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Update on α-particle and nucleon widths in ^{19}F and ^{19}Ne

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We present updated information and analysis for several states in ^{19}F and ^{19}Ne and correct a mistake in an earlier article.

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This short article concerns α-particle and/or nucleon widths for several states in ^{19}F and ^{19}Ne. It addresses questions arising from new experiments or calculations. Many of the states involved are of interest in connection with reaction-rate calculations in astrophysics. For each state, or set of states, we discuss the new information in the context of what was previously known.

Our recent article [1] concerned states above 6.5 MeV in ^{19}F. Except for one of those states, the present article primarily involves only states below 6.5 MeV. Unless otherwise noted, our energies and J^π values are from the latest compilation. [2]

I. ^{19}F (3.91)/^{19}Ne (4.03)

We have made several attempts [3–5] to determine the α width of this $3/2^+$ state in ^{19}Ne by using α transfer to its mirror in ^{19}F. The calculated width depends somewhat on the number of oscillator quanta q assumed for the (core + α) relative motion. For the states discussed in this article, all of which have positive parity, the only reasonable values of q are 7 and 9. The $(sd)^3$ states have $q = 7$, while the a-cluster states are dominated by $q = 9$. Some other states could contain mixtures of the two. If the structure of a state is such that one value of q is clearly indicated, we present calculations only for that q. If ambiguity exists, or the state likely contains both $q = 7$ and $q = 9$, we give results for both.

In an α-transfer experiment, the spectroscopic factor S_α is proportional to $\sigma_{\rm exp}/\sigma_{\rm DWBA}$, while the α width is given by $\Gamma_\alpha = S_\alpha\ \Gamma_{sp}$. Calculations of $\sigma_{\rm DWBA}$ and Γ_{sp} involve what some have called "nuisance parameters"—such as the number of quanta q or the geometrical parameters of the α-particle well. Because $\sigma_{\rm DWBA}$ and Γ_{sp} behave similarly with changes in these parameters, the dependence on them of Γ_α nearly vanishes. Some authors have claimed—incorrectly—that α widths extracted from α-transfer experiments can be wrong by an order of magnitude. There is no evidence for that statement. If care is taken to do a consistent calculation, the uncertainty in the procedure is usually less than 10%. Of course, uncertainty in the data can be much larger. This point is treated more fully in Refs. [3,4]. The uncertainty in the procedure is especially small if there is a "normalizing state"—a state in the same or a nearby nucleus that is reached by the same L transfer, has a similar Q value, is strong in α transfer, and has a known α width [5]. This is the case for states discussed here.

Whenever appropriate, we quote results for both values of q so that if a nuclear structure model provides a specific mixture of $q = 7$ and 9, then the width can be computed. A simple average of the results for $q = 7$ and 9 would not be appropriate. For $q = 7$, the ^{15}N(^{6}Li,d) results [3,4] led to an α spectroscopic factor $S_\alpha = 0.076$ for ^{19}F(3.91) and (assuming equal S_α in ^{19}F and ^{19}Ne) an α width of 11 μeV for ^{19}Ne(4.03) (Table I). That analysis involved subtracting a nondirect [presumably compound-nucleus (CN)] contribution to the cross section. Reference [4] estimated the uncertainty in the width as about 15%. In ^{15}N(^{7}Li,t), the result [5] was $S_\alpha = 0.052$ and $\Gamma_\alpha = 7.5\mu$eV without subtracting any CN cross section. If some CN contribution is present in (^{7}Li,t) (but not subtracted out), the width will be somewhat smaller. If $q = 9$, rather than $q = 7$, is appropriate, the width is about 82% of the values quoted earlier. The α width of this level is so small that the total width is virtually identical to the gamma width. Thus the value of $\omega\gamma = 2\ \Gamma_\alpha\Gamma_\gamma/\Gamma$ that is needed for astrophysics reaction-rate calculations will be essentially just $\omega\gamma = 2\ \Gamma_\alpha$. Of course, if the total width and the $\alpha/(\alpha+\gamma)$ branching ratio (BR) were known, then Γ_α and $\omega\gamma$ could be easily computed. Several measurements of the lifetime of ^{19}Ne(4.03) have been made. Three recent results for the mean life are (all in fs, all 1σ uncertainties) 13^{+9}_{-6} [6], 11^{+4}_{-3} [7], and $6.9 \pm 1.5 \pm 0.7$ [8] (see Table I). The latter is the combined value for decays to two separate states. The two values are [8] 7.1[19(6)] (to gs) and $6.6^{+2.4}_{-2.1} \pm 0.7$ (to 1.54 MeV) fs. We have combined the separate values [6–8] to get 7.9(15) fs, which we use. Most attempts [9,10] to determine the Γ_α/Γ BR resulted only in upper limits. But the most recent article [11] has a value of $2.9(21) \times 10^{-4}$. Previous upper limits are consistent with this value. Combining this BR with the average mean life gives Γ_α [^{19}Ne(4.03)] = 24(18) μeV. These are very difficult experiments, but we await future reduction in the BR uncertainty. The new excitation energy [6] of 4034.5(8) keV is within the uncertainty of the old value of 4032.9(24), but the increase in the central value causes an increase of 4% in our α width.

