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High-spin states of $(fp)^2$ character in ^{34,35,36}Cl and ^{37,39}Ar[†]

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Angular distributions of the (α,d) reaction on ^{32,33,34}S and ^{35,37}Cl have been measured at 40 MeV bombarding energy. High-spin states of $(fp)^2$ character in the final nuclei were identified on the basis of their strength and characteristic $L = 4$ and $L = 6$ angular distributions. For some states, spin assignments are suggested. The properties of the high-spin states are discussed.

[NUCLEAR REACTIONS ^{32,33,34}S, ^{35,37}Cl(α,d); $E = 40$ MeV; measured (E_d, θ); enriched targets; deduced L transfer.]

I. INTRODUCTION

Within the last several years increasing information about high-spin states at the onset of the *fp* shell has become available. These high-spin states were studied via γ-ray spectroscopy utilizing either heavy-ion induced fusion evaporation[1,2] or (α,n)[3,4] and (α,p)[5,6] reactions, experiments which typically yield information only about states along the yrast line.

In an effort to determine the possible configurations of these high-spin states, and beyond that to get information about high-spin states away from the yrast line, we have performed the (α,d) reaction on ^{32}S, ^{33}S, ^{34}S, ^{35}Cl, and ^{37}Cl. Using the known selectivity of direct (α,d) transfer reactions,[7-9] particularly the preferential transfer of the proton-neutron pair in a completely aligned configuration with maximum possible spin, high-spin states in ^{34}Cl, ^{35}Cl, ^{36}Cl, ^{37}Ar, and ^{39}Ar of

$$[(\text{target})_J \otimes (f_{7/2})^2{}_{J=7,\,T=0}]$$

and

$$[(\text{target})_J \otimes (f_{7/2}p_{3/2})_{J=5,\,T=0}]$$

configurations are located. The transitions to these states are characterized by $L = 6$ and $L = 4$ angular distributions, respectively. A preliminary account[10] of the present data concentrated upon identification of the highest spin states $(\frac{17}{2}^+)$ which can be reached via $(f_{7/2})^2{}_{7,0}$ transfer on $J^\pi = \frac{3}{2}^+$ targets.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A 40 MeV α-particle beam from the Michigan State University cyclotron was used for carrying out the present experiments. The sulfur targets consisted of a layer of the enriched S isotopes sandwiched between layers of Formvar and carbon foils in order to inhibit evaporation during the bombardment. The chlorine targets were made by evaporation of NaCl or LiCl onto a thin carbon backing. One difficulty with the Cl targets, however, was that some deuteron groups from the Cl(α,d)Ar reaction coincided with groups from the contaminant Na(α,d)Mg or Li(α,d)Be reactions. In such cases, the results from the runs with the different targets were combined. Details of the targets are given in Table I. The target thicknesses were determined by measuring the elastic differential cross sections with the same experimental configurations as used for the transfer measurements and normalizing these data to calculations with standard optical-model parameters. A silicon detector placed in the scattering chamber allowed continuous monitoring of the target conditions. The reaction products were detected in the focal plane of an Enge split-pole magnetic spectrograph with a proportional-counter plastic-scintillator combination.

Deuteron spectra from the various targets are shown in Fig. 1. The resolution obtained was between 40 and 60 keV, full width at half maximum. Although the known level densities in the excitation energy regions of interest are quite high,[11] only a few states are observed to be strongly excited. In some cases the observed levels are considerably above the threshold for particle emission. For example, in ^{35}Cl the strongest excited

TABLE I. Target details.

Target	Thickness (μg/cm^2)	Isotopic abundance
^{32}S	110	99.9% ^{32}S
^{33}S	15	22.3% ^{32}S, 76.8% ^{33}S, 0.9% ^{34}S
^{34}S	140	9.6% ^{32}S, 0.4% ^{33}S, 90.0% ^{34}S
Li^{35}Cl	56	99.4% ^{35}Cl, 0.6% ^{37}Cl
Na^{35}Cl	95	99.4% ^{35}Cl, 0.6% ^{37}Cl
Li^{37}Cl	45	3.9% ^{35}Cl, 96.1% ^{37}Cl
Na^{37}Cl	74	4.0% ^{35}Cl, 96.0% ^{37}Cl

