$^{17}O(^{3}He,p)^{19}F$ and the structure of ^{19}F

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Angular distributions have been measured for 18 levels of ^{19}F populated in the reaction $^{17}O(^{3}He,p)$ at a bombarding energy of 18 MeV. Within the experimental resolution of 28 keV all levels below 5.7 MeV were observed. Nine states were excited with peak differential cross sections greater than 50 μb/sr, all others had maximum cross sections of less than 12 μb/sr. Eight of the nine strong levels are easily identifiable with $(sd)^3$ shell-model states. The ninth is the state at 5.11 MeV, previously assigned $J^\pi = 5/2^-$, but suggested by the present results to have positive parity. Angular distributions were analyzed with the distorted-wave Born approximation. For the strong states, transfer amplitudes were taken from an $(sd)^3$ shell-model calculation. Agreement in both shape and magnitude is good. Negative-parity hole states and positive-parity core-excited states are very weakly populated, but in many cases, their angular distributions are also well fitted with admixtures of the allowed L values.

[NUCLEAR REACTION $^{17}O(^{3}He,p)$, E=18.0 MeV; ^{19}F deduced levels, L, Π. DWBA analysis.]

I. INTRODUCTION

In the $^{18}O(^{3}He,p)^{20}F$ reaction,[1] a comparison of measured angular distributions with those predicted using microscopic wave functions provided an excellent means of identifying the $(sd)^4$ states in ^{20}F. The present report concerns a similar investigation of the reaction $^{17}O(^{3}He,p)^{19}F$. The nucleus ^{19}F has been studied with a variety of reactions, including $^{18}O(^{3}He,d)$,[2,3] $^{18}O(d,n)$,[4] $^{16}O(\alpha,p)$,[5] $^{16}O(^{6}Li,^{3}He)$,[6] $^{16}O(^{7}Li,\alpha)$,[7] $^{15}N(^{7}Li,t)$,[8] $^{17}O(\alpha,d)$,[9] $^{15}N(\alpha,\gamma)$,[10,11] $^{19}F(p,p')$,[12] and $^{19}F(\alpha,\alpha')$.[13] All the

