Observation of the Astrophysically Important 3^+ State in ^{18}Ne via Elastic Scattering of a Radioactive ^{17}F Beam from ^{1}H

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The ^{17}F$(p,\gamma)^{18}$Ne reaction is important in stellar explosions, but its rate has been uncertain because of an expected 3^+ state in ^{18}Ne that has never been conclusively observed. This state would provide a strong $\ell = 0$ resonance and, depending on its excitation energy, could dominate the stellar reaction rate. We have observed this missing 3^+ state by measuring the ^{1}H$(^{17}$F$,p)^{17}$F excitation function with a radioactive ^{17}F beam at the ORNL Holifield Radioactive Ion Beam Facility. We find that the state lies at a center-of-mass energy of $E_r = 599.8 \pm 1.5_{\mathrm{stat}} \pm 2.0_{\mathrm{sys}}$ keV ($E_x = 4523.7 \pm 2.9$ keV) and has a width of $\Gamma = 18 \pm 2_{\mathrm{stat}} \pm 1_{\mathrm{sys}}$ keV.

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There are a number of extremely hot, dense astrophysical environments where hydrogen is expected to burn explosively. These include novae, supernovae, and x-ray bursts [1]. In a classical nova explosion, hydrogen gas accretes onto a white dwarf star and burns explosively with the CNO nuclei present, creating a substantial quantity of ^{13}N, ^{14}O, ^{15}O, and ^{17}F [2]. The fate of the ^{17}F is uncertain and depends on the ^{17}F$(p,\gamma)^{18}$Ne rate. If the proton-capture rate is slower than the ^{17}F-beta-decay rate at temperatures characteristic of nova explosions [$T_9 \leq 0.2$, where $T_n = T/(10^n$ K)], then the reaction sequence ^{17}F$(e^+\nu_e)^{17}$O$(p,\alpha)^{14}$N$(p,\gamma)^{15}$O occurs. This contributes to the ^{15}O enrichment which is needed to explain the large overabundance of nitrogen (originating from ^{15}O beta decay) observed in nova ejecta [3].

If, on the other hand, the ^{17}F$(p,\gamma)^{18}$Ne rate is significant, there can be a substantial flow through the reaction sequence ^{17}F$(p,\gamma)^{18}$Ne$(e^+\nu_e)^{18}$F, and the ^{18}F/^{17}F abundance ratio would be altered. Convection can bring ^{18}F and unburned ^{17}F to the cooler surface regions where they can only beta decay. This is important for two reasons. First, the release of the decay energy further increases the luminosity to a level in excess of $10^5 L_\odot$ which can cause rapid expansion and ejection of the envelope [4]. Second, the 511-keV gamma rays produced by the annihilation of positrons from the decay of ^{18}F could be detectable because the longer half-life of ^{18}F allows it to survive until the envelope becomes more transparent [5].

The ^{17}F$(p,\gamma)^{18}$Ne reaction is also important for understanding other explosive events such as x-ray bursts and supernovae. During the ignition phase of x-ray bursts, the energy production is peaked by two reaction sequences: ^{12}C$(p,\gamma)^{13}$N$(p,\gamma)^{14}$O and ^{16}O$(p,\gamma)^{17}$F$(p,\gamma)^{18}$Ne$(e^+\nu_e)^{18}$F$(p,\alpha)^{15}$O [4]. The second sequence and thus the x-ray burst energy production depend sensitively on the ^{17}F$(p,\gamma)^{18}$Ne reaction rate. For massive stars in the presupernova phase, the temperature in the Ne-burning shell can rise to $T_9 = 1$–2 [6]. At these temperatures, ^{16}O can burn to form ^{17}F which, depending on its proton-capture rate, may undergo subsequent burning. To understand the abundances produced in these events, we must know the ^{17}F$(p,\gamma)^{18}$Ne stellar reaction rate.