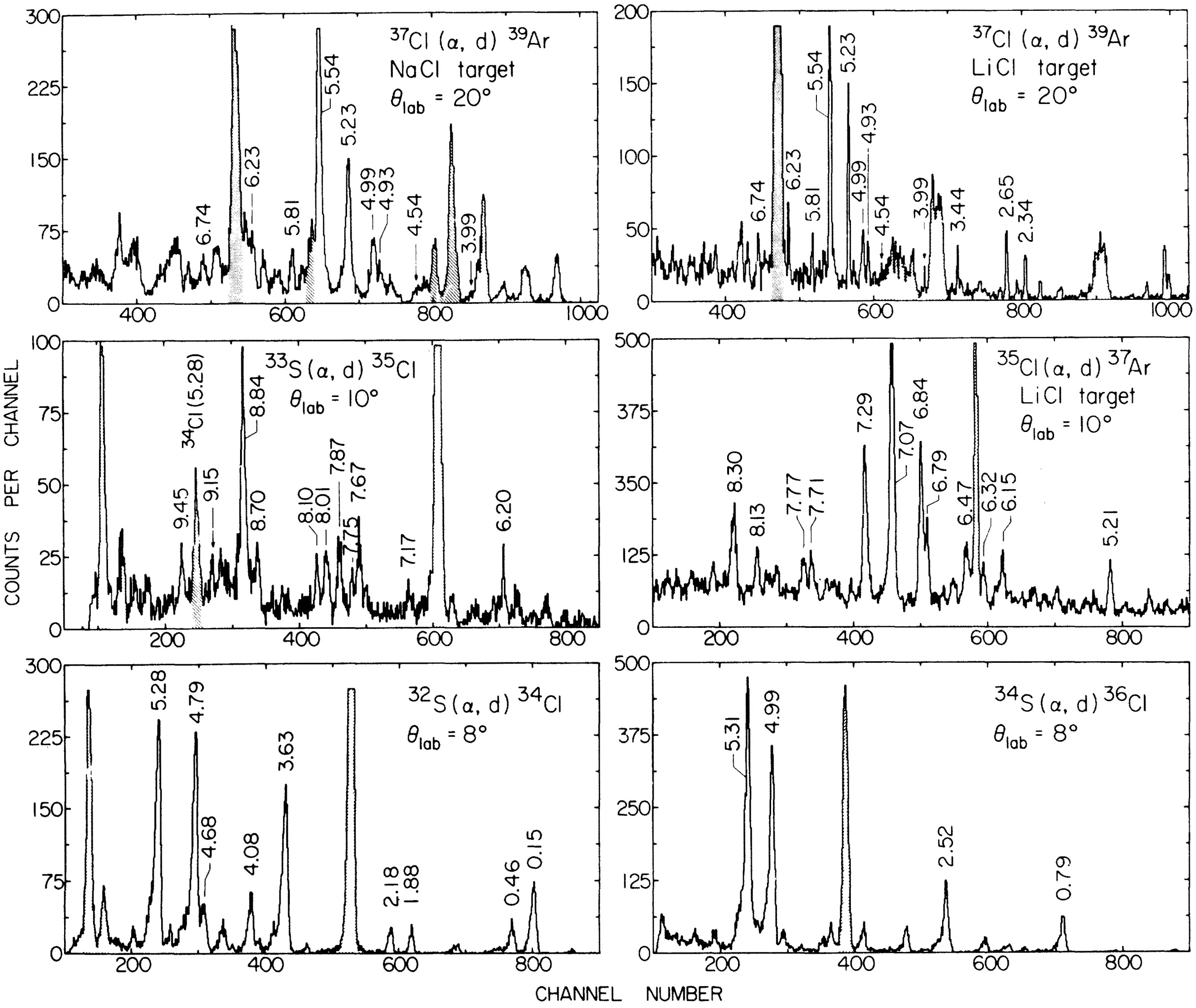

FIG. 1. The (α,d) spectra obtained from the various targets. The peaks are labeled by their excitation energy in MeV. Contaminant peaks are hatched.

state at 8.84 MeV lies about 2.5 MeV above the proton separation energy. The spectra were analyzed with the peak fitting program AUTOFIT,[12] and angular distributions were obtained over the region from 6° to 55°. These are displayed in Figs. 2–7. The error bars shown reflect the statistical errors and the uncertainties in unfolding close lying states. The accuracy of the absolute differential cross sections is estimated to be ±30%.

Tables II–VI show the results of the present work. For comparison, some other existing data are included. Our excitation energies can only be considered accurate to ±10 keV.

III. DISCUSSION

It has been demonstrated[7-9] that the (α,d) reaction preferentially populates high-spin $[J_i+(j_p j_n)J_{\max}]J_f$ configuration states. Accordingly, at the onset of the fp shell, levels of

$$[(\text{target})_J \otimes (f_{7/2})^2{}_{J=7,\,T=0}]$$

and

$$[(\text{target})_J \otimes (f_{7/2}p_{3/2})_{J=5,\,T=0}]$$

are expected to be strongly excited by $L=6$ and $L=4$ angular distributions, respectively.[9] In order to identify the expected $L=6$ and $L=4$ angular distributions, experimental $L=6$ and $L=4$ shapes were obtained from the ^{40}Ca(α,d) reaction[9] leading to the known 7^+ and 5^+ states in ^{42}Sc at 0.62 and 1.51 MeV,[11] respectively. These shapes are superimposed on the angular distributions in Figs. 2–7. An experimental $L=5$ shape was taken from the ^{32}S(α,d) transition to the known 5^- state in ^{34}Cl at 3.63 MeV.[11] The $L=4$, 5, and 6 patterns are

