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Kinematically complete measurement of the ^{1}H(^{18}F,p)^{18}F excitation function for the astrophysically important 7.08-MeV state in ^{19}Ne

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Knowledge of the astrophysical ^{18}F(p,α)^{15}O rate is important for understanding gamma-ray emission from novae and heavy-element production in x-ray bursts. A state with $E_x \simeq 7.08$ MeV in ^{19}Ne provides an *s*-wave resonance and, depending on its properties, could dominate the ^{18}F(p,α)^{15}O rate. By measuring a kinematically complete ^{1}H(^{18}F,p)^{18}F excitation function with a radioactive ^{18}F beam at the ORNL Holifield Radioactive Ion Beam Facility, we find that the ^{19}Ne state lies at a center-of-mass energy of 665.3±1.7 keV (E_x =7077±2 keV), has a total width of 38.5±3.4 keV, and a proton partial-width of 15.8±1.6 keV.

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Novae are violent stellar explosions, exceeded in energy release only by supernovae and gamma ray bursts [1]. About 35 nova explosions are thought to occur in our galaxy each year; of these typically two or three are observed [2,3]. A nova explosion occurs on the white dwarf component of a close binary star system in which the companion star is losing hydrogen-rich material onto the white dwarf. The accreted layers accumulate until they reach temperatures exceeding 10^7 K at their base [1]. If these layers are sufficiently dense, nuclear reactions are ignited which can lead to a runaway thermonuclear explosion and the ejection of part of the accreted material. Despite intensive efforts to understand the nova mechanism, current models fail to reproduce many global properties such as the ejected mass [1], and as a result the parameters of the models such as the initial white dwarf mass and accreted envelope mass are not well constrained [4].

It has been suggested [5,6] that the observation of gamma rays from nova ejecta would provide a rather direct test of the models. The most powerful emission in gamma rays immediately after the explosion comes at energies of 511 keV and below (down to ~20–30 keV), originating from electron-positron annihilation following the beta decay of proton-rich radioactive nuclei produced in the explosion [7]. The main sources of positrons in nova envelopes are expected to be ^{13}N and ^{18}F. When ^{13}N ($t_{1/2}$=9.97 m) decays, the envelope is most likely still too opaque for gamma-ray transmission; therefore, the decay of ^{18}F ($t_{1/2}$=109.8 m) is the most significant for observations within the first several hours after the explosion. The amount of radiation emitted depends strongly on the ^{18}F content of the nova envelope which in turn is severely constrained by its destruction rate in the burning shells. This destruction occurs most rapidly by the ^{18}F(p,α)^{15}O reaction. Unfortunately, it has been found that the current uncertainties in the ^{18}F(p,α)^{15}O rate result in a factor of ~300 variation in the amount of ^{18}F produced in models [8]. It is impossible to say whether gamma-ray observations by orbital detectors are feasible without a more precise value of the ^{18}F(p,α)^{15}O stellar reaction rate.

Knowledge of the ^{18}F(p,α)^{15}O rate is also important for understanding heavy-element production in x-ray bursts, where much higher peak temperatures and densities are reached than in novae [9]. In these conditions, there may be a transition to heavy element production via the reaction sequence ^{18}F(p,γ)^{19}Ne(p,γ)^{20}Na(p,γ)^{21}Mg,... [10]. Whether there is a significant flow through this reaction sequence in x-ray bursts depends sensitively on the competition between the ^{18}F(p,γ)^{19}Ne and ^{18}F(p,α)^{15}O reactions, and thus we must know their relative rates in this high-temperature astrophysical environment.

The ^{18}F(p,α)^{15}O rate is thought to be dominated at high temperatures by a resonance near $E_{\mathrm{c.m.}}$=660 keV in ^{19}Ne [11]. This state may have $J^{\pi}=\frac{3}{2}^{+}$ and would be primarily an *s*-wave resonance for the ^{18}F+p system since the ground state of ^{18}F has $J^{\pi}=1^{+}$. Utku *et al.* [11] populated the state using the ^{19}F(^{3}He,t)^{19}Ne reaction. They measured the resonance energy (E_r), total width (Γ), and proton partial width (Γ_p) to be 659±9 keV, 39±10 keV, and 14±4 keV, respectively. Coszach *et al.* [12] found E_r=638±15 keV, Γ =37±5 keV, and Γ_p=13 keV by deconvoluting the ^{1}H(^{18}F,p)^{18}F and ^{1}H(^{18}F,α)^{15}O energy spectra measured with a thick (200-μg/cm^2) polyethylene target. Rehm *et al.* [13] extracted E_r=652±4 keV, Γ=13.6±4.6 keV, and Γ_p=5.0±1.6 keV from a measurement of the yield of the ^{1}H(^{18}F,^{15}O)^{4}He reaction as a function of beam energy with a thinner (60-μg/cm^2) target. These discrepancies (as much as a factor of 3 in the width and 21 keV in the resonance energy) result in up to a factor of 3 variation in the ^{18}F(p,α)^{15}O rate [14].

