Negative-parity alpha clusters in ^{19}F

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States populated in the ^{15}N(^{6}Li,d)^{19}F reaction at 22 MeV are compared with those in ^{16}O(^{6}Li,d)^{20}Ne at the same energy. Cross section ratios are in good agreement with a weak-coupling model, in contrast to previous observations via the (^{7}Li,t) reaction. Two strong transitions are observed to states at $E_x=8.288$ and 8.957 MeV in ^{19}F. The measured angular-distribution shapes and alpha-transfer strengths for these states are consistent with their being, respectively, the $\frac{13}{2}^-$ and $\frac{11}{2}^-$ members of the $K^\pi=\frac{1}{2}^-$ band in ^{19}F. A comparison between the measured alpha-particle widths for these states and the single-particle alpha widths calculated in a Woods-Saxon well supports the above assignments.

I. INTRODUCTION

The ground state (g.s.) rotational band of ^{20}Ne is strongly populated in alpha transfer on ^{16}O, indicating the large α parentage of these states. According to weak-coupling arguments it is expected that the low-lying $K^\pi=\frac{1}{2}^-$ band in ^{19}F, whose structure is predominantly a $p_{1/2}$ hole coupled to the g.s. band of ^{20}Ne, will also be strongly populated in alpha transfer on ^{15}N. In the (^{7}Li,t) reaction on ^{15}N and ^{16}O, an enhancement of the cross section (cs) in the ^{15}N(^{7}Li,t)^{19}F transitions by a factor of about 2 over that in the ^{16}O(^{7}Li,t)^{20}Ne transitions was observed.[1] It has been suggested that this phenomenon might imply a greater α clustering in ^{19}F than in ^{20}Ne.

According to the weak-coupling model the $K^\pi=\frac{1}{2}^-$ band in ^{19}F has the same $(sd)^4$ structure as the corresponding states in ^{20}Ne, but coupled to a $p_{1/2}$ hole or ^{20}Ne$\otimes$^{15}N(g.s.) in weak-coupling notation. States coupled to a $p_{3/2}$ hole state in ^{15}N should lie at least 6 MeV higher. More precisely, the weak coupling model makes the following predictions about ^{19}F:

(1) Each positive-parity state in ^{20}Ne with spin $J>0$ has two corresponding negative-parity states in ^{19}F with $j=J\pm\frac{1}{2}$. The $(2j+1)$ weighted energy centroid of the pair should be equal to the energy of the "parent" 4p-0h state in ^{20}Ne.

(2) In the absence of Q-value effects, the only difference between ^{15}N(^{6}Li,d)^{19}F and ^{16}O(^{6}Li,d)^{20}Ne cross sections should be in the statistical factor

$$(2j_f+1)/[(2j_i+1)(2J+1)]\ .$$

Thus the cross sections for the two members of a doublet should be proportional to $(2j_f+1)$ and their sum should equal the cs of the parent state in ^{20}Ne.

(3) Each 0^+ state in ^{20}Ne should have a corresponding $\frac{1}{2}^-$ state in ^{19}F whose cs would be identical in shape and magnitude, but for Q-value effects.

We have used the ^{15}N(^{6}Li,d)^{19}F and ^{16}O(^{6}Li,d)^{20}Ne reactions to try to locate the 4p-1h states in ^{19}F and, in particular, the $\frac{11}{2}^-$ member of the $K^\pi=\frac{1}{2}^-$ band, whose location has long been a serious problem. These two reactions are ideal for comparing absolute cross sections because gas targets with accurately known thickness can be used.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with a 22-MeV ^{6}Li beam from the University of Pennsylvania Tandem Ac-

