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Neutron Pickup from ^{36}Ar†

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The ^{36}Ar(^{3}He, α)^{35}Ar reaction has been studied at a bombarding energy of 18 MeV using a multiangle spectrograph and a windowless gas cell. Levels in ^{35}Ar have been observed up to 8.3 MeV excitation with an energy resolution of 35 keV. Many new levels are reported. Angular distributions for the strong states have been compared with distorted-wave predictions. Spectroscopic factors have been extracted and are compared with the results of recent shell-model calculations. The agreement is good.

I. INTRODUCTION

Recent detailed shell-model calculations[1-3] for nuclei in the upper half of the $2s$-$1d$ shell have promoted experimental interest in these nuclei. Unfortunately, the experimental study of nuclei in this mass region is often difficult because most of the appropriate targets exist only in gaseous form or as relatively unstable compounds. The nucleus ^{35}Ar is a case in point, since it can be conveniently reached by only two direct reactions: neutron pickup from ^{36}Ar and charge exchange on ^{35}Cl.

The nucleus ^{35}Ar has previously been investigated by means of the ^{36}Ar(^{3}He, α), ^{36}Ar(p, d), and ^{36}Ar(d, t) reactions.[4-7] The most extensive of those studies is the ^{36}Ar(p, d) work of Johnson and Griffiths,[5] at a bombarding energy of 27.5 MeV. Those authors present angular distributions for 11 levels in ^{35}Ar with an energy resolution of 120 keV full width at half maximum.

The mirror nucleus, ^{35}Cl, has been investigated in more detail—both by particle-transfer reactions[8] and by γ-decay scheme studies.[9, 10]

In the present study of the ^{36}Ar(^{3}He, α) reaction, at a bombarding energy of 18 MeV, 34 levels have been identified up to 8.02 MeV in excitation. A distorted-wave analysis of the angular distributions for 17 transitions enables several new spin-parity assignments to be made.

II. EXPERIMENTAL PROCEDURE

The experiment was performed using an 18-MeV ^{3}He^{++} beam from the University of Pennsylvania tandem Van de Graaff accelerator. The reaction α particles were detected in Ilford $K-1$ nuclear emulsions after being momentum-analyzed in a multiangle spectrograph.

The target consisted of >99.9% pure argon gas enriched to 99.8% in ^{36}Ar. The gas was contained in a gas cell with no entrance window.[11] The exit window for outgoing α particles was ~295-μg/cm^2 Mylar foil.[12] The beam exited through a thin Ni window. A sealed pump was used to back the 61-cm oil diffusion pump on the spectrograph chamber. The escaping gas was recovered from the sealed pump and purified before being returned to the gas cell. Condensible materials were removed from the gas in a trap cooled to liquid-nitrogen temperatures. The oxygen and nitrogen contaminants were removed by chemical combination with heated titanium coils in an inert gas purifier. The arrangement is shown schematically in Fig. 1. The content of the residual gas in the spectrograph chamber was continuously monitored with a partial pressure analyzer and chart recorder. No buildup of contaminants was observed, except for trace quantities of ^{40}Ar from the atmosphere. The cell pressure was maintained at about 18 Torr during the course of the experiment. A total volume of 40 atm cm^3 of ^{36}Ar was required to maintain this pressure.

III. RESULTS

A spectrum of α particles obtained at a laboratory angle of 15° is shown in Fig. 2. The over-

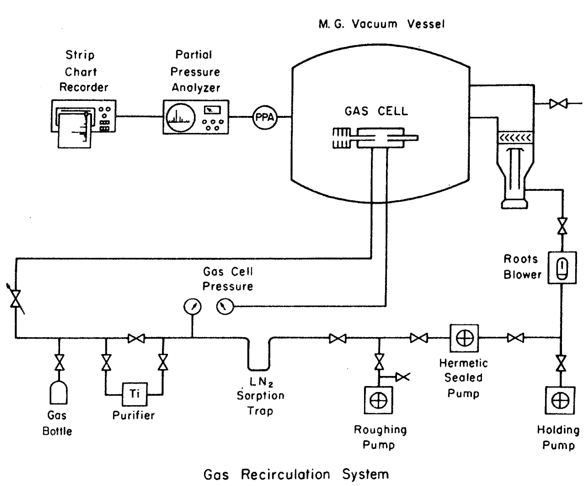

FIG. 1. Schematic diagram of the gas cell and recirculating system.

all resolution of 35 keV contains comparable contributions from target thickness and from straggling in the exit window. Levels identified as belonging to ^{35}Ar are labeled numerically. No evidence was found for any contaminant peaks in the spectrum.

The beam energy was calculated from the measured position of the ground-state group and the known Q_0 value of 5325.7 keV from the mass tables.[13] Excitation energies were calculated at several forward angles and averaged. These average excitation energies are listed in Table I, along with values from the literature,[4-7] whenever available. Many new levels were observed in the present study.

Angular distributions were extracted for 17 of the stronger transitions and are shown in Figs. 3 and 4. The absolute cross-section scale was determined from the measured gas pressure, known cell geometry, and total collected charge and is believed accurate to within 20%.