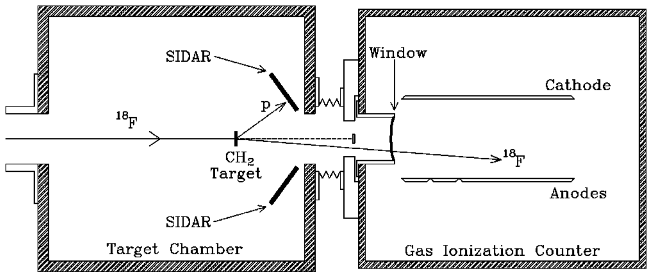

FIG. 1. Our experimental configuration is shown with the ^{18}F ions impinging on a polypropylene target. The scattered protons were detected in the SIDAR, while recoil ^{18}F ions were detected in coincidence in a gas-filled ionization counter.

To resolve these discrepancies, we have measured the ^{1}H(^{18}F,p)^{18}F excitation function using a radioactive ^{18}F beam at the ORNL Holifield Radioactive Ion Beam Facility (HRIBF). The yield of the ^{1}H(^{18}F,α)^{15}O reaction was measured simultaneously, and detailed analysis of this data set is in progress. Our method utilized a thin (35-μg/cm^2) polypropylene target which, along with the excellent energy resolution of the beam ($\Delta E/E \sim 10^{-3}$), allowed for a more precise measurement of the resonance properties. The ^{18}F beam was produced at the HRIBF by an isotope separator online-type target/ion source [15] via the ^{16}O(α,pn)^{18}F reaction using a fibrous refractory HfO$_2$ target [16] bombarded with $\sim 1\,\mu$A of 85 MeV ^{4}He ions from the Oak Ridge Isochronous Cyclotron. The radioactive species diffused from the target material and effused to a kinetic-ejection negative-ion source [17] where the ^{18}F atoms were ionized and extracted. After two stages of mass analysis, the ^{18}F ions were injected into the HRIBF tandem accelerator and accelerated to the appropriate energies ($\sim$0.7 MeV/nucleon) for the experiment. The average beam current on target was 2×10^{5} ^{18}F ions per second, and a total of 2×10^{10} ^{18}F ions were incident on the target over the course of the experiment. The beam was contaminated by ^{18}O (^{18}F/^{18}O$\sim$0.1), and our experiment had to be designed to overcome this difficulty.

The experimental configuration is shown in Fig. 1. The ^{18}F beam bombarded a 35-μg/cm^2 polypropylene (CH$_2$)$_n$ foil, and the scattered protons were detected in a silicon detector array (SIDAR) [18]. The detectors (each having 16 radial divisions) were tilted upstream at a 41° angle in order to cover a large angular range. The array covered laboratory angles $15° \leqslant \theta_{lab} \leqslant 43°$, allowing detection of the forward-focused scattered protons while allowing the ^{18}F beam to pass out of the target chamber. The recoil ^{18}F ions were detected in coincidence with the scattered protons in an isobutane-filled ionization counter. The counter provided energy loss and total energy information for particle identification and allowed us to readily distinguish the ^{18}F$+p$ scattering events from the more intense ^{18}O$+p$ events. A particle spectrum from the ionization counter is shown in Fig. 2. A similar experimental configuration was used previously in a measurement of the ^{1}H(^{17}F,p)^{17}F excitation function and was found to be highly reliable [18]. The coincidence efficiency was measured at several beam energies between 10 and 14 MeV. It was found to be $\sim$93% and to only vary by

