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BRIEF REPORTS

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Comparison of low-energy resonances in $^{15}N(\alpha,\gamma)^{19}F$ and $^{15}O(\alpha,\gamma)^{19}Ne$ and related uncertainties

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A disagreement between two determinations of Γ_α of the astrophysically relevant level at $E_x=4.378$ MeV in ^{19}F has been stated in two recent papers by Wilmes *et al.* and de Oliveira *et al.* In this work the uncertainties of both papers are discussed in detail, and we adopt the value $\Gamma_\alpha = (1.5^{+1.5}_{-0.8})\times 10^{-9}$ eV for the 4.378 MeV state. In addition, the validity and the uncertainties of the usual approximations for mirror nuclei $\Gamma_\gamma(^{19}F)\approx\Gamma_\gamma(^{19}Ne)$, $\theta^2_\alpha(^{19}F)\approx\theta^2_\alpha(^{19}Ne)$ are discussed, together with the resulting uncertainties on the resonance strengths in ^{19}Ne and on the $^{15}O(\alpha,\gamma)^{19}Ne$ rate. [S0556-2813(97)00306-3]

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In a recent publication, Wilmes *et al.* [1] present experimental and theoretical results on the $^{15}N(\alpha,\gamma)^{19}F$ reaction which is crucial for fluorine production in asymptotic giant branch (AGB) stars [2]. In their experiment, Wilmes *et al.* [1] used a windowless ^{15}N gas target and a high purity Ge detector covering the angles between 60° and 120°. They determined the strength of the $E_{\alpha,\mathrm{lab}}$ = 687 keV resonance ($E_x=4.556$ MeV ^{19}F level) relative to the strength $\omega\gamma=(97\pm20)$ μeV [3] of the $E_{\alpha,\mathrm{lab}}$ = 679 keV resonance ($E_x=4.550$ MeV level). Their result $\omega\gamma=(8\pm3)$ μeV is in good agreement with the previous upper limit of 10 μeV given by Magnus *et al.* [3].

de Oliveira *et al.* [4] have also investigated the α capture on ^{15}N and extracted the α widths Γ_α of some levels in ^{19}F. This experiment used a confined ^{15}N gas target and a 27.3 MeV ^7Li beam to study the $^{15}N(^7Li,t)^{19}F$ transfer reaction. The resulting tritons were analyzed by a split-pole magnetic spectrometer and detected in the focal plane by a multiwire drift chamber giving position and angle informations. Finite range DWBA analysis was used to extract the Γ_α of levels. Great care was paid to the study of the influence of the various parameters entering in the analysis. Furthermore, experiments [4,5] using solid targets (^{15}N enriched melamine) were carried out. In all these transfer experiments it was shown that the reactions were essentially direct.

Some discrepancies between the results presented in these papers have been stated [1]. In this work, the authors of both series of papers analyze together the reasons for these discrepancies.

We start with the discussion of the α width Γ_α of the $E_x=4.378$ MeV level in ^{19}F which is of astrophysical interest. The corresponding resonance dominates the reaction rate at the typical temperatures of thermal pulses in AGB stars [2] ($T\approx 2\times 10^8$ K). The experimental value $\Gamma_\alpha = (1.5^{+1.5}_{-0.8})\times 10^{-9}$ eV, deduced from the transfer experiment [4], is 60 times lower than the estimate used by Caughlan and Fowler in their last compilation [6] where they assumed a value equal to 10% of the Wigner limit (θ^2 = 0.1). Wilmes *et al.* [1] provided no *experimental* information on the $E_x=4.378$ MeV level. They assume the identity of the alpha structure for the $E_x=4.378$ MeV and $E_x=4.550$ MeV levels and hence the equality of the reduced alpha widths θ^2_α of both states. With this assumption, they derive the value $\Gamma_\alpha = 2.4\times 10^{-8}$ eV, higher by more than 1 order of magnitude than the result of de Oliveira *et al.* [4].

