^{19}F α widths and the ^{18}F+p reaction rates

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Understanding the properties of ^{19}F levels in the range $E_x = 6.4$–7.5 MeV is important for constraining the contributions of ^{19}Ne levels to the ^{18}F$(p,\alpha)^{15}$O and ^{18}F$(p,\gamma)^{19}$Ne thermonuclear reaction rates. We have reanalyzed ^{15}N$(\alpha,\alpha)^{15}$N data from H. Smotrich *et al.* [Phys. Rev. **122**, 232 (1961)] to determine properties of ^{19}F levels in this energy range. We find the energies and widths of broad levels to be different than previously reported and have set upper limits on the widths of postulated $3/2^+$ resonances, analogs of which are important for the ^{18}F+p rates.

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The rates of the ^{18}F$(p,\alpha)^{15}$O and ^{18}F$(p,\gamma)^{19}$Ne reactions are important for understanding production of the long-lived radioisotope ^{18}F in novae and heavy element production in x-ray bursts. The accurate calculation of these rates requires a detailed knowledge of the spectroscopy of levels in ^{19}Ne. In particular, the energies, spins, and decay widths of important ^{19}Ne resonances must be determined. A knowledge of the widths of ^{19}Ne levels is especially important for determining the contributions made by the tails of low-lying resonances to the reaction rates and the extent to which interference between resonances modifies the calculated rates. For the most part, the widths of the important levels are dominated by the α partial widths, which are not known and must be extrapolated from the isospin mirror nucleus ^{19}F. A good understanding of the level structure and, in particular, the α widths of analog levels in ^{19}F is therefore extremely useful in the calculation of the ^{18}F+p reaction rates.

The properties of levels in ^{19}F have been determined from a large number of experiments [2]. The levels of interest for understanding the ^{18}F+p reactions are in the energy range $E_x = 6.4$–7.5 MeV, and for the most part, the widths of levels in this range were determined in papers by Smotrich *et al.* [1] and Mo and Weller [3]. These publications present analyses of ^{15}N $(\alpha,\alpha)^{15}$N cross-section data measured by Smotrich *et al.* [1]. Unfortunately, in the analysis of ^{15}N$(\alpha,\alpha)^{15}$N data, there is an ambiguity in the assigned spin of observed resonances because levels with $J = \ell \pm 1/2$ are populated with the same orbital angular momentum transfer, and the shape of the excitation function depends primarily upon this ℓ value. In subsequent measurements [2], it was found that about half of the spin values for levels in this energy range were incorrectly assigned by Smotrich *et al.* [1] to be the wrong member of this spin pair. Despite this, α widths from Ref. [1] with the wrong spins are still used today [2]. Also, as discussed in Ref. [1], broad resonances could not be handled properly, with the result that energies of broad levels were quoted to the nearest 10 keV as opposed to the 1-keV precision with which the other resonance energies are quoted. An analysis of the ^{15}N$(\alpha,\alpha)^{15}$N data using an R-matrix approach and the correct spins is needed to obtain the best values for ^{19}F energies and widths.

Additional motivation comes from recent papers by Fortune [4] and Butt *et al.* [5]. In the work by Fortune [4], α-transfer reactions were studied, and α widths were deduced for levels in ^{19}F. Of particular importance for the ^{18}F+p reactions was an α width of $\Gamma_\alpha = 23 \pm 4$ keV deduced for the $J^\pi = 3/2^+$, $E_x = 6.4967$ MeV level in ^{19}F. The ^{19}Ne analog to this level could provide an important low-energy ^{18}F$(p,\alpha)^{15}$O resonance, and such a large α width would result in significant interference between this level and a higher-lying $3/2^+$ level at 7.076 MeV. A study of the ^{15}N$(\alpha,\gamma)^{19}$F reaction by Butt *et al.* [5] reported a ^{19}F level at 7.101 MeV with a width $\Gamma_\alpha = 28 \pm 1$ keV. From the observed decay scheme, this level was tentatively given a $3/2^+$ assignment and linked to the ^{19}Ne mirror level at 7.076 MeV. This mirror assignment, however, now appears unlikely based upon subsequent calculations of the expected level shifts [6] and the lack of single-particle strength observed at $E_x \sim 7.1$ MeV in recent ^{18}F$(d,p)^{19}$F experiments [7,8]. Both of these $3/2^+$ levels are reported to have rather large α widths and should be observable in the ^{15}N$(\alpha,\alpha)^{15}$N data of Smotrich *et al.* [1]. We have analyzed the ^{15}N$(\alpha,\alpha)^{15}$N data in order to search for these levels.