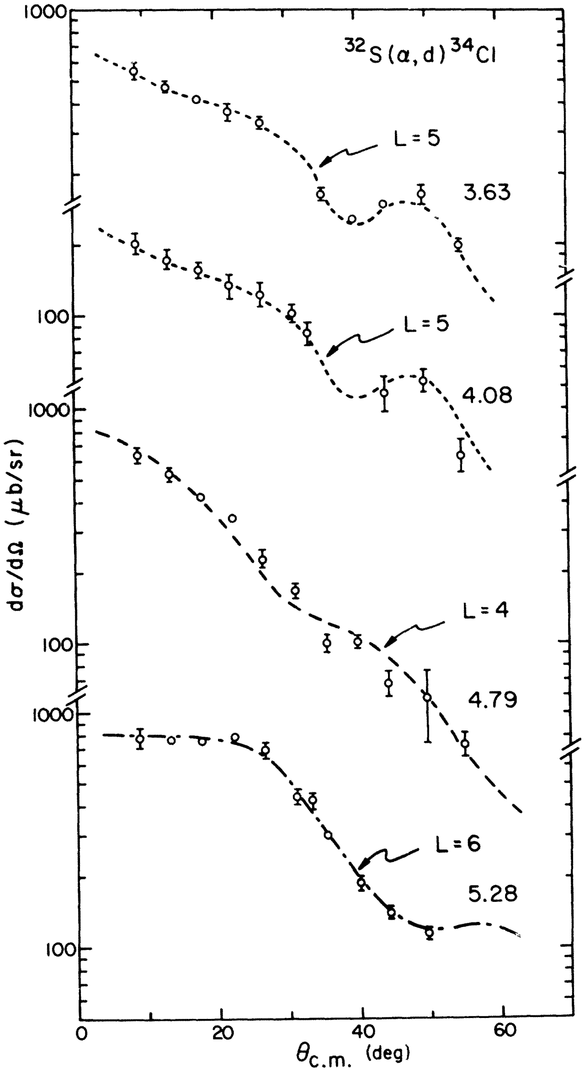

FIG. 2. The (α,d) angular distributions. The curves are empirical L shapes.

strongly structured and distinguishable from each other (see Fig. 2 where all three types are displayed). It should be noted that at higher bombarding energies (e.g., 50 MeV) the minima are shifted to smaller angles, which causes the distinctive features between the different L shapes to become less pronounced.[7] At lower bombarding energies (e.g., 30 MeV) the minima shift to larger angles and again the different L patterns become less distinctive.[13]

^{34}Cl

The experimental results are presented in Fig. 2 and Table II. The states at 3.63 (5^-), 4.79, and 5.28 MeV are very strongly excited by $L = 5$, $L = 4$, and $L = 6$ angular distributions, respectively. The $L = 5$ and $L = 6$ assignments are in agreement with the (α,d) work of Del Vecchio, Kouzes, and Sherr,[13] but our $L = 4$ assignment for the 4.79 MeV transition disagrees with their assignment of $L = 6$ for this state. The data points in our angular distribution were measured over a greater angular range and with more statistical accuracy than were those of the earlier work.

If it is assumed that the 5^- state at 3.63 MeV and the (7^+) state at 5.28 MeV have, respectively, pure $(d_{3/2}f_{7/2})_{5,0}$ (see Ref. 14) and $(f_{7/2})^2{}_{7,0}$ (see Refs. 7, 13, and 15) two-particle configurations relative to a ^{32}S core, then the (α,d) cross section ratio for these two transitions is 11 : 15, neglecting the small Q-value dependence. The experimental ratio of 0.71 supports the assumption of the pure nature of the two states.

The observed $L = 4$ strength for the 4.79 MeV transition relative to the $L = 6$ strength for the 5.28 MeV transition cannot be explained by pure $(f_{7/2})^2{}_{5,0}$ transfer, since DWBA calculations predict the $(f_{7/2})^2{}_{5,0}$ transfer cross section to be about a factor of 5 smaller than the $(f_{7/2})^2{}_{7,0}$ transfer cross section. Most likely, the $(f_{7/2}p_{3/2})_{5,0}$ configuration, which also leads to $L = 4$ and which yields a cross section of about an order of magnitude larger than the $(f_{7/2})^2{}_{5,0}$ configuration, contributes considerably to the observed strength. We suggest that this state has most probably the spin and parity 5^+.