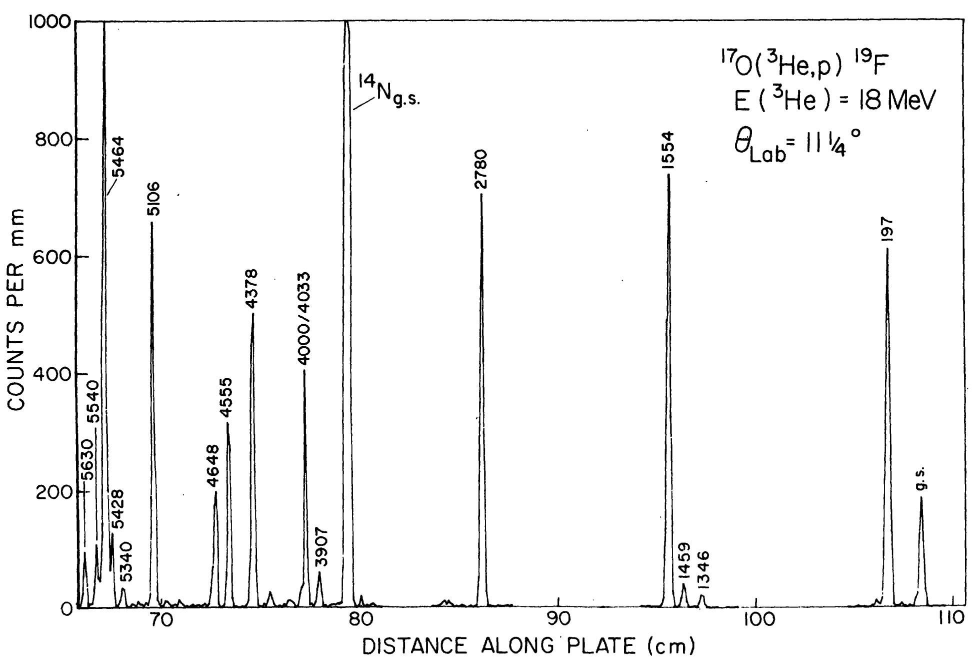

FIG. 1. Spectrum of the $^{17}O(^{3}He,p)^{19}F$ reaction at a bombarding energy of 18 MeV and a laboratory angle of 11.25°. Peaks are labeled with energies from a previous compilation. Excitation energies measured in the present work are listed in Table I. Small unidentified peaks arise from the (^{3}He,p) reaction on other isotopes of oxygen.

low-lying states[14] now have definite J^π assignments, and for most of the levels the dominant configuration is apparent. The nature of the ^{17}O ground state ($J^\pi = \frac{5}{2}^+$, $T=\frac{1}{2}$) allows, in the ^{17}O(^{3}He,p) reaction, for a variety of transferred L values to a given final state. Also, both $T=1$ and $T=0$ can contribute. This reaction thus provides a sensitive test of the shell-model wave functions.[15]

II. EXPERIMENTAL PROCEDURE

The reaction was performed at the University of Pennsylvania tandem accelerator. An 18-MeV ^{3}He beam bombarded a ^{12}C-backed target of WO_3, made from oxygen gas enriched in ^{17}O. Protons were analyzed in a multiangle spectrograph and detected in nuclear emulsions. Absorbers stopped all particles except protons. A monitor counter recorded the elastic scattering, from which the absolute cross-section scale was determined.

Data for the ^{17}O(^{3}He,p) reaction were obtained at eleven angles in 7.5° steps, beginning at 3.75°. A spectrum measured at 11.25° is displayed in Fig. 1. Energy resolution was 28 keV (full width at half maximum). Data were analyzed for all levels[14] below 5.7 MeV in excitation. The spectrum contains a peak from the (^{3}He,p) reaction on the ^{12}C-backing material and small peaks from (^{3}He,p) on ^{16}O and ^{18}O. No other contaminant peaks were observed.

III. RESULTS AND ANALYSIS

Average excitation energies obtained in the present work are compared with those from the literature[14] in Table I. The good resolution allowed the separation of all known levels below 5.7 MeV, with the exception of doublets near 4.0, 4.55, 4.65, and 5.5 MeV. Three of these doublets were resolvable at some angles. From those data

TABLE I. Levels of ^{19}F observed in ^{17}O(^{3}He,p)^{19}F.

Label	E_x (keV)[a]	Literature[b] E_x (keV)	J^π	σ_{max} (μb/sr)	L
g.s.	0.0	0.0	$\frac{1}{2}^+$	53	2(+4)
110	106 ± 10	109.89 ± 0.005	$\frac{1}{2}^-$	1.4	(1 +3)
197	188 ± 5	197.24 ± 0.19	$\frac{5}{2}^+$	330	0
1346	1346 ± 10	1345.67 ± 0.13	$\frac{5}{2}^-$	3.8	3(+5)
1459	1460 ± 8	1458.7 ± 0.3	$\frac{3}{2}^-$	6.2	1 +3
1554	1556 ± 3	1554.0 ± 0.2	$\frac{3}{2}^+$	340	0
2780	2783 ± 3	2779.8 ± 0.6	$\frac{9}{2}^+$	150	2
3907	3902 ± 9	3905.7 ± 0.8	$\frac{3}{2}^+$	9.8	2 +0
4000	3993 ± 5	3998.7 ± 0.7	$\frac{7}{2}^-$	12	3(+5)
4033	4026 ± 12	4032.5 ± 1.2	$\frac{9}{2}^-$	6.8	
4378	4373 ± 4	4376.7 ± 0.7	$\frac{7}{2}^+$	160	0 +2
4555	4545 ± 6	4549.9 ± 0.8	$\frac{5}{2}^+$	59	2
		4556.1 ± 0.5	$\frac{3}{2}^-$		
4648	4644 ± 6	4647 ± 20	$\frac{13}{2}^+$	94	4
		4682.5 ± 0.7	$\frac{5}{2}^-$		
5106	5099 ± 4	5105.3 ± 1.7	$\frac{5}{2}^-$	73	0 +2
5340	5332 ± 10	5336 ± 2	$\frac{1}{2}^{(+)}$	4.4	(2 +4) or (1 +3)
5428	5414 ± 8	5425 ± 7	$\frac{7}{2}^-$	12	3(+5)
5464	5465 ± 3	5465 ± 2	$\frac{7}{2}^+$	220	2
		5500 ± 3	$\frac{3}{2}^+$		
5540	5533 ± 8	5540 ± 5	$\frac{5}{2}^+$	12	2 +4
5630	5621 ± 7	5623 ± 3	$\frac{3}{2}^-$	9.3	1 +3