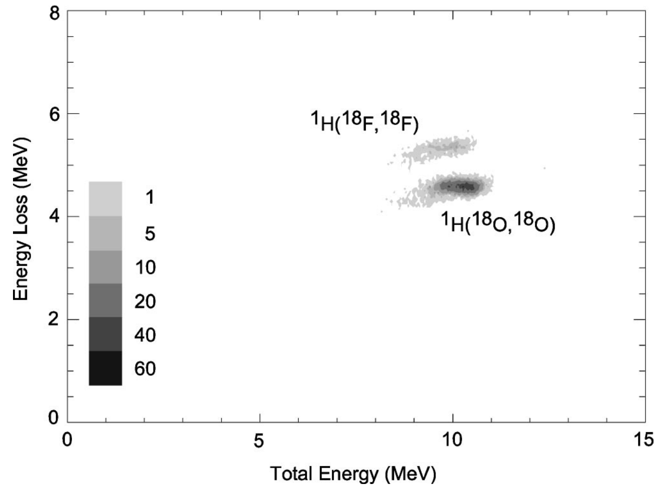

FIG. 2. A plot of the energy lost in the first two anodes vs the total energy deposited in the ion counter is shown. This spectrum was produced when a coincidence with a proton detected by the SIDAR was required. The ^{18}F scattering events were readily distinguished from the ^{18}O events.

$\pm 1\%$ as a function of energy. 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 ^{18}F ions were not blocked by the disk. When the beam energy was changed, 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.

Proton yields were measured at 15 beam energies between 10 and 14 MeV. The yield at each energy was determined by summing the coincident proton yields, Y_{coin}, in the inner 12 strips of the SIDAR and normalizing to the incident beam current. The resonance scattering is small with respect to Rutherford scattering at larger lab (smaller center-of-mass) angles, and therefore the proton yields extracted from the inner 12 strips were found to be more sensitive to the resonance parameters than those extracted from the entire detector. The beam current normalization was achieved by monitoring the amount of ^{18}F, Y_F, that was scattered from carbon in the target and detected by the ionization counter. The normalized proton yields, $(Y_{coin}/Y_F E_{in} E_{out})\times$const, where $E_{in}(E_{out})$ is the energy the beam has before (after) it traverses the target, are displayed in Fig. 3 along with the expected yield for nonresonant elastic scattering and a fit to the data. The presence of a resonance which interferes with the elastic scattering is clear.

From the magnitude and shape of the scattering anomaly, the resonance must have been populated by an $l=0$ partial wave, and thus the state must have $J^{\pi}=\frac{3}{2}^{+}$ or $\frac{1}{2}^{+}$. A fit to the data was performed using two different formalisms. The first used the Breit-Wigner methodology detailed in Blatt and Biedenharn [19], and the second utilized the *R*-matrix code MULTI [20]. In both cases the fit was performed with four fit parameters: the normalization, resonance energy, total width, and proton partial-width. Assuming a $J^{\pi}=\frac{3}{2}^{+}$ resonance, the

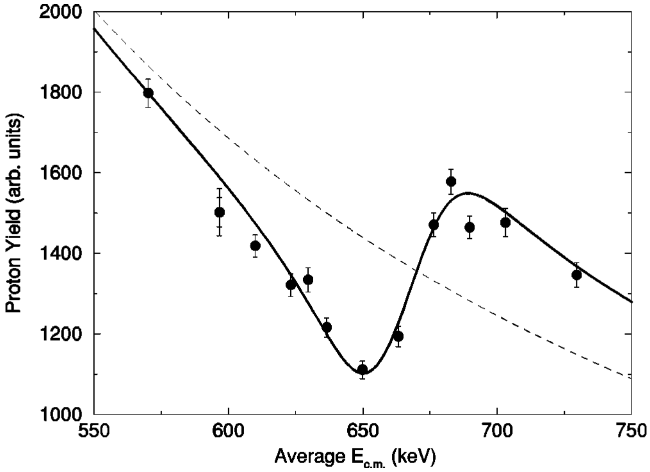

FIG. 3. The normalized proton yields are plotted as a function of the average center-of-mass energy in the target. The solid line is an *R*-matrix fit to the data with four fit parameters: the normalization, the resonance energy, the total width, and the proton partial-width of the $\frac{3}{2}^{+}$ state. The dashed line shows the excitation function expected if there were no states in this excitation energy region.

