Simultaneous measurement of the ^{18}F(p,p)^{18}F and ^{18}F(p,α)^{15}O reactions: Implications for the level structure of ^{19}Ne, and for ^{18}F production in novae

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(Received 31 January 2008; revised manuscript received 16 March 2009; published 14 May 2009)

The largest nuclear physics uncertainty in studies of gamma-ray emission from novae arises from the ^{18}F(p,α)^{15}O reaction rate that affects the abundance of ^{18}F. Direct measurements have been made of the ^{18}F(p,p)^{18}F and ^{18}F(p,α)^{15}O reaction differential cross sections in the energy range $0.6 \leqslant E_{\rm c.m.} \leqslant 1.6$ MeV. Several resonances have been observed in both measurements, with simultaneous R-matrix fits used to determine the properties of corresponding states in ^{19}Ne. A recently reported state at 7.420 MeV is not seen, while new states are seen including one of $J^\pi = \frac{3}{2}^+$. A candidate for a recently predicted broad $J^\pi = \frac{1}{2}^+$ state is seen, which would have significant impact on the low energy ^{18}F(p,α)^{15}O reaction rate, but its alpha width is significantly smaller than expected.

DOI: 10.1103/PhysRevC.79.058801 PACS number(s): 21.10.Hw, 27.20.+n, 25.60.Dz, 26.30.Ca

Novae provide an opportunity for direct observation of stellar nucleosynthesis through a satellite-based measurement of gamma-ray emission from newly synthesized radioisotopes [1]. The isotopic abundances inferred would provide significantly tighter constraints on models of novae than presently possible [2]. Of particular importance is the abundance of ^{18}F, as the annihilation radiation from its β^+ decay is thought to dominate the γ-ray flux. It is produced via the ^{17}O(p,γ)^{18}F reaction and by β^+ decay of ^{18}Ne, while it is destroyed by the ^{18}F(p,γ)^{19}Ne and ^{18}F(p,α)^{15}O reactions. For peak temperatures reached in novae, around 0.1–0.4 GK, the uncertainty in the ^{18}F(p,α)^{15}O reaction is the greatest contribution to the variation in ^{18}F abundance. Thus, this reaction rate contributes the largest uncertainty in the nuclear physics of gamma-ray astronomy of novae, both in terms of their detectability and of interpretation once an observation has been made. At these energies, the reaction rate is dominated by the s- and p-wave resonant contributions of states in ^{19}Ne in the vicinity of the ^{18}F + p threshold, but despite extensive measurements of (p,p) and (p,α) reactions using ^{18}F beams, and transfer reactions populating states in ^{19}Ne and ^{19}F, significant uncertainties remain; see [3] for a comprehensive review. Foremost among these is the unknown character of the interference between $J^\pi = \frac{3}{2}^+$ resonances possibly resulting in a significantly reduced rate [4]. However, a recent calculation [5] using the generator coordinate method has predicted two new $\frac{1}{2}^+$ states in ^{19}Ne, one of which is thought to be located ~1.5 MeV above the ^{18}F + p threshold. The predicted s-wave population of this state, together with significant decay widths ($\Gamma_p = 157$ keV, $\Gamma_\alpha = 139$ keV), result in a changed low-energy reaction rate and reduced dependence on the unknown interference between the low-energy $\frac{3}{2}^+$ states. While previous studies have concentrated on the lower energy region, the properties of the new state suggest it should be readily visible in ^{18}F(p,p)^{18}F and ^{18}F(p,α)^{15}O reaction data.

A new experiment has been undertaken at the ISAC-I facility, TRIUMF [6] using the TRIUMF-UK Detector Array (TUDA) [7–9]. A 1.750 MeV/nucleon beam of ^{18}F was stopped in a 28.0 ± 1.4 μm thick polyethylene ((CH_2)$_n$) target, sufficient to just stop beam particles. An additional <5 μg/cm^2 of gold was evaporated onto the upstream surface of the target foil. ^{18}O contamination of the beam was removed through use of a post-acceleration stripper foil such that only ^{18}F^{9+} ions were delivered to the experiment. Furthermore, a hyperpure germanium detector placed close to the target did not observe the 1042 keV γ-rays that would have indicated the presence of target-stopped ^{18}Ne ions, translating to $\leqslant$5 pps of contaminant ^{18}Ne ions (90% confidence limit). A typical ^{18}F beam intensity of $(4.0 \pm 0.2) \times 10^4$ pps was achieved.