[a] Present work.
[b] Reference 14.

and from the average excitation energies extracted, we conclude that about $\frac{2}{3}$ of the yield to the 4.00-4.03-MeV doublet arises from the $\frac{7}{2}^-$ member at 4.00 MeV, virtually all of the yield of the 4.65-MeV doublet is due to the $\frac{13}{2}^+$ member, and most of the cross section of the 5.5-MeV peak arises from the 5.54-MeV $\frac{5}{2}^+$ state. From the shape of the angular distribution for the 4.55-MeV doublet (discussed below), it appears that the $\frac{3}{2}^-$ member is extremely weakly excited.

Table I also lists the peak differential cross section observed for each level. The maximum cross section for the strongest state is about 300 times that for the weakest state. Within the limits of our resolution, all the known levels were observed. The results are easily separated into two categories—(1) those with $\sigma_{max} \gtrsim 50$ μb/sr and (2) those with $\sigma_{max} \lesssim 12$ μb/sr.

The former group contains all the states normally thought to be $(sd)^3$ in character and one additional state—the $\frac{5}{2}^-$ level[14] at 5.11 MeV. All the other negative-parity states are only weakly excited—consistent with their interpretation as dominantly hole states. The very small cross sections observed for the other positive-parity states may imply they are of a core-excited nature.

Angular distributions for all the states are displayed in Figs. 2 and 3, where they are compared with curves calculated with the distorted-wave Born-approximation (DWBA) code DWUCK.[16] No attempt was made to vary optical-model parameters. One of the sets of Ref. 1 (listed in Table II) was used. For the dominantly $(sd)^3$ states, the DWBA calculations used as input two-nucleon transfer amplitudes from a shell-model calculation[15] that took ^{16}O as a closed core and allowed nucleons to occupy the $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ orbitals. [These amplitudes also assume ^{17}O (g.s.) to be a $1d_{5/2}$ single-particle state.]

Experimental cross sections were related to the calculated ones via the expression[17]

$$\sigma_{\rm exp}(\theta) = N\frac{(2J_f+1)}{(2J_i+1)}\sum_{LSJT} b_{ST}{}^2 D_{ST}{}^2 (T_i T_{iz} T0\,|\,T_f T_{fz})^2 \times (2S+1)\frac{\sigma_{\rm DW}(\theta)}{2J+1}.$$

The sum is over transferred orbital and total angular momenta L and J, and transferred spin S and isospin T, with the selection rule $S+T=1$. The quantity $b_{ST}{}^2$ is $\frac{1}{2}$ for both values of S, T. We used[17] $D_{10}{}^2 = 0.30$ and $D_{01}{}^2 = 0.72$. The square of the Clebsch-Gordan coefficient depends on initial, transferred, and final isospin T_i, T, and T_f, respectively, and is 1.0 for $T=0$ transfer and $\frac{1}{3}$ for $T=1$ transfer. The quantities J_f and J_i are final and initial total angular momenta, respectively.