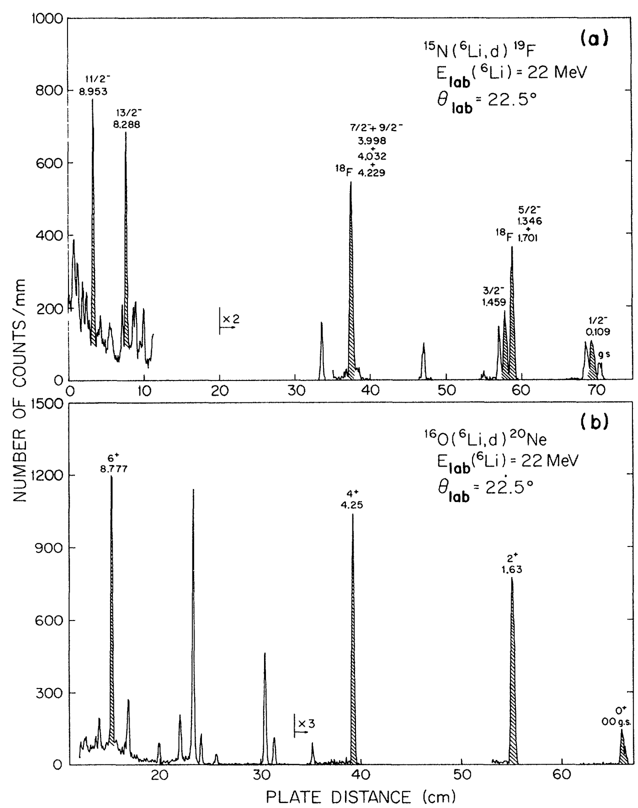

FIG. 1. (a) Spectrum of the ^{15}N(^{6}Li,d)^{19}F reaction at a bombarding energy of 22 MeV and a laboratory angle of 22.5°. Peaks are labeled with excitation energies. (b) Spectrum of the ^{16}O(^{6}Li,d)^{20}Ne reaction measured at the same bombarding energy and laboratory angle.

celerator. The oxygen or nitrogen gas targets were enriched to 99.5% in ^{16}O and ^{15}N, respectively, and contained in a closed gas cell with a 295 μg/cm^2 Mylar window. Gas pressure was 14.0 Torr. Outgoing deuterons were momentum analyzed with a multiangle spectrograph and recorded on Ilford K5 nuclear emulsion plates in the angular range of 7.5°–90° lab, in 7.5° steps. The exposure was 9000 μC. Mylar foil absorbers of variable thickness (0.25–0.5 mm) were placed in front of the focal plane to stop all heavier particles.

Displayed in Fig. 1 are spectra from ^{15}N(^{6}Li,d)^{19}F and ^{16}O(^{6}Li,d)^{20}Ne reactions measured at 22 MeV and 22.5° lab. The spectra cover an excitation energy region of about 9 MeV. Groups leading to final states of interest for the present study are shown hatched. The energy resolution was about 15 keV full width at half maximum (FWHM). Absolute cross sections were obtained from the measured gas pressure. The uncertainty in the overall cross sections is estimated at 20%, but relative uncertainties are significantly smaller.

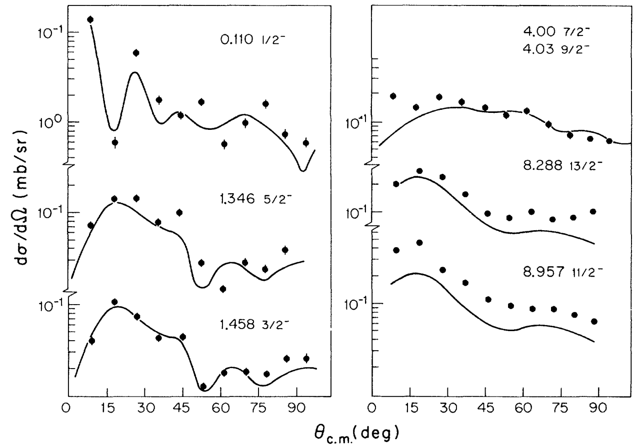

FIG. 2. Angular distributions of the ^{15}N(^{6}Li,d)^{19}F reaction at 22 MeV. Solid lines are smooth curves passed through the ^{16}O(^{6}Li,d)^{20}Ne angular distributions measured in the present study at the same bombarding energy, normalized by the factors $(2j+1)_{^{19}\mathrm{F}}/2(2J+1)_{^{20}\mathrm{Ne}}$.

III. DISCUSSION

Angular distributions for several low-lying states in ^{19}F are displayed in Fig. 2. The lines in the figure are smooth curves passed through the data obtained in the ^{16}O(^{6}Li,d)^{20}Ne reaction, normalized by the geometrical factors indicated in the figure. On the basis of the weak-coupling predictions we make the following observations:

The 0.110 MeV $\frac{1}{2}^-$ state in ^{19}F and the ^{20}Ne ground-state transition are virtually identical, in both shape and magnitude, as expected.

The cross sections for the $\frac{5}{2}^-$ state at 1.346 MeV and the $\frac{3}{2}^-$ state at 1.458 MeV are in the ratio of 1.3:1, which is very close to the weak coupling prediction of 1.5. Each angular distribution is virtually identical to that of the first 2^+ state in ^{20}Ne. In addition, the summed cs for the two is in excellent agreement with the cs for the 1.63-MeV 2^+ state of ^{20}Ne (Table I).

The summed cs for the two states at 4.00 and 4.03 MeV is compared in Fig. 2 with the experimental angular distribution obtained for the 4.248-MeV 4^+ state in ^{20}Ne. It is clear that there is good agreement in both shape and magnitude. An upper estimate of the ratio

$$\Sigma\sigma(^{19}\mathrm{F})/\sigma(^{20}\mathrm{Ne},\ E_x=4.248\ \mathrm{MeV})$$

is 1.2 instead of 1 as expected from weak coupling.