^{36}Cl

The data are collected in Fig. 3 and Table III. Only the states at 4.99 and 5.31 MeV are strongly excited. The presumed 5^- state at 2.52 MeV is considerably weaker than the 5^- state in ^{34}Cl. The transition to the 4.99 MeV state shows a clear $L = 4$ angular distribution in disagreement with the results of Del Vecchio *et al.*,[13] who assign an $L = 1$ angular distribution. The state at 5.31 MeV is excited by an $L = 6$ transfer. Based on the selectivity of the (α,d) reaction discussed above we suggest the spin assignments 5^+ and 7^+

TABLE II. Results of the ^{32}S$(\alpha,d)^{34}$Cl reaction.

Present work			Reference 13		Reference 11	
E_x (MeV)	L	J^π	E_x (MeV)	L	E_x (MeV)	J^π
0.15			0.147	2	0.146	3^+
0.46			0.461	2	0.461	1^+
1.88					1.887	2^+
2.18					2.181	$(2,3^+)$
3.63	5	$(5)^-$	3.633	5	3.632	5^-
4.08	5	$(4-6)^-$	4.075	5	4.075	4^-
4.68						
4.79	4	$(5)^+$	4.789	6		
5.28	6	$(7)^+$	5.283	6		

TABLE III. Results of the $^{34}S(\alpha,d)^{36}Cl$ reaction.

Present work			Reference 13		Reference 1		Reference 11	
E_x (MeV)	L	J^π	E_x (MeV)	L	E_x (MeV)	J^π	E_x (MeV)	J^π
0.79					0.788	3^+	0.789	3^+
2.52	5	$(4-6)^-$			2.518	5^-	2.517	$(1-5)^-$
4.99	4	$(5)^+$	5.000	1			5.000	$(0-3)^-$
5.31	6	$(7)^+$	5.303	6	5.313	$(7)^+$		

for the states at 4.99 and 5.31 MeV. The latter assignment is consistent with the results of the heavy-ion induced γ-ray work of Warburton *et al.*[1]

^{35}Cl

A summary of the present data is given in Fig. 4 and Table IV. Ten $L = 6$ angular distributions have been observed in the present $^{33}S(\alpha,d)^{35}Cl$ experiment leading mostly to previously unknown states. A state at 8.84 MeV excitation is by far the most strongly populated, thus suggesting[10] a spin of $\frac{17}{2}^+$. The $L = 6$ shape associated with these states leads to the suggestion that their wave functions have significant components of the type $[^{33}S(\frac{3}{2}^+)\otimes(f_{7/2})^2{}_{7,0}]$. Their spins range from $\frac{11}{2}^+$ to $\frac{17}{2}^+$. A state at 7.87 MeV is excited by a mixture of $L = 4$ and $L = 6$ transfer. Again invoking the established selectivity of the direct (α,d) reaction, the $L = 6$ admixture can be attributed to a $(f_{7/2})^2{}_{7,0}$ transfer whereas the $L = 4$ component is associated with a mixture of $(f_{7/2})^2{}_{5,0}$ and $(f_{7/2}p_{3/2})_{5,0}$ transfers. This limits the spin and parity for the 7.87 MeV state to $\frac{11}{2}^+$ or $\frac{13}{2}^+$.

Levels at 7.87 and 8.84 MeV in ^{35}Cl have been observed by Warburton *et al.*,[1] in their heavy-ion induced γ-ray spectroscopy work. Based on the γ-ray angular distributions and the relative strength of the direct feeding of these levels they suggested the spin assignment of $\frac{13}{2}$ and $\frac{17}{2}$. The present results are consistent with these assignments and in addition yield an even parity for these two levels.

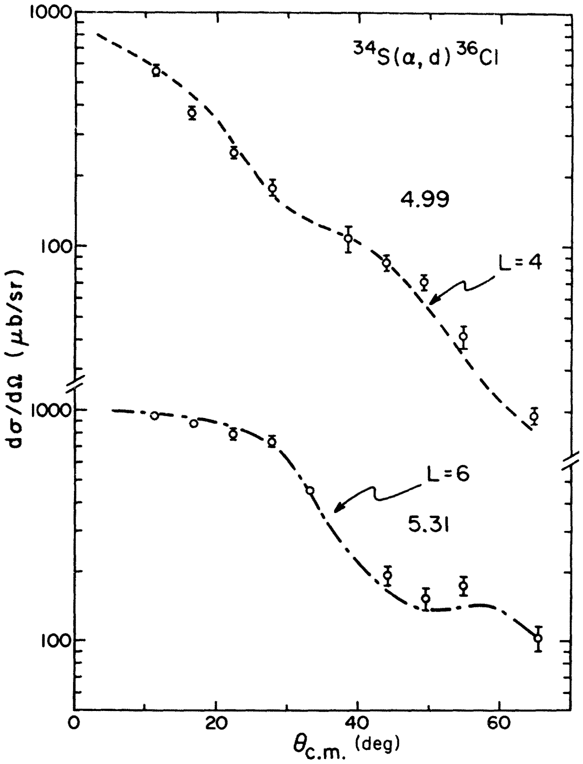

FIG. 3. See caption to Fig. 2.

