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Reaction ^{36}Ar$(d, p)^{37}$Ar†

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The level structure of ^{37}Ar has been investigated via the reaction ^{36}Ar$(d,p)^{37}$Ar at an incident deuteron energy of 9.162 MeV and with an over-all energy resolution of approximately 30 keV. A total of 53 states of ^{37}Ar with excitation energies up to 9.012 MeV have been observed. The orbital-angular-momentum-transfer values and the spectroscopic factors for 29 of the observed states have been extracted using finite-range distorted-wave Born-approximation calculations corrected for nonlocality of the optical potential. One $l=0$, two $l=2$, three $l=3$, and twenty-three $l=1$ transfer values have been assigned. Spin assignments have been made on the basis of the conventional shell-model ordering of states, by comparison of the states of ^{37}Ar with those of the mirror nucleus ^{37}K, and on the basis of the Lee-Schiffer effect. The spin, parity, excitation energies, and the spectroscopic factors obtained for the lowest few states in ^{37}Ar are in fair agreement with those predicted through recent shell-model calculations.

I. INTRODUCTION

The deuteron stripping reaction has proved to be an extremely useful tool for obtaining nuclear spectroscopic information, because of the unique dependence of the shape of the (d,p) angular distribution on the orbital-angular-momentum transfer.[1] The energy levels of the ^{37}Ar nucleus via the reaction ^{36}Ar$(d,p)^{37}$Ar have not been extensively investigated.[2-5] Rosner and Schneid[4] studied this reaction with an ^{36}Ar gas target enriched to >99%, using a cyclotron and solid-state detectors. The limited energy resolution (of the order of 80 keV) allowed spin assignments to be made for only seven relatively strongly excited states. Holbrow *et al.*[5] studied the same reaction using a tandem accelerator in conjunction with a magnetic spectrograph and obtained an energy resolution of approximately 20 keV. They observed a total of 76 excited states of ^{37}Ar, but since angular-distribution measurements were not carried out, spin and parity assignments were not made. The present work was carried out to bridge the gap. A 99.96% isotopically enriched ^{36}Ar target was used in conjunction with a tandem accelerator and Si(Li) solid-state detectors. The energy resolution was approximately 30 keV, permitting the identification of most of the states observed by Holbrow *et al.*[5] At the same time, it has been possible to determine unambigously the angular momentum transfer to the target nucleus for a large number of excited states of ^{37}Ar.

In recent years, several authors[6-9] have reported a series of shell-model calculations for the level structure of nuclei in the mass range $A = 17-39$. In addition, a detailed investigation of the level structure of the mirror nucleus ^{37}K has been performed by Goosman and Kavanagh[10] via various reactions. Thwaites[11] has studied the states of ^{37}K with excitation energies between 4.0 and 7.0 MeV by proton elastic scattering from ^{36}Ar. In view of the theoretical calculations and extensive measurements involving the mirror nucleus ^{37}K, a more thorough look at the energy levels of ^{37}Ar via the (d, p) reaction on ^{36}Ar seemed in order.

II. EXPERIMENTAL PROCEDURE AND Q-VALUE DETERMINATION

The sample of ^{36}Ar isotopically enriched to 99.96% was enclosed in a 3-in.-diam gas cell mounted at the center of a 20-in.-diam gas scattering chamber. The gas pressure was approximately 0.034 atm, corresponding to a target thickness of approximately $(400/\sin\theta_{1ab})$ μg/cm^2. The cell walls were of clear Mylar, 120 μ in. thick, affixed by epoxy to a cylindrical brass frame. The beam entrance and exit windows were $\frac{5}{16} \times \frac{7}{16}$-in. nickel foils, 10 and 25 μin. thick, respectively. Two movable Li-drifted Si detectors, 2 mm thick and with an active area of approximately 100 mm^2, placed 20° apart from each other were used. The detectors were cooled to approximately −40°C. The $^{36}Ar(d, p)^{37}Ar$ cross sections were measured at 21 lab angles between 20 and 160° at an incident center-of-target deuteron energy of 9.162 MeV. The over-all experimental proton resolution was approximately 30 keV. Proton groups leading to 53 states of ^{37}Ar were identified. A typical pulse-height spectrum taken at the laboratory angle of 50° is shown in Fig. 1. The excitation energies of the more prominent states are indicated in the figure. The spectrum also indicates the presence of a small amount of contamination, attributed to carbon, nitrogen, and oxygen. The over-all experimental uncertainty in the measured cross sections is of the order of ±5% (standard deviation).