Wiescher, Görres, and Thielemann [7] have proposed that a low energy 3^+ state in ^{18}Ne, the mirror to the 3^+ state at $E_x = 5.378$ MeV in ^{18}O, dominates the ^{17}F$(p,\gamma)^{18}$Ne stellar reaction rate for temperatures greater than $T_9 = 0.2$, which is in the range of peak temperatures produced in these explosive events. On the basis of a shell model calculation, they predicted this state to have an excitation energy $E_x = 4.328$ MeV and width $\Gamma \simeq \Gamma_p = 5$ keV. Subsequently, others have also done analyses of the mass $A = 18$ isobars and arrived at a wide variety of results. García *et al.* calculated $E_x = 4.53$ MeV and $\Gamma = 22$ keV [8], while Sherr and Fortune predicted $E_x = 4.642$ MeV and $\Gamma = 42$ keV [9].

Many experimental studies have also been conducted to examine states in ^{18}Ne in this excitation energy range, none of which found conclusive evidence for the existence of this 3^+ state [10]. Nero, Adelberger, and Dietrich determined the properties of many ^{18}Ne states using the ^{16}O(^{3}He, n)^{18}Ne and ^{20}Ne(p, t)^{18}Ne reactions but found no evidence for the 3^+ state [11]. García *et al.* studied the ^{16}O(^{3}He, n)^{18}Ne reaction and reported evidence at one energy and angle for a peak which has generally been interpreted as locating the missing 3^+ state at $E_x = 4.561 \pm 0.009$ MeV [8]. This state was not seen in subsequent high resolution studies of ^{20}Ne(p, t)^{18}Ne [12,13].

All of the above studies were hindered from seeing the 3^+ state because the reactions used suppress the population of states with unnatural spin and parity. We, therefore, have performed a measurement of the ^{1}H(^{17}F, p)^{17}F excitation function using a radioactive ^{17}F beam at the ORNL Holifield Radioactive Ion Beam Facility (HRIBF) [14]. Since the ground state of ^{17}F has $J^\pi = \frac{5}{2}^+$, the ^{17}F + p system populates 3^+ and 2^+ states in ^{18}Ne with $\ell = 0$ angular momentum transfers, and thus this reaction is very sensitive to the missing 3^+ state. Furthermore, we were able to determine the resonance energy and width of the state being populated from the shape of the excitation function.

A radioactive ^{17}F beam was produced by an isotope separator online-type target/ion source [14,15] via the ^{16}O(d, n)^{17}F reaction using a fibrous refractory HfO_2 target bombarded with 8 μA of 44.5 MeV deuterons from the $K = 105$ Oak Ridge Isochronous Cyclotron. Aluminum vapor was fed into the target to form Al^{17}F molecules which transported the highly reactive ^{17}F atoms out of the target material and through a short (10 cm) transfer tube to a modular ion source, where they were ionized and extracted. After a first stage of mass analysis, the Al^{17}F$^+$ molecules entered a charge exchange cell where the molecules were dissociated. The resulting ^{17}F$^-$ ions went through a second stage of mass analysis following the charge exchange cell and were then accelerated to the appropriate energy by the 25-MV tandem. After passing through an energy-analyzing magnet, the ^{17}F beam was delivered to the experimental station. The average beam current was 8×10^3 ^{17}F ions per second, and a total of 2×10^9 ^{17}F ions were incident on the target over the course of the experiment.

The ^{17}F beam bombarded a 48-μg/cm^2 polypropylene $(CH_2)_n$ foil, and the scattered protons were detected in an annular array of single-sided silicon strip detectors 10.5 cm downstream from the target location. The silicon detector array (SIDAR) is comprised of 128 segments with 16 radial (from 5 to 13 cm) and 8 azimuthal divisions, similar to the Louvain-Edinburgh Detector Array array used at Louvain-la-Neuve [16]. The array covered angles $25° \leq \theta_{\rm lab} \leq 51°$ allowing detection of the forward-focused scattered protons while passing the ^{17}F beam out of the target chamber. The experimental configuration is shown in Fig. 1. The recoil ^{17}F ions were detected in coincidence with the protons in an isobutane-filled ionization counter. This detector provides ΔE-E information for particle identification and is described in Ref. [17]. This experimental configuration was tested previously with a ^{1}H(^{17}O, p)^{17}O measurement, and the coincidence efficiency was found to be greater than 90%. The unscattered primary beam was prevented from entering the ionization counter by a 1.5-cm-diameter disk which was inserted in front of the ionization counter entrance window during each run. The size of the disk was chosen so that for the proton angles covered by the SIDAR, the corresponding recoil ^{17}F ions were not blocked by the disk. In between runs, this disk was removed and a 4-mm aperture was inserted for beam tuning and beam purity measurements via particle identification in the ion counter. Typical beam purities were found to be ^{17}F/^{17}O $\sim$ 1000.