^{37}Ar

The results of the present experiment are collected in Figs. 5 and 6 and Table V. The transitions to the states at 5.21, 6.43, and 7.07 MeV excitation energy (see Fig. 5) exhibit clear $L = 6$ angular distributions. The dominant cross section of the 7.07 MeV state suggests[10] a spin of $\frac{17}{2}^+$. The

TABLE IV. Results of the $^{33}S(\alpha,d)^{35}Cl$ reaction.

Present work			Reference 1	
E_x (MeV)	L	J^π	E_x (MeV)	J^π
6.20	6	$(\frac{11}{2}-\frac{17}{2})^+$		
7.17	6	$(\frac{11}{2}-\frac{17}{2})^+$		
7.67	6	$(\frac{11}{2}-\frac{17}{2})^+$		
7.75	6	$(\frac{11}{2}-\frac{17}{2})^+$		
7.87	4 + 6	$(\frac{11}{2}-\frac{13}{2})^+$	7.873	$(\frac{13}{2})$
8.01	6	$(\frac{11}{2}-\frac{17}{2})^+$		
8.10	6	$(\frac{11}{2}-\frac{17}{2})^+$		
8.70	6	$(\frac{11}{2}-\frac{17}{2})^+$		
8.84	6	$(\frac{17}{2})^+$	8.844	$(\frac{17}{2})$
9.15	6	$(\frac{11}{2}-\frac{17}{2})^+$		
9.45	6	$(\frac{11}{2}-\frac{17}{2})^+$		

states at 6.15, 7.71, 7.77, and 7.89 MeV are populated by pure $L=4$ transfers (see Fig. 5), whereas the transitions to the 6.47, 6.79, 6.84, 7.29, 8.13, and 8.30 MeV states show mixtures of $L=4$ and $L=6$ transfers (see Fig. 6). The observed $L=6$ transfer can be attributed to a $(f_{7/2})^2{}_{7,0}$ configuration of the transferred proton-neutron pair, whereas the $L=4$ transfer can be associated with a mixture of the $(f_{7/2})^2{}_{5,0}$ and $(f_{7/2}p_{3/2})_{5,0}$ configurations. These configurations are the ones most likely to

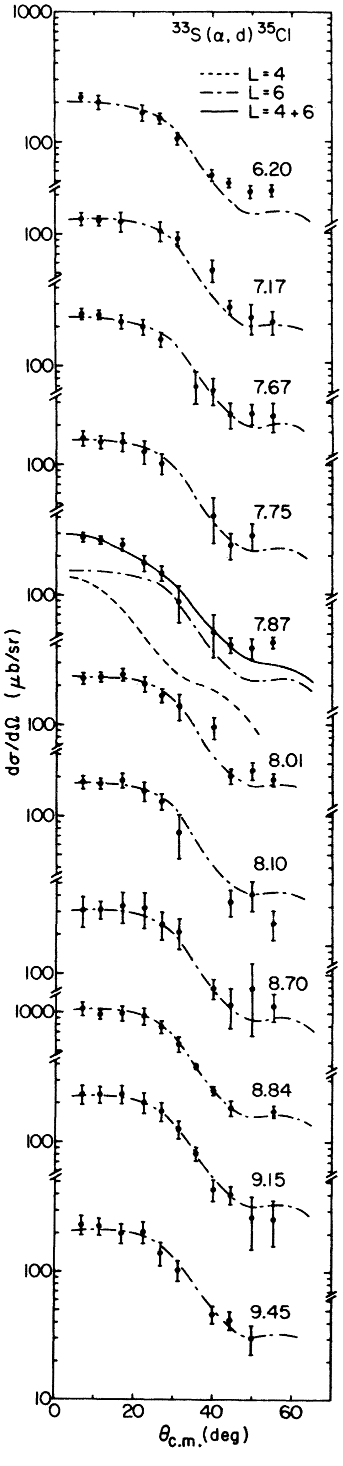

FIG. 4. See caption to Fig. 2.