The $^{36}Ar(d, p)^{37}Ar$ ground-state Q value was taken to be 6.566 MeV.[12] Using the peak locations of (1) the ^{37}Ar ground state, (2) the deuteron elastic state, and (3) the first deuteron inelastic state, of excitation energy 1.975 MeV,[13] the Q values of all the observed proton groups were obtained using a least-squares fitting code. Corrections were applied for the energy loss of the reaction particles in passing through the exit gas and Mylar walls, using the tables of Williamson and Boujot.[14] Since this energy loss is nonlinear and additional nonlinearity may be introduced by the electronics, a quadratic fit was employed. The procedure was repeated at each observed angle. The Q-value determinations for a given group were checked for consistancy and averaged. The absolute uncertainty in the Q-value determinations is believed to be ±20 keV.

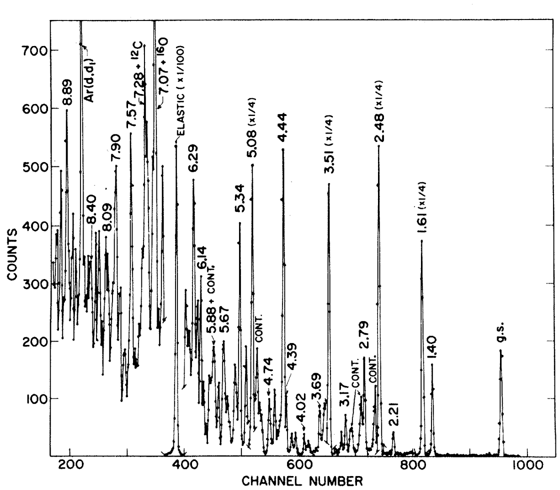

FIG. 1. $^{36}Ar(d,p)^{37}Ar$ pulse-height spectrum, at a center-of-target deuteron energy of 9.162 MeV and lab angle of 50.0°.

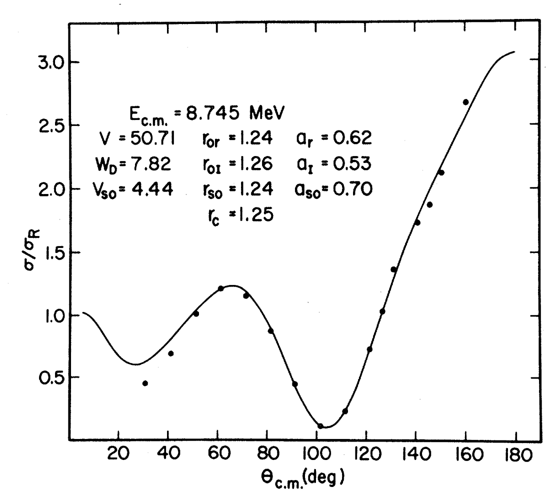

FIG. 2. Optical-model fit to the $^{36}Ar(p,p)$ elastic scattering data. The cross section is shown as a ratio to the corresponding Rutherford cross section.

III. OPTICAL ANALYSIS

The optical-model potential parameters needed to calculate the incoming deuteron and outgoing proton distorted waves for the distorted-wave Born-approximation (DWBA) calculations were obtained by fitting $^{36}Ar(d,d)^{36}Ar$ and $^{36}Ar(p,p)^{36}Ar$ [13] elastic angular distributions at center-of-target deuteron and proton energies of 9.162 and 8.980 MeV, respectively. The proton optical-model parameters were determined using the code written by Perey,[15] and the deuteron parameters were obtained using a code written by Smith.[16] In both cases the following form for the potential, with a surface-peaked imaginary term and a real Thomas-type spin-orbit term, was used:

$$V(r) = -Vf(r, r_{0r}, a_r) + i4a_i W_D \frac{d}{dr} f(r, r_{0i}, a_i) \quad \text{(central)}$$

$$+ \left(\frac{\hbar}{mc}\right)^2 V_{so} \frac{1}{r}\frac{d}{dr} f(r, r_{0r}, a_r) \quad \text{(spin-orbit)}$$

$$+ V_C(r) \quad \text{(Coulomb)},$$

where

$$V_C(r) = (Ze^2/2r_C)(3 - r^2/r_C^2), \quad r \le r_C$$
$$= Ze^2/r, \quad r > r_C$$

and

$$f(r, r_0, a) = [1 + e^{(r-r_0)A^{1/3}/a}]^{-1}$$

is the usual Woods-Saxon shape.

