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The first proton-transfer study of $^{18}\mathrm{F}+p$ resonances relevant for novae

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The $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ reaction is the predominant destruction mechanism in novae of the radionuclide $^{18}\mathrm{F}$, a target of γ-ray observatories. Its rate is thus important for understanding $^{18}\mathrm{F}$ production in novae. We have studied resonances in the $^{18}\mathrm{F}+p$ system by making the first measurement of a proton-transfer reaction $^{18}\mathrm{F}(d,n)$. We have observed 15 $^{19}\mathrm{Ne}$ levels, five of which are below the proton threshold, including a subthreshold state, which has significant $l_p = 0$ strength. Our data provide the first direct determination of the spectroscopic strength of these states and new constraints on their spins and parities, thereby resolving a controversy involving the 8- and 38-keV resonances. The $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ reaction rate is re-evaluated, taking into account the subthreshold resonance and other new information determined in this experiment.

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The emission of γ-rays by novae is dominated by e^-e^+ annihilation resulting from the β^+ decay of radioactive nuclei during the first few hours following the initiation of the outburst. The long half-life of $^{18}\mathrm{F}$ ($\mathrm{T}_{1/2} \approx 110$ m) and its relative abundance make it a leading candidate for observable γ-ray production by satellites such as INTEGRAL [1]. The detection of $^{18}\mathrm{F}$ γ-rays would provide a direct test of nova models [2]. So far, only high-energy (>100 MeV) γ rays associated with nova outbursts have been detected [3]. For the detection of nuclear γ ray lines in the keV or MeV range, the sensitivity requirements and maximum detection distances are poorly known due to uncertainties in the nuclear processes that create and destroy $^{18}\mathrm{F}$.

The accurate determination of the $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ reaction rate is critical for calculating the sensitivity required to make γ-ray observations since this reaction destroys a significant fraction of the $^{18}\mathrm{F}$ nuclei created in the initial nova outburst before they are carried by convection to the top of the explosion envelope. The $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ reaction rate is determined by several resonances in $^{19}\mathrm{Ne}$ (thresholds for proton and α emission are at $\mathrm{S}_{p\gamma} = 6411$ and $\mathrm{S}_{\alpha\gamma} = 3529$ keV, respectively). The rate is dominated at high temperatures by the two known resonances at $E_{c.m.} = 665$ keV ($3/2^+$) and 330 keV ($3/2^-$) that arise from $^{19}\mathrm{Ne}$ levels at $E_x = 7076$ and 6741 keV, respectively [4, 5]. As the cross section has only been measured directly down to 330 keV, the last remaining major uncertainty has been the unknown properties of levels near the $\mathrm{S}_{p\gamma}$. Since the discovery by Utku [6] of possible resonances at 8 and 38 keV, there has been considerable speculation during the ensuing decade concerning their properties (see Ref. [7] and references therein). This has only increased in recent years after the discovery [8, 9] of large single-particle strength in the mirror nucleus, $^{19}\mathrm{F}$, that may be concentrated in these near-threshold levels in $^{19}\mathrm{Ne}$. Higher energy resonances [10, 11] only have a minimal effect at nova temperatures. There have been many publications [11–15] considering the effects that these resonances may have on $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ reaction rate and nature of the single particle strength. As a result of these uncertainties in the rate, the predicted amount of $^{18}\mathrm{F}$ produced in nova explosions is uncertain by over a factor of 10.

To locate this large single particle strength in $^{19}\mathrm{Ne}$, we have made the first measurement of a proton-transfer $^{18}\mathrm{F}(d,n)$ reaction. The proton-transfer reaction enables us to study resonances that have a yield too small to measure directly. Despite years of use as a spectroscopic tool, only a few attempts have been made to apply the (d,n) reaction to radioactive beams [16–18], none of which achieved the necessary resolution to resolve excited states. The present approach not only elucidates the astrophysically-important structure of $^{19}\mathrm{Ne}$ near the proton threshold, but also represents the first successful spectroscopic application of the (d,n) reaction to a radioactive beam. While the excitation energies of the levels determined in this work agree with previous determinations, our measurements provide the first direct determination of their spectroscopic strength and also new constraints on their spin and parity.