IV. DISTORTED-WAVE ANALYSIS

Theoretical angular distributions were calculated using the code DWUCK.[14] Two sets of optical-model parameters were taken from the work of Kattenborn, Mayer-Böricke, and Mertens[15] and are listed in Table II. The depth of the bound-state well was adjusted to give the correct binding energy as determined by the separation energy procedure. The calculations were performed in the local zero-range approximation, and a lower cutoff of zero was used in the evaluation of the radial integrals. Examples of the quality of fits obtained with the two parameter sets are shown in Fig. 5 for the ground-state ($\frac{3}{2}^+$) and 1.179-MeV ($\frac{1}{2}^+$) transitions. Both parameter sets give an

TABLE I. Energy levels of ^{35}Ar.

Level	(^{3}He, α) Present work (MeV ± keV)	(^{3}He, α) (Ref. 4) (MeV ± keV)	(p,d) (Ref. 5) (MeV ± keV)	(p,d) (Ref. 6) (MeV ± keV)	(d,t) (Ref. 7) (MeV ± keV)
0	0	0	0	0	0
1	1.179 ± 10	1.24	1.18 ± 20	1.18 ± 20	1.180 ± 10
2	1.738 ± 10	1.84	1.70 ± 30		
3	2.637 ± 10	2.75	2.60 ± 20	2.63 ± 20	2.635 ± 20
4	2.982 ± 10	3.14	2.95 ± 20	2.99 ± 20	2.985 ± 20
5	3.193 ± 10	3.35	3.19 ± 20	3.21 ± 20	3.200 ± 20
6	3.884 ± 10				
7	4.012 ± 10				
8	4.110 ± 10	4.24			
9	4.142 ± 10				
10	4.350 ± 10				
11	4.530 ± 10				
12	4.721 ± 10		4.70 ± 40		
13	4.782 ± 10			4.77 ± 20	
14	5.048 ± 10		} 5.07 ± 40		
15	5.116 ± 10			5.11 ± 20	
16	5.205 ± 10				
17	5.387 ± 10		5.40 ± 50		
18	5.484 ± 10				
19	5.591 ± 10			5.61 ± 20	
20	5.911 ± 10				
21	6.033 ± 10		6.01 ± 30	6.03 ± 20	
22	6.153 ± 10				
23	6.258 ± 10				
24[a]	6.631 ± 10		6.62 ± 30	6.70 ± 20	
25	6.827 ± 10		6.82 ± 30		
26	6.959 ± 10				
27	7.055 ± 10			7.03 ± 20	
28	7.117 ± 10				
29	7.293 ± 10				
30	7.423 ± 10				
31	7.502 ± 10				
32	7.840 ± 20				
33	8.019 ± 10				

[a] Probable doublet.

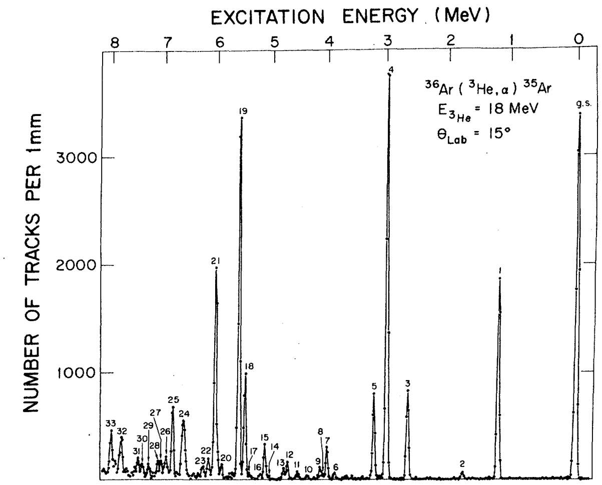

FIG. 2. Spectrum of the $^{36}Ar(^3He, \alpha)$ reaction measured at a bombarding energy of 18 MeV and a laboratory angle of 15°. Groups identified as belonging to ^{35}Ar are labeled numerically.

equally good account of the experimental $l_n = 2$ shapes, but there is a difference of about 20% in the predicted magnitudes. Potential set I gives a better fit to the observed $l_n = 0$ shape of the 1.179-MeV transition. Therefore, all the other theoretical angular distributions were calculated using Set I.

These optical-model parameter sets have previously been used[15] to account for j-dependent effects in the shapes of $l_n = 2$ ($^3He, \alpha$) transitions in this mass region. In Fig. 6, calculated $l = 2$ shapes (obtained using Set I) for both $j = \frac{3}{2}$ and $\frac{5}{2}$ are shown, together with the data for the ground-state ($\frac{3}{2}^+$) and 2.982-MeV ($\frac{5}{2}^+$) transitions. The differences are small in both experimental and theoretical shapes. It is therefore concluded that, in the present case, it is not possible to differentiate between the two allowed j values for $l_n = 2$ transitions.

