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Direct Measurement of the Key $E_{\mathrm{c.m.}} = 456$ keV Resonance in the Astrophysical $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ Reaction and Its Relevance for Explosive Binary Systems

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We have performed a direct measurement of the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction in inverse kinematics using a beam of radioactive $^{19}\mathrm{Ne}$. The key astrophysical resonance in the $^{19}\mathrm{Ne}+p$ system has been definitely measured for the first time at $E_{\mathrm{c.m.}} = 456^{+5}_{-2}$ keV with an associated strength of 17^{+7}_{-5} meV. The present results are in agreement with resonance strength upper limits set by previous direct measurements, as well as resonance energies inferred from precision (^{3}He, t) charge exchange reactions. However, both the energy and strength of the 456 keV resonance disagree with a recent indirect study of the $^{19}\mathrm{Ne}(d,n)^{20}\mathrm{Na}$ reaction. In particular, the new $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction rate is found to be factors of ~8 and ~5 lower than the most recent evaluation over the temperature range of oxygen-neon novae and astrophysical x-ray bursts, respectively. Nevertheless, we find that the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction is likely to proceed fast enough to significantly reduce the flux of ^{19}F in nova ejecta and does not create a bottleneck in the breakout from the hot CNO cycles into the rp process.

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Cataclysmic binary systems, such as classical novae and astrophysical x-ray bursts, constitute the most frequent stellar explosions to occur in our Galaxy and, thereby, act as key research environments for the field of nuclear astrophysics.

In the case of classical novae, hydrogen-rich material from a main sequence star is accreted onto the surface of a white dwarf companion. This material mixes with the heavier elements already present on the companion star, causing a thermonuclear runaway that eventually results in explosive mass ejections from the white dwarf with periodicities of $\sim 10^4$–10^5 yr [1]. Fascinatingly, elemental analyses of nova ejecta have revealed that the exact nature of a nova outburst depends strongly on the composition of the underlying white dwarf star. In particular, more massive oxygen-neon (ONe) novae achieve significantly higher peak temperatures ($T \sim 0.4$ GK) than those found in carbon-oxygen (CO) novae ($T \sim 0.2$ GK) and, as such, are expected to be responsible for the synthesis of nuclei up to the Si-Ca mass region [1,2]. Consequently, an accurate determination of the underlying white dwarf star composition is crucial to meaningfully compare theoretical models of nova nucleosynthesis with observational data.

Recently, highly ionized fluorine lines were observed in the optical spectra of Nova Mon 2012 [3], and in a detailed study of different nova models by José and Hernanz [4], the significant detection of ^{19}F was one of only four isotopic signatures highlighted as a potential key identifier of an underlying massive ONe white dwarf star. In astrophysical environments, ^{19}F is produced via the reaction sequence $^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}(\beta^+)^{19}\mathrm{F}$. However, due to the high peak temperatures achieved in ONe novae (~0.4 GK), synthesis of ^{19}F can be complicated by the bypass reaction $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}(\beta^+)^{20}\mathrm{Ne}$. Furthermore, in investigating the effect of thermonuclear reaction rate uncertainties on nova nucleosynthesis, Iliadis *et al.* [5] highlight that varying the rate of the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction up and down by a factor of 100 can result in a change in the final ejected abundance of ^{19}F by up to a factor of 7. Consequently, in order to fully understand the latest astronomical data, it is essential that a detailed knowledge of the rate at which the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction proceeds in ONe novae is obtained.

The astrophysical $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction is also expected to play a significant role in type-I x-ray bursts. In contrast to classical novae, the companion star involved in x-ray bursts is a neutron star, which results in significantly higher peak temperatures (~1.5 GK) and culminates in an intense flash of x rays. In between bursts, energy is generated at a constant rate by the β-limited hot CNO cycles. However, during the burst, it is possible to "breakout" from the hot CNO cycles into a whole new set of thermonuclear reactions, known as the rp process—a series of rapid proton captures resulting in the synthesis of material up to the Sn-Te mass region [6]. In this case, the breakout reaction sequence $^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$ is expected to provide the main link between the hot CNO cycles and the rp process, and it is now thought that its strength may determine not only the conditions for ignition to occur but also the burst recurrence rate [6–8].