The $^{18}\mathrm{F}$ beam was produced at the Oak Ridge Na-

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tional Laboratory's Holifield Radioactive Ion Beam Facility (HRIBF). A 716-μg/cm^2 CD_2 target was bombarded with an isotopically-pure, 150-MeV ^{18}F beam with an intensity of $\approx 2.2 \times 10^6$/s. In inverse kinematics, the reaction neutrons are emitted predominantly at backward angles in the laboratory system while the ^{19}Ne is limited to a narrow cone at forward angles. The ^{19}Ne states near the $S_{p\gamma}$ promptly decay into $\alpha + ^{15}$O and were detected in coincidence using position-sensitive E-ΔE telescopes located downstream of the target, in a geometry optimized for the detection of the breakup of states near the $S_{p\gamma}$ in ^{19}Ne. Two of the telescopes covered $2.5° - 8.5°$ on either side of the beam axis and were optimized to measure heavier particles. The remaining four telescopes covered $10.5° - 16.5°$ on either side of the beam axis and were optimized to detect the α particles. The energy calibrations of the detectors were determined by measuring the elastic scattering of ^{16}O and α beams from a Au foil. The determination of the positions and energies of the detected α and ^{15}O allowed their momenta to be reconstructed. The excitation energy of the decaying state relative to the $\alpha +^{15}$ O threshold ("relative energy"), and the momentum of the undetected neutron were calculated.

The coincidence and particle identification requirements eliminated nearly all sources of background. The resulting $\alpha + ^{15}$O relative energy spectrum is shown in Fig. 1. Our Excitation energies compare well with compilation results in Refs. [7, 19]. We were able to extract neutron angular distributions for the (d, n) reaction to strongly-populated states at E_x = 6089(2), 6289(2), 6419(6), 6747(5), and 7085(5) keV (statistical uncertainties are given in parentheses). The coincidence efficiency is excitation-energy dependent and was calculated for our geometry and kinematics with a Monte Carlo simulation which assumes the $\alpha + ^{15}$O breakup is isotropic in the center-of-mass system. We have assumed that $\Gamma_\alpha/\Gamma = 1$ for all states, except for the 7085-keV level where the known proton branching ratio [5] was taken into account. In order to determine angular momentum transfer and deduce spectroscopic factors of the transferred proton, a distorted-wave Born approximation (DWBA) analysis on the neutron angular distributions was performed with the zero-range code DWUCK4 [20] and the finite-range code FRESCO [21]. The two calculations agreed to within 3% for proton-bound states; only DWUCK4 was used for proton-unbound states. Spectroscopic factors were then extracted by comparison of experimental neutron angular distributions with the results of DWBA calculations. The angular distributions extracted for levels at E_x = 6747 and 7085 keV support their known $J^\pi = 3/2^-$ and $3/2^+$ assignments, respectively. We have determined the partial proton width of these states using the relation $\Gamma_p = S_p \Gamma_{sp}$ [22], where Γ_{sp} is the single-particle proton width as calculated by DWUCK4 and S_p is the spectroscopic factor. The errors reported for the E_x, S_p, and Γ_p in this work are statistical. Systematic errors are estimated to be 10 keV for the E_x, 12% for the differential cross sections, 40% for S_p and 30% for Γ_p. The details of the error analysis are available in Ref. [23].