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TABLE I. ^{19}F(3.91) and ^{19}Ne(4.03).

Quantity measured	Measured value	Γ_α [^{19}Ne(4.03)] (μeV)	Ref.
S[^{15}N(^{6}Li,d)]	0.076[a]	11.0(16)	[3,4]
S[^{15}N(^{7}Li,t)]	0.052[b]	7.5(13)	[5]
τ(^{19}Ne)[c] (fs)	13^{+9}_{-6}		[6]
	11^{+4}_{-3}		[7]
	$6.9 \pm 1.5 \pm 0.7$		[8]
Γ_α/Γ (^{19}Ne)[c]	$2.9(21) \times 10^{-4}$	24(18)[d]	[11]

[a]After subtracting a CN cross-sectional component of 18(2)%.
[b]No CN subtracted.
[c]One σ uncertainty.
[d]Combining τ's to get 7.9 ± 1.5 fs, and then combining with BR.

II. WEAK $L = 3$ STATES IN ^{19}F

If α widths are computed from a single-particle width and a spectroscopic factor extracted from results of an α-transfer reaction [e.g., (^{6}Li,d) or (^{7}Li,t)], one source of uncertainty is from the determination of the fraction of the experimental cross section that corresponds to direct one-step α transfer. The only competing process for which the cross sections add is a CN reaction mechanism. For other possibilities, the amplitudes must be added. For strong states, this uncertainty is small, but it can be large for weak states—as in this section. States that are weak but that are connected by a strong $E2$ transition to a state that is abnormally strong in α transfer could possess an amplitude of inelastic scattering preceding or following α transfer. None of the states discussed here fit this category. Whenever appropriate, we estimate the uncertainty in subtracting the CN component. Throughout, the quoted uncertainties include those from all sources, except the one involving q.

We tried to estimate the reliability of extracting S_α for very weak states [12] by comparing results of (^{7}Li,t) (at bombarding energies of 15, 20 [12] and 28 [13] MeV) and the (^{6}Li,d) reaction at 22 MeV [3,4] for three states with small values of S_α. The values of S_α from the various reactions were in approximate agreement, but only at about the 50% level for the two weakest states, and only after correcting for a nondirect component in the cross sections. Goerres [14] has questioned the α widths derived from those S_α's, and it does appear that a numerical mistake of a factor 2–3 was made [12] in converting S_α to Γ_α. After considerable scrutiny and checking against calculations with other computer codes, we conclude that the S_α's were correctly extracted, but the published α widths are too large. Corrected values are listed in Table II. We have recomputed many of the α sp widths we have published in other articles, and we have found no other errors. Goerres [14] has also checked a number of our published numbers and has found no other mistakes.

III. WEAK $L = 3$ STATES IN ^{19}Ne

The three weak $L = 3$ states in ^{19}F discussed in the previous section all have identified mirror states in ^{19}Ne, which are listed in Table III. Using S_α's from ^{19}F and Γ_{sp}'s calculated for ^{19}Ne, we have computed the expected α widths in ^{19}Ne, also listed in Table III. The first two of these states have recently had their lifetimes measured [6]. Because the very small BR is poorly known for the 4.379 MeV level, we use our calculated α width and the new lifetime to compute the expected BR, for which we get $1.14^{+.82}_{-0.65} \times 10^{-3}$, to be compared with three measured values of 16(5), 44(32), and <3.9 (all $\times 10^{-3}$) (Table III). All of the three are larger than our calculated value, but the upper-limit measurement is intriguingly close. The published upper limit is at a 90% confidence level (CL). The 68% CL upper limit is 2.6×10^{-3} [15]. The large uncertainty on the calculated BR comes primarily from the uncertainty in the lifetime. The uncertainty on the calculated α width is 40%.