The cross section calculated by the code DWUCK for the ($^3He, \alpha$) reaction on a spin-zero target is related to the experimentally observed cross section by the expression[14]

$$\sigma_{\exp}(\Theta) = NC^2 S_{nlj} \frac{\sigma_{nlj}(\Theta)}{2j+1},$$

where $\sigma_{nlj}(\Theta)$ is the theoretical cross section and j is the transferred angular momentum. C is an isospin Clebsch-Gordan coefficient of the form

$$\langle T_f T_{zf} \tfrac{1}{2} \tfrac{1}{2} | T_i T_{zi} \rangle .$$

In the present case, $C^2 = \frac{1}{2}$. The quantity N, the

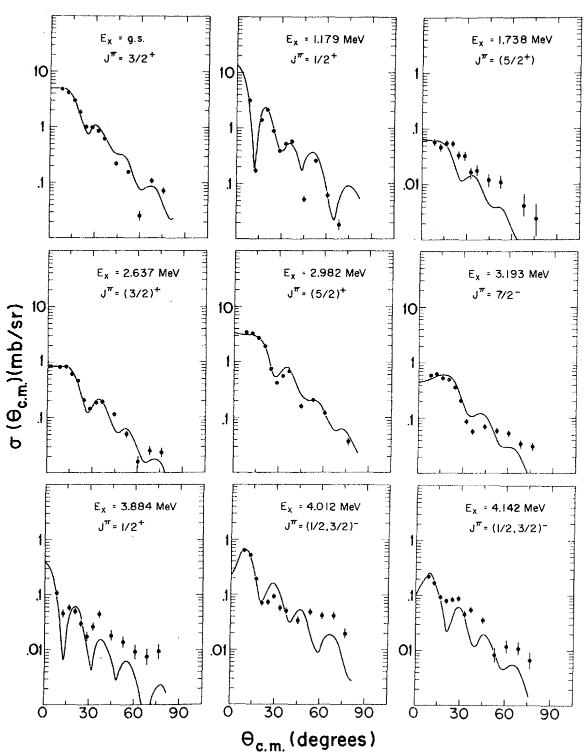

FIG. 3. Angular distributions of the $^{36}Ar(^3He, \alpha)$ reaction at 18-MeV bombarding energy.

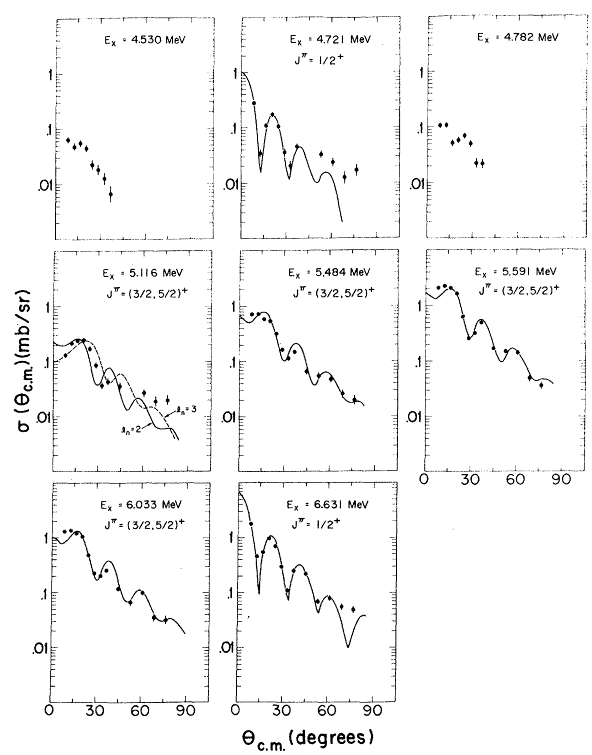

FIG. 4. Angular distributions of the $^{36}Ar(^3He, \alpha)$ reaction at 18-MeV bombarding energy.

TABLE II. Optical-model parameters used in the distorted-wave analysis of the ^{36}Ar(^{3}He, α)^{35}Ar reaction.

Channel		V_0 (MeV)	$r_0=r_{so}$ (fm)	$a=a_{so}$ (fm)	W (MeV)	W' (MeV)	r_0' (fm)	a' (fm)	r_{0c} (fm)	V_{so} (MeV)
Set I	^{36}Ar + ^{3}He	130	1.31	0.61	24	⋯	1.43	1.01	1.40	10
	^{35}Ar + α	180	1.42	0.56	16.5	⋯	1.42	0.56	1.40	⋯
Set II	^{36}Ar + ^{3}He	130	1.31	0.61	16	⋯	1.43	1.01	1.40	10
	^{35}Ar + α	180	1.35	0.60	17	⋯	1.35	0.60	1.40	⋯
Bound state		a	1.26	0.60	⋯	⋯	⋯	⋯	⋯	$\lambda=25$

[a] The depth of the bound-state well was adjusted to give the correct binding energy as determined by the separation energy procedure. $B=[20.578\text{ MeV}-Q(^3\text{He},\alpha)]$.

over-all normalization for the (^{3}He, α) reaction, is not well determined. We must therefore resort to empirical means to determine N, as discussed in Sec. V.

The experimental and theoretical angular distributions are compared in Figs. 3 and 4. The values of NS obtained from normalizing the theory to the data are listed in Table III, together with l_n and J^π assignments resulting from the present work. Whenever the spin of a level is in doubt, the extracted values of NS are given for both allowed J values.

V. NORMALIZATION

As mentioned previously, the value of the over-all normalization factor for the (^{3}He, α) reaction is not well determined. Values ranging from 10–60 have been reported experimentally,[16–18] whereas theoretical estimates are generally up to an order of magnitude smaller.[19,20] Previous experimental determinations of N have been made either by normalizing the observed summed strengths to theoretical values of these quantities or by normalizing measured (^{3}He, α) strengths to spectroscopic factors measured for analog transitions. In the present case both alternatives are available.