The argument of Wilmes *et al.* [1] is that both levels belong to the same $K^\pi=3/2^+$ band and have the same cluster structure: $^{12}C\otimes{}^7Li$, quoting Descouvemont and Baye [7] who also propose $^{11}B\otimes{}^8Be$ while Wiescher *et al.* [8] favor $^{14}N\otimes{}^5He$. However, everybody agrees that the $^{15}N\otimes{}^4He$ component contributes very little to the global wave function. In these conditions, it appears too simplistic to assume equal alpha reduced widths. Furthermore, the hypothesis of equal reduced widths within the $K^\pi=3/2^+$ band agrees with the results of Pringle and Vermeer [9] only to within a factor of 10. They measured the Γ_γ/Γ ratio for various ^{19}F levels, deduced the Γ_α from the previously known $\omega\gamma$

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TABLE I. Properties of some levels in ^{19}F corresponding to resonances in ^{15}N$(\alpha,\gamma)^{19}$F.

E_x (MeV)	J^π	Γ[a] (meV)	Γ_γ/Γ[b]	Γ_α[b] (meV)	θ_α^2[c,d] ($\times 10^{-2}$)	Γ_α[c] (meV)	$\omega\gamma$[e] (meV)	θ_α^2[d] ($\times 10^{-2}$)	Γ_α[e] (meV)
4.378	$(7/2)^+$	>60	>0.96		0.56	1.5×10^{-6}			
4.550	$(5/2)^+$	101 ± 55		$(32\pm 7)\times 10^{-3}$	4.2	16×10^{-3}	$(96\pm 12)\times 10^{-3}$	8.4	$(32\pm 4)\times 10^{-3}$
4.556	$(3/2)^-$	38^{+23}_{-19}		$<3\times 10^{-3}$			$(6.4\pm 2.5)\times 10^{-3}$	0.84	$(3.2\pm 1.3)\times 10^{-3}$
4.683	$(5/2)^-$	43 ± 8	>0.85	2.0 ± 0.3	2.4	3.0	5.6 ± 0.6	1.5–1.8	1.9–2.2
5.107	$(5/2)^+$	>22	0.97 ± 0.03	4.5 ± 2.7	0.33	33	9.7 ± 1.6	0.033	3.3 ± 0.6

[a] From Ref. [17], $\Gamma(4.550)$ from Ref. [18].
[b] From Ref. [9].
[c] From Ref. [4].
[d] Using $R_N = 5.0$ fm.
[e] From Refs. [15,16].

and calculated the corresponding reduced widths $\Gamma_\alpha/\Gamma_\alpha(\text{s.p.})$. The values corresponding to four members of the $K^\pi = 3/2^+$ band: $E_x(J^\pi) = 4.55(5/2^+)$, $6.50(11/2^+)$, $6.59(9/2^+)$, and $10.43(13/2^+)$ MeV they provide are $\Gamma_\alpha/\Gamma_\alpha(\text{s.p.}) = (1.1\pm 0.2)\times 10^{-1}$, $\geqslant 8.2\times 10^{-3}$, $(1.8\pm 0.4)\times 10^{-2}$, and $(2.\pm 0.5)\times 10^{-2}$, respectively.

The $(^7\text{Li},t)$ transfer reaction has been recognized as a powerful tool to analyze alpha structures [10–13] and experimental data show that the two levels have not the same alpha strength. This can be seen directly in Fig. 4b of [4] where the triton energy spectrum for both levels is displayed. (The peaks corresponding to the $E_x = 4.550$ and 4.556 MeV levels are not resolved but the second is known to be much weaker than the first [3,1].) Experiments using solid targets [4,5] also showed large differences in the $E_x = 4.378$ MeV and $E_x = 4.550$ MeV formation through alpha transfer. The ratio between the $E_x = 4.550$ and 4.378 MeV reduced widths obtained in transfer experiments is 7.5 [4] and therefore within the dispersion of values obtained by Pringle and Vermeer [9] for the same ^{19}F band.

As result of this discussion we adopt the value of $\Gamma_\alpha = (1.5^{+1.5}_{-0.8})\times 10^{-9}$ eV, obtained from the α-transfer experiment, for the alpha width of the level $E_x = 4.378$ MeV of astrophysical interest. From the transfer study summarized in [4] and fully discussed in [14], an uncertainty of a factor of 2 on $\Gamma_\alpha(4.378)$ was estimated. Together with $\Gamma_\gamma/\Gamma > 0.96$ [9] a resonance strength is obtained: $\omega\gamma = 6^{+6}_{-3}$ meV.

