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First Direct Measurement of the ^{17}F(p,γ)^{18}Ne Cross Section

Kelly Chipps[∗ †]
Colorado School of Mines
E-mail: kchipps@mines.edu

D.W. Bardayan, C.D. Nesaraja, S.D. Pain, M.S. Smith

Oak Ridge National Laboratory

J.C. Blackmon

Louisiana State University

K.Y. Chae, B.H. Moazen, S.T. Pittman

University of Tennessee Knoxville

U. Greife

Colorado School of Mines

R. Hatarik, W.A. Peters

Rutgers University

R.L. Kozub, J.F. Shriner, Jr.

Tennessee Technological University

C. Matei

Oak Ridge Associated Universities, Oak Ridge, TN 37830

The rate of the ^{17}F(p,γ)^{18}Ne reaction is of significant importance in astrophysical events like novae and x-ray bursts. The decay of ^{17}F is thought to help drive the expansion of the nova envelope, and the ^{17}F(p,γ)^{18}Ne reaction affects the production of ^{18}F, a target of gamma-ray astronomy, as well as being an important link in the (α,p) reaction chain during the ignition phase of x-ray bursts. A 3^+ state in ^{18}Ne predicted to dominate the rate was found at 599.8 keV using the ^{17}F(p,p)^{17}F reaction [1], but the resonance strength was unknown. For the first time, the ^{17}F(p,γ)^{18}Ne reaction has been measured directly with the Daresbury Recoil Separator, using a mixed beam of radioactive ^{17}F and stable ^{17}O from the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory. A γ width was found for the 599.8 keV resonance in ^{18}Ne, and an upper limit on the direct capture S factor was determined at an intermediate energy of 800 keV.

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1. Motivation

During novae events, hydrogen gas accretes onto a white dwarf star, which, through a thermonuclear runaway with the CNO cycle nuclei already present, creates large quantities of the hot-CNO cycle nuclei ^{13}N, ^{14,15}O, and ^{17,18}F [2]. The nuclei ^{18}F is produced mainly through beta-decay of ^{18}Ne and proton capture on ^{17}O, and destroyed via the charged-particle reaction ^{18}F$(p,\alpha)^{15}$O as well as via beta-decay to ^{18}O. The two 511 keV annihilation γ-rays from ^{18}F β-decay could be directly observable in gamma-ray astronomy, because the longer half-life of ^{18}F ($\sim$ 110 min) allows it to survive until the nova envelope becomes more transparent [1], but the amount of ^{18}F produced is uncertain partly because of the unknown ^{17}F$(p,\gamma)^{18}$Ne rate. At typical novae temperatures, the reaction sequence ^{17}F$(e^+\nu_e)^{17}$O$(p,\alpha)^{14}$N$(p,\gamma)^{15}$O$(e^+\nu_e)^{15}$N takes place, which contributes to the observed overabundance of ^{15}N in novae ejecta [1] and lowers the amount of ^{18}F produced. However, at about 0.4 GK, which is at the upper end of the range of nova temperatures, the reaction chain ^{17}F$(p,\gamma)^{18}$Ne$(e^+\nu_e)^{18}$F becomes important, and the ratio of ^{18}F/^{17}F abundances is altered. Similarly, during an x-ray burst, the (α,p) chain is initiated through the reaction sequence ^{14}O$(\alpha,p)^{17}$F$(p,\gamma)^{18}$Ne$(\alpha,p)^{21}$Na [3], increasing the rate of energy generation by two orders of magnitude [4] and allowing for rp-process synthesizing of nuclei even heavier than iron [5]. Therefore, the ^{17}F$(p,\gamma)^{18}$Ne reaction is crucial to our understanding of these astrophysical scenarios. The proton capture in the energy range relevant to novae and x-ray bursts, however, had never been measured directly.

A low energy 3^+ state in ^{18}Ne, which would play an important role in the resonant capture cross section at the temperatures typical of novae and x-ray bursts, was predicted based on a mirror state in ^{18}O [6]; however, subsequent analyses arrived at differing results for parameters of this "missing" state [7, 8, 9]. Previous studies of the energy region corresponding to temperatures found in novae and x-ray bursts using a multitude of reactions were unable to find the resonance (see Reference [3] and references therein); the ^{17}F$(p,p)^{17}$F measurement [1, 3] was the first to conclusively observe the "missing" 3^+ state in ^{18}Ne. A subsequent high-resolution ^{16}O$(^3He,n)$ experiment [10] was in good agreement with the scattering measurement [1], which determined the resonance to be located at an energy of 599.8 keV with a total width of $\Gamma = 18 \pm 2$ keV. Theoretical shell model calculations predicted a partial γ width for this 3^+ state at 25 [7] or 33 meV [9], but the value had never been experimentally measured. Since only a few states in ^{18}Ne, including the relatively broad 3^+ resonance, will have a significant contribution to the resonant cross section in this temperature range, the reaction rate can be calculated definitively, once the properties of these states are well known.