Proton yields were measured at 12 beam energies between 10 and 12 MeV. A spectrum from the SIDAR is shown in Fig. 2. The proton peak was clearly distinguishable by its energy, angular dependence, and narrow width. Only the proton peak remained when coincidence with ^{17}F ions in the ionization counter was required. The yield at each energy was determined by summing the coincident proton yields, $Y_{\rm coin}$, in all strips of the SIDAR and normalizing to the incident beam current. This normalization was achieved by monitoring the amount of ^{17}F, Y_F, that was scattered from carbon in the target and detected by the ionization counter. The normalized proton yields, $\frac{Y_{\rm coin}}{Y_F E_{\rm in} E_{\rm out}} \times$ const where $E_{\rm in}$ ($E_{\rm out}$) is the energy the beam has before (after) it transverses the target, are displayed in Fig. 3 along with a fit to the data and clearly show the presence of a resonance. It was preferential to use the coincidence spectrum to extract proton yields, because at some energies and angles, beta particles and scattered ^{17}F ions overlap with the proton peak in the singles spectrum. There was no appreciable target degradation or dead time during the experiment. The measurement at 10.5 MeV was repeated to test the reproducibility of the system and found to lie within the uncertainty of the measurements. The beam energy calibration [18] was checked with a precision of ± 4 keV by measuring the ^{1}H(^{19}F, α)^{16}O excitation function in the region of the ^{20}Ne resonance at $E_r = 828$ keV [19]. This introduces a negligible uncertainty in the center-of-mass energy of 0.2 keV.

A fit to the data was performed using a Breit-Wigner formalism [20] with three fit parameters: the normalization, resonance energy, and width. The theoretical cross section assuming a $J^\pi = 3^+$ resonance was integrated over the angles covered by the SIDAR and then averaged over the energy loss in the target. The average energy loss was measured with a ^{19}F beam, corrected for the mass of ^{17}F, and found to be 690 ± 50 keV. The energy loss in the target changes only by 20 keV as the bombarding energy changes from 10 to 12 MeV. The best fit ($\chi^2_\nu = 1.20$) was obtained for a center-of-mass resonance energy of $E_r = 599.8 \pm 1.5$ keV and a total resonance width of $\Gamma = 18 \pm 2$ keV. The statistical uncertainties were determined in the standard way from the least-squares fit to the data [21]. The fitting procedure was varied to estimate systematic uncertainties. The singles data set was used instead of

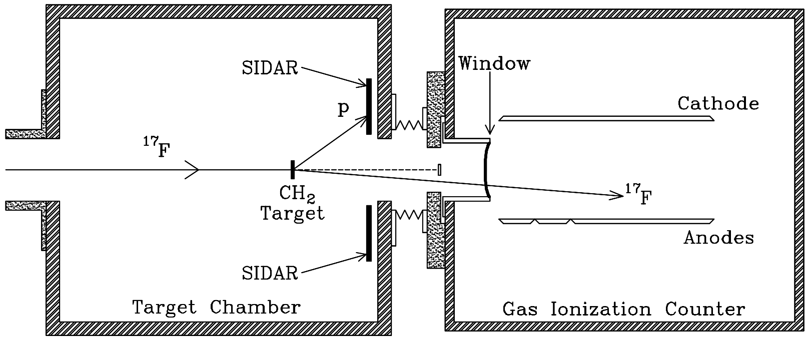

FIG. 1. Our experimental configuration is shown with the ^{17}F ions impinging on a polypropylene target. The scattered protons were detected in the SIDAR, while recoil ^{17}F ions were detected in coincidence in a gas-filled ionization counter.

the coincidence data, and an *R*-matrix fit was performed using the code MULTI [22] instead of the Breit-Wigner formalism. Additionally, the dependence of the fit results on the target thickness was examined. All of these resulted in variations in the resonance energy of less than 2 keV and in the width of less than 1 keV. From this and from a previous study of the ^{1}H(^{17}O, p)^{17}O excitation function [23], we estimate the systematic uncertainty for the resonance energy to be 2 keV and for the width to be 1 keV.