Under ONe novae and x-ray burst conditions, the $^{19}Ne(p,\gamma)^{20}Na$ reaction is thought to be dominated by the contributions of a single low-energy resonance located ~450 keV above the proton-emission threshold energy of 2190.1(11) keV in ^{20}Na [9], corresponding to an excited state at $E_x \sim 2650$ keV. However, the strength of this resonance has remained the subject of intense debate for over two decades [10–22] and, in recent years, its energy has come into question as well [21,22]. Previous direct measurements of the $^{19}Ne(p,\gamma)^{20}Na$ reaction have been performed using radioactive beams of ^{19}Ne [14–18]. However, none of the studies thus far have been able to identify the resonance of interest or measure its strength and, as such, only upper limits for the strength of 18 [16], 21 [17], and 15 meV [18] have been reported. Moreover, it was concluded from the work of Page *et al.* [16] that the unknown spin-parity assignment of the ~450 keV resonance represented the dominant remaining uncertainty in the $^{19}Ne(p,\gamma)^{20}Na$ reaction. Early (^{3}He,t) charge exchange reactions gave conflicting 1^+ and 3^+ assignments for the $E_x \sim 2650$ keV state in ^{20}Na [10,11]. However, the recent nonobservation of an allowed Gamow-Teller β-delayed proton branch from the decay of ^{20}Mg has now strongly indicated that a 3^+ assignment should be favored [21]. Furthermore, Ref. [21] reexamined data from a previous high-precision (^{3}He, t) study by Smith *et al.* [12] and, together with the most recent, precise proton threshold energy [9], established a new resonance energy of $E_{\mathrm{c.m.}} = 457(3)$ keV. It is interesting to note that, in examining the effect of proposed spin-parity assignments on resonance strengths, a theoretical study by Fortune, Sherr, and Brown [19] derived a lower limit on the resonance strength of 16 meV for a 3^+ assignment, which is tantalizingly close to the experimental upper limits of direct measurements [16–18]. In fact, Fortune, Sherr, and Brown comment that the resonance strength is likely to be ~18 meV [19]. On the other hand, an earlier estimate based on a 1^+ assignment led to a value for the strength of 6 meV [17], which is more clearly compatible with the upper limits found by direct measurements.

Most recently, Belarge *et al.* used a radioactive beam of ^{19}Ne to populate proton-unbound levels in ^{20}Na via the $^{19}Ne(d,n)$ reaction, while resulting proton decays were detected using silicon strip detectors [22]. In that work, strong proton decay branches at 440 and 200 keV to the ground and first excited state of ^{19}Ne, respectively, were reported for the key resonance in the $^{19}Ne(p,\gamma)^{20}Na$ reaction. Partial proton widths for the two decays were deduced from a coupled-channel Born approximation, and an angular distribution analysis of the 200 keV decay to the first excited state established a 3^+ assignment for the $E_x \sim 2650$ keV level in ^{20}Na, in agreement with Ref. [21]. The lifetime of a proposed mirror state in ^{20}F at 2966.11(3) keV [23] was then used to establish $\Gamma_\gamma = 82^{\pm 18_{\mathrm{stat}}}_{\pm 22\mathrm{syst}}$ meV and determine resonance strengths of $69^{\pm 15_{\mathrm{stat}}}_{\pm 17\mathrm{syst}}$ and $21^{\pm 5_{\mathrm{stat}}}_{\pm 6\mathrm{syst}}$ meV for proton capture on the ground state of ^{19}Ne and proton capture on the excited state of ^{19}Ne, respectively. The reported resonance strength in Ref. [22] is in complete contradiction with earlier direct measurements [16–18], and the reported resonance energy is in disagreement with previous indirect studies [12,21]. Because of the significantly enhanced strength and considerable reduction in resonance energy, the rate of the $^{19}Ne(p,\gamma)^{20}Na$ reaction was found to be a factor of ~20 higher than previous evaluations [5,12].

In this Letter, we present a new direct experimental study of the $^{19}Ne(p,\gamma)^{20}Na$ reaction, in which an intense radioactive ion beam (RIB) of ^{19}Ne was utilized to measure, for the first time, the energy and strength of the key astrophysical resonance in the $^{19}Ne + p$ system, for the temperature range of ONe novae and x-ray bursts. Direct measurements are an invaluable tool in the investigation of astrophysical reactions, as they most closely resemble the actual reaction occurrence within the star, out of all presently available techniques, and the definitive results obtained are independent of spin-parity assignments, the adoption of partial widths from mirror states, and precise knowledge of the proton-emission threshold energy.