The detailed shell-model calculations that have been performed[3] for ^{35}Ar all predict four $\frac{1}{2}^+$ states in the excitation range 0–7 MeV, and in all the calculations the predicted $l_n=0$ spectroscopic factors sum to 3.52. This number, together with the experimental quantity $N\sum S_{l=0}=54.6$ give a value of $N=15.5$.

Alternatively, the measured[21] spectroscopic factor for the ^{35}Cl(^{3}He, d)^{36}Ar(g.s.) transition is 4.73. The value of NS for the ^{36}Ar(^{3}He, α)^{35}Ar(g.s.) transition from the present work is 85.4. The two spectroscopic factors should be identical; hence, this technique gives $N=18.1$. The close agreement between the two values obtained for N lends credence to the methods used. (Of course, the choice of N thus determined makes the resulting spectroscopic factors absolute. Systematic errors arising from uncertainties in target thickness and beam integration, or in N are eliminated by normalizing to a known absolute spectroscopic factor.) The mean of these two values, $N=16.8$, was used to extract spectroscopic factors from the measured

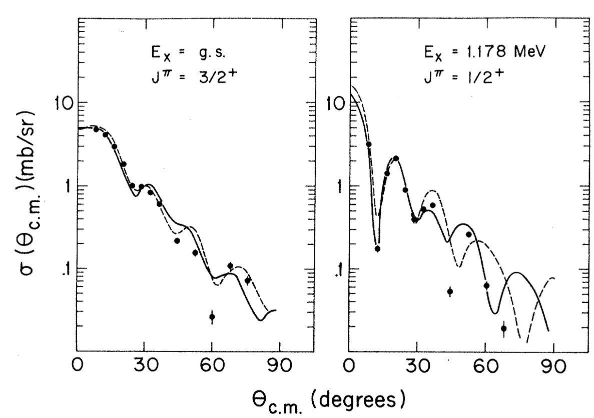

FIG. 5. Examples of fits obtained using parameter sets I (solid line) and II (dashed line) for the ground state and 1.179-MeV transitions.

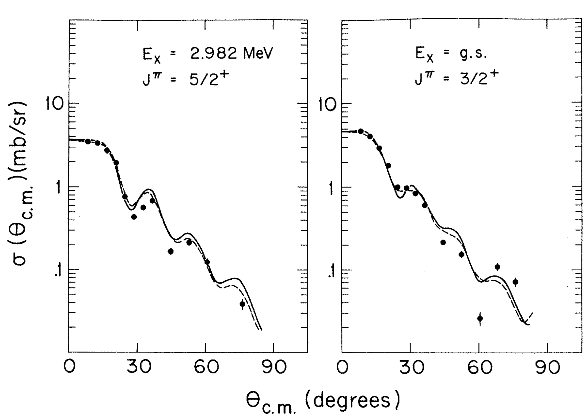

FIG. 6. Calculations with $j=\frac{3}{2}$ (solid line) and $j=\frac{5}{2}$ (dashed line) using parameter set I for the ground state and 2.982-MeV transitions.

TABLE III. Results of the distorted-wave analysis of the $^{36}Ar(^{3}He,\alpha)$ reaction.

Level	E_x [a] (MeV)	J^π (Lit.)	l_n [b] (^{3}He, α)	J^π (Assigned)	NS	S (N = 16.8)
0	0	$\frac{3}{2}^+$	2		85.4	5.09
1	1.179	$\frac{1}{2}^+$	0		40.0	2.38
2	1.738	$\frac{5}{2}^+$	2		0.81	0.05
3	2.637	$\frac{3}{2}^+$	2		19.0	1.13
4	2.982	$\frac{5}{2}^+$	2		46.7	2.78
5	3.193	$\frac{7}{2}^-$	3		13.2	0.78
6	3.884		0	$\frac{1}{2}^+$	0.70	0.04
7	4.012		1	$(\frac{3}{2})^-$	2.24	0.13
8	4.110					
9	4.142		1	$(\frac{3}{2})^-$	0.85	0.05
10	4.350					
11	4.530					
12	4.721		0	$\frac{1}{2}^+$	1.72	0.10
13	4.782					
14	5.048					
15	5.116		2	{ $\frac{3}{2}^+$ { $\frac{5}{2}^+$	8.44 4.88	0.50 } 0.29 }
16	5.205					
17	5.387					
18	5.484		2	{ $\frac{3}{2}^+$ { $\frac{5}{2}^+$	25.9 14.9	1.54 } 0.89 }
19	5.591	{ $\frac{3}{2}^+$ { $\frac{5}{2}^+$	2		{ 66.4 { 38.3	3.96 } 2.28 }
20	5.911					
21	6.033	{ $\frac{3}{2}^+$ { $\frac{5}{2}^+$	2		{ 43.7 { 25.3	2.60 } 1.51 }
22	6.153					
23	6.258					
24	6.631		0	$\frac{1}{2}^+$	12.2	0.72
25	6.827	{ $\frac{3}{2}^+$ { $\frac{5}{2}^+$				
26	6.959					
27	7.055					
28	7.117					
29	7.293					
30	7.423					
31	7.502					
32	7.840					
33	8.019					

[a] Excitation energies from present work.
[b] Present work.

values of *NS*. These spectroscopic factors are also listed in Table III.