Combining the resonance energy with the measured mass excess of ^{18}Ne [24] and the well-known mass excesses of ^{1}H and ^{17}F [25] yields an excitation energy in ^{18}Ne of 4523.7 $\pm$ 2.9 keV. This is very close to the known 1^- state in ^{18}Ne at 4519 $\pm$ 8 keV and explains why this 3^+ state was not observed during measurements of reactions which more readily populate states of natural spin and parity. The resonance we have observed is not the known 1^- state because this spin and parity would require an $\ell = 1$ transfer and, as demonstrated in Fig. 3, would not be observable above the Rutherford scattering background. Furthermore, the expected width (0.1 keV) of the 1^- state [8] is inconsistent with our results. We conclude that we are populating either a 3^+ or 2^+ state in ^{18}Ne. From examination of the nuclear level diagrams, we see there are no 2^+ states in ^{18}O whose analogs have not been identified in ^{18}Ne. While it is possible that the mirror assignments are not well known, and that we are observing the mirror to the 2^+ state at $E_x = 5.255$ MeV in ^{18}O, this seems highly unlikely based upon an examination of the expected widths of the states. If we take the spectroscopic factors for the 2^+ and 3^+ states in ^{18}O from Li *et al.* [26] and an appropriate single particle width [27], we estimate a proton width for the 2^+ (3^+) state in ^{18}Ne of 7 (19) keV. If we fit our data assuming that the resonance is a 2^+ state, the best fit ($\chi^2_\nu = 1.72$ compared to 1.20 for the 3^+ case) is obtained

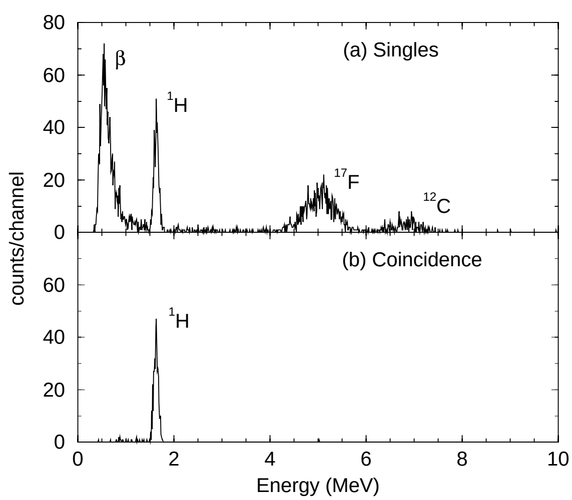

FIG. 2. (a) The raw particle spectrum from a ring of SIDAR strips at $\theta = 27.7°-29.9°$ is shown. A 10-MeV ^{17}F beam impinged on a 48-μg/cm^2 polypropylene target. (b) Same as (a) when coincidence with recoil ^{17}F ions in the ionization counter was required.