Proton widths of 7.3(6) keV and 13.5(7) keV were determined for the 6747-keV and 7085-keV states, respectively. The result for the 7085-keV state agrees well with the previously determined Γ_p of 15.2(1.0) keV [5]. For the 6747-keV state, our result is significantly larger than the previously determined value of 2.22(69) keV [4]. We note that the experimental uncertainties are still rather large and contibutions from nearby levels cannot be ruled out. In the calculation of the ^{18}F$(p, \alpha)^{15}$O reaction rate, the levels at E_x = 6419 and 6449 keV (corresponding to resonance energy E_r = 8 and 38 keV, respectively) have previously been thought to contribute significantly [14]. We observed the 6419-keV level but we see no evidence of a 6449-keV level in our data. The angular distribution of the 6419 keV state shown in Fig. 2(a) is well reproduced with $l_p = 1$ transfer and does not agree with $l_p = 0$ assumed previously for the state. The Γ_p determined for this state is $2.54(8) \times 10^{-38}$ or $1.27(4) \times 10^{-38}$ keV assuming $J^\pi = 1/2^-$ or $3/2^-$, respectively. Considering that the 6419- and 6449-keV levels are 30 keV apart, we cannot completely eliminate the possibility of the 6449-keV level in our data. Allowing for a second Gaussian in the fitting with a centroid fixed at the known value, we find the following upper limits for the 6449-keV state: $S_p \leq 0.028$ corresponding to $\Gamma_p \leq 2.35 \times 10^{-15}$ keV for $J^\pi = 3/2^+$. The assumed analog levels in ^{19}F by previous workers (see Ref. [7] and references therein) utilizing mirror symmetry has $J^\pi = 3/2^+$ for both the 8- and 38-keV resonances with either of them having a relatively large S_p. We have determined in this work that the 8-keV resonance has a different spin and the S_p of the 38-keV resonance is significantly smaller.

The angular distribution of the subthreshold ^{19}Ne(6289 keV) state is shown in Fig. 2(b). The spin of 1^+ for the $^{18}F_{g.s.}$ allowed for more than one angular momentum transfer for a given final state

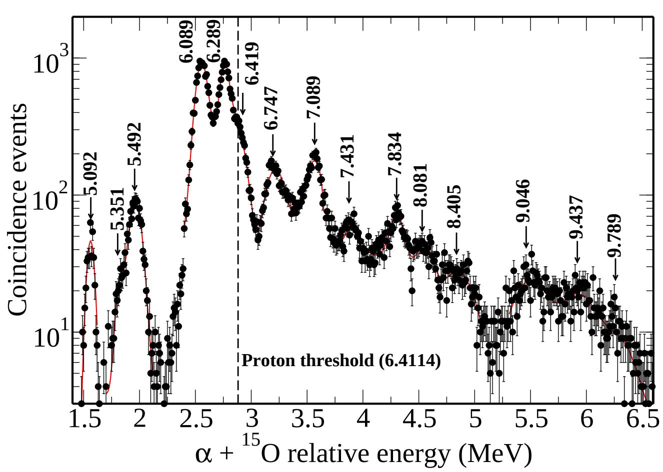

FIG. 1: (Color online) $\alpha + ^{15}$O coincidences versus relative energy in ^{19}Ne. The shaded circles are experimental data while the red curves are the fit. Excitation energies in MeV are indicated.

in ^{19}Ne. The fit shown in Fig. 2(b) corresponds to a combination of $2s_{1/2}$ and $1d_{5/2}$ with $(2J+1)S_p = 0.909(24)$ and $0.545(22)$, respectively. The two possible J^π for the final state in ^{19}Ne(6289 keV) are $1/2^+$ (via proton transferred to the $2s_{1/2}$ or/and $1d_{3/2}$) or $3/2^+$ (via proton transferred to the $2s_{1/2}$ or/and $1d_{5/2}$ or/and $1d_{3/2}$), making it a likely mirror candidate for one of the three states in ^{19}F at $E_x = 6255$ keV ($1/2^+$), 6497 keV ($3/2^+$) and 6528 keV ($3/2^+$). The discovery of $l_p = 0$ for the subthreshold state in this measurement is consistent with the recent theoretical prediction of an s-wave state below the $S_{p\gamma}$ [13]. Using R-matrix formalism, the proton reduced width amplitudes (γ_p) for the 6289-keV state were deduced from our measured asymptotic normalization coefficients of 3479(92) or 6972(183) fm^{-1} for this state assuming $J^\pi = 3/2^+$ or $1/2^+$, respectively. We investigated the maximum and minimum contributions of the high energy tail of the 6289-keV state by utilizing the largest and smallest γ_p and their associated γ_α obtained from the Γ_α of the mirror candidate in ^{19}F at $E_x = 6225$ keV ($1/2^+$) and 6497 keV ($3/2^+$), respectively using Eq. (5) in Ref. [7].