VI. COMPARISON WITH PREVIOUS RESULTS

Table IV lists the values of the spectroscopic factors obtained from the present study, together with those obtained in the ^{36}Ar(p, d) studies of Johnson and Griffiths[5] and Kozub[6] and in the ^{36}Ar-(d, t) work of Whitten, Mermaz, and Bromley.[7] The over-all agreement between the present values and those from previous work is good—well within the uncertainties usually associated with distorted-wave calculations. There are, however, two cases in which the l-value assignments from the present work disagree with those from Ref. 5. These are the levels observed at 2.637 and 5.116 MeV. Both are seen with $l_n=2$ in the ^{36}Ar$(^3$He$, \alpha)$ reaction but were assigned $l_n=1$ and 3, respectively, in the (p, d) study. The $l_n=1$ assignment for the 2.637-MeV transition in the ^{36}Ar(p, d) reaction is probably in error, since no known

TABLE IV. Comparison of spectroscopic factors for neutron pickup from ^{36}Ar.

Level	E_x [a] (MeV)	J^{π} [b]			S	
			$(^3$He$,\alpha)$ [a]	(p,d) [c]	(p,d) [d]	(d,t) [e]
0	0	$\frac{3}{2}^+$	5.09	5.84	6.06	6.8
1	1.179	$\frac{1}{2}^+$	2.38	5.0	2.58	2.8
2	1.738	$\frac{5}{2}^+$	0.05		0.20	<0.4
3	2.637	$\frac{3}{2}^+$	1.13	f	0.84	1.0
4	2.982	$\frac{5}{2}^+$	2.78	4.94	4.62	5.2
5	3.193	$\frac{7}{2}^-$	0.78	1.26	1.28	0.66
6	3.884	$\frac{1}{2}^+$	0.04			
7	4.012	$(\frac{3}{2})^-$	0.13			
8	4.110					
9	4.142	$(\frac{3}{2})^-$	0.05			
10	4.330					
11	4.530					
12	4.721	$\frac{1}{2}^+$	0.10	0.34	0.10	
13	4.782					
14	5.048					
15	5.116	$\frac{3}{2}^+$ / $\frac{5}{2}^+$	0.50 / 0.29	g		
16	5.205					
17	5.387					
18	5.484	$\frac{3}{2}^+$ / $\frac{5}{2}^+$	1.54 / 0.89			
19	5.591	$\frac{3}{2}^+$ / $\frac{5}{2}^+$	3.96 / 2.28	5.86 / 4.74	3.54	
20	5.911					
21	6.033	$\frac{3}{2}^+$ / $\frac{5}{2}^+$	2.60 / 1.51	3.16 / 2.62	2.36	
22	6.153					
23	6.258					
24	6.631	$\frac{1}{2}^+$	0.72		1.44	

[a] Present work.
[b] Literature and present work.
[c] Reference 5.
[d] Reference 6.
[e] Reference 7.
[f] Seen with $l_n=1$, $S=0.24$ (Ref. 5).
[g] Seen with $l_n=3$, $S=0.92$ (Ref. 5).

negative-parity state exists near this excitation energy in the mirror nucleus, ^{35}Cl. Furthermore, the 2.637-MeV level of ^{35}Ar corresponds well with a known $\frac{3}{2}^+$ state at 2.695 MeV in ^{35}Cl. For the 5.116-MeV transition, assigned $l_n = 3$ from the (p, d) reaction, the cross section is small and (with a resolution of 120 keV) the observed "level" probably corresponds to two or three unresolved states. A calculation for $1f_{7/2}$ pickup for this state is compared with the present data in Fig. 3. It is clear that $l_n = 2$ gives a much better account of the data than does $l_n = 3$.

VII. COMPARISON WITH MODEL CALCULATIONS

Detailed shell-model calculations using the full $2s$-$1d$ shell basis have recently been performed[3] for $A = 35-38$. The calculations assumed an inert ^{16}O core and did not allow promotion of particles into the $1f$-$2p$ or higher shells. The diagonalization of the residual interaction was carried out in a variety of ways, and a variety of single-particle energies were used. The calculations of interest here are those labeled 11.0h + ASPE, 12.5p + ^{17}O, and 12.5pA. (See Ref. 3 for details.) In the 11.0h + ASPE label, the 11.0h denotes that the matrix elements of the realistic two-body interaction were calculated using a harmonic-oscillator parameter of $\hbar\omega = 11.0$ MeV and the renormalizations were calculated in hole formalism. The ASPE denotes that the single-particle energies were adjusted according to a least-squares fit of binding and excitation energies.

The 12.5p + ^{17}O calculation utilized a harmonic-oscillator parameter of 12.5 MeV with particle-formalism renormalization and single-particle energies taken from the observed splittings in ^{17}O. The 12.5pA calculation incorporates an adjusted form of the 12.5p Hamiltonian. Pickup spectroscopic factors which were generated[3] using the ^{35}Ar and ^{36}Ar(g.s.) wave functions calculated with the above Hamiltonians are compared with the experimental values in Table V and Fig. 7.