For the 4.600 MeV ($5/2^+$) state, the BR is reliably known [9,16], the average being 0.285(28). In this case, we use the BR and our calculated α width to compute the mean life, for which we get 2.0(5) fs—to be compared with the new measurements of 7^{+5}_{-4} fs [6] and $7.6^{+2.1}_{-2.0} \pm 0.9$ fs [8].

For the third state, S_α in ^{19}F is only an upper limit. Combined with Γ_{sp} in ^{19}Ne, the upper limit on the α width in ^{19}Ne is 0.35 eV. Combining with the measured BR of 0.90(5) [9] leads to a lifetime limit of $\tau > 1.6$ fs, probably not an interesting limit. The γ branch of 0.10(5) leads to an upper limit on the gamma width of 62 meV.

IV. ^{19}F(5.337)/^{19}Ne(5.351)

The $1/2^+$ state at 5.337 MeV in ^{19}F has a very large S_α. Its measured α width [17] is 1.3(5) keV, and the α width computed from S_α(^{7}Li,t) = 0.64(7) is Γ_α = 1.9(2) keV [5]. Again, assuming equality of S_α for mirror states, this value of S_α, together with the sp width of 12 keV in ^{19}Ne, leads to a

TABLE II. Weak $L = 3$ states in ^{19}F.

E_x (MeV)	E_α (MeV)	J^π	S_α[a]	Γ_{sp}[b] (eV)	Γ_α[c] (eV)	$\omega\gamma$[d] (eV)
4.378	0.364	$7/2^+$	0.008(3)	1.8×10^{-7}[e]	$1.4(5) \times 10^{-9}$	$5.8(19) \times 10^{-9}$
4.550	0.536	$5/2^+$	0.12(3)	2.5×10^{-4}[e]	$3.0(8) \times 10^{-5}$	$9.0(22) \times 10^{-5}$
5.107	1.093	$5/2^+$	<0.005	5.6	<0.028	<0.084

[a]From column 8 of Table I of Ref. [12].
[b]Using r_0, a = 1.40, 0.60 fm for $q = 7$.
[c]$\Gamma_\alpha = S_\alpha \Gamma_{sp}$.
[d]$\omega\gamma = (2J+1)\Gamma_\alpha\Gamma_\gamma/(2\Gamma)$.
[e]Reference [14] gets 1.6×10^{-7} and 2.2×10^{-4} for these two quantities.

TABLE III. Weak $L = 3$ states in ^{19}Ne.

E_x (MeV)	J^π	S_α [a]	Γ_{sp} [b] (eV)	Γ_α (meV)	BR		τ (fs)	
					Exp.	Calc. [f]	Exp.	Calc. [i]
4.379	7/2+	0.008(3)	0.019	0.15(6)	$16(5) \times 10^{-3}$ [c] $44(32) \times 10^{-3}$ [d] $< 3.9 \times 10^{-3}$ [e]	$1.14^{+.82}_{-.65} \times 10^{-3}$	5^{+3}_{-2} [g]	–
4.600	(5/2+)	0.12(3)	0.80	96(24)	0.32(4) [e] 0.25(4) [d]	–	7^{+5}_{-4} [g] 7.6(21) [h]	2.0(5) [j]
5.092	5/2+	<0.005	70	<350	0.90(5) [e]	–	–	>1.6

[a]From ^{19}F (Table II).
[b]For $q = 7$.
[c]Reference [10].
[d]Reference [16].
[e]Reference [9]. Number given is for 90% CL for 4.379 MeV state; 68% CL limit is $<2.6 \times 10^{-3}$ [15].
[f]Present. Computed from Γ_α and τ.
[g]Reference [6].
[h]Reference [8].
[i]Present. Computed from Γ_α and BR.
[j]Present. Computed from Γ_α and average of two BR values in column 6.