In contrast to the $E_x = 4.378$ MeV level, for the $E_x = 4.550$ MeV, 4.683 MeV, and 5.107 MeV levels a comparison between experimental results of alpha transfer [4] and alpha capture [1,15,16] is possible. The comparison is made in Table I, columns 5, 7, and 10.

In column 3 we list the total widths Γ of these states extracted from the master table of Tilley *et al.* [17]. The value for the 4.550 MeV level is deduced from a lifetime measurement by Kiss *et al.* [18]. Additionally, in the work of Endt [19] one can find a reduced transition strength for the ground state transition: $S(\gamma_0) = 1.0\pm 0.2$ W.u., i.e., $\Gamma_{\gamma_0} = 4.8\pm 1.0$ meV. Together with the branching ratio of $4\pm 2\%$ for this transition [16] one obtains $\Gamma_\gamma = 120\pm 60$ meV which agrees reasonably well with the result of Kiss *et al.* [18].

In columns 4 and 5 the results of Pringle and Vermeer [9] are given: They determined the alpha widths Γ_α from their measured branchings Γ_γ/Γ and the previously known resonance strengths.

In columns 6 and 7 we list the reduced alpha widths θ_α^2 derived from the alpha transfer experiment [4] and the extracted alpha widths Γ_α.

Columns 8, 9, and 10 show the results of Wilmes *et al.* [15,16]. The resonance strengths $\omega\gamma$ of 14 resonances in ^{15}N$(\alpha,\gamma)^{19}$F have been measured directly; using the branching ratios Γ_γ/Γ from Ref. [9], values for Γ_α and θ_α^2 have been deduced. (Note that $\omega\gamma(4.556)$ differs slightly from the value given in Ref. [1]: the previous value was determined from an experiment by Magnus *et al.* [3], the new value is the result of the absolute determination.)

For both levels $E_x = 4.550$ MeV and $E_x = 4.683$ MeV the agreement between the alpha-transfer [4] and the alpha-capture results [1,3,15,16] is good within a factor of 2. But in the case of the $E_x = 5.107$ MeV level the results disagree by one order of magnitude. This level is the most weakly produced, has the highest compound nucleus contribution and the highest excitation energy of the levels studied by de Oliveira *et al.* [4]. This last point is likely the source of the discrepancy since the FR-DWBA analysis was performed by de Oliveira *et al.* within the approximation that the relevant levels are bounds. However, in the case of the $E_x = 5.107$ MeV level, unbound by ≈ 1.1 MeV this approximation is questionable. On the contrary, Table I shows a reasonable agreement for the low lying levels when comparison is possible.

In addition, for the 4.378 MeV level, Wilmes *et al.* [1] pointed out an apparent contradiction between the value Γ_α deduced from the alpha-transfer experiment on ^{15}N and a value deduced from the ratio Γ_α/Γ obtained by Magnus *et al.* [20] in the mirror nucleus ^{19}Ne. This estimate is based on both the assumptions that $M1$ transition strengths and reduced alpha widths are equal for analog levels. The first hypothesis is known to be an useful approximation for moderately strong $M1$ transitions where the isovector spin contribution is expected to dominate. But for such $M1$ transitions, unlike in the $E1$ ones, the *quasirule* is that transitions in conjugate nuclei are expected to be of approximately equal strengths only to within a factor of ≈ 2 [21]. This *quasirule* is further broken in most cases when considering isospin mixing (see, for instance, a recent comparison of transition strengths in ^{15}O and ^{15}N by Raman *et al.* [22]). The hypothesis of equality of alpha reduced widths in analog levels is a quite common practice in the absence of direct measurement. But it is clearly an approximation whose precision is hard to estimate but would become more and more questionable when the alpha structure of the involved levels is getting weaker.

TABLE II. Properties of some mirror levels in ^{19}F and ^{19}Ne corresponding to resonances in ^{15}N$(\alpha,\gamma)^{19}$F and ^{15}O$(\alpha,\gamma)^{19}$Ne.