The general over-all agreement between experiment and theory is excellent. The measured spectroscopic factors for the first two $\frac{3}{2}^+$ states (at $E_x = 0$ and 2.64 MeV) are both somewhat larger than those predicted, but the ratios are in good agreement. All the calculations predict that the first $\frac{5}{2}^+$ state has a very small S, as observed. The $d_{5/2}$ hole strength is predicted to be split among three higher $\frac{5}{2}^+$ states. The first of these is the second $\frac{5}{2}^+$ state at $E_x = 2.98$ MeV, for which the measured and predicted S factors are in good agreement. The question of the higher $\frac{5}{2}^+$ states is discussed further below.

The measured strength for the $\frac{1}{2}^+$ first excited state is in excellent agreement with the calculated values. The splitting of the remaining $2s_{1/2}$ hole strength among three higher states is not in such good agreement. In particular, the states $\frac{1}{2}^+_3$ and $\frac{1}{2}^+_4$ appear to have inverted in the 12.5p + ^{17}O and 12.5pA calculations, resulting in rather poor agreement with the observed energies for

TABLE V. Comparison of experimental and theoretical spectroscopic factors for the ^{36}Ar(^{3}He, α)^{35}Ar reaction.

	Experiment		11.0h + ASPE [a]		12.5p + ^{17}O [a]		12.5pA [a]	
J^{π}_N	E_x (MeV)	S	E_x (MeV)	S	E_x (MeV)	S	E_x (MeV)	S
$\frac{3}{2}^+_1$	0	5.09	0	4.30	0	4.33	0	3.92
$\frac{1}{2}^+_1$	1.18	2.38	0.51	2.56	1.11	1.94	0.72	2.58
$\frac{5}{2}^+_1$	1.74	0.05	1.68	0.03	1.70	0.02	1.71	0.02
$\frac{3}{2}^+_2$	2.64	1.13	1.86	0.63	2.17	0.83	2.11	0.80
$\frac{5}{2}^+_2$	2.98	2.78	2.65	3.35	2.43	4.83	2.58	3.59
$\frac{1}{2}^+_2$	3.88	0.04	4.17	0.30	4.01	0.64	4.02	0.03
$\frac{1}{2}^+_3$	4.72	0.10	5.77	0.12	6.75	0.19	6.35	0.32
$\frac{1}{2}^+_4$	6.63	0.72	6.28	0.51	5.83	0.77	5.68	0.61
$\frac{3}{2}^+_3$	(4.53)	$\lesssim$0.12	4.98	0.06	5.09	0.07	4.78	0.03
$\frac{3}{2}^+_4$	(4.78)	$\lesssim$0.15	5.52	0.00	6.07	0.02	5.11	0.00
$\frac{5}{2}^+_3$	(5.59)	2.28	5.44	3.31	5.82	2.92	5.02	2.90
$\frac{5}{2}^+_4$	(6.03)	1.51	6.06	1.52	5.89	0.93	5.49	1.00

[a] Reference 3.

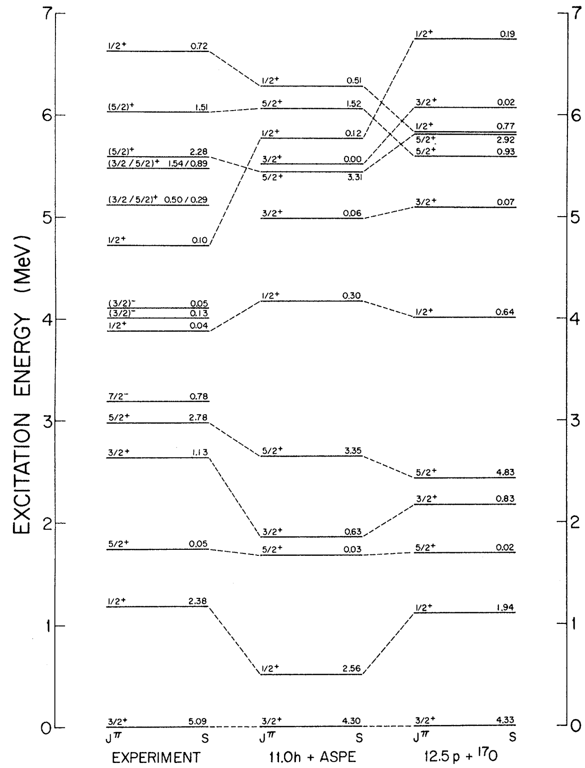

FIG. 7. Comparison between the present experimental results and the predictions of the model calculations (Ref. 3).

those two states.