prediction of $\Gamma_\alpha = 7.7(8)$ keV for the state at 5.351 MeV in ^{19}Ne. We use the expression $\Gamma_{\rm calc} = S_\alpha \Gamma_{sp}$ and have calculated Γ_{sp} for $q = 9$ in this case [18]. Throughout, we have used $r_0, a = 1.40$, 0.60 fm for the geometry of the α potential well, where $R = r_0(15)^{1/3}$. A very recent measurement [19] using a beam of ^{15}O incident on a He gas target yielded the result $\Gamma_\alpha(^{19}\mathrm{Ne}) = 3.2(16)$ keV. Again, the uncertainties are large, but these are extremely difficult experiments. Results are summarized in Table IV. For all our computations, we carry an extra significant digit and round at the end. This procedure may occasionally make it appear (as in Table IV) that the percentage uncertainty is (slightly) smaller in a derived quantity than in the experimental number. Before rounding, this was not the case.

V. ^{19}F(6.497, 3/2$^+$)

The result [5] of the reaction ^{15}N(^{7}Li,t) gave a value of $S_\alpha = 0.07(1)$ and $\Gamma_\alpha = 23(4)$ keV for this state, using $q = 9$. Because this state was not observed in ^{15}N(α,α) [20], and a state with that width should have been [20,21], we have reexamined that analysis. The $3/2^+$ state is not resolved from a nearby $11/2^+$ state at 6.500 MeV, whose direct α-transfer cross section should be small, as discussed later. The cross section for the doublet, at 20 MeV and 15°, is 48 μb/sr. In Ref. [5], the analysis attributed all the cross section to the $3/2^+$ level. The $9/2^+$ state at 6.59 MeV and the $11/2^+$ at 6.50 MeV both require $L = 5$ in α transfer, expected to be considerably weaker than $L = 1$ and 3 at the 20 MeV beam energy involved in this study. [Within the *gs* band, the $7/2^+$ state ($L = 3$) at 5.47 MeV is 13 times as strong as the $9/2^+$ ($L = 5$) at 2.78 MeV.] The $3/2^+$ state at 6.497 MeV is probably to be identified with the second $3/2^+(sd)^3$ shell-model state, predicted to occur at 6.6 MeV. It is seen in ^{18}F(d,p) [22] with reasonably large $\ell = 0$ and 2 spectroscopic factors, and in ^{18}O(d,n) [23] with $C^2S(d3/2) = 0.13$. So, $q = 7$ may be more appropriate (see later).

In what follows, we try to unravel the contributions to the (^{7}Li,t) cross section for the 6.5-MeV $3/2^+/11/2^+$ doublet, making use of the results from other states in the same region of excitation energy. For the present purposes, we can estimate the upper limit on a possible CN contribution by looking at the results for the 6.55 MeV $7/2^+$ and 7.11 MeV $5/2^+$ states, both of which are reached via $L = 3$ and have quite different S_α's—0.05 and 0.25, respectively [18]. [The state at 7.11 MeV is listed as $7/2^+$ in the latest compilation. It has $L = 3$ in (α,α), requiring $5/2^+$ or $7/2^+$. Reference [18] first suggested

TABLE IV. ^{19}F(5.337) and ^{19}Ne(5.351).

$\Gamma_\alpha(^{19}\mathrm{F})$	$S_\alpha(^{19}\mathrm{F})$	$\Gamma_\alpha(^{19}\mathrm{Ne})$
1.3(5) keV [a]	0.44(17) [b]	5.3(20) keV [c]
1.9(2) keV [d]	0.64(7) [e]	7.7(8) keV [f]
Direct measurement		3.2(16) keV [g]

[a]Direct measurement [17].
[b]From measured width [17] and ^{19}F sp width [18].
[c]From S_α and ^{19}Ne sp width (present).
[d]Computed from S_α in column 2 for $q = 9$.
[e]From analysis of (^{7}Li, t) [5].
[f]Calculated, assuming same S_α in ^{19}F and ^{19}Ne.
[g]Reference [19].

TABLE V. ^{19}F(6.497, 3/2$^+$).

Assumption	S_α	Γ_α (keV)
All cross section is $3/2^+$	0.07(1) [a]	23(4) [a]
Subtracting doublet CN and $11/2^+$ direct	0.05(2) [b]	16(6) [b]
As one row above, but $q = 7$	0.07(3)	20(8)

[a]Reference [5], $q = 9$.
[b]Present, $q = 9$.

TABLE VI. ^{19}Ne(7.42).