The angular distributions for the states at 8.288 and 8.957 MeV are displayed together with the experimental angular distribution for the 8.777-MeV 6^+ state in ^{20}Ne scaled down by a factor of $\frac{14}{26}$ and $\frac{12}{26}$, respectively. There is a very good fit in shape and magnitude (within 11%) for the 8.288-MeV state, indicating that it is actually produced by the coupling of the ^{20}Ne, 8.777-MeV 6^+ state to a $1p_{1/2}$ hole. However, there is a significant discrepancy in magnitude for the 8.957-MeV state in comparison with the parent state in ^{20}Ne.

TABLE I. Comparison of results for ^{15}N(^{6}Li,d)^{19}F and ^{16}O(^{6}Li,d)^{20}Ne.

$E_x(_{19}\mathrm{F})$ (MeV)	J^π	E_x (MeV) ^{19}F $2j+1$ weighted energy centroid	E_x (MeV) ^{20}Ne	J^π	$\sigma(J_>)/\sigma(J_<)$ Experiment	$\sigma(J_>)/\sigma(J_<)$ Weak coupling	$\frac{\Sigma\sigma(^{19}\mathrm{F})}{\sigma(^{20}\mathrm{Ne})}$
0.109	$\frac{1}{2}^-$	0.109	0	0^+			1.0
1.346	$\frac{5}{2}^-$	1.391	1.634	2^+	1.3	1.5	1.0
1.459	$\frac{3}{2}^-$						
3.998	$\frac{7}{2}^-$	4.017	4.248	4^+	a	1.25	1.2
4.032	$\frac{9}{2}^-$						
8.288	$\frac{13}{2}^-$	8.596	8.777	6^+	$\gtrsim 0.92$	1.17	$<1.6^{\mathrm{b}}$
8.957	$\frac{11}{2}^-$						

[a]Unresolved.

[b]The upper limit is calculated before subtracting the contribution from the unresolved states at 8.919 and 8.928 MeV from ^{19}F (8.957 MeV) data.

The location of the $\frac{11}{2}^-$ member has long posed a serious problem. The level at 8.96 MeV was strongly populated in both (^{7}Li,t) (Ref. 2) and (^{13}C,^{9}Be) reactions,[3] and therefore was considered as a natural candidate for the $\frac{11}{2}^-$ member. However, it was indicated that its γ decay is anomalous for an α-cluster state.[3]

Positive parity was assigned for the same state by Underwood *et al.*[4] using the ^{15}N(α,γ) reaction. Fifield *et al.*[5] and Symons *et al.*[6] reassigned $\frac{11}{2}^-$ for the same state from measurements of strengths and γ-ray angular distributions in the ^{15}N(α,γ) reaction. The situation complicated further when it was found that this state is strongly populated also in ^{16}O(α,p)^{19}F and ^{16}O(^{10}B,^{7}Be)^{19}F triton-transfer reactions.[7,8] Thus the 8.96-MeV level contains a substantial triton cluster state in addition to the α-particle cluster state. Theoretical calculations based on the SU(3) shell model in a $p^{-1}(sd)^4$ basis and a cluster model[5,9] have both predicted two $\frac{11}{2}^-$ levels between approximately 8 and 10 MeV in ^{19}F.

It may be that some of the deviation between present experimental results for the 8.957-MeV state and weak-coupling predictions arises from contributions of the 8.919-MeV $\frac{3}{2}$ and 8.928-MeV $\frac{3}{2}^-$ states, which are only about 25 keV lower in energy and thus could not be resolved in the present work. Figure 3 again shows the angular distribution for the 8.957-MeV state. The dashed line is the measured cs for the 8.777-MeV state in ^{20}Ne scaled down by a factor of $\frac{12}{26}$, which is just the $2j+1$ ratio. The solid and dotted lines labeled as $L=1$ and $L=2$ are the experimental angular distributions measured for the 1.554-MeV $\frac{3}{2}^+$ state and the 1.459-MeV $\frac{3}{2}^-$ states in ^{19}F, respectively. These are assumed to represent the shapes of the angular distributions of the above unbound unresolved states. The solid (dotted) line shown with the data points represents the best fit obtained to the data by adding the $L=1$ ($L=2$) contribution to the ^{20}Ne (8.777) data. The solid curve gives a somewhat improved fit, indicating that the $L=1$ mixing with the 8.957-MeV distribution is probably the dominant one.

