

First Direct Measurement of the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ Cross Section

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The rate of the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction is important in various astrophysical events. A previous $^{17}\text{F}(p,p)^{17}\text{F}$ measurement identified a 3^+ state providing the strongest resonance contribution, but the resonance strength was unknown. We have directly measured the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction using a mixed beam of ^{17}F and ^{17}O at ORNL. The resonance strength for the 3^+ resonance in ^{18}Ne was found to be $\omega\gamma = 33 \pm 14(\text{stat}) \pm 17(\text{syst})$ meV, corresponding to a γ width of $\Gamma_\gamma = 56 \pm 24(\text{stat}) \pm 30(\text{syst})$ meV. An upper limit on the direct capture of $S(E) \leq 65$ keV b was determined at an energy of 800 keV.

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In novae, hydrogen gas accretes onto a white dwarf star, causing a thermonuclear runaway and creating large quantities of the hot-CNO cycle nuclei ^{13}N , $^{14,15}\text{O}$, and $^{17,18}\text{F}$ [1]. The isotope ^{18}F is produced mainly through β decay of ^{18}Ne and proton capture on ^{17}O , and destroyed via the charged-particle reaction $^{18}\text{F}(p,\alpha)^{15}\text{O}$ as well as via β decay to ^{18}O . The 511 keV annihilation γ rays from ^{18}F β decay could be directly observable by gamma-ray telescopes, because the longer half-life of ^{18}F (~ 110 min) allows it to survive until the nova envelope becomes more transparent [2]. However, the amount of ^{18}F produced is uncertain, in part because of the unknown $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ rate. At lower temperatures, the reaction sequence $^{17}\text{F}(e^+\nu_e)^{17}\text{O}(p,\alpha)^{14}\text{N}(p,\gamma)^{15}\text{O}(e^+\nu_e)^{15}\text{N}$ takes place, which contributes to the observed overabundance of ^{15}N in novae ejecta [2]; novae are thought to be important contributors to galactic ^{15}N abundances. At temperatures above about 0.2 GK (depending on density), the reaction chain $^{17}\text{F}(p,\gamma)^{18}\text{Ne}(e^+\nu_e)^{18}\text{F}$ becomes important, increasing production of ^{18}F and altering the ratio of $^{18}\text{F}/^{17}\text{F}$ abundances.

During an x-ray burst, the α - p chain is initiated through the reaction sequence $^{14}\text{O}(\alpha,p)^{17}\text{F}(p,\gamma)^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$ [3], increasing the rate of energy generation by 2 orders of magnitude [4] and allowing for rp -process synthesis of nuclei even heavier than iron [5]. During the preburst phase of an x-ray burst event, two peaks in energy production are seen, one being “caused by . . . the conversion of ^{16}O into ^{15}O initiated by two subsequent proton capture reactions—which depends on the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ rate” [6]; in all of the burst scenarios considered, between 10% and 100% of the total flux will proceed through the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction [6]. Thus, the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction is crucial to preburst energy generation.

The understanding of these astrophysical scenarios is linked to the understanding of the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction, but the proton capture rate had never been measured directly. A low energy 3^+ state in ^{18}Ne , which dominates the resonant capture cross section at the temperatures typical of the astrophysical scenarios described above, was predicted based on a known mirror state in ^{18}O [7]. A $^{17}\text{F}(p,p)$ study was the first to conclusively observe the “missing” 3^+ state in ^{18}Ne (see Refs. [2,3] and references therein). The resonance was located at an energy of 599.8 keV above the proton threshold, with a total width of $\Gamma = 18 \pm 2$ keV. However, both the resonance strength and direct capture cross section thought to dominate at nova temperatures [3,8] remained experimentally unknown.