Particles emitted from the target were detected in a 1 mm thick MSL type YY1 (LEDA) segmented annular silicon strip detector [10] located downstream to cover laboratory angles of 7°–16.6°. Upstream of the target a further LEDA detector covered laboratory angles from 150°–170°, allowing normalization through measurement of Rutherford back-scattering (RBS) of ^{18}F ions from the gold layer of the target. For each event, energy and time-of-flight relative to the accelerator RF were recorded. Projection of energy as a function of the time-of-flight provided particle identification with protons and alpha particles clearly identified. To determine how detected

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proton energy in the laboratory was related to the center of mass energy at which reactions had occurred, calculations were performed combining two-body kinematics with energy loss estimates [11], both of the beam particle to the point of interaction and of the proton or alpha particle through the remainder of the target and the dead layer of the silicon detector. A well behaved, monotonic, third-order polynomial was then employed to convert detected proton energy to center of mass energy. The calculations suggest the mean distance the ^{18}F ion penetrated the target was 24.9 μm (0.7 μm rms longitudinal straggling). The resulting excitation functions for the ^{18}F(p,p)^{18}F and ^{18}F(p,α)^{15}O reactions are presented as the data points in Fig. 1. Error bars indicate Poisson statistics only. Since the detectors used were highly segmented projection of these spectra for each angular segment was possible. However, doing so provided no additional information, with no deviation from isotropy in the center of mass frame being established.

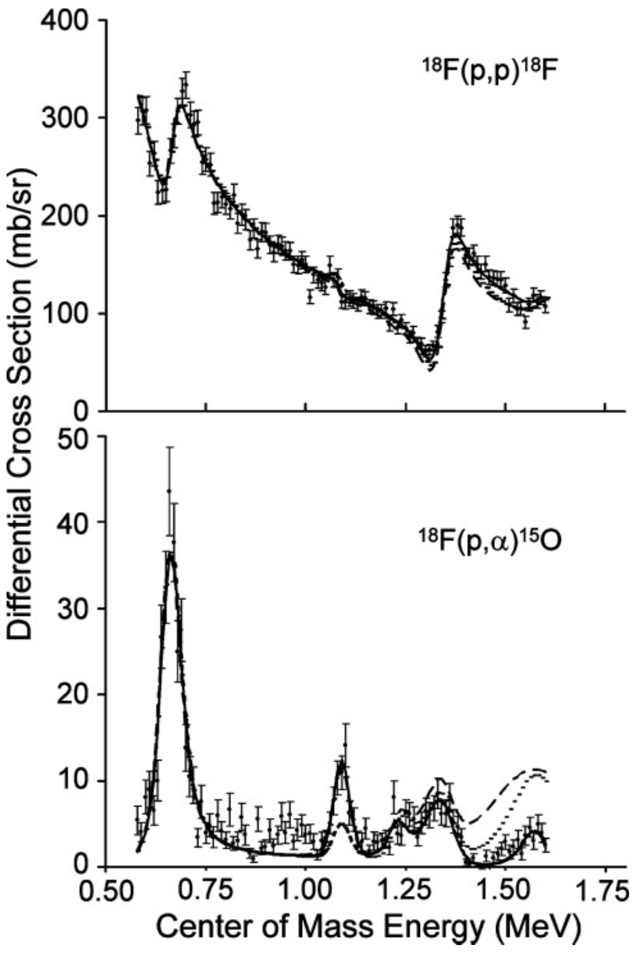

FIG. 1. Differential cross section for the ^{18}F(p,p)^{18}F and ^{18}F(p,α)^{15}O reactions as a function of center of mass energy. Error bars indicate statistical errors only. The solid lines are the result of a simultaneous multichannel R-matrix fit to both data sets, i.e., the preferred parameters in Table I. The short dashed line is the result of a fit performed when the properties of the resonance at 1089 keV are constrained to those of a previous work [3]. The long-dashed curve shows the excitation function calculated with the same parameters as the solid line, except for the 1573 keV, $\frac{1}{2}^+$ state where the proton and alpha widths are taken from [5]; for the dotted line we assume the widths are half those proposed in [5].