2. Experiment

With a ^{17}F beam produced at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL), the ^{17}F$(p,\gamma)^{18}$Ne proton capture reaction was measured directly using the Daresbury Recoil Separator (DRS). A mixed beam of ^{17}F (typically $\sim 35-70\%$) and stable ^{17}O was produced and accelerated into a differentially-pumped, windowless hydrogen

*Speaker.

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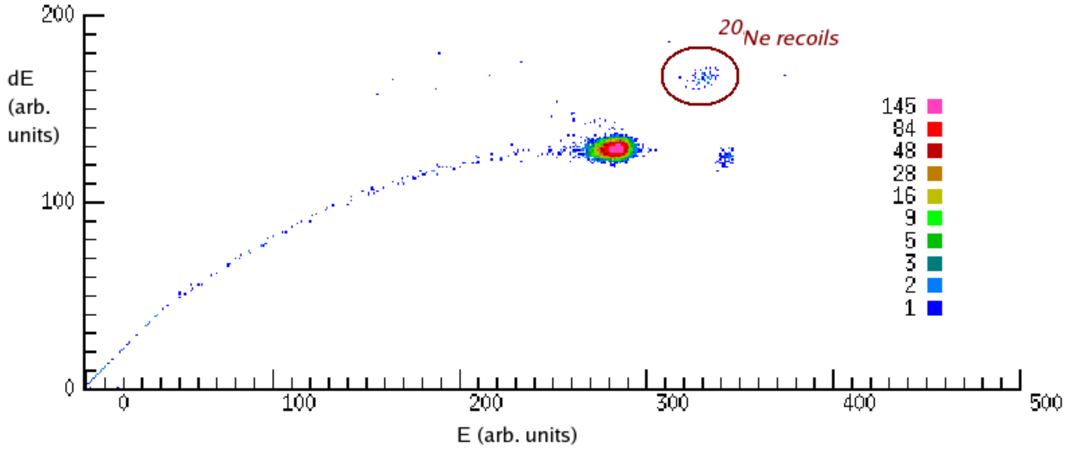

Figure 1: Ionization chamber spectrum for the ^{17}O+^{20}Ne scattering measurement with neon recoils indicated, performed in order to determine the location of ^{18}Ne recoils during the ^{17}F$(p,\gamma)^{18}$Ne measurements.

gas target (WGT), the pressure of which could be controlled to within 0.002 Torr. Monitoring of the beam current was achieved using two methods: silicon surface barrier detectors inside of the gas target measured elastic scattering from the beam for a known solid angle, and a new beam sampling setup, comprised of two plastic scintillator paddles on either side of a pneumatically-controlled actuator that repeatedly moved a copper or aluminum plate to sample the beam current via the counting of ^{17}F decays.

Recoils from the reaction of interest were detected in the focal plane ionization chamber. Investigations of the experimental system, including transmission studies, were performed by measuring several ^{17}O$(p,\gamma)^{18}$F resonances. A measurement of the 1036.5 keV resonance in ^{17}O$(p,\gamma)^{18}$F resulted in a resonance strength of 0.31 ± 0.03 eV, in good agreement with the previously adopted value [11]. The anticipated location of the ^{18}Ne recoils relative to any unreacted beam in the ionization chamber spectra was determined using ^{17}O+^{20}Ne elastic scattering, as displayed in Figure 1. For the ^{17}F$(p,\gamma)^{18}$Ne reaction, both the ^{18}Ne recoils and the unreacted ^{17}F and ^{17}O of the beam exited the WGT into the DRS, which was tuned to transmit the recoils to the focal plane, where they were identified as demonstrated in Figure 2.

At an off-resonance beam energy of 14.3 MeV, corresponding to about 800 keV above the proton threshold, data were recorded for a total of almost 53 continuous hours, in order to determine the experimental background from both the ^{17}O and ^{17}F beam constituents. 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. The yield was also measured directly at a beam energy corresponding to the 599.8 keV, astrophysically significant 3^+ state in ^{18}Ne. Data were recorded at this beam energy for a total of nearly 87 hours, with beam currents ranging between ~1-10 million ^{17}F particles per second, at three different charge states of ^{18}Ne recoils. The three resulting charge state fractions were used to calculate the total charge state distribution. This measurement resulted in a resonance strength and partial width larger than the value predicted by theory [7, 9].

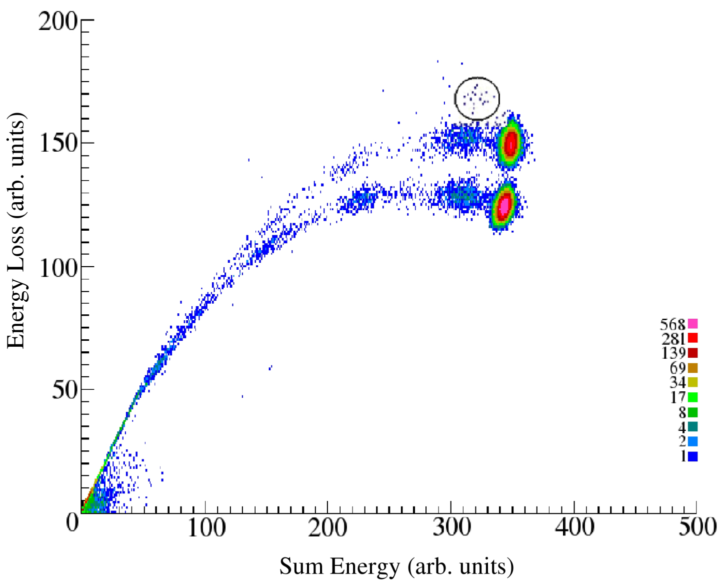

Figure 2: Energy loss versus total energy from the ionization chamber for the 599.8 keV resonance; ^{18}Ne recoils are indicated by the black circle.