For the states whose angular distributions are displayed in Fig. 2, the various $LSJT$ contributions were added together as required by the shell-

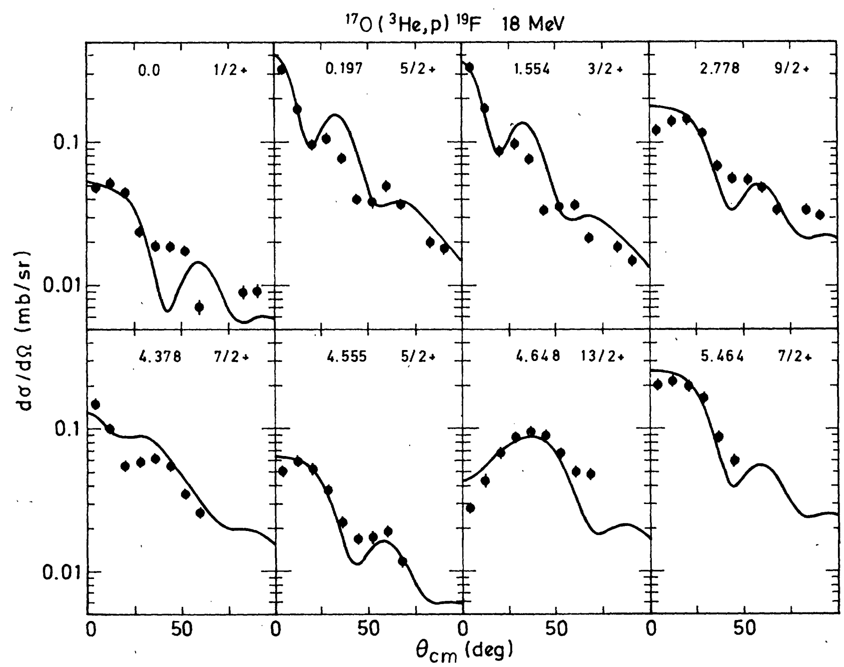

FIG. 2. Angular distributions for the $^{17}O(^3He,p)$ reaction populating eight levels of ^{19}F that are identifiable as dominantly $(sd)^3$ in character. DWBA curves were calculated as outlined in the text using two-nucleon transfer amplitudes from an $(sd)^3$ shell-model calculation.