Final motivation comes from consideration of the broad ($\Gamma_\alpha \simeq 280$ keV) $1/2^-$ resonance reported by Smotrich *et al.* [1] to be at $E_\alpha = 3.07$ MeV. No other experimental study has confirmed the existence of this level, and there is little indication in Fig. 4 of Ref. [1] that it is actually needed to describe the ^{15}N$(\alpha,\alpha)^{15}$N data. In fact, subsequent studies [3] have found other levels reported by Smotrich *et al.* [1] (e.g., the $3/2^+$ resonance at $E_\alpha = 3.94$ MeV) that were not actually needed to understand the observed data. Based largely upon the assumed existence of this state, Utku *et al.* [9] analyzed a subtle change in the background of their ^{19}F$(^3$He$,t)$ ^{19}Ne data in terms of a broad level in ^{19}Ne at 6.437 MeV and reported a total width of 216 keV. Because recent studies [10] have postulated that the tail of this resonance could provide significant contributions to the low-temperature behavior of the ^{18}F+p reactions, its existence should be confirmed. For this reason, we have analyzed the ^{15}N$(\alpha,\alpha)^{15}$N cross sections reported by Smotrich *et al.* [1] to determine whether this broad resonance is truly needed to describe the data.

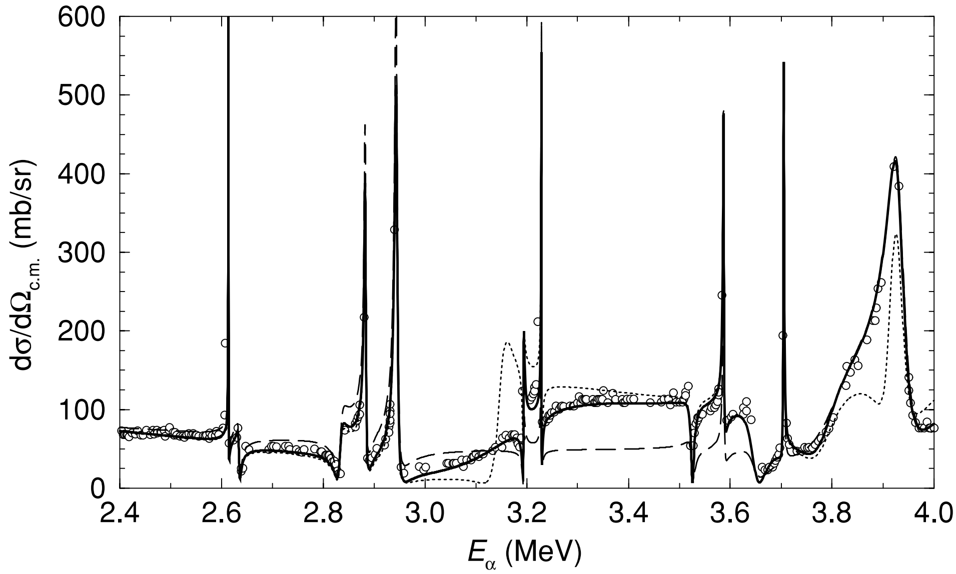

FIG. 1. The $^{15}N(\alpha,\alpha)^{15}N$ data from Ref. [1] measured at $\theta_{c.m.} = 169.1^{\circ}$ are shown as open circles. The solid line shows the best fit resulting from the resonance parameters in Table I. The dashed line shows the excitation function expected in the absence of a broad $1/2^{-}$ level at $E_{\alpha} \sim 3.2$ MeV. The dotted line results from the inclusion of two $3/2^{+}$ resonances reported in Ref. [4] and Ref. [5] at $E_{\alpha} = 3.150$ and 3.916 MeV, respectively.