The experimental resolution for these data has contributions from three principal sources; energy straggling of ions leaving the target, the angular resolution of detector strips, and the intrinsic energy resolution of the apparatus [12]. The resulting FWHM energy resolution for protons (alpha particles) emitted from reactions at the upstream surface of the target is ~35 keV (47 keV), and ~ 49 keV (61 keV) from a depth corresponding to a 665 keV center of mass energy.

In both the proton and alpha particle data sets resonant structures are observed. To interpret these, multichannel R-matrix calculations [13–15] that include the energies, widths, spins, angular momenta, and interference sign for each candidate resonance have been performed. Incorporated are a target-depth dependent energy resolution and a channel radius set at 5.0 fm, appropriate for the ^{18}F + p system; the effect of small changes to this radius are included in the errors presented below. Calculations were performed for the mean center of mass angles of the detector, 156° for (p,p) data and 151° for the (p,α) reaction. A comparison of the measured cross section to the R-matrix expectation suggested a 9% error in the normalization, within the uncertainty of the RBS measurement; the normalization for both data sets was adjusted accordingly. For each spin, angular momentum, and interference possibility a fit is performed in which the energies and widths of the resonances are varied until a minimum in the χ^2 value is obtained; the combination of parameters resulting in the lowest overall χ^2 indicates the likely values for the resonances. The lowest order partial wave was included for each resonance; higher order partial waves made no significant contribution.

The R-matrix calculated excitation function, optimized to simultaneously match both the proton and alpha particle data, is presented as the solid line in Fig. 1, while the parameters deduced are presented in Table I. The reduced χ^2 per degree of freedom of the fit to the proton data has a value of 1.25, to the alpha particle data a value of 2.17, and a value of 1.70 for the combined fit. In the alpha particle data, the clearest features are resonant structures around $E_{\text{c.m.}}$ = 665, 1090, 1345, and

TABLE I. Properties of states in ^{19}Ne extracted from analysis of the present data. The entries at 1225 and 1233 keV are alternatives, with the former slightly preferred. Errors are derived by combining, in quadrature, uncertainties arising from the parameter fitting routine, the value of channel radius, the energy resolution, and the absolute normalization.

$E_{\text{c.m.}}$ (keV)	E_x(^{19}Ne) (keV)	J$^\pi$	Γ_p (keV)	Γ_α (keV)	Sign of interference
663(2)	7074	$\frac{3}{2}^+$	14(2)	28(3)	+
1089(3)	7500	$\frac{5}{2}^+$	1.0(1)	1.5(1)	
1225(20)	7636	($\frac{1}{2}^-$)	3(2)	6(5)	
1233(18)	7644	($\frac{3}{2}^-$)	1(1)	3(3)	
1347(5)	7758	$\frac{3}{2}^+$	42(10)	5(2)	−
1573(8)	7984	($\frac{1}{2}^+$)	8($^{+8}_{-4}$)	34(13)	

1575 keV, with correlated features seen in the proton data. The lowest energy of these is well reproduced in both data sets with a state of excitation energy 7074 ± 2 keV in ^{19}Ne (resonance energy $E_r = 663 \pm 2$ keV), of $\frac{3}{2}^+$ spin assignment, and with proton and alpha widths of 14 and 28 keV, respectively, consistent with previous results [16–21].

In the present ^{18}F$(p,\alpha)^{15}$O data a clear peak is observed at $E_{\rm c.m.} \sim 1090$ keV; examination of the proton data in this region reveals evidence for a feature here too. These are well described by a $\frac{5}{2}^+$ state in ^{19}Ne located at 7500 ± 3 keV ($E_r = 1089 \pm 3$ keV) with $\Gamma_p = 1.0$ keV and $\Gamma_\alpha = 1.5$ keV. A state at 7500 ± 9 keV was observed by Utku *et al.* [17] via the ^{19}F(^{3}He, t) reaction, leading to a measured total width of $\Gamma = 16 \pm 16$ keV, and a ratio $\Gamma_p/\Gamma_\alpha = 5.25$. Subsequent work based on elastic scattering data [19] led to values of $\Gamma_p = 1.25 \pm 1.25$ and $\Gamma_\alpha = 0.24 \pm 0.24$ keV being recommended [3]. Also shown on Fig. 1 as the short dashed line is the global fit when the proton and alpha widths are constrained to these previously recommended values. As one can see, the alpha width is clearly insufficient, leading to a severe underestimation of the yield. Fits to the data with a state of any other spin-parity resulted in a significantly poorer reduced χ^2, strengthening the case for a $\frac{5}{2}^+$ assignment.