The experiment was carried out using the Detector of Recoils And Gammas Of Nuclear reactions (DRAGON) recoil separator [24] at the ISAC-I radioactive beam facility at TRIUMF. An intense RIB of ^{19}Ne in a 1^+ charge state was produced by bombarding a SiC target with 500 MeV protons. Products of mass ~19 amu were extracted and ionized in a Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source [25] and filtered using a high-resolution mass separator. This beam was injected into a radio-frequency quadrupole accelerator for an initial acceleration up to 150 A keV and stripped to a 5^+ charge state using a thin carbon foil. The $^{19}Ne^{5+}$ beam was then further accelerated to an energy of 9.24 MeV before impinging on a windowless gas target filled with H_2 at 5 Torr for 89 hr, resulting in a total integrated beam flux of $2.36(7) \times 10^{12}$. The beam energy was chosen in order to cover a center-of-mass energy range $E_{\mathrm{c.m.}} = 447$–465 keV across the volume of the gas target. A highly efficient array of 30 bismuth germanate (BGO) detectors [24] surrounding the windowless gas target was used to detect γ rays resulting from the (p,γ) reaction, while $^{20}Na^{6+}$ recoils were transmitted to the focal plane of DRAGON. Recoils were identified using a local time-of-flight (TOF) system based on two microchannel plates (MCPs) detecting secondary electron emission from thin diamondlike carbon foils and an isobutane-filled ionization chamber, and distinguished from scattered and/or charge-changed ("leaky") beam using a dual TOF technique [26]. Finally, stopping powers were determined by performing measurements with gas in and out of the target system, and charge state distributions for recoils were measured using a stable beam of ^{23}Na. In order to determine resonance strengths, an accurate determination of the number of incident ^{19}Ne ions was required. This was achieved by measuring β decays in two 6-mm-thick plastic scintillators located near an intermediate focus of the separator where the 6^+ component of the unreacted beam was stopped. In total, the average ^{19}Ne beam intensity was found to be $\sim 7\times 10^6$ pps. However, it should be noted that ^{19}F was also present as an isobaric beam contaminant at a level of $\sim 2\times 10^7$ pps. Nevertheless, reactions involving ^{19}F were easily separable from those involving ^{19}Ne in the ionization chamber.

Figure 1 shows the γ-gated MCP vs separator TOF results obtained for the incident beam energy $E_{\mathrm{beam}} = 486$ A keV. There is a clear clustering of 15 recoil events free from background, indicating the presence of an $A = 20$ radiative capture resonance. By also requiring a coincidence ^{20}Na event to be observed in the ionization chamber, we obtain a total of eight "golden" $^{19}Ne + p$, recoil-γ coincidences, as shown in Fig. 2. Furthermore, from Fig. 2, it is clear that any events resulting from the contaminant $^{19}F(p,\gamma)^{20}Ne$ reaction are easily separable from the events of interest. A negative log-likelihood (NLL) analysis [27] was used over a grid of resonance strengths and energies to account for the observed shape of the BGO hit pattern in comparison with simulated data. A single well-defined minimum was observed [28], and we obtain a resonance energy of $E_{\mathrm{c.m.}} = 456^{+5}_{-2}$ keV and determine a resonance strength $\omega\gamma = 17^{+7}_{-5}$ meV at the 68% confidence level (C.L.). Significant sources of systematic uncertainty result from beam normalization (3%), stopping powers (6.4%), BGO detection efficiency (5.6%), which assumes dominant γ-decay branches to the ground and 4^+_1 levels in similarity to the decays of the 2966 keV 3^+ excited state in the mirror nucleus ^{20}F [23], and heavy-ion detection efficiency at the focal plane (14.3%). Thus, the strength of the presently observed 456 keV resonance in the $^{19}Ne + p$ system is $\omega\gamma = 17^{+7}_{-5}(\mathrm{stat})^{+3}_{-3}(\mathrm{syst})$ meV. Both the presently observed resonance energy and resonance strength are in disagreement with the most recent indirect study of the $^{19}Ne(p,\gamma)^{20}Na$ reaction [22]. However, the newly reported energy is in excellent agreement with that of Ref. [20], and the measured strength is consistent with the upper limits set by the direct studies of Page *et al.* [16], Vancraeynest *et al.* [17], and Couder *et al.* [18], at a 90% C.L. or better. Moreover, it is interesting to note that an early resonance strength estimate by Görres *et al.* [29] based on ^{20}F lifetimes, in which the proton widths used are adopted from Brown *et al.* [30], and similar to those of Belarge *et al.* [22], is also in agreement with the present work. As such, a possible explanation for the considerable discrepancy in resonance strength between the current study and Ref. [22] could relate to a potential error in