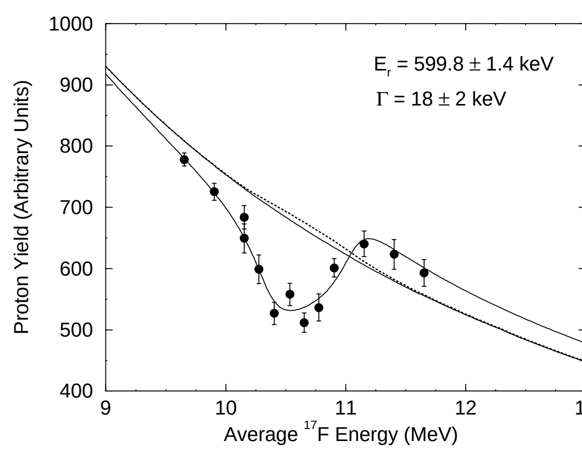

FIG. 3. The normalized proton yields are plotted as a function of the average ^{17}F beam energy in the target. The heavy solid line is a fit to the data with three fit parameters: the normalization, the resonance energy, and the width of the 3^+ state. The thin solid line shows the excitation function expected if the only resonances in this region were the previously observed 1^- and 0^+ states in ^{18}Ne. The dotted line shows the excitation function if the width of the 1^- state were 20 keV instead of the expected 0.1 keV. This curve demonstrates that the scattering anomaly could not be caused by an $\ell = 1$ resonance.

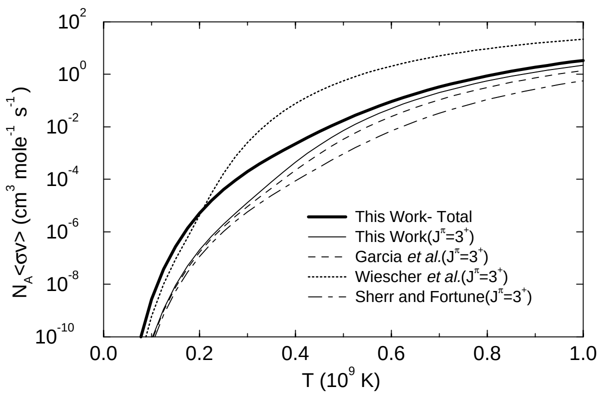

FIG. 4. The contribution to the $^{17}F(p,\gamma)^{18}Ne$ reaction rate from the 3^+ state is plotted as a function of stellar temperature. This is compared to estimates of the rate from previously published predictions of the resonance parameters from García *et al.* [8], Wiescher *et al.* [7], and Sherr and Fortune [9]. The total reaction rate, which includes contributions from nearby resonances as well as direct capture, is also shown.

for a width of 30 keV. This exceeds the total possible $1s_{1/2}$ single particle strength and is a factor of 4 greater than the estimated width. On the other hand, the 3^+ fit result of 18 ± 2 keV for the width agrees very well with the estimate of 19 keV. We, therefore, conclude that we are observing the long-sought 3^+ state in ^{18}Ne.

Using these new resonance parameters, we have recalculated the $^{17}F(p,\gamma)^{18}Ne$ stellar reaction rate as a function of temperature. The new rate is plotted in Fig. 4 along with rates using previous predictions of the resonance parameters. The calculation of the total reaction rate uses resonance properties for the nearby 0^+ and 1^- states as well as the direct capture rate from García *et al.* [8]. Our calculation follows the prescription in Ref. [28] but uses our new resonance parameters for the 3^+ state.

In conclusion, by measuring the $^1H(^{17}F,p)^{17}F$ excitation function with a radioactive ^{17}F beam, we have found the missing 3^+ state in ^{18}Ne. We measure its resonance energy to be $599.8 \pm 1.5_{\rm stat} \pm 2.0_{\rm sys}$ keV and width to be $18 \pm 2_{\rm stat} \pm 1_{\rm sys}$ keV. Because its resonance energy is 37 keV lower than was found in Ref. [8], its contribution to the $^{17}F(p,\gamma)^{18}Ne$ stellar reaction rate is a factor of ~2 larger at $T_9 = 0.5$ than the prediction in Ref. [28]. It is different, however, by orders of magnitude from the predictions of Wiescher *et al.* [7] and Sherr and Fortune [9]. Because of its excitation energy, the 3^+ state contributes strongly to the rate at temperatures above $T_9 = 0.5$ and is thus very important for explosive events such as x-ray bursts and supernovae. In the lower temperature environments of novae, the rate is dominated by the (unmeasured) direct capture contribution. While discovery of the 3^+ state resolves the greatest uncertainty in the rate, a direct measurement of the $^{17}F(p,\gamma)^{18}Ne$ cross section is needed to address the remaining uncertainties.

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