The structure at $E_{\rm c.m.} = 1347$ keV is well reproduced in both data sets only with a $\frac{3}{2}^+$ spin assignment, and appears to correspond to no previously known state in ^{19}Ne. To the left of this peak in the ^{18}F$(p,\alpha)^{15}$O data there is additional strength. Matching this in the ^{18}F$(p,p)^{18}$F data there is also an indication for some yield. Motivated by the observation of a ^{19}Ne state at an excitation energy of 7644 ± 12 keV in the work of Utku *et al.* [17], assigned $J^\pi = (\frac{1}{2}^-)$ through comparison to levels in the mirror nucleus [3], the inclusion of a $\frac{1}{2}^-$ state at 7636 ± 20 keV with $\Gamma_p \approx 3$ keV and $\Gamma_\alpha \approx 6$ keV adequately reproduces these features. A $\frac{3}{2}^-$ state with similar widths has a comparable effect. The partial widths deduced here are significantly less than those found by Utku *et al.* [17], indeed, if the widths (especially Γ_α) were as large as suggested in Ref. [17] a much clearer feature would be expected.

A $J^\pi = \frac{3}{2}^+$ state has previously been reported at an excitation energy in ^{19}Ne of 7608 ± 11 keV ($E_{\rm c.m.} = 1197$ keV), with proton and alpha decay partial widths of 2 ± 1 and 43 ± 16 keV, respectively [17,22]. The absence of a distinct feature in the present data, especially in the ^{18}F(p,α) channel, is consistent only with the decay widths at their lower limits, or with an alternative spin assignment.

The structure at $E_{\rm c.m.} = 1573$ keV is reasonably well reproduced in the alpha particle data set with a $J^\pi = \frac{1}{2}^+$ state at an excitation of 7984 keV in ^{19}Ne, though the fit to the proton data set is poorer. As discussed, a state of this spin-parity at about this energy has been predicted by Dufour and Descouvemont, but the widths observed here, $\Gamma_p = 7.5$ keV and $\Gamma_\alpha = 34$ keV, are significantly narrower than those proposed, $\Gamma_p = 157$ keV and $\Gamma_\alpha = 139$ keV [5]. To illustrate the sensitivity of the present measurements to the decay widths, the long-dashed curve in Fig. 1 shows the excitation function calculated with widths of the $\frac{1}{2}^+$ state constrained to be those predicted in Dufour and Descouvemont, while the dotted curve shows the expected excitation function with the decay widths set at half of those predicted. The elastic scattering data shows limited sensitivity to the proton width, while the (p,α) data clearly suggest a smaller alpha width. If the structure at 1573 keV is the predicted new $\frac{1}{2}^+$ state, the proton width must be a significantly larger fraction of its total width. However, it should be noted that interference from higher-lying states of the same spin and parity could affect the excitation function such that this conclusion is incorrect. While attempts to fit this resonance with alternative spin-parities resulted in slightly poorer fits, the proximity to the highest energies measured precluded a firmer spin assignment.

In the work of Bardayan *et al.* [19], which used a near-identical experimental setup and technique to this work, clear features were seen in ^{18}F$(p,p)^{18}$F data at $E_{\rm c.m.} = 665$ and 1009 keV. From an R-matrix analysis, they suggested that the higher structure implied a state at excitation energy 7420 keV in ^{19}Ne, with proton width 27 ± 4 keV and spin-parity of $\frac{7}{2}^+$. A mirror to the 7560 keV state in ^{19}F was suggested. Fortune and Sherr [23] have commented that the spectroscopic factor corresponding to these parameters seems unphysical as it is eight times the theoretical single particle width. Scaling the Bardayan *et al.* data to those acquired here (their data having an arbitrary normalization), one sees excellent agreement up to an energy of ~1000 keV, but then their yield falls dramatically (see Fig. 3 of Ref. [19]), with their interpretation of the resulting shape being that it indicated a resonance. In contrast, the present data show no such feature. It seems therefore that there is no such 7420 keV state in ^{19}Ne.