In order to further investigate the $\frac{11}{2}^-$ assignment for the state at 8.957 MeV, we have calculated the α-particle reduced widths $\Gamma_\alpha/\Gamma_\alpha(sp)$ for all known unbound $\frac{11}{2}^-$ states in ^{19}F around 9 MeV excitation as well as for the 8.298-MeV $\frac{13}{2}^-$ state, and for the corresponding 6^+ state at 8.777 MeV in ^{20}Ne. The calculations of $\Gamma_\alpha(sp)$ were done in a real Woods-Saxon well of radius parameter $r_0=1.33$ fm and diffusivity $a=0.65$ fm. The $2N+L=8$ configuration was assumed, and for each state the well depth was adjusted to obtain a resonance of appropriate L value ($\delta_L=\pi/2$) at the measured energy E_R. Widths were calculated from the expression

$$4/\Gamma = d\,\mathrm{Im}\eta/dE\,|_{E=E_R}\ ,$$

where $\eta=e^{2i\delta}$. The results are displayed in Table II. It can be seen that there are no candidates for the $\frac{11}{2}^-$,

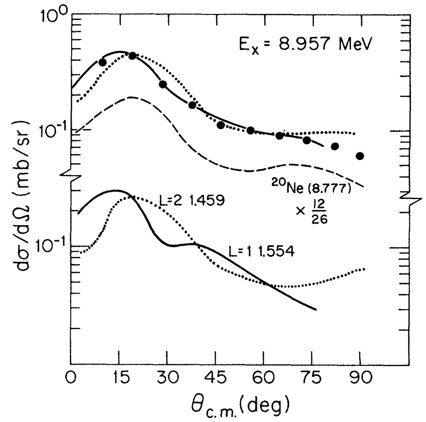

FIG. 3. Angular distributions for the deuteron group at 8.95 MeV measured in the ^{15}N(^{6}Li,d)^{19}F reaction compared with the sum (solid) of weak-coupling model predictions (dashed) taken from ^{20}Ne 8.777 MeV data scaled down by $\frac{12}{26}$ and an $L=1$ contribution for the unresolved state at 8.919 MeV. The latter is assumed to have the shape of the 1.554-MeV $\frac{3}{2}^+$ state. The dotted curve shown with the data represents the above sum but with an $L=2$ contribution due to the unresolved $\frac{3}{2}^-$ state at 8.928 MeV. The $L=2$ shape is taken from the transition to the lowest $\frac{3}{2}^-$ state at 1.459 MeV.

TABLE II. Energies and reduced α widths for $\frac{11}{2}^-$ and $\frac{13}{2}^-$ states in ^{19}F.

	E_x[a] (MeV±keV)	J^π	$\left[\frac{d\sigma}{d\Omega}\right]_{max}$ (μb/sr)	$\Gamma_{c.m.}$[a] (keV)	E_α (c.m.) (MeV)	Γ_α sp (keV)[b]	$\frac{\Gamma_{c.m.}}{\Gamma_\alpha sp}$
^{19}F $L=6$	7.166±0.7	$\frac{11}{2}^-$	51		3.152	0.082	
	8.288±2	$\frac{13}{2}^-$	275	<1	4.274	1.6	<0.63
	8.953±3	$\frac{11}{2}^-$	449	4.2±1	4.939	6.0	0.7
	9.873±1.7	$\frac{11}{2}^-$		$\lesssim 1.5$	5.859	26.0	$\lesssim 0.058$
^{20}Ne $L=6$	8.777±2.3	6^+	455	<3	4.046	0.53[c]	<5.66

[a]Reference 11.
[b]Calculated in a real Woods-Saxon well with $R=3.28$, $a=0.65$.
[c]Calculated in a real Woods-Saxon well with $R=3.35$, $a=0.65$.

$2N+L=8$ state except for that at 8.953 MeV. The lowest $\frac{11}{2}^-$ state at 7.166 MeV has no measurable width, but its small α strength in the (^{6}Li,d) reaction (Table II) excludes the possibility that it is the missing state—as has been actually suggested in a previous ^{15}N(α,γ)^{19}F reaction.[10,12] The state at 9.873 MeV has much too small a reduced α width to be associated with the $K^\pi=\frac{1}{2}^-$ band. Thus the $L=6$ ^{15}N$+\alpha$ strength seems to reside almost exclusively in the $\frac{13}{2}^-$ and $\frac{11}{2}^-$ states at 8.288 and 8.953 MeV, respectively. In ^{20}Ne only an upper limit on the α width for the 8.777 MeV state is given,[11] yielding an upper limit of 5.66 for the α reduced width for the $2N+L=8$ parent state in ^{20}Ne. We thus expect $\Gamma \lesssim 0.37$ keV for this ^{20}Ne 6^+ level.

We appear to have identified the members of the $K^\pi=\frac{1}{2}^-$ band in ^{19}F up to 9 MeV. The summed cs's in ^{19}F are within a factor of 1–1.6 of those in ^{20}Ne. The $(2J+1)$ weighted energies agree very well with weak-coupling predictions. The measured strength for the 8.953 MeV state as well as its calculated α reduced width strongly indicate that it is indeed the missing $\frac{11}{2}^-$ member of the $K^\pi=\frac{1}{2}^-$ band in ^{19}F.

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