theoretical cross section was integrated over the angles covered by the inner 12 strips of the SIDAR and averaged over the energy loss in the target. The results from the fits are summarized in Table I along with the average of the resonance properties. The results from the two techniques agree at the 1σ level. The quoted uncertainties from each fit are statistical in nature and were determined in the standard way from the least-squares fit to the data. The best *R*-matrix fit is shown in Fig. 3 and includes the contributions from nearby resonances with resonance parameters from Utku *et al.* [11]. If we fit the same data assuming that the populated state has $J^{\pi}=\frac{1}{2}^{+}$, the best fit is achieved with a proton to total width ratio of $\Gamma_p/\Gamma=0.82\pm0.04$. While we cannot rule out this possibility, it would be inconsistent with the previous measurement of Γ_p/Γ [11] and would require a much larger spectroscopic factor, $S_p=\Gamma_p/\Gamma_{\text{s.p.}}$, than predicted [21].

A number of systematic uncertainties were carefully considered. There was no appreciable target degradation or dead time during the experiment. The measurement at 11.5 MeV ($E_{\text{c.m.}}=597$ keV) was repeated near the end of the run (~26 h of beam on target between measurements) to test the reproducibility of the system and found to lie within the uncertainty of the measurements. Uncertainties in the beam energy calibration [22] were recently checked [23] and found to be negligible. The best-fit results showed a mild dependence on the target energy loss used in the fitting routine. The energy loss of alphas in the target was measured using a ^{244}Cm source. This energy loss was then converted to an expected energy loss for the ^{18}F ions and found to be 490 ±50 keV. This energy loss was consistent with the observed energy spread of the detected protons from the ^{1}H(^{18}F,p)^{18}F reaction. In the fitting routine, the energy loss was varied by its uncertainty, and the best-fit results changed by 1.5 keV for the resonance energy, by 1.7 keV for the total width, and by 0.01 for the ratio of Γ_p/Γ. Other systematic uncertainties were negligible.

We adopt resonance parameters that are the average of the values obtained from the two fits ($E_r=665.3\pm0.7$ keV, $\Gamma=38.5\pm2.3$ keV, and $\Gamma_p/\Gamma=0.408\pm0.011$). The uncertainty in the width was increased to ±3 keV to cover the difference between the fit results. The uncertainties in the averages were then combined in quadrature with the systematic uncertainties to obtain $E_r=665.3\pm1.7$ keV, $\Gamma=38.5\pm3.4$ keV, and $\Gamma_p/\Gamma=0.41\pm0.02$. Our results agree with those given in Utku *et al.* [11] and agree with Coszach *et al.* [12] for the total and proton partial widths. However, our findings for the width, resonance energy, and proton partial-width do not agree (i.e., are not within 1σ) with those in Rehm *et al.* [13]. They also do not agree with the resonance energy found by Coszach *et al.* [12]. Our results imply a proton partial width for this state of 15.8 ± 1.6 keV which agrees with that recently calculated by Fortune and Sherr [21]. From these resonance parameters, we calculate the resonance strength of this state for the ^{18}F(p,α)^{15}O reaction to be

$$\omega\gamma=\frac{2J_r+1}{(2J_1+1)(2J_2+1)}\,\frac{\Gamma_p\Gamma_\alpha}{\Gamma}=6.2\pm0.6\ \text{keV},$$

where J_r, Γ_p, Γ_α, and Γ are the spin, proton partial width, alpha partial width, and total width of the resonance, respectively. J_1 and J_2 are the spins of the incident nuclei, and Γ_α was extracted from the relation $\Gamma\simeq\Gamma_p+\Gamma_\alpha$. The effect of our results on the calculated ^{18}F(p,α)^{15}O and ^{18}F(p,γ)^{19}Ne rates will be the subject of a forthcoming paper [24].

In conclusion, the ^{18}F(p,α)^{15}O stellar reaction rate was uncertain, in part because of discrepant results from previous measurements [11–13] concerning the properties of a resonance near 7.08 MeV in ^{19}Ne. These measurements differed by as much as a factor of 3 in their adopted widths and by as much as 21 keV in their excitation energy for the state. By measuring the ^{1}H(^{18}F,p)^{18}F excitation function with a thin

TABLE I. A summary of the resonance properties from previous measurements is shown along with the best-fit results from this work.