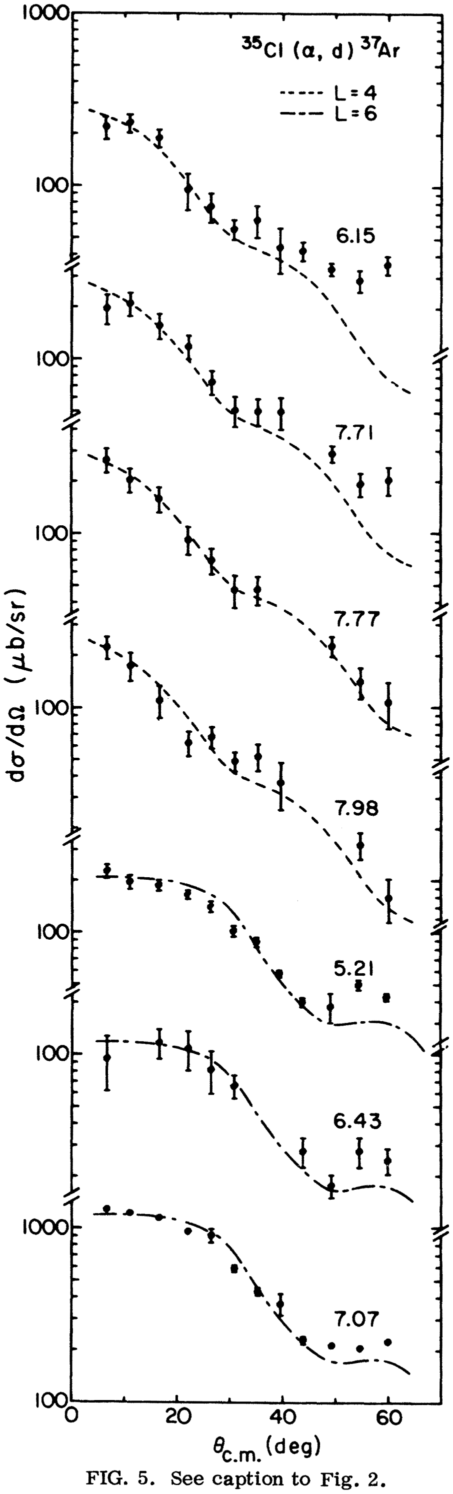

FIG. 5. See caption to Fig. 2.

produce $L=6$ and $L=4$ angular distributions.[9]

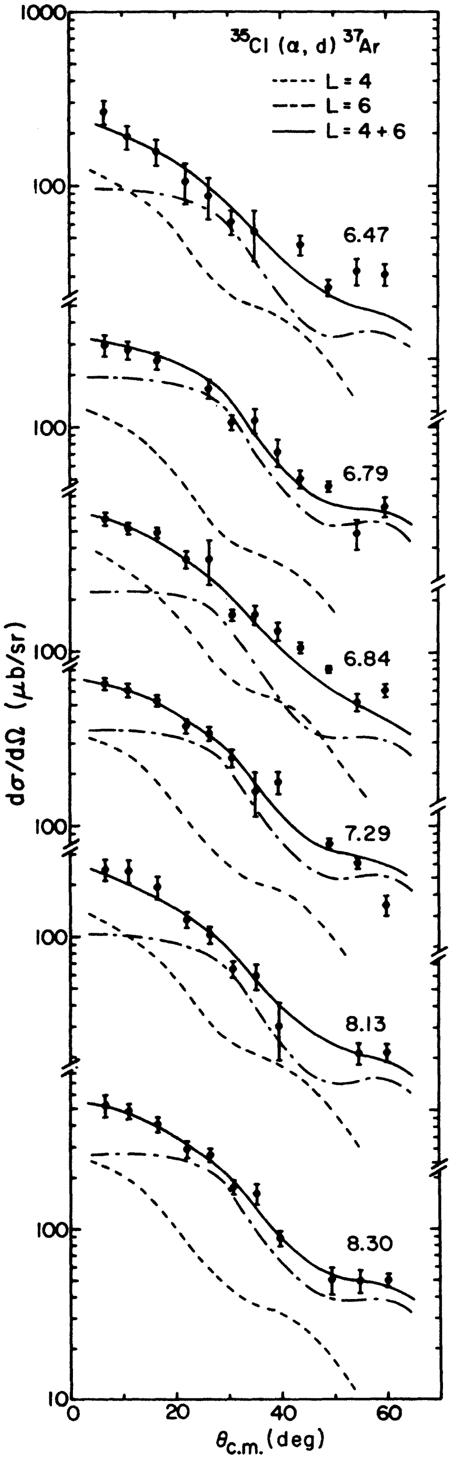

FIG. 6. See caption to Fig. 2.

TABLE V. Results of the ^{35}Cl$(\alpha,d)^{37}$Ar reaction.