Two $\frac{3}{2}^+$ states and two $\frac{5}{2}^+$ states predicted by the calculations remain to be identified experimentally. Four $l_n=2$ transitions are observed in the required excitation range, those to the 5.12-, 5.48-, 5.59-, and 6.03-MeV levels of ^{35}Ar. This might suggest that these levels are to be associated with the remaining $\frac{3}{2}^+$ and $\frac{5}{2}^+$ states predicted by the shell-model calculations. However, both remaining $\frac{3}{2}^+$ transitions are predicted to be extremely weak, in contrast to the experimental observations. On the other hand, the two remaining theoretical $\frac{5}{2}^+$ states are both predicted to have large pickup spectroscopic factors, one having $S\simeq 3$ and the other $S\simeq 1$ in all three calculations. This would suggest an identification of the experimental 5.59-MeV level with the level predicted at 5.44 MeV in the 11.0h +ASPE calculation, and similarly the 5.48-MeV experimental state with the 6.06-MeV level of that calculation. The remaining two experimental $l_n=2$ transitions, those to the 5.12- and 6.03-MeV levels, are both too strong to be associated with the $\frac{3}{2}^+$ levels predicted in this excitation range. Further, an analysis of the sum rules suggests spin-parity $\frac{5}{2}^+$ for these levels. (See Sec. VIII.) It is possible that the weak transitions observed to the levels at 4.53 and 4.78 MeV correspond to the two predicted $\frac{3}{2}^+$ levels, although those two angular distributions are not unambiguously characteristic of $l_n=2$ transfer.

Calculations of the negative-parity levels in the $A=35$ nuclei have been performed by Maripuu and Hokken.[22] Their calculation assumed an inert ^{32}S core, with the valence nucleons occupying the $1d_{3/2}$, $1f_{7/2}$, and $2p_{3/2}$ orbits. The two-body matrix elements were calculated using a modified surface δ interaction. Many negative-parity states are predicted in the excitation range 0–7 MeV. In particular, the $\frac{7}{2}^-$ state predicted at 3.44 MeV may be associated with the level observed at 3.193 MeV in the present study. The two lowest $\frac{3}{2}^-$ states are predicted to lie at 3.99 and 8.00 MeV. However, two low-lying states, at 4.012 or 4.142 MeV, are observed with $l_n=1$ in the present work. One of these experimental states should probably be identified with the 3.99-MeV model state. The second $l=1$ level observed near 4 MeV may have a dominant configuration that involves the promotion of $1d_{5/2}$ or $2s_{1/2}$ particles (rather than $1d_{3/2}$) to the fp shell. Such a state would not be contained in the calculation of Ref. 22. Many other negative-parity levels are predicted to occur in the excitation range studied, but it is not possible to associate these with any of the experimental levels. Of the strongly excited states, only the 3.193-, 4.012-, and 4.142-MeV levels are observed to have negative parity. However, the weak states remain as candidates for these theoretical negative-parity states.

VIII. SUM RULES

The summed $l_n=0$ spectroscopic factors, $\sum S$, total 3.24, in close agreement with the predicted[3] summed strength of 3.52. This agreement, however, is to be expected, in view of the manner in which the over-all normalization was obtained.

The value of the summed $l_n=2$ spectroscopic factors depends strongly on whether spins of $\frac{3}{2}$ or $\frac{5}{2}$ are assigned to the four strong $l_n=2$ transitions observed in the excitation range 5–6 MeV. The two extreme values are 17.65 and 14.02. The larger value is obtained assuming spins of $\frac{3}{2}$ for all four of these levels. The smaller value arises from assuming spins of $\frac{5}{2}$ for all four levels. The larger value exceeds the simple shell-model sum-rule limit of 16 for combined $1d_{3/2}$ and $1d_{5/2}$ pickup. Comparison with the summed spectroscopic factors predicted by the detailed shell-model calculations suggests that all four of these levels probably have $J^\pi=\frac{5}{2}^+$.

For $l_n=2$, the summed $j=\frac{3}{2}$ and $j=\frac{5}{2}$ spectroscopic factors as calculated[3] using the 11.0h +ASPE Hamiltonian are 4.99 and 8.21, respectively. The experimental values for these quantities are 6.22 and 7.80, if we assume that all four $l_n = 2$ transitions near 5.5 MeV have $J^\pi = \frac{5}{2}^+$. The $12.5\text{p} + {}^{17}\text{O}$ calculation[3] gives $\sum S_{l=2, j=3/2} = 5.23$ and $\sum S_{l=2, j=5/2} = 8.70$. Both theoretical values are in good agreement with those observed experimentally.

The summed $l_n = 1$ and $l_n = 3$ spectroscopic factors are 0.18 and 0.78, respectively, indicating that correlations involving $1f_{7/2}$ particles (and to a lesser extent $2p_{3/2}$ particles) are important in the ^{36}Ar ground state.

The sum of all the spectroscopic factors is 18.22, in rather good agreement with the value of 20 expected for 20 nucleons outside ^{16}O.

If all the available *sd*-shell strength has been observed in the present study, then the splitting of the centroids of the various orbits should be equal to the corresponding single-particle splitting. The observed splitting of the centroids is $E_{1d_{3/2}-1d_{5/2}} = 4.35$ MeV, $E_{2s_{1/2}-1d_{5/2}} = 2.30$ MeV. These are in fair agreement with the values obtained by the least-squares fit in the calculations[3] ($E_{1d_{3/2}-1d_{5/2}} = 5.18$ MeV and $E_{2s_{1/2}-1d_{5/2}} = 2.95$ MeV) for the 11.0h + ASPE calculation. It should be noted that small, unobserved fractions of the total strength at high excitations can considerably change the values of the splittings. However, the $1d_{3/2}$-$1d_{5/2}$ splitting in ^{17}O is 5.08 MeV, in reasonable agreement with the value of 4.35 MeV obtained in the present work. The $2s_{1/2}$-$1d_{5/2}$ splitting measured in the present study is considerably larger than the 0.87 MeV observed in ^{17}O, as expected from nuclear-size considerations.