Theoretical shell model calculations predicted a partial γ width for this state of 25 ± 16 [9] or 33 meV [10], but the value had never been experimentally measured. The uncertainty quoted by García *et al.* [9] was based upon experimental lower limits of the mirror transition in ^{18}O , but no account of the inherent uncertainties in the theory is made. Because of the lack of experimental information, Iliadis *et al.* [11] assigned an estimated uncertainty to the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction rate in the region of nova temperatures of an order of magnitude. Theoretical predictions of widths and reaction rates can often be incorrect by orders of magnitude [12–15], however, making direct experimental measurements crucial [16]. As the resonant reaction rate depends sensitively upon Γ_γ , it is a critical parameter to measure. Only a few states in ^{18}Ne will have a significant contribution to the resonant cross section, the 3^+ resonance being expected to dominate. Once the properties of these states, as well as the direct capture component, are well known, the reaction rate can be calculated.

Using a ^{17}F beam produced at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL), the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ proton capture reaction was measured directly using the Daresbury Recoil Separator (DRS). A mixed beam of ^{17}F (typically $\sim 35\%$ – 70% of the total) and stable ^{17}O was produced and accelerated into a differentially pumped, windowless hydrogen gas target (WGT) [17] at 4 Torr, similar to a design used by the NABONA Collaboration [18]. Monitoring of the beam current was achieved using two methods. First, doubly collimated silicon surface barrier detectors inside the central disk of the gas target detected protons elastically scattered by the beam. From the measured yield of scattered protons, the ^{17}F beam rate could be deduced after correcting for purity, which was monitored continuously from the “leaky” beam that was transmitted through the DRS. Second, an additional beam sampling setup, composed of two plastic scintillator paddles on either side of a pneumatically controlled actuator that was installed just above the beam line, was used. The pneumatic actuator repeatedly moved a metal plate into the beam for a short period in order to sample the beam current, then retracted the plate between the two scintillator paddles (located outside of the beam line vacuum) for a longer period to count the ^{17}F decays. The two annihilation 511 keV photons detected in coincidence in the plastic scintillators were the characteristic signature of the decay of a radioactive ^{17}F beam particle implanted on the plate.

Both beam current normalization methods were calibrated by correlating their count rates to a measurement of the rate of fluorine nuclei in the ionization chamber at the focal plane. The charge state fractions of the ^{17}F were measured after exiting the WGT by tuning selectively through the DRS and counting with the ionization chamber, to determine the ratio of charge state $3+$ to the full beam current. The DRS was then tuned to transmit the $q = 3+$ beam to the focal plane while the beam monitors counted, so a calibration between $^{17}\text{F}^{3+}$ (and thus total ^{17}F) and beam monitor count rate was found, without requiring knowledge of, for example, the total solid angle of the silicon detectors, the Rutherford scattering cross section, or the efficiency of the plastic scintillators. With two separate methods for beam current normalization, however, a systematic uncertainty had to be introduced to account for the difference in the resonance strength values derived from each method.

For the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction in inverse kinematics, the resulting ^{18}Ne nuclei were very forward focused, with a maximum recoil cone of only 0.443° in the laboratory frame. Both the ^{18}Ne recoils and the unreacted ^{17}F and ^{17}O of the beam exited the WGT into the DRS [19,20]. The DRS was tuned to transmit the ^{18}Ne recoils unobstructed to the focal plane, where they were detected unambiguously in a gas-filled ionization chamber containing three anodes. By plotting the energy loss of the particles versus total energy, the recoils of interest were easily distinguished from the scattered beam.

Transmission studies and tests of the experimental system were performed by measuring various ^{18}F resonances via the $^{17}\text{O}(p,\gamma)^{18}\text{F}$ reaction. The excellent separation of particle groups was demonstrated at the appropriate energy using the 557 keV resonance in $^{17}\text{O} + p$ [21], as shown in Fig. 1. Furthermore, the transmission was checked with a measurement of the well-known 1036.5 keV resonance in $^{17}\text{O}(p,\gamma)^{18}\text{F}$, resulting in a resonance strength of 0.31 ± 0.04 eV, in good agreement with the previously adopted value of 0.36 ± 0.10 eV [21]. Additionally, the expected location of the ^{18}Ne recoils relative to any unreacted beam in the ionization chamber spectra was determined using $^{17}\text{O} + ^{20}\text{Ne}$ elastic scattering, where a specific recoil energy was tuned through the DRS. Figure 2 shows the spectrum from the elastic scattering measurement (it should be noted that the ionization chamber gain differs between the spectra in Figs. 1 and 2).