$E_x(^{19}Ne)$ (MeV)	J^π	Assumed mirror in ^{19}F (MeV)	Comment
7.42[a]	7/2[a]	7.56	Leads to $S_p(\ell = 2) = 8$ [1]
7.42	1/2[b]	8.138	Large $S_p(\ell = 0)$ provides large energy shift; we expect $\Gamma_p \approx 75(15)$ keV

[a]Reference [26] (but not observed by Ref. [27]).
[b]Suggested here. Not relevant if the state does not exist in ^{19}Ne.

it should be $5/2^+$, from a consideration of $L = 3$ α-cluster widths. The clear $\ell = 2$ angular distribution in ^{18}O(d,n) [23] confirms the $5/2^+$ assignment.] The conclusion is that the upper limit to any CN contribution to the 6.50 MeV doublet is 19 μb/sr, with a reasonable value being about half that, that is, $\sigma_{CN} \sim 10$ μb/sr, with a large uncertainty. This value includes σ_{CN} for both $3/2^+$ and $11/2^+$ states.

We can put a limit on any direct cross section to the $11/2^+$ state by using the $9/2^+$ state at 6.59 MeV, which also has $L = 5$. Its α width is known [2] to be 7.3(17) eV, which gives $S_\alpha = 0.021(5)$. The α width for the $11/2^+$ state is not known, but $\omega\gamma$ is known [24]—$\omega\gamma = 6\,\Gamma_\alpha\Gamma_\gamma/\Gamma = 2.3(4)$ eV. Following ^{12}C(^{11}B, α), which favors high-J states, the limit on the branching ratio of the doublet is $\Gamma_\gamma/\Gamma > 0.18$ [25]. Even though this limit is for the doublet, it seems a safe lower limit for the $11/2^+$ state, which should have a larger value of Γ_γ/Γ than the $3/2^+$ state. Combining the value of $\omega\gamma$ with the BR limit results in a limit on the α width of $\Gamma_\alpha \leqslant 2.5$ eV. (And, of course, $\Gamma_\alpha \geqslant 0.31$ eV from $\omega\gamma$.) Any direct α transfer cross section to the $11/2^+$ state is thus (by comparison with the $9/2^+$ state) in the range 1.3–10 μb/sr. Putting all this together, a reasonable lower limit for the $3/2^+$ cross section is $48 - 19 - 10 = 19$ μb/sr, and a likely value is 32 μb/sr—quite a wide range. The lower value results in a lower limit on S_α of 0.03, with a likely value of 0.05. We suggest $S_\alpha = 0.05(2)$ [replacing 0.07(1)], giving $\Gamma_\alpha = 16(6)$ keV, again for $q = 9$. For $q = 7$, we have $S = 0.07(3)$ and $\Gamma_\alpha = 20(8)$ keV. We may have over-estimated the CN cross section, so it is difficult to see how the width could be less than 10 keV. It would be interesting to obtain a rigorous upper limit on the width from the ^{15}N(α, α) analysis. The present analysis is summarized in Table V.

VI. ^{19}Ne(7.42)

In [1] we pointed out that, for this state, if the J^π assignment [26] of $7/2^+$ and the measured widths were correct, the proton spectroscopic factor was about 8—a very unwelcome value. It would thus appear that the proton width and/or the J^π is incorrect, or at least two states are present. A large proton width might imply $\ell = 0$, that is, $J^\pi = 1/2^+$ or $3/2^+$. In searching for a mirror candidate in ^{19}F, we were immediately drawn to the $1/2^+$ state at 8.1 MeV in ^{19}F that has a large S_n in ^{18}F(d,p) [22]. The spectroscopic factor of 0.32(6) becomes even larger, 0.45(9), if our bound-state geometry is used in the analysis [21]. This large $2s1/2$ occupancy would cause a large downward shift from ^{19}F to ^{19}Ne (estimated to be about 410(80) keV for this component of the wave function). This suggestion is summarized in Table VI. If our suggestion is correct, the proton width should be about 75(15) keV for a state at 7.42 MeV. If this is not the mirror of the 8.14 MeV state, another strong $1/2^+$ resonance should exist in ^{19}Ne not very far away. However, a recent paper [27] on ^{18}F(p,p) and ^{18}F(p,α) did not observe this state.

In conclusion, we have presented updated information and analyses for several states in ^{19}F and ^{19}Ne and have corrected a mistake in the Γ_α values of Ref. [12].

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