We re-evaluated the ^{18}F$(p,\alpha)^{15}$O reaction rate using the new information from this work summarized in Table I, merged with other recent measurements [7, 12]. The ratio of previous rate calculated using the resonance parameters in Ref. [7] to the present rate, which assumed $J^\pi = 3/2^-$ for the 8-keV resonance and $J^\pi = 3/2^+$ for the 6289-keV subthreshold state, is shown as black curve in Fig. 3. The present rate is a factor of ∼2 less than the previous rate at T < 0.1 GK. This is mostly due to the reduction of strength found for the 8- and 38-keV resonances. The uncertainty in the rate was calculated by varying each resonance's contribution within its uncertainty and combining the resulting rate variation in quadrature. The previous and present uncertainties normalized to the present rate are shown as red and blue curves, respectively in Fig. 3. These curves only consider the uncertainty in the strengths of the 8- and 38-keV resonances, not interference effects. The uncertainty has been reduced from roughly a factor of 5 to a factor of ∼1.3 in the present rate.

The angular momentum transfer of $l_p = 1$ determined for the 8-keV resonance in this measurement eliminates

TABLE I: Resonance parameters of levels in ^{19}Ne near the $S_{p\gamma}$ determined in this work, except where indicated.

E_x (keV)	E_r (keV)	J^π	Γ_p (keV)	Γ_α (keV)
6289^a	−122	$1/2^+$ or $3/2^+$	–	11.62 or 0.44
6419	8	$1/2^-$	2.54×10^{-38}	0.27^b
		$3/2^-$	1.27×10^{-38}	
6449	38	$3/2^+$	$\leq 2.35\times10^{-15}$	4.0^c
6749	330	$3/2^-$	7.3×10^{-3}	2.7^c
7089	665	$3/2^+$	13.5	24.0^c

^{a}The largest and smallest Γ_α were obtained from the the mirror candidate in ^{19}F at $E_x = 6225$ keV ($1/2^+$) and 6497 keV ($3/2^+$), respectively using Eq. (5) in Ref. [7]
^{b}Taken from Ref. [7]
^{c}Taken from Ref. [12]