At an off-resonance beam energy of 14.3 MeV, corresponding to 800 keV above the proton threshold, data were recorded in order to determine the experimental background. This also provided an upper limit on the astrophysical $S(E)$ factor for direct capture, since the off-resonance energy was selected so as to be far from the broad resonances at 600 and 1178 keV. At this beam energy, the target had a thickness of 16.2 ± 1.6 keV in the center of mass frame, and model predictions [9,10] indicated that the direct capture component should essentially be a constant value of ~ 3 keV b over this energy range. Based on the yield measured at this energy, an experimental 2σ upper limit on the direct capture was determined to be $S(E) \leq 65$ keV b.

The yield was measured directly at a beam energy of 10.83 MeV, corresponding to the 599.8 keV, astrophysically significant 3^+ state in ^{18}Ne , as shown in Fig. 3. Data were recorded with beam currents ranging between $\sim (1-10) \times 10^6$ ^{17}F per second. At this beam energy, the target was 16.6 ± 1.7 keV wide, 92% of the total resonance width. Three different charge states of ^{18}Ne recoils were measured by tuning each individually through the DRS, in order to experimentally determine the charge state distribution, which provided the raw on-resonance yield. The net yield was calculated by subtracting the $\sim 20\%$

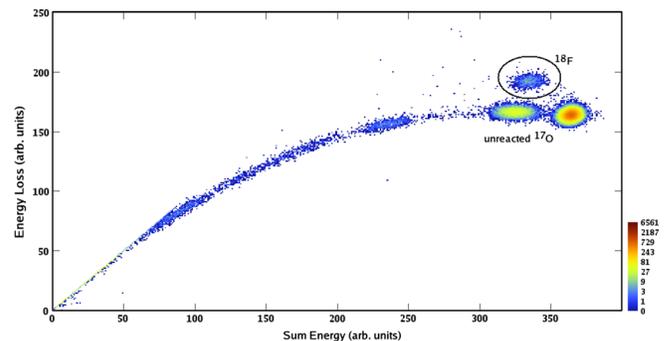


FIG. 1 (color online). Energy loss versus total energy from the ionization chamber for the 557 keV resonance in $^{17}\text{O}(p,\gamma)^{18}\text{F}$.

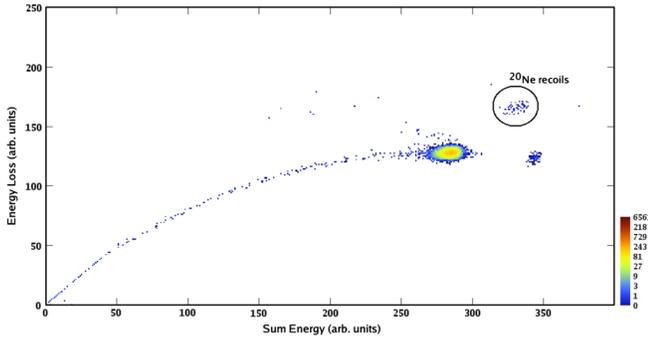


FIG. 2 (color online). Ionization chamber spectrum for the $^{17}\text{O} + ^{20}\text{Ne}$ scattering measurement with neon recoils indicated, performed in order to determine the location of ^{18}Ne recoils during the $^{17}\text{F}(p, \gamma)^{18}\text{Ne}$ experiment.

background as estimated from the off-resonance measurement (this yield being comprised of both direct capture and experimental background components, assumed to be constant over the relevant energy range), as well as the relatively small estimated yield from the nearby 1^- resonance ($\Gamma_\gamma = 15$ meV) [9]. The total yield due to the 3^+ resonance was thus determined, which resulted in a resonance strength of $\omega\gamma = 33 \pm 14(\text{stat}) \pm 17(\text{syst})$ meV, where the systematic uncertainty is dominated by the beam current normalization methods. Based on this strength, a partial width $\Gamma_\gamma = 56 \pm 24(\text{stat}) \pm 30(\text{syst})$ meV was found, larger than (but within the uncertainties of) the values predicted by model calculations [9,10,22].