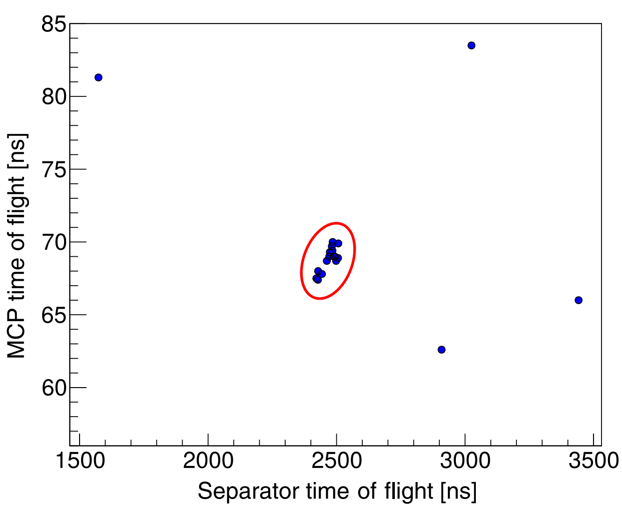

FIG. 1. MCP vs separator TOF. The red oval indicates the expected location of $A = 20$ recoils.

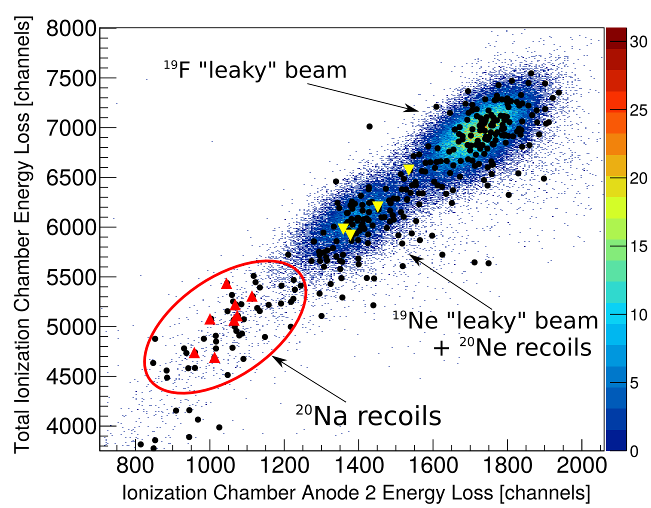

FIG. 2. Total energy loss in the ionization chamber vs energy loss in the second anode. Black dots indicate all singles events observed from all production runs. Attenuated beam runs are also included as shaded underlays, and two clear loci of F and Ne recoils are visible. Red triangles represent golden recoil-γ $^{19}Ne + p$ resonance events, while the location of easily distinguishable contaminant $^{19}F + p$ resonance events are highlighted by yellow triangles.

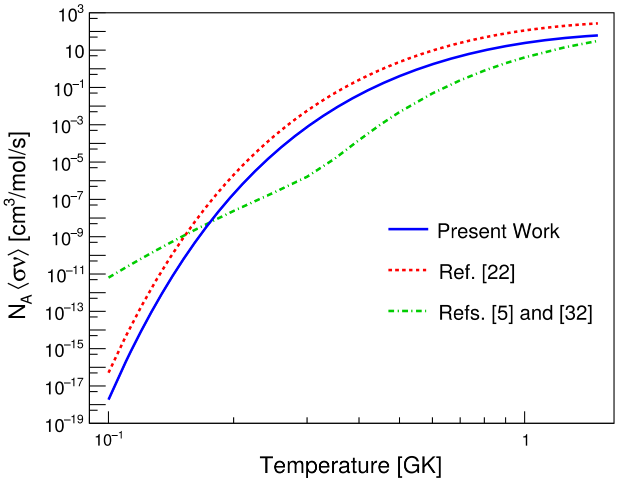

FIG. 3. Total contribution of the 456 keV resonance to the $^{19}Ne(p,\gamma)^{20}Na$ stellar reaction rate in comparison with the rate reported in Ref. [22]. Also shown (green line) is the total $^{19}Ne(p,\gamma)^{20}Na$ rate adopted in Ref. [5], which is based upon an earlier analytic expression describing the reaction process [32].