The widths obtained by the fitting methodology used have a dependence on the energy resolution assumed. To investigate this, fits were performed with alternative values of energy resolution: Γ_p and Γ_α values were found to be stable over a reasonable range of possible energy resolution values and error bars quoted in Table I include contributions from this uncertainty.

In the ^{18}F$(p,\alpha)^{15}$O data, states of the same spin-parity interfere. In the present data there are two $\frac{3}{2}^+$ states, and it is found that opposite sign interference terms are required leading to constructive interference between the two resonances. Under the assumption of destructive interference (same sign interference terms), a much poorer overall reduced χ^2 of 4.6 is obtained. Recent work by de Séréville *et al.* [21] explored the complex possibilities for the interference of the $\frac{3}{2}^+$ states in ^{19}Ne. That work considered the two states thought to exist just above threshold, $E_r \sim 8$ and 38 keV, the 665 keV resonance, and the 7238 keV state that gives rise to a narrow resonance at 827 ± 6 keV ($\Gamma_p = 0.35$ keV, $\Gamma_\alpha = 6$ keV, too narrow to be seen in the present data). Estimation of the cross section in the region of interest for novae requires the interference terms to be known, and the addition of another broad $\frac{3}{2}^+$ state adds further complexity although the data presented here could provide additional constraints.

Over the range of ^{19}Ne excitation energies studied in this measurement, several further states have previously been reported (for example the 7238 keV state mentioned above). No significant improvement to the overall fit to the data is obtained with their inclusion, when using the presently accepted parameter set [3]. Moreover, inclusion of these states is found not to alter the present analysis. The fit to the (p,α) data in the region $0.8 \leqslant E_{\text{c.m.}} \leqslant 1.0$ MeV is poorer than elsewhere, possibly indicating additional states or a need for revision of the present parameter set. For example, increasing the alpha width of the known $\frac{1}{2}^+$ state at 7253 keV in ^{19}Ne ($E_{\text{c.m.}} = 842$ keV) [22] from 23 to ~100 keV improves the match to the data, but with no statistically significant structure in the spectra such a revision is purely speculative.

To estimate the impact of these results, the ^{18}F$(p,\alpha)^{15}$O astrophysical reaction rate has been calculated based on the resonance properties of Table I, including additional contributions made by resonances known but not measured here (parameters taken from [3]). To judge the effect of the poor fit in the region $E_{\text{c.m.}} = 0.8$–1.0 MeV, the rate was also calculated assuming a 7253 keV state with increased alpha width. In both cases, the reaction rate at temperatures relevant to novae differs only slightly from the recent descriptions by de Séréville *et al.* [24] and by Kozub *et al.* [4], lying within their high and low recommended rates. Thus, no change to the accepted ^{18}F$(p,\alpha)^{15}$O reaction rate is required based on these new data. Also, despite the perhaps more relevant temperature range, changes to the reaction rate at higher energies have been shown to be unlikely to affect nucleosynthesis occurring in x-ray bursters [25].

In summary, measurements of the ^{18}F$(p,p)^{18}$F and ^{18}F$(p,\alpha)^{15}$O reactions have been performed, extracting differential cross sections between 0.6 and 1.6 MeV in the center of mass. Several resonances have been observed, which, through the R-matrix fitting procedure, have been used to determine the properties of states in ^{19}Ne. The properties of the 7076 keV $\frac{3}{2}^+$ state are found to be consistent with previous measurements. The existence of a $\frac{5}{2}^+$ state at 7500 keV is confirmed, but with revised widths. The new data are found to be consistent with a 7636 keV ($\frac{1}{2}^-$) state. Two new states have been observed, a $\frac{3}{2}^+$ state at 7742 keV and a tentatively assigned $\frac{1}{2}^+$ state at 7984 keV. This latter state appears to be too narrow to be the state predicted by Dufour and Descouvemont, which would have had a significant astrophysical impact. Also, a state recently reported at 7420 keV is not seen, and appears not to exist.

The authors would like to thank the beam development and ISAC operations groups of TRIUMF. UK personnel were supported by the Science and Technologies Facilities Council (UK); Canadian personnel were supported by the Natural Sciences and Engineering Research Councils of Canada; J.J. recognizes the support of the Spanish MEC grant AYA2007-66256, and EU FEDER funds.

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