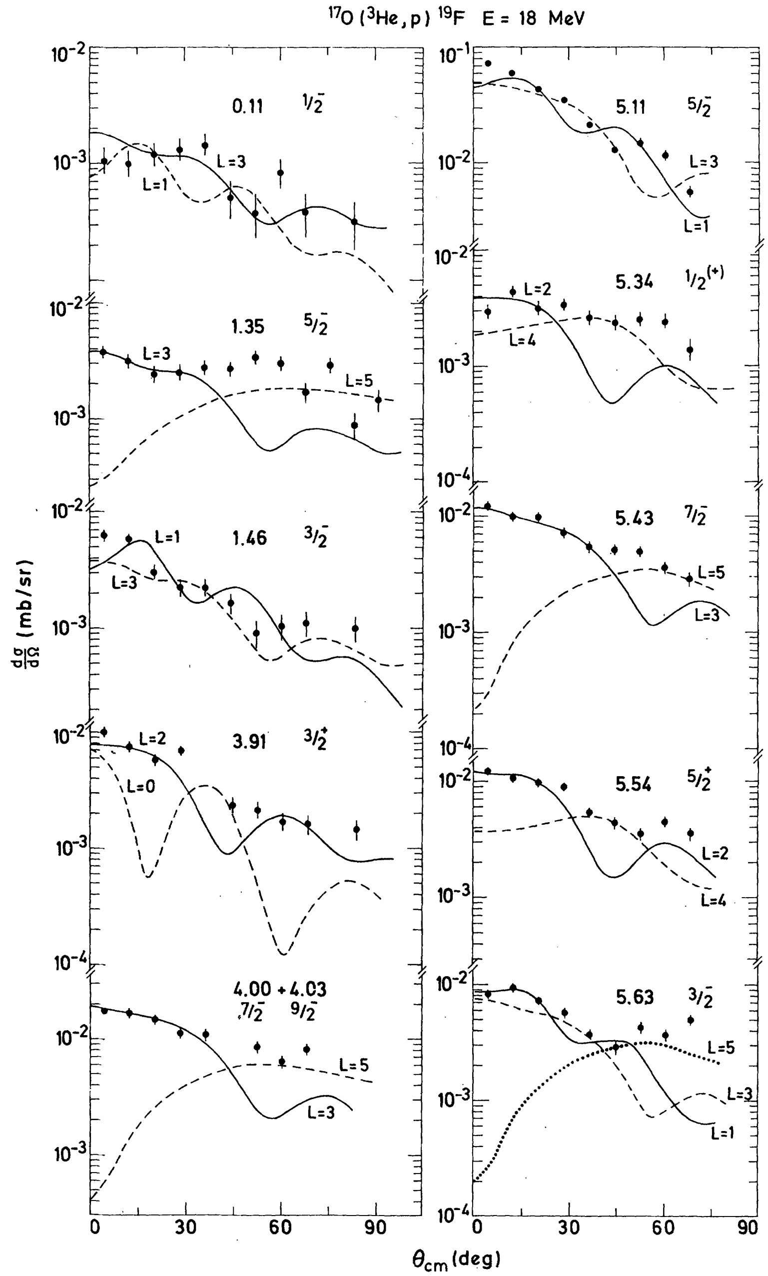

FIG. 3. Additional $^{17}O(^3He,p)^{19}F$ angular distributions compared with DWBA curves calculated for the allowed L values.

model amplitudes,[15] and then the sum was normalized to the data as shown in Fig. 2. The resulting normalization factors, N, thus extracted are listed in Table III.

Selection rules (in an sd basis) require the $\frac{13}{2}^+$ level to the populated via pure $L=4$. An $L=4$ curve is seen to give a reasonable account of the data. All the other states can be excited with a mixture of L values. The shell-model amplitudes correctly predict the dominance of $L=2$ for the $\frac{1}{2}^+$ (g.s.) and 2.78-MeV $\frac{9}{2}^+$ states and the dominance of $L=0$ for the 1.55-MeV $\frac{3}{2}^+$ level. They also correctly account for the dominance of $L=0$ for the first $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states and the dominance of $L=2$ for the second, though the calculations put somewhat too much $L=2$ in the 4.38-MeV state. For the g.s. and for other states dominated by $L=2$, the DWBA curves possess more of a minimum than is present in the data. For dominantly $L=0$ angular distributions, the magnitude of the second max-

TABLE II. Optical-model parameters used in analysis of $^{17}O(^3He,p)^{19}F$. Strengths in MeV, lengths in fm.

Channel	V	$r_0=r_{s0}$	$a=a_{s0}$	W	$W'=4W_D$	r_0'	a'	V_{s0}	r_{0c}
^{3}He	177	1.138		18	0				
p [a]	$V(E)$	$r_0(E)$	0.57	0	$W'(E)$	$r_0'(E)$	0.50	5.5	$r_0(E)$
Bound state	Varied	1.26	0.60	···	···	···	···	$\lambda=25$	1.26

[a] $V(E)=60+0.04Z/A^{1/3}+27(N-Z)/A-0.3E$, $W'(E)=4\times 10(N-Z)/A+9.6-0.06E$, $r_0(E)=r_0'(E)=1.15-0.001E$, from B. A. Watson, P. P. Singh, and R. E. Segel, Phys. Rev. 182, 977 (1969).

imum is overpredicted. But, overall, the shapes are roughly correct, especially near the cross-section maxima. The normalization factors fluctuate about a factor of 2 from an average value of 290. Changing the relative D^2 for $T=0$ and 1 by a factor of 2 in either direction does not produce better agreement with shapes for magnitudes. We conclude that the $(sd)^3$ shell-model calculations provide an adequate description of the (^{3}He,p) results for the levels whose angular distributions are displayed in Fig. 2.