IX. COMPARISON WITH ^{35}Cl LEVEL SCHEME

The level structure of the mirror nucleus ^{35}Cl has been extensively studied by several workers.[8,9] The energy levels and spin-parity assignments are shown in Fig. 8 in comparison with the results for ^{35}Ar. The correspondence is unambiguous for the first three levels. Also, the 2.637-MeV ($\frac{3}{2}^+$), 2.982-MeV ($\frac{5}{2}^+$), and 3.193-MeV ($\frac{7}{2}^-$) levels in ^{35}Ar may be associated with the levels at 2.695, 3.003, and 3.162 MeV, respectively, in ^{35}Cl. No evidence was found in the present work for the mirror of the 2.646-MeV ($\frac{7}{2}^+$) ^{35}Cl level. It is not expected that this level would be appreciably excited in the $^{36}\text{Ar}(^3\text{He}, \alpha)^{35}\text{Ar}$ reaction, since its direct population is forbidden for a simple one-step pickup reaction. However, the absence of any observable state near here leads us to suppose that the Coulomb energy shift of this level is such as to make it degenerate (within the resolution of the present experiment) with the strong 2.637-MeV level in ^{35}Ar.

A mirror correspondence between the 3.884-MeV

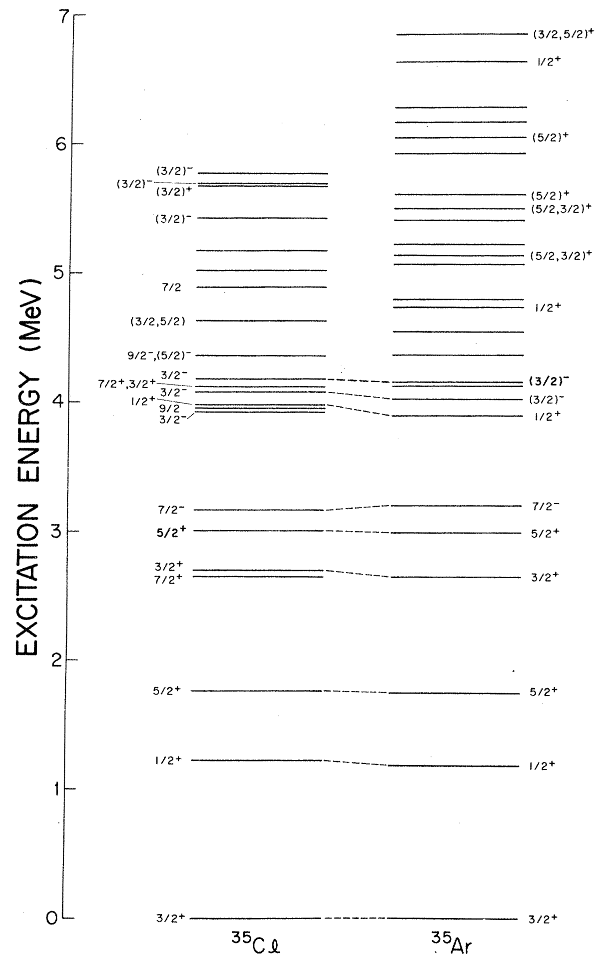

FIG. 8. Comparison between the experimental level schemes of the mirror nuclei ^{35}Cl and ^{35}Ar. Suggested mirror correspondences are indicated with dashed lines.

($\frac{1}{2}^+$) ^{35}Ar and 3.968-MeV ($\frac{1}{2}^+$) ^{35}Cl levels is suggested.

Additionally, the two $(\frac{3}{2})^-$ levels in ^{35}Ar at 4.012 and 4.142 MeV may be associated with the levels at 4.058 and 4.171 MeV in ^{35}Cl, which are populated with $l = 1$ in the $^{34}\text{S}(^3\text{He}, d)^{35}\text{Cl}$ reaction.

No additional mirror correspondence can be established for the higher-lying states. A study of proton pickup from ^{36}Ar would be most useful in this respect.

X. CONCLUSIONS

The present study of ^{35}Ar using the $^{36}\text{Ar}(^3\text{He}, \alpha)$ reaction has revealed the existence of 34 levels in ^{35}Ar up to 8.3 MeV in excitation. Of these, 17 have not been previously reported. New spin-parity assignments have been made for the following levels: 3.884 MeV, $\frac{1}{2}^+$; 4.012 MeV, $(\frac{3}{2})^-$; 4.142 MeV, $(\frac{3}{2})^-$; 4.721 MeV, $\frac{1}{2}^+$; 5.116 MeV,

$(\frac{5}{2},\frac{3}{2})^+$; 5.484 MeV, $(\frac{5}{2},\frac{3}{2})^+$ and 6.631, $\frac{1}{2}^+$.

The results of a spectroscopic analysis are in relatively good agreement with the predictions of detailed shell-model calculations,[3] with the exception being the probable existence of too many experimental $\frac{5}{2}^+$ states.

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