the lifetime of the mirror state used in extracting the γ-ray partial width, which in this case largely determines the overall strength.

For the evaluation of the $^{19}Ne(p,\gamma)^{20}Na$ stellar reaction rate, we consider only the contributions of the lowest-energy resonance in the $^{19}Ne + p$ system, incorporating the newly determined resonance energy of 456 keV and resonance strength of 17 meV. In considering the influence of proton capture to this resonant level from the first excited state of ^{19}Ne [$E_x = 238.27(11)$ keV [31]], we determine a resonance energy of $E_{\mathrm{c.m.}} = 218^{+5}_{-2}$ keV. Furthermore, by adopting the proton partial widths $\Gamma_{p0} = 615$ meV and $\Gamma_{p1} = 584$ meV reported in Ref. [22], as well as a 3^+ spin-parity assignment for the 456 keV resonant state, we estimate a γ-ray partial width of $\Gamma_\gamma = 19.2^{+8.1}_{-5.7}$ meV, leading to an excited state resonance strength of $5.7^{+2.3}_{-1.7}$ meV. Consequently, we expect the ground and excited state proton captures to the 456 keV resonance to contribute to the stellar reaction rate in approximately equal amounts, in agreement with Ref. [22]. Figure 3 displays the total contribution of the ground and first excited state captures of the 456 keV resonance to the $^{19}Ne(p,\gamma)^{20}Na$ stellar reaction rate in comparison with the total contribution reported in Ref. [22]. Also shown in Fig. 3 is the total $^{19}Ne(p,\gamma)^{20}Na$ stellar reaction rate used in the sensitivity study of Iliadis *et al.* [5] to predict its influence on final isotopic abundances in nova ejecta. At temperatures of 0.3 and 1.0 GK, respectively, the current rate is factors of ~8 and ~5 lower than that of Belarge *et al.* [22]. In contrast, the new rate is a factor of ~250 higher than that used in the highest-temperature nova nucleosynthesis model of Ref. [5]. As such, we expect the $^{19}Ne(p,\gamma)^{20}Na$ reaction to significantly deplete the final abundance of ^{19}F present in the ejecta of ONe novae compared to that predicted in Ref. [5], which may help to explain the scarcity of fluorine observations from nova explosions. However, although the current rate is lower in x-ray bursts than that recently reported, it is still considerably higher than the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction and, thus, we do not expect it to form a bottleneck in the breakout from the hot CNO cycles into the *rp* process, in agreement with Ref. [22].

In summary, using the DRAGON recoil separator, we have performed a direct measurement of the $^{19}Ne(p,\gamma)^{20}Na$ reaction in inverse kinematics. The energy and strength of the key resonance in the $^{19}Ne + p$ system, that entirely determines the rate of the $^{19}Ne(p,\gamma)^{20}Na$ reaction in ONe novae and x-ray bursts, have been successfully measured for the first time as $E_{\mathrm{c.m.}} = 456^{+5}_{-2}$ keV and $\omega\gamma = 17^{+7}_{-5}(\mathrm{stat})^{+3}_{-3}(\mathrm{syst})$ meV. These results are in agreement with earlier work but disagree with the most recent evaluation of the $^{19}Ne(p,\gamma)^{20}Na$ reaction. Based on the present results, it is expected that the rate of the $^{19}Ne(p,\gamma)^{20}Na$ reaction is now sufficiently well constrained that its influence in explosive binary systems can be accurately modeled and meaningfully compared to the latest astronomical data. However, questions still remain over the pairing of analog states in the mirror nuclei ^{20}Na and ^{20}F, as well as the lifetimes of excited levels in ^{20}F, that should be addressed in the future.

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