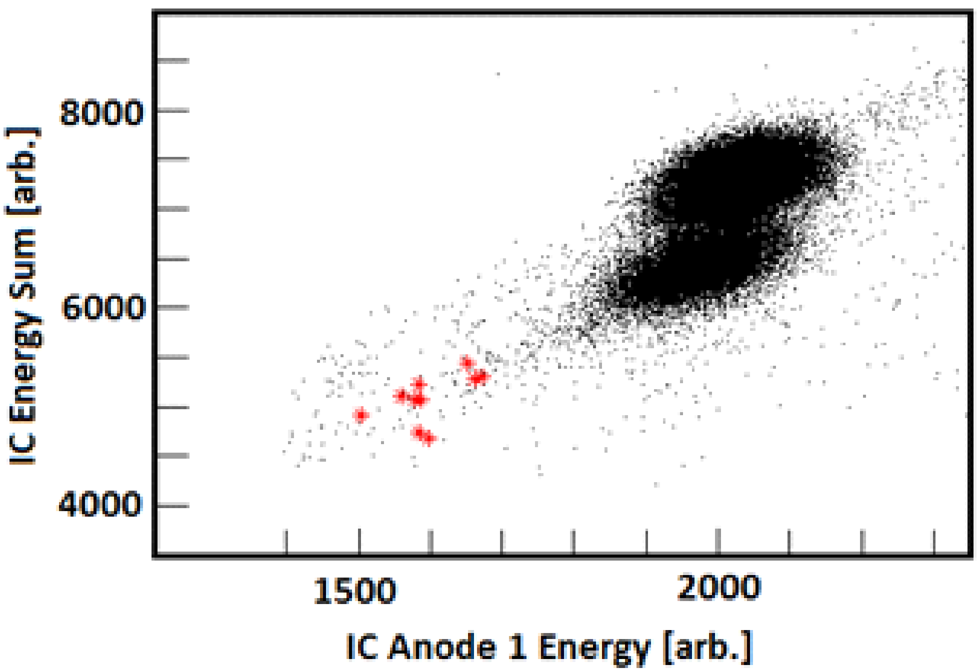

FIG. 1. Ionization chamber total energy loss vs. energy loss in the first anode. The events denoted by red stars also appear clustered in MCP vs. Separator TOF and correspond to ^{20}Na recoils.

evidence that these events correspond to ^{20}Na recoils. Overall, ten preliminary coincidence recoils were identified based on this analysis of the separator–MCP TOF and the ion chamber E-ΔE signals. Based on this and the preliminary coincidence detection efficiency of 15%; charge state fraction of 45%; integrated beam current of 2×10^{12} particles; and ^{19}Ne+H_2 stopping power of 4.3×10^{-15} eV/cm^2, we calculate a preliminary resonance strength of $\omega\gamma$ = 30 meV for the E_r = 457 keV resonance in ^{19}Ne(p, γ)^{20}Na. Additionally, the location of the resonance in the extended DRAGON gas target is consistent with the most recent resonance energy determination of 457(3) keV. The preliminary strength value deduced from the present measurement is significantly larger than the upper limit of 15 meV established in the previous attempt at a direct measurement [6]. This gives conclusive evidence that the resonance is indeed 3^+ as suggested in Ref. [7]. The analysis of this experiment is ongoing; future efforts will focus on finalizing the resonance strength measurement and on extracting an independent measurement of the resonance energy from the γ-ray hit pattern in the BGO array [11]. Following completion of the analysis, we will integrate our results into nova model calculations, examining the influence of our measurement on the predicted synthesis of ^{19}F in ONe classical novae.

[1] J. Jose, M. Hernanz, and C. Iliadis, Nucl. Phys. **A777**, 550 (2006).
[2] J. Jose, M. Hernanz, S. Amari, K. Lodders, and E. Zinner, Astrophys. J. **612**, 414 (2004).
[3] J. Jose and M. Hernanz, Astrophys. J. **494**, 680 (1998).
[4] L.O. Lamm *et al.*, Nucl. Phys. **A510**, 503 (1990).
[5] N.M. Clarke *et al.*, J. Phys. G **19**, 1411 (1993).
[6] R.D. Page *et al.*, Phys. Rev. Lett. **73**, 3066 (1994).
[7] J.P. Wallace *et al.*, Phys. Lett. B **712**, 59 (2012).
[8] C. Wrede *et al.*, Phys. Rev. C **81** 055503 (2010).
[9] M.S. Smith *et al.*, Nucl. Phys. **A536**, 333 (1992).
[10] D.A. Hutcheon *et al.*, Nucl. Instrum. Methods Phys. Res. **A498**, 190 (2003).
[11] D.A. Hutcheon *et al.*, Nucl. Instrum. Methods Phys. Res. **A689**, 70 (2012).