The reaction rate calculation has been improved by utilizing the newly measured experimental γ width from this work, the resonance energy and total width previously determined [3], and information on two other narrow resonances near this 3^+ state [9]; the resonance parameters are listed in Table I. The direct capture contribution was calculated from the García *et al.* model prediction [9] for consistency with the previously adopted rate [3], though newer predictions also agree to within uncertainty [10,23]. Because the strength of the resonance was higher than previously predicted, the reaction rate has been determined

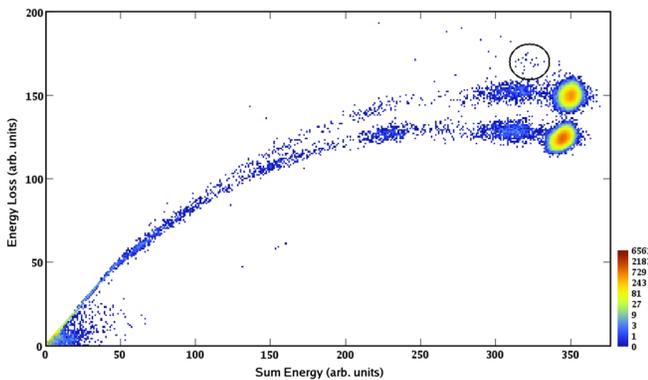


FIG. 3 (color online). Energy loss versus total energy from the ionization chamber for the 599.8 keV resonance; ^{18}Ne recoils are indicated by the black circle.

TABLE I. Resonance parameters used for the reaction rate calculation.

E_{cm} (keV)	J^π	Γ_p (keV)	Γ_γ (meV)
597 ± 5^a	1^-	0.1^a	15 ± 3^a
599.8 ± 2^b	3^+	18 ± 2^b	56 ± 38^c
665 ± 5^a	0^+	1.0^a	1.0 ± 0.2^a

^aFrom Ref. [9].

^bFrom Ref. [3].

^cCurrent work.

to be faster than the previously calculated rate [3] above nova temperatures, by a maximum factor of ~ 1.8 around a temperature of 1 GK; however, between ~ 0.3 – 0.4 GK the resonant contribution does play a role in nova nucleosynthesis. Below ~ 0.3 GK, we find direct capture is likely to still dominate the reaction rate. Most significant to this measurement was the reduction of the orders of magnitude uncertainty in the resonant contribution due to lack of experimental information [11] to $<55\%$ for the temperature range $0.1 \leq T_9 \leq 1.0$, which has a significant impact on both nova and x-ray burst model calculations. Figure 4 shows the experimentally measured 3^+ component, in addition to the theoretical predictions for the direct capture and resonant reaction rates.

The rate was parametrized according to the Thielemann *et al.* analytic form [24] over the temperature range of $0.1 \leq T_9 \leq 1.0$ using an online suite of computational tools [25]. The coefficients calculated from the resulting parametrization are listed in Table II. The nova nucleosynthesis of several isotopes has been investigated using the updated $^{17}\text{F}(p, \gamma)^{18}\text{Ne}$ rate by using the framework available through the Computational Infrastructure for Nuclear Astrophysics [25]. A “postprocessing” approach was utilized (as in Ref. [8]), following a full reaction rate network with 169 isotopes, from ^1H to ^{54}Cr , through time profiles of