The $^{15}N(\alpha,\alpha)^{15}N$ data were obtained from the National Nuclear Data Center's CSISRS database [11]. The cross sections were analyzed using the multilevel *R*-matrix code MULTI [12]. Because only the data at $\theta_{c.m.} = 169.1^{\circ}$ were available, only the data at this angle were analyzed quantitatively. All MULTI calculations were, however, compared with the spectra shown at other angles in Fig. 4 of Ref. [1], and good qualitative agreement was observed. Resonance parameters from Smotrich *et al.* [1] and Mo and Weller [3] were modified to reflect the currently accepted spin assignments. MULTI calculations were then fitted to the data in the range $E_{\alpha} = 2.7$–4.0 MeV by varying the energies and widths of resonances until the chi-square was minimized. The best fit along with the data is shown in Fig. 1, and the resonance parameters resulting in the best fit are tabulated in Table I. The quantities listed with uncertainties are those that needed to be varied to achieve a reasonable fit, and the quoted uncertainties reflect the uncertainty in the fit and do not reflect any systematic uncertainties. The excitation energies extracted from this procedure appear to be on average ~7 keV higher than the accepted values [2], possibly indicating a systematic uncertainty of that order. Several of the observed resonances for which spins were changed from those in Ref. [1] could easily be fitted with little or no change in their width. Other resonances (mostly broad) required greater changes, and we discuss these below.

TABLE I. ^{19}F level parameters are given for resonances resulting in the best fit. Those quantities listed with uncertainties were varied in the fit, and the quoted uncertainty is statistical in nature. The compilation [2] is also shown for comparison.

Present work				Previous [2]	
E_{α} (MeV)	E_x (MeV)	J^{π}	Γ_{α} (keV)	E_x (MeV)	Γ_{α} (keV)
1.878	5.496	$3/2^{+}$	3.2	5.501	4
2.614	6.077	$7/2^{+a}$	1.2	6.070	1.2
2.635	6.094	$3/2^{-a}$	3.9	6.088	4
2.833	6.250	$1/2^{+}$	7.9	6.255	8
2.883	6.289	$5/2^{+}$	2.4	6.282	2.4
2.944	6.338	$7/2^{+}$	3.6 ± 0.4^{a}	6.330	2.4
3.194	6.535	$3/2^{+a}$	1.2 ± 0.4^{a}	6.528	4
3.195 ± 0.006^{a}	6.536 ± 0.005^{a}	$1/2^{-}$	245 ± 6^{a}	6.429	280
3.229	6.563	$7/2^{+a}$	0.3 ± 0.2^{a}	6.554	1.6
3.525	6.796	$3/2^{-}$	4.3 ± 0.5^{a}	6.787	not listed
3.587	6.845	$5/2^{+}$	1.2	6.838	1.2
3.651 ± 0.003^{a}	6.896 ± 0.002^{a}	$3/2^{-a}$	22 ± 2^{a}	6.891	28
3.705	6.938	$7/2^{-a}$	0.9 ± 0.2^{a}	6.927	2.4
3.818 ± 0.005^{a}	7.028 ± 0.004^{a}	$1/2^{-}$	96 ± 6^{a}	6.989	51
3.933 ± 0.005^{a}	7.118 ± 0.004^{a}	$5/2^{+a}$	25 ± 4^{a}	7.114	32
4.230	7.353	$7/2^{+}$	65	not listed	not listed

[a]Modified from Refs. [1,3].

Extensive calculations were performed to determine whether the broad $1/2^-$ level reported by Smotrich *et al.* [1] at $E_\alpha = 3.07$ MeV was actually required to fit the $^{15}N(\alpha,\alpha)^{15}N$ data. We find that the inclusion of this broad level does indeed have profound effects on the observed spectra, and that without it, the calculated cross section is only about one-half of the observed value at $E_\alpha \sim 3.4$ MeV (see Fig. 1). We find, however, that its energy is considerably higher than reported in Ref. [1]. Our best fit results from an excitation energy of $E_x = 6.536 \pm 0.005$ keV ($E_\alpha = 3.195 \pm 0.006$ MeV), which is some 107 keV above the previously reported value. We also obtain a width $\Gamma_\alpha = 245 \pm 6$ keV; this value is 280 keV in Ref. [1]. This needed change in resonance energy is not really surprising considering the admitted inability to extract resonance energies for broad levels in Ref. [1]. These results give credence to the observation of a broad $1/2^-$ level reported in Ref. [9]. The upper limit on the neutron spectroscopic factor reported in Ref. [8] for this level needs to be reconsidered in light of these updated properties.