	Ref. [11]	Ref. [12]	Ref. [13]	This work Breit-Wigner	This work *R* matrix	This work adopted
E_r (keV)	659 ± 9	638 ± 15	652 ± 4	665.1 ± 1.1	665.4 ± 0.9	665.3 ± 1.7
Γ (keV)	39 ± 10	37 ± 5	13.6 ± 4.6	41.5 ± 4.6	35.5 ± 2.6	38.5 ± 3.4
Γ_p/Γ	0.37 ± 0.04	0.4–0.6	0.37[a]	0.405 ± 0.017	0.411 ± 0.014	0.41 ± 0.02

[a]Analysis assumed $\Gamma_p/\Gamma=0.37$ from Ref. [11].

target and a high-resolution ^{18}F beam, we were able to determine the properties of this resonance with a greater precision than had been done previously. Our results for the total width and resonance strength clearly favor those found in Refs. [11,12] over the one in Ref. [13]. While our measurement has resolved the discrepancy in the resonance strength of this state, the $^{18}F(p,\alpha)^{15}O$ rate is still uncertain at lower temperatures owing to the unknown properties of lower-energy states in ^{19}Ne [25]. Further work with ^{18}F beams is planned at the HRIBF in order to address these uncertainties.

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[1] S. Starrfield, Phys. Rep. **311**, 371 (1999).
[2] S. Starrfield and S. N. Shore, Sci. Am. (Special Ed.) **9**, 56 (1998).
[3] M. Hernanz and J. José, in *Cosmic Explosions*, Proceedings of the 10th Annual October Maryland Astrophysics Conference, College Park, MD, edited by S. S. Holt and W. W. Zhang, AIP Conf. Proc. No. 522 (AIP, Melville, 2000), p. 339.
[4] S. Wanajo, M. Hashimoto, and K. Nomoto, Astrophys. J. **523**, 409 (1999).
[5] M. D. Leising and D. D. Clayton, Astrophys. J. **323**, 159 (1987).
[6] M. J. Harris, J. E. Naya, B. J. Teegarden, T. L. Cline, N. Gehrels, D. M. Palmer, R. Ramaty, and H. Seifert, Astrophys. J. **522**, 424 (1999).
[7] M. Hernanz, J. José, A. Coc, J. Gómez-Gomar, and J. Isern, Astrophys. J. Lett. **526**, L97 (1999).
[8] A. Coc, M. Hernanz, J. José, and J.-P. Thibaud, Astron. Astrophys. **357**, 561 (2000).
[9] R. E. Taam, S. E. Woosley, T. A. Weaver, and D. Q. Lamb, Astrophys. J. **413**, 324 (1993).
[10] A. E. Champagne and M. Wiescher, Annu. Rev. Nucl. Part. Sci. **42**, 39 (1992).
[11] S. Utku *et al.*, Phys. Rev. C **57**, 2731 (1998).
[12] R. Coszach *et al.*, Phys. Lett. B **353**, 184 (1995).
[13] K. E. Rehm *et al.*, Phys. Rev. C **53**, 1950 (1996).
[14] N. Shu (private communication).
[15] G. D. Alton and J. R. Beene, J. Phys. G **24**, 1347 (1998).
[16] R. F. Welton, R. L. Auble, J. R. Beene, J. C. Blackmon, J. Kormicki, P. E. Mueller, D. W. Stracener, and C. L. Williams, Nucl. Instrum. Methods Phys. Res. B **159**, 116 (1999).
[17] G. D. Alton, Y. Liu, C. Williams, and S. N. Murray, Nucl. Instrum. Methods Phys. Res. B (in press).
[18] D. W. Bardayan *et al.*, Phys. Rev. Lett. **83**, 45 (1999).
[19] J. M. Blatt and L. C. Biedenharn, Rev. Mod. Phys. **24**, 258 (1952).
[20] R. O. Nelson, E. G. Bilpuch, and G. E. Mitchell, Nucl. Instrum. Methods Phys. Res. A **236**, 128 (1985).
[21] H. T. Fortune and R. Sherr, Phys. Rev. C **61**, 024313 (2000).
[22] D. K. Olsen, K. A. Erb, C. M. Jones, W. T. Milner, D. C. Weisser, and N. F. Ziegler, Nucl. Instrum. Methods Phys. Res. A **254**, 1 (1987).
[23] D. W. Bardayan, Ph.D. thesis, Yale University, 1999.
[24] N. Shu *et al.* (unpublished).
[25] J. S. Graulich *et al.*, Nucl. Phys. **A626**, 751 (1997).