3. Reaction Rate

A new reaction rate was calculated, including the two narrow resonances [7] near the 599.8 keV 3^+ resonance, based on the preliminary γ width from this work and the resonance energy and total width previously determined [3]. Because the strength of the resonance was higher than previously predicted, the reaction rate has been determined to be faster than the previously calculated rate [3], especially above nova temperatures, where the 3^+ resonance dominates. The most significant achievement of this measurement was the reduction of the uncertainty in the reaction rate from factor of 10 [12] to $<$ 55%, demonstrated in Figure 3.

The uncertainty in the γ width has been greatly improved over the theoretical predictions with this first direct measurement, resulting in a more precise reaction rate.

4. Summary

The ^{17}F$(p,\gamma)^{18}$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}F$(p,\gamma)^{18}$Ne reaction products separated with the Daresbury Recoil Separator. The ^{18}Ne recoils were detected in an ionization chamber at the focal plane. Based on this measurement, 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. This measurement is key in constraining the reaction rate of ^{17}F proton capture at energies found in novae and x-ray bursts. However, though the ^{17}F$(p,\gamma)^{18}$Ne reaction rate is significant, it is only one step in a much larger reaction network which controls the energy production and element generation in astrophysical events. Pre-

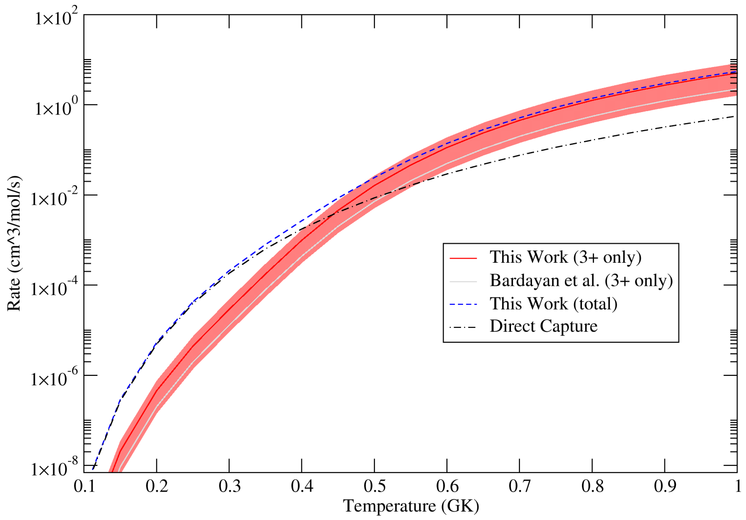

Figure 3: Reaction rate over the temperature range $0.1 \leq T_9 \leq 1.0$ for the 3^+ contribution from this work as well as the previous estimate, based on resonance parameters from Bardayan *et al.* [3] and direct capture predictions from Garcia *et al.* [7].

cise determination of the direct capture cross section to the three states in ^{18}Ne just below the proton threshold would allow for a more precise reaction rate, and knowledge of the rates of other reactions, such as ^{18}F$(p,\alpha)^{15}$O which serves to destroy ^{18}F, in addition to the ^{17}F$(p,\gamma)^{18}$Ne rate, is crucial in our search for a complete understanding of the astrophysics of such violent celestial events.

References

[1] D.W. Bardayan *et al*, *Phys. Rev. Letters* **83** (1999).

[2] S.A. Glasner, E. Livne, and J.W. Truran, *Astrophys. J.* **475**, 754 (1997).

[3] D.W. Bardayan *et al*, *Phys. Rev. C* **62**, 055804 (2000).

[4] M. Wiescher, H. Schatz, and A.E. Champagne, *Philos. Trans. R. Soc. London, Ser. A* **356**, 2105 (1998).

[5] H. Schatz *et al*, *Phys. Rep.* **294**, 167 (1998).

[6] M. Wiescher, J. Gorres and F.K. Thielemann, *Astrophys. J.* **326** (1988).

[7] A. Garcia *et al*, *Phys. Rev. C* **43**, 2012 (1991).

[8] R. Sherr and H.T. Fortune, *Phys. Rev. C* **58**, 3292 (1998).

[9] M. Dufour and P. Descouvemont, *Nucl. Phys. A* **730**, 316 (2004).

[10] Y. Parpottas *et al*, *Phys. Rev. C* **72**, 025802 (2005).

[11] C. Rolfs, A.M. Charlesworth and R.E. Azuma, *Nucl. Phys. A* **199**, 257 (1973).

[12] C. Iliadis *et al.*, *Ap. J. Suppl. Series* **142**, 105 (2002).