Next, calculations were performed searching for evidence of a $3/2^+$ level at $E_x = 6.497$ MeV ($E_\alpha = 3.150$ MeV) calculated in Ref. [4] to have a width $\Gamma_\alpha = 23 \pm 4$ keV. The ^{19}Ne analog of this level could provide a ^{18}F+p resonance at $E_{\rm c.m.} = 8$ keV [13], and the interference between it and the $3/2^+$ ^{18}F+p resonance at $E_{\rm c.m.} = 665$ keV could be significant [14] if the width is as large as suggested in Ref. [4]. We show in Fig. 1 the MULTI calculation with the inclusion of this resonance with a width of 23 keV. Clearly, such a resonance is not consistent with the $^{15}N(\alpha,\alpha)^{15}N$ data, and we set an upper limit on the width of this resonance of $\Gamma_\alpha < 0.5$ keV at the 99% confidence level. Such a small width means interference between $3/2^+$ resonances is unlikely to be significant in the ^{18}F+p reactions, but further study is needed to make definite conclusions.

Evidence for the $3/2^+$ level reported in Ref. [5] at $E_x = 7.101$ MeV was also searched for in the $^{15}N(\alpha,\alpha)^{15}N$ data. Figure 1 shows the expected excitation function with the addition of a $3/2^+$ level at $E_x = 7.101$ MeV ($E_\alpha = 3.916$ MeV) with $\Gamma_\alpha = 28$ keV. Clearly the data are not consistent with such a level, and we set an upper limit on the width of this resonance of $\Gamma_\alpha < 3.7$ keV at the 99% confidence level. The lack of evidence for this level in the $^{15}N(\alpha,\alpha)^{15}N$ data provides some constraints on the properties of the resonance that was observed in Ref. [5]. It is interesting to note that the resonance reported in Ref. [5] is only 13 keV away from the $7/2^+$ level tabulated in Ref. [2] to be at $E_x = 7.114$ MeV with nearly the same width (32 keV in Ref. [2] compared with 28 keV in Ref. [5]). It was argued in Ref. [5] that the observed level could not be the same as the $7/2^+$ level observed by Smotrich *et al.* [1] because the strongest γ decay was observed in Ref. [5] to populate a $3/2^-$ level at $E_x = 1.459$ MeV, and that would be highly unlikely to originate from a $7/2^+$ state. It does not appear that the authors of Ref. [5] considered the possibility that the previously observed level was actually a $5/2^+$ state, which would then decay to a $3/2^-$ with the same multipolarity as a $3/2^+$. As mentioned above, there is an ambiguity in the analysis of $^{15}N(\alpha,\alpha)^{15}N$ data in that states with $J = \ell \pm 1/2$ are populated with the same ℓ transfer, and thus the excitation function can be fitted nearly as well with either spin assignment. In this case, an $\ell = 3$ transfer could populate either $5/2^+$ or $7/2^+$ resonances with nearly the same excitation function produced. In fact, there is significant corroborating evidence that the resonance observed in Smotrich *et al.* [1] is a $5/2^+$ level. First, the only other experimental studies published with significant sensitivity to the spin of this level come from measurements of the $^{18}O(^3He,d)$ ^{19}F reaction [15,16]. These studies found that the level was populated with $\ell = 2$ transfers, implying a $3/2^+$ or $5/2^+$ assignment for this level. Only the $5/2^+$ assignment is consistent with the $^{15}N(\alpha,\alpha)^{15}N$ data, and thus it is shown with a $5/2^+$ assignment in Table 19.21 of Ref. [2]. Second, it was found in Ref. [17] that the total $5/2^+$ and $7/2^+$ α strengths in ^{19}F are much more reasonable if the 7.114-MeV level has $J^\pi = 5/2^+$. Finally, the lack of neutron strength at $E_x \sim 7.1$ MeV observed in studies of the $^{18}F(d,p)^{19}F$ reaction [7,8] make it clear that the level observed in Ref. [5] is not the analog to the $3/2^+$ ^{19}Ne level at 7.076 MeV, and there is little evidence to support a $J^\pi = 3/2^+$ assignment. In light of this overwhelming evidence, we have fit the $^{15}N(\alpha,\alpha)^{15}N$ data assuming that the resonance observed at $E_\alpha = 3.93$ MeV has $J^\pi = 5/2^+$. As can be seen in Fig. 1, the fit is quite reasonable for a width of $\Gamma_\alpha = 25 \pm 4$ keV (compare with 28 ± 1 keV in Ref. [5]). It is not clear why we extract a resonance energy higher than that quoted in Ref. [5], but (as noted above) the resonance energies extracted from the $^{15}N(\alpha,\alpha)^{15}N$ data of Ref. [1] are systematically higher than accepted values by ~7 keV. The greatest effect this change in spin assignment has on the calculated ^{18}F+p rates is for the contribution of the $E_x = 7.076$ MeV ($E_{\rm c.m.} = 665$ keV) to the $^{18}F(p,\gamma)^{19}Ne$ reaction rate. In previous evaluations [10,18], the γ width measured in Ref. [5] had been used to calculate this contribution. It now appears that there is no experimental constraint on the γ width of this resonance, as the analog assignment in Ref. [5] is incorrect, and thus its contribution to the rate is more uncertain than previously thought. Additionally, there should be a ^{19}Ne analog to this $5/2^+$ ^{19}F level, and it is most likely in the astrophysically important excitation energy region. However, since it requires an $\ell = 2$ transfer to populate a $5/2^+$ resonance in the ^{18}F+p system, and no significant strength was seen in the $^{18}F(d,p)^{19}F$ reaction at $E_x \simeq 7.1$ MeV [7,8], it should have a proton width $\Gamma_p \ll 1$ keV and thus should not contribute significantly to the ^{18}F+p reaction rates compared to the much stronger $E_{\rm c.m.} = 665$-keV resonance.