Angular distributions for other levels are given in Fig. 3. They are compared with DWBA curves calculated assuming pure configurations for the transferred np pair. (The shapes for a given L are insensitive to the microscopic configuration assumed.) As mentioned above, the low-lying negative-parity states are extremely weak. Of course, if their configuration is pure $(sd)^4(1p)^{-1}$, they can be excited in a direct (^{3}He,p) reaction only through core-excited components in the ^{17}O (g.s.). In fact, if we assume the five lowest negative-parity states to be pure $(sd)^4(1p_{1/2})^{-1}$, then their summed cross section in the present work is consistent with a very small ($\lesssim 8\%$) amount of $(sd)^3(1p_{1/2})^{-2}$ in the ^{17}O (g.s.). Any nondirect reaction mechanism, if it adds incoherently to the cross section, would make this number even smaller.

The angular distribution of the 0.11-MeV $\frac{1}{2}^-$ state can be reasonably well fitted with a mixture of $L=1$ and 3. However, the cross section is small and the errors are large. The 1.35-MeV $\frac{5}{2}^-$

TABLE III. Normalization factors extracted in $^{17}O(^3He,p)$ for eight strong states.

E_x (MeV)	J^π	N
0.0	$\frac{1}{2}^+$	250
0.20	$\frac{5}{2}^+$	420
1.55	$\frac{3}{2}^+$	550
2.78	$\frac{9}{2}^+$	170
4.38	$\frac{7}{2}^+$	360
4.55	$\frac{5}{2}^+$	140
4.65	$\frac{13}{2}^+$	190
5.46	$\frac{7}{2}^+$	250

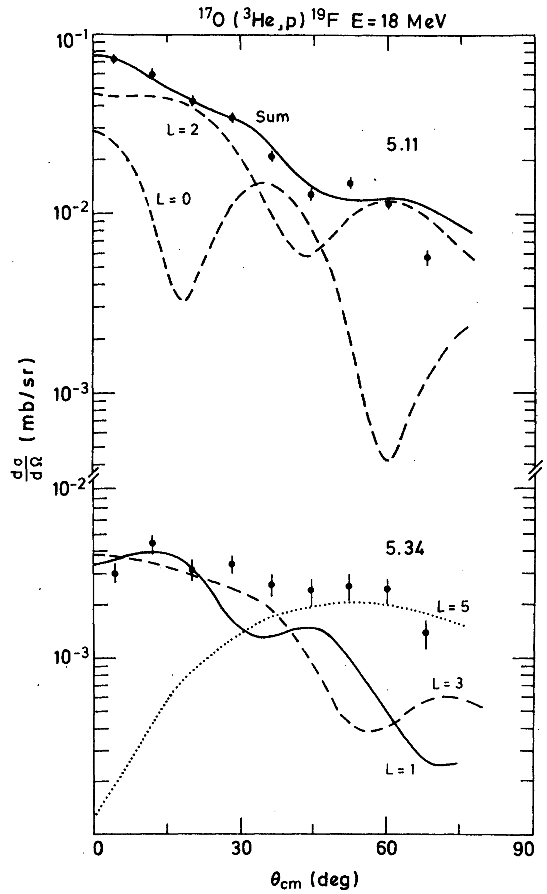

FIG. 4. $^{17}O(^3He,p)^{19}F$ angular distributions for states at 5.11 MeV (top) and 5.34 MeV (bottom), compared with alternative L values. The present results suggest the 5.11-MeV level (previously assigned $\frac{5}{2}^-$) actually has positive parity.