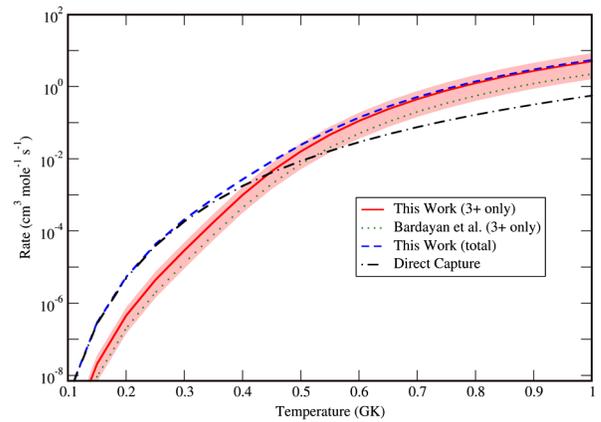


FIG. 4 (color online). Reaction rates over the temperature range $0.1 \leq T_9 \leq 1.0$ for this work (both 3^+ contribution and total), with the shaded red band displaying the uncertainties from this work, as well as the previous 3^+ rate contribution based on the resonance parameters from Bardayan *et al.* [3]. The predicted direct capture component previously used [9] is also shown.

TABLE II. Rate parametrization based on the Thielemann *et al.* [24] analytical form.

Parameter	Value	Parameter	Value
a_{11}	$0.275\,778 \times 10^2$	a_{21}	$-0.784\,708 \times 10^1$
a_{12}	$-0.495\,969 \times 10^1$	a_{22}	$-0.323\,504 \times 10^{-1}$
a_{13}	$-0.213\,249 \times 10^2$	a_{23}	$-0.142\,191 \times 10^2$
a_{14}	$-0.230\,774 \times 10^0$	a_{24}	$0.340\,647 \times 10^2$
a_{15}	$0.917\,931 \times 10^0$	a_{25}	$-0.165\,698 \times 10^2$
a_{16}	$-0.440\,377 \times 10^{-1}$	a_{26}	$0.248\,116 \times 10^1$
a_{17}	$-0.736\,014 \times 10^1$	a_{27}	$-0.213\,376 \times 10^1$

density and temperature in one of 28 radial, one-dimensional, hydrodynamic “zones” of nova outbursts (see Ref. [25] and references therein). With the exception of $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$, reaction rates used were the same as in Ref. [8]. Calculations with the parametrized rate indicate that the abundance of ^{18}F in the hottest zones of 1.35 solar mass white dwarf nova are increased by a factor of 1.6 over the previously adopted rate. Within the hottest zone, varying the previous resonant contribution by a factor of 10 resulted in a spread of as much as 15–16 times in the final abundance of ^{18}F . Using the rate derived in this work, with the measured uncertainties in the resonant contribution, resulted in a spread of only $\sim 2.4X$, a large improvement in constraining the final abundances. The impact on x-ray bursts is potentially even greater, due to the higher temperatures involved; calculations of the ignition phase which included a reaction network of 298 isotopes coupled to exhaustive hydrodynamics (as described in more detail by Roberts *et al.* [26]) indicate that the abundances of ^{17}O and ^{17}F can be altered by an order of magnitude or more, with reductions in uncertainty from a factor of roughly 100 to a factor of ~ 5 .

The $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction rate is critical to our understanding of novae and x-ray bursts, but the reaction had never been measured directly. Using a mixed ^{17}F and ^{17}O beam from the Holifield Radioactive Ion Beam Facility, a windowless hydrogen gas target was bombarded and the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction products separated with the Daresbury Recoil Separator. Based on this directly measured proton capture, a direct capture $S(E)$ factor upper limit was determined, as well as a resonance strength for the astrophysically important 599.8 keV state stronger than originally predicted. Experimental knowledge of this resonance strength provides a tremendous improvement upon the uncertainties introduced by a theoretically inferred strength and was key in constraining the reaction rate of ^{17}F proton capture near energies found in novae and x-ray bursts. Additional measurements, such as determination of the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ direct capture cross section and the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction cross section, are needed to further reduce uncertainties in ^{18}F production in novae.

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