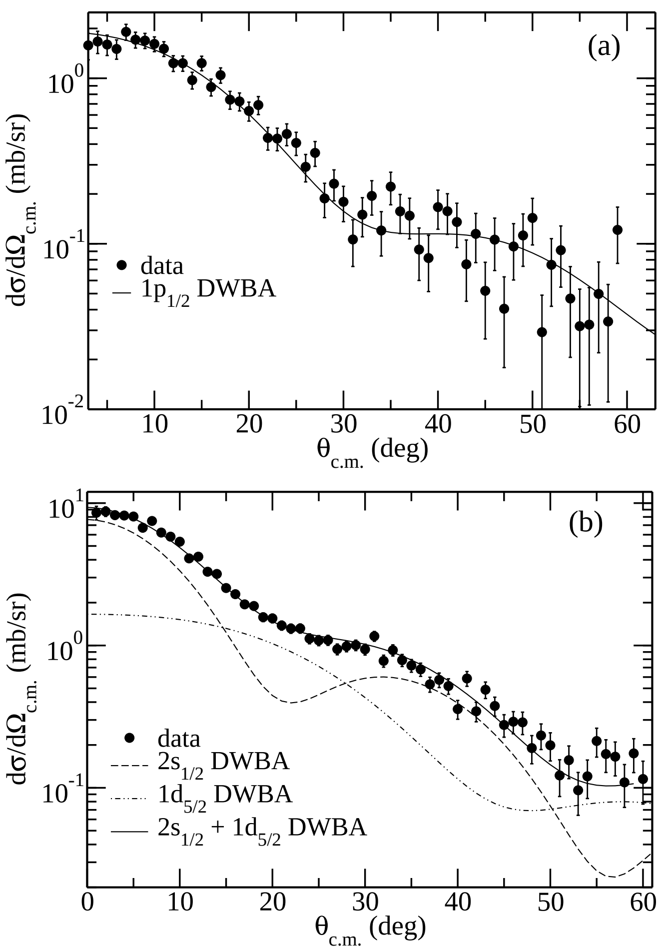

FIG. 2: Neutron angular distributions for (d,n) transfer to the 6419-keV (top) and 6289-keV (bottom) states in ^{19}Ne.

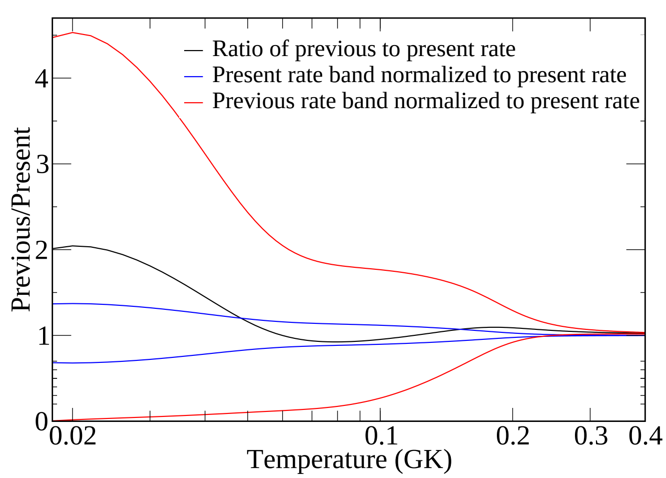

FIG. 3: (Color online) Ratio of previous [7] to present ^{18}F$(p,\alpha)^{15}$O reaction rate and variation in the rate due to uncertainty in the 8- and 38-keV proton widths at nova temperatures.

TABLE II: The 14 coefficients a_{ij} used to parametrize the central values of our ^{18}F$(p,\alpha)^{15}$O reaction rate. The parameterization was done in the analytic format of Ref. [24].

i\j	1	2	3	4	5	6	7
1	0.256233×10^4	-0.215677×10^1	0.458944×10^3	-0.393599×10^4	0.148367×10^4	-0.619343×10^3	0.802081×10^3
2	0.281111×10^3	-0.199098×10^1	0.186456×10^3	-0.485524×10^3	0.359873×10^2	-0.264243×10^1	0.196608×10^3

its contribution to interference between the $3/2^+$ resonances. In evaluating this effect on ^{18}F$(p,\alpha)^{15}$O reaction rate, we have limited ourselves to interference due to three $3/2^+$ resonances at $E_r = -122$, 38, and 665 keV. The combinations of interference signs $(--+)$ and $(+++)$ yield the respective maximum and minimum contribution to the rate at nova temperatures. However, the assumption of $J^\pi = 1/2^+$ for the subthreshold state reduces interference terms to between the 38- and 665-keV resonances and consequently interference signs to $(-+)$ and $(++)$. The interference with the recently observed resonances at $E_r = 1347$ keV $(3/2^+)$ [10] and 1452 keV $(1/2^+)$ [11] have not been included since we find them to have negligible impact on the ^{18}F$(p,\alpha)^{15}$O reaction rate at nova temperatures. The discovery of the new important subthreshold state, that has uncertain spin, leads to additional uncertainties in the reaction rate that have not been considered previously. The uncertainties from interference between the $3/2^+$ states are shown as red+green and green bands in Fig. 4 with $J^\pi = 3/2^+$ and $1/2^+$, respectively assumed for the subthreshold state. The high rates in both cases are essentially the same while their low rates are different over the whole temperature region. The interference between the p-wave states when investigated makes a negligible change to the rate