state is well fitted at forward angles by $L=3$, but the data at larger angles appear to require an $L=5$ contribution. Any $L=5$ component would require fp-shell excitations, since $L=5$ is not allowed in a psd basis. An $L=1+3$ fit to the 1.46-MeV $\frac{3}{2}^-$ state is only marginally satisfactory. The combined angular distribution for the $\frac{7}{2}^- - \frac{9}{2}^-$ pair near 4.0 MeV is well fitted by $L=3$ with again a hint of a small $L=5$ component. Of course, all these states are so weak that an appreciable fraction of the observed cross section may arise from nondirect processes. Hence, we draw no firm conclusions from the extracted L values.

The $\frac{7}{2}^-$ and $\frac{3}{2}^-$ states at 5.43 and 5.63 MeV, respectively, are significantly stronger. The former is well fitted by $L=3$ and the latter by a mixture of $L=1$ and 3, with some evidence of $L=5$ for both. The state at 5.11 MeV, previously assigned[14] $J^\pi=\frac{5}{2}^-$, is by far the strongest of the negative-parity states and its angular distribution is *not* well fitted by any mixture of odd L values. For this reason, we show in Fig. 4 the angular distribution for this level, fitted with an arbitrary admixture of $L=0$ and 2. The fit is seen to be quite good. Our results thus cast doubt on the J^π assignment of $\frac{5}{2}^-$ for this level. An $L=0+2$ admixture would require $J^\pi=(\frac{3}{2},\frac{5}{2},\frac{7}{2})^+$. It is interesting to note that in a study[11] of this state via $^{15}\mathrm{N}(\alpha,\gamma)$, $J=\frac{5}{2}$ was assigned, with positive-parity preferred. It is seen[2,3] with $l=2$ or 3 in $^{18}\mathrm{O}(^3\mathrm{He},d)$. Inelastic scattering gives conflicting results: $L=3$ in (α,α')[13] and a preference for $L=2$ in (p,p')[12]. It would be of interest to establish the parity of this state by an independent method. Of course the possibility exists (as always when J^π assignments conflict) that two levels may be present. But if so, they lie very close together ($\lesssim$10 keV). This point is discussed further in Ref. 19.

The positive-parity states whose angular distributions are displayed in Fig. 3 are also weakly populated. The 3.91-MeV $\frac{3}{2}^+$ state has long been ascribed[18] to core excitation. Despite its low cross section, its angular distribution is well fitted with an admixture of $L=0$ and 2, with $L=2$ dominant. The $\frac{5}{2}^+$ state at 5.54 MeV is populated with a mixture of $L=2$ and 4. The angular distribution of the $\frac{1}{2}^{(+)}$ level at 5.34 MeV is only moderately well fitted by a mixture of $L=2$ and 4. Since the parity of this level is uncertain, we display in Fig. 4 a comparison of the data with DWBA curves for odd L values. The quality of the fit is perhaps slightly better than that with even L values, but we make no definite parity assignment.

In summary, angular distributions have been measured for 18 levels of $^{19}\mathrm{F}$ populated in the $^{17}\mathrm{O}(^3\mathrm{He},p)$ reaction. Peak differential cross sections span a range of about 300. Except for a state at 5.11 MeV, all the strong states can be identified with $(sd)^3$ shell-model states. Agreement between experiment and theory for these eight strong states is quite good, both in angular distribution shape and cross-section magnitude, with only a slight difficulty in that too much $L=2$ is predicted for the lowest $\frac{7}{2}^+$ state. Our data appear to favor positive parity for the 5.11-MeV state, previously assigned $J^\pi=\frac{5}{2}^-$. Of the weak states, most are previously known to be negative-parity single-hole states, or positive-parity levels of more complicated structure than $(sd)^3$. Even for most of these states, the angular distributions are reasonably well fitted with admixtures of the allowed L values.

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