The only other resonance for which we get significantly different results than those obtained in Ref. [1] is the broad $1/2^-$ resonance at $E_\alpha \sim 3.8$ MeV. Again, this is not surprising given that their analysis could not adequately describe broad resonances. We achieve a best fit for this level for $E_x = 7.028 \pm 0.004$ MeV with a width $\Gamma_\alpha = 96 \pm 6$ keV. This would seem to contradict the excitation energy ($E_x = 6.989 \pm 0.003$ MeV) extracted from an analysis of γ rays observed in the decays of ^{19}F resonances in the $^{18}O(p,\gamma)^{19}F$ reaction [19]. The energy extracted for this level in Ref. [19], however, was based on a single γ-ray line depopulating a single ^{19}F resonance with a 0.5% branching ratio. It is not at all clear that the small peak observed in Ref. [19] (see Fig. 10 in Ref. [19]) is due to the decay of the $1/2^-$ level observed in the $^{15}N(\alpha,\alpha)^{15}N$

study. Unfortunately, neither the spin nor width of the level observed in Ref. [19] could be extracted, so there is really very little indication as to the nature of the observed peak, and it is not at all clear that our study contradicts the results in Ref. [19].

In conclusion, we have analyzed data from Ref. [1] in order to answer questions that have arisen regarding ^{19}F levels and their astrophysically important ^{19}Ne analogs. We find that the energies and widths for broad ^{19}F levels are somewhat different than previously reported [1]. We set upper limits of $\Gamma_\alpha < 0.5$ and 3.7 keV for $3/2^+$ levels postulated previously at $E_x = 6.497$ and 7.101 MeV, respectively [4,5]. Such small widths suggest that interference between $3/2^+$ resonances is unlikely to be significant. We additionally contend that the resonance observed in Ref. [5] most likely had a spin-parity of $5/2^+$ instead of the reported $3/2^+$. There is, therefore, no experimental constraint on the γ width of the important $E_{\mathrm{c.m.}} = 665$-keV resonance, and the rate of the ^{18}F$(p,\gamma)^{19}$Ne reaction is still quite uncertain.

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