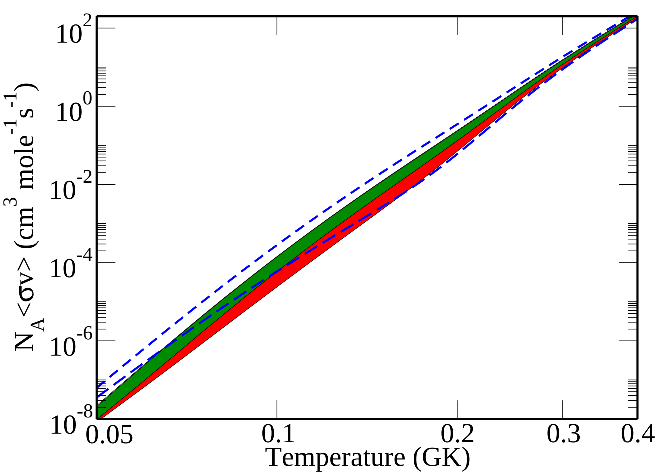

FIG. 4: (Color online) Interference uncertainties on ^{18}F$(p,\alpha)^{15}$O reaction rate at nova temperatures. The red+green and green bands are for $J^\pi = 3/2^+$ and $1/2^+$, respectively assumed for the subthreshold state. The high rates in both cases are the same at nova temperatures. The blue dashed-lines are the lower and higher rates of Chae *et al.* [12].

and has therefore been neglected in this work. We additionally show in this figure the lower and higher rates of Chae *et al.* [12] in blue dashed-line calculated from their S-factors where only interference uncertainties were considered. We parameterized our new ^{18}F$(p,\alpha)^{15}$O reaction rates in the analytic format of Ref. [24] using the online tools available from the Computational Infrastructure for Nuclear Astrophysics [25]. We present only the coefficients of parameterization for the central values of our rate in Table II.

The astrophysical implications of our new rates have been studied by calculating nova nucleosynthesis of ^{18}F from a nova outburst on ONeMg white dwarfs in the mass range 1.15 - 1.35$M_\odot$ [26] with initial abundances adopted from Politano *et al.* [27]. The calculation was done in the framework employed in the Computational Infrastructure for Nuclear Astrophysics [25]. The reaction network has 169 isotopes from ^{1}H to ^{54}Cr with reaction rates taken from Refs. [24, 28], except for the ^{18}F$(p,\alpha)^{15}$O reaction and its inverse that came from this work. Using the central values of our ^{18}F$(p,\alpha)^{15}$O reaction rate, we find that ^{18}F production increases by about $10-15\%$ when compared to calculations using the rate of Chae *et al.*, for all the masses of ONeMg white dwarfs considered. This has implications for ongoing searches in our Galaxy for ^{18}F decay with the INTEGRAL satellite. When comparing the interference uncertainties in our new rate to those of Chae *et al.* [12], we find the uncertainty in the ^{18}F production is decreased by a factor of $\sim$1.4 in the hottest zone of a nova explosion, and decreased by a factor of $\sim$2 when averaging over all zones ejected in the outburst for all the masses of ONeMg white dwarfs considered. The new ^{18}F$(p,\alpha)^{15}$O reaction rate eliminates the uncertainties inherent in using ^{19}Ne $-$ ^{19}F mirror symmetry to determine properties of resonances that contribute to the rate.

Our experiment revealed for the first time that a subthreshold resonance makes a very important contribution to the ^{18}F$(p,\alpha)^{15}$O reaction rate, provided the first direct determination of the spectroscopic strengths of the controversial 8- and 38-keV resonances and provided new constraints on the J^π values of these resonances, thereby showing unequivocally that these resonances play very minor roles in the ^{18}F$(p,\alpha)^{15}$O reaction rate. The new information has helped to improve our understanding of the ^{18}F$(p,\alpha)^{15}$O reaction rate under nova conditions and decreased the uncertainty significantly. Using model calculations, we find that ^{18}F production is increased by $\approx 15\%$ compared to the recent reaction rate evaluation of

Chae *et al.* The technique of reconstructing the relative energy and neutron angle from the detected charged particles has never been reported previously and will likely be used for future RIB measurements.

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