Present work			Reference 4		Reference 1	
E_x (MeV)	L	J^π	E_x (MeV)	J^π	E_x (MeV)	J^π
5.21	6	$(\frac{11}{2}-\frac{17}{2})^+$	5.213	$\frac{11}{2}^+$	5.213	$\frac{11}{2}^+$
6.15	4	$(\frac{7}{2}-\frac{13}{2})^+$	6.150	$\frac{13}{2}^+$	6.151	$\frac{13}{2}^+$
6.32						
6.43	6	$(\frac{11}{2}-\frac{17}{2})^+$				
6.47	4 + 6	$(\frac{11}{2},\frac{13}{2})^+$	6.473	$\frac{15}{2}^+$	6.474	$\frac{15}{2}^+$
6.79	4 + 6	$(\frac{11}{2},\frac{13}{2})^+$				
6.84	4 + 6	$(\frac{11}{2},\frac{13}{2})^+$				
7.07	6	$(\frac{17}{2})^+$	7.071	$\frac{13}{2}^+,\frac{17}{2}^+$	7.072	$\frac{17}{2}^+$
7.29	4 + 6	$(\frac{11}{2},\frac{13}{2})^+$				
7.71	4	$(\frac{7}{2}-\frac{13}{2})^+$				
7.77	4	$(\frac{7}{2}-\frac{13}{2})^+$				
7.89	4	$(\frac{7}{2}-\frac{13}{2})^+$				
8.13	4 + 6	$(\frac{11}{2},\frac{13}{2})^+$				
8.30	4 + 6	$(\frac{11}{2},\frac{13}{2})^+$				

In Ref. 4 it is suggested that the states at 5.21 ($\frac{11}{2}^+$), 6.15 ($\frac{13}{2}^+$), 6.47 ($\frac{15}{2}^+$), and 7.07 ($\frac{13}{2}^+,\frac{17}{2}^+$) belong to the $[(f_{7/2})^2{}_{7,0}d^{-5}{}_{3/2}]$ configurations. Accordingly, these four states should be excited in the ^{35}Cl(α,d) reaction by pure $L=6$ angular distributions. The observed $L=6$ patterns for the transitions to the 5.21 and 7.07 MeV states are in agreement with this suggestion. However, we observe an $L=4$ angular distribution for the transition to the 6.15 ($\frac{13}{2}^+$) MeV state and a $L=4$ plus $L=6$ mixture for the transition to the 6.47 ($\frac{15}{2}^+$) MeV state. The $L=4$ transfer to the 6.15 MeV state is consistent with the $J^\pi=\frac{13}{2}^+$ assignment but not with the suggested configuration. According to the selection rules of a direct (α,d) reaction, a $\frac{15}{2}^+$ state can only be reached from a $\frac{3}{2}^+$ target nucleus by an orbital angular momentum transfer of $L\geqslant 6$. Therefore, the observation of an $L=4$ admixture in the 6.47 MeV transition can be reconciled with the $\frac{15}{2}^+$ assignment of Ref. 4 only by the postulation of a close lying doublet of which one member is the 6.473 ($\frac{15}{2}^+$) state reported in Refs. 1 and 4 and the other the $J^\pi\leqslant\frac{13}{2}^+$ level excited in the (α,d) reaction with, at least in part, $L=4$.

^{39}Ar

The experimental ^{39}Ar informations are presented in Fig. 7 and Table VI. Four $L=6$ angular distributions have been observed in the present ^{37}Cl$(\alpha,d)^{39}$Ar reaction leading to states at 3.44, 4.99, 5.54, and 5.81 MeV. States at 4.93, 5.23, and 6.23 MeV are excited by a mixture of $L=4$ and $L=6$ transfers.

Recently, Warburton *et al.*,[2] observed high-spin yrast levels in ^{39}Ar at 3.99, 4.54, and 5.54 MeV and suggested spin assignments of $\frac{13}{2}^+$, $\frac{15}{2}^+$, and $\frac{17}{2}$, respectively. The first two states were so weakly excited in the present $^{37}\mathrm{Cl}(\alpha,d)^{39}\mathrm{Ar}$ experiment so that no angular distributions could be extracted.