$E_x(^{19}\mathrm{F})$ (MeV)	$E_x(^{19}\mathrm{Ne})$ (MeV)	J^π	Γ_γ [a] (meV)	$B_\alpha(^{19}\mathrm{Ne})$ [b]	$\Gamma_\alpha(^{19}\mathrm{Ne})$ (meV)	$\theta_\alpha^2(^{19}\mathrm{Ne})$ [c] $(\times 10^{-2})$	$\theta_\alpha^2(^{19}\mathrm{F})$ [d] $(\times 10^{-2})$
4.378	4.379	$(7/2)^+$	>60	0.044 ± 0.032	>2.8	>7.8	0.56
4.550	4.600	$(5/2)^+$	101 ± 55	0.25 ± 0.04	33 ± 18	3.2	4–8
4.556	4.549	$(3/2)^-$	38^{+23}_{-19}	0.07 ± 0.03	$2.9^{+1.7}_{-1.4}$	0.06	0.84
4.683	4.712	$(5/2)^-$	43 ± 8	0.82 ± 0.15	195 ± 36	0.67	1.5–2.4
5.107	5.092	$(5/2)^+$	>22	0.90 ± 0.09	>200	>0.19	0.033–0.33

[a] Assuming $\Gamma_\gamma(^{19}\mathrm{Ne}) = \Gamma_\gamma(^{19}\mathrm{F}) = \Gamma(^{19}\mathrm{F})$ because $\Gamma_\gamma/\Gamma(^{19}\mathrm{F}) \approx 1$ (Ref. [9]).

[b] From Ref. [20].

[c] Using $R_N = 5.0$ fm.

[d] From Table I, columns 6 and 10.

The alpha strength of the levels under consideration is weak. One can combine the experimentally available data on ^{19}F with the Γ_α/Γ data from Magnus *et al.* [20] in ^{19}Ne to test the hypothesis of equal θ_α^2 values in the mirror nuclei ^{19}F and ^{19}Ne assuming the equality of Γ_γ values for the mirror states (as mentioned above, this assumption is questionable). The results are listed in Table II. Columns 1–4 give E_x, J^π, and Γ_γ, column 5 gives the experimental values for $B_\alpha = \Gamma_\alpha/\Gamma$ in ^{19}Ne [20]. In columns 6 and 7 we calculate $\Gamma_\alpha = \Gamma_\gamma \cdot B_\alpha/(1-B_\alpha)$ in ^{19}Ne and $\theta_\alpha^2(^{19}\mathrm{Ne})$. The reduced widths $\theta_\alpha^2(^{19}\mathrm{F})$ are given in column 8; the values are taken from columns 6 and 10 of Table I. One can see that the disagreement exceeds one order of magnitude. Because of the missing experimental information on the resonance strengths in ^{19}Ne the approximations $\Gamma_\gamma(^{19}\mathrm{F}) \approx \Gamma_\gamma(^{19}\mathrm{Ne})$ and/or $\theta_\alpha^2(^{19}\mathrm{F}) \approx \theta_\alpha^2(^{19}\mathrm{Ne})$ have been used in several papers. From the new experimental results one can estimate the validity of these approximations for the mirror nuclei ^{19}F and ^{19}Ne: the resulting resonance strengths in ^{19}Ne are uncertain by at least a factor of 10.

In conclusion, the resonance strengths in ^{19}F are well established within an uncertainty of a factor of 2. Hence, the value $\Gamma_\alpha = (1.5^{+1.5}_{-0.8}) \times 10^{-9}$ eV is adopted for the 4.378 MeV state in ^{19}F excluding the value used by Caughlan and Fowler in their compilation [6]. However, in the case of ^{19}Ne the resonance strengths remain very uncertain because the validity of the usual approximations $\Gamma_\gamma(^{19}\mathrm{F}) \approx \Gamma_\gamma(^{19}\mathrm{Ne})$ and $\theta_\alpha^2(^{19}\mathrm{F}) \approx \theta_\alpha^2(^{19}\mathrm{Ne})$ is questionable. Hence, it results that the ^{15}O$(\alpha,\gamma)^{19}$Ne rate, which relies on α-transfer data on the mirror nucleus ^{15}N, is not known to a precision better than one order of magnitude.

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