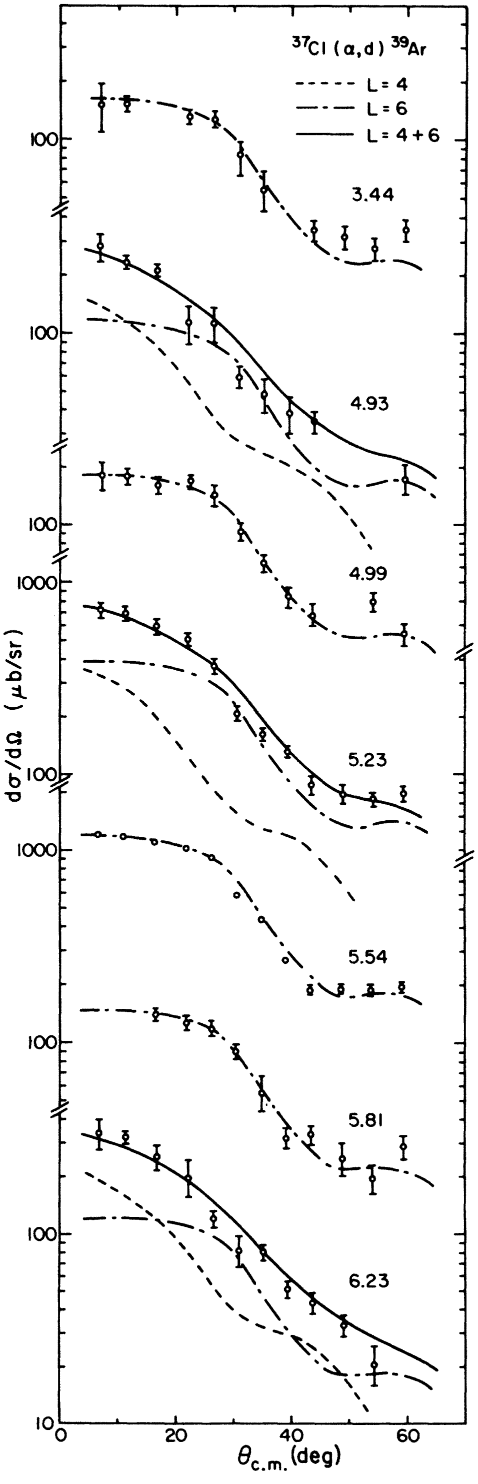

FIG. 7. See caption to Fig. 2.

TABLE VI. Results of the $^{37}\mathrm{Cl}(\alpha,d)^{39}\mathrm{Ar}$ reaction.

Present work E_x (MeV)	L	J^π	Reference 2 E_x (MeV)	J^π
3.44	6	$(\frac{11}{2}-\frac{17}{2})^+$		
			3.992	$(\frac{13}{2}^+)$
			4.543	$(\frac{15}{2}^+)$
4.93	4 + 6	$(\frac{11}{2},\frac{13}{2})^+$		
4.99	6	$(\frac{11}{2}-\frac{17}{2})^+$		
5.23	4 + 6	$(\frac{11}{2},\frac{13}{2})^+$		
5.54	6	$(\frac{17}{2})^+$	5.536	$(\frac{17}{2})$
5.81	6	$(\frac{11}{2}-\frac{17}{2})^+$		
6.23	4 + 6	$(\frac{11}{2},\frac{13}{2})^+$		

The large cross section of the 5.54 MeV state suggests[10] a spin assignment of $\frac{17}{2}^+$, in agreement with Ref. 2.

IV. SUMMARY AND CONCLUSIONS

The preferential excitation of high-spin states in the (α,d) reaction at suitable bombarding energies can be used not only to identify those states but also to infer their main configurations. At the onset of the fp shell, levels with

$$[(\text{target})_J \otimes (f_{7/2})^2{}_{J=7,\,T=0}]$$

configurations are strongly excited by $L = 6$ angular distributions. The observation of strong $L = 4$ transitions can be attributed to a mixture of the

$$[(\text{target})_J \otimes (f_{7/2}p_{3/2})_{J=5,\,T=0}]$$

and

$$[(\text{target})_J \otimes (f_{7/2})^2{}_{J=5,\,T=0}]$$

configurations in the final state.

In the $^{32,34}\mathrm{S}(\alpha,d)$ reactions, the 4.79 MeV state in $^{34}\mathrm{Cl}$ and the 4.99 MeV state in $^{36}\mathrm{Cl}$ are strongly excited by $L = 4$ angular distributions. This leads to the suggestion that both states have spin and parity 5^+ and that their wave functions have significant components of the type

$$[(\text{target})_{0^+} \otimes (f_{7/2})^2{}_{5,0}]$$

and

$$[(\text{target})_{0^+} \otimes (f_{7/2}p_{3/2})_{5,0}]\,.$$

The fact that the magnitudes of the observed differential cross sections for these two transitions are approximately equal points to a close similarity of their wave functions. An interesting feature is that these two states lie a few hundred keV below the known $[(\text{target})_{0^+} \otimes (f_{7/2})^2{}_{7,0}]_{7^+}$ configuration states which are excited by $L = 6$ angular distributions.

In the ^{33}S, ^{35,37}Cl(α, d) reaction many states are excited by $L = 6$ angular distributions. The $L = 6$ shape associated with these states leads to the suggestion that their wave functions have components of the type $[(\text{target})_{3/2} \otimes (f_{7/2})^2{}_{7,0}]$. The spins of these states can vary from $\frac{11}{2}^+$ to $\frac{17}{2}^+$. Several others states are excited either by pure $L = 4$ or mixed $L = 4$ plus $L = 6$ angular distributions. Here the $L = 4$ pattern can be attributed to components of the type $[(\text{target})_{3/2^+} \otimes (f_{7/2})^2{}_{5,0}]$ and $[(\text{target})_{3/2^+} \otimes (f_{7/2}p_{3/2})_{5,0}]$ in the wave functions of these states.

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