The optical-model fits to the proton and deuteron elastic scattering and the corresponding parameters are shown in Figs. 2 and 3, respectively. The search for proton parameters was made by starting with Perey's average parameters.[17] Searches for deuteron parameters were made by starting with parameters given by several workers,[4,18,19] for elastic scattering of deuterons in the mass neighborhood of ^{36}Ar. A number of sets of deuteron parameters which gave equally good fits to the elastic scattering data were obtained. A set of parameters that gave reasonably good DWBA fits to the angular-distribution data in ^{37}Ar over wide ranges of excitation energy and for different values of the angular momentum transfer was chosen as the optimum set. The various proton groups detected have energies different in general from that at which the proton elastic fit was made. As is well known, the real and imaginary well depths are energy dependent. A choice of $V = (54.31 - 0.4E)$ MeV and $W = (6.02 + 0.2E)$ MeV was found to improve slightly the ground-state (d,p) fit, and so was used.

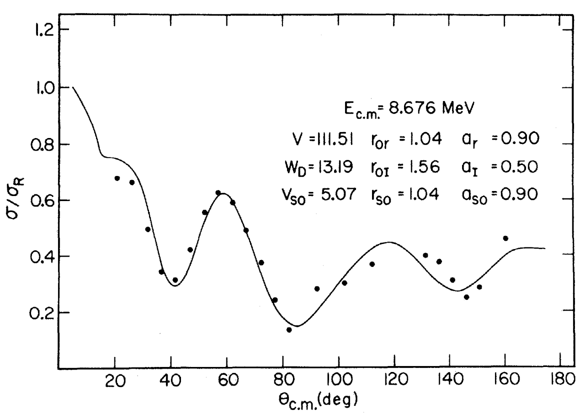

FIG. 3. Optical-model fit to the $^{36}Ar(d,d)$ elastic scattering data. The cross section is shown as a ratio to the corresponding Rutherford cross section.

IV. DWBA ANALYSIS AND RESULTS

The (d,p) angular-distribution data were fitted using a zero-range DWBA code VENUS written by Tamura[20] and modified to include an approximation for the nonlocality of the optical potential and a finite-range correction.[21] The nonlocality lengths $\beta(p)$ and $\beta(d)$ for the proton and deuteron channels were chosen to be[22]

$$\beta(p) = 0.85 \text{ F}, \quad \beta(d) = 0.54 \text{ F}.$$

Inclusion of nonlocality increased the spectroscopic factor for the ground state and for the first f and p transitions by approximately 12%. The $s_{1/2}$-state spectroscopic factor was essentially unchanged and that of the rest of the states was increased between 5 and 8%. The finite-range correction was done in the local-energy approximation.[23,24] This correction was found to have a negligible effect on the spectroscopic factors for all the states as expected, since the inclusion of nonlocality corrections suppresses the contributions from the nuclear interior where finite range is most effective.[25]

The bound-state neutron wave functions or the form factors were calculated using a Woods-Saxon well having the same geometry as the real part of the proton optical potential, the code used being NEPTUN, also written by Tamura.[20] The spin-orbit depth was chosen to be 6.2 MeV on the basis of proton elastic polarization measurements in the mass-40 neighborhood by Rosen, Beery, and Goldhaber.[26] A search was made on the Woods-Saxon well depth to reproduce the experimentally determined separation energy of each level.

Use of a standard geometry for the neutron well, namely, $r_0 = 1.25$ F and $a = 0.65$ F, resulted in an over-all reduction in the predicted cross sections of approximately 7% for $2p_{1/2}$ and $2p_{3/2}$ transitions, 10% for both $1f_{7/2}$ and $1d_{5/2}$ transitions, and 12%

for $1d_{3/2}$ transitions. Predicted $2s_{1/2}$ cross sections were not changed significantly by use of a standard geometry.

The experimental angular distributions together with DWBA predictions are displayed in Fig. 4. The errors shown are statistical, and where error bars are not used, the size of the data point indicates approximate statistical errors. For states with excitation energies between 6.921 and 9.012 MeV, shown in Figs. 4(f)–4(h), experimental data from 20 to 90° only could be extracted. All DWBA calculations were performed with no radial cutoff. The agreement between the data and the DWBA predictions is reasonably good in most cases.

Since we have a 0^+ target (even-even nucleus), the experimental absolute cross section and the single-particle cross section calculated by DWBA theory are related through

$$\sigma_{\text{expt}} = (2J+1)\sigma_{\text{DWBA}} S_J ,$$

where J denotes the spin of the final state observed in the $^{36}Ar(d,p)^{37}Ar$ stripping process. In the present work we have used the definition

$$\sigma_{\text{Theory}} = (2J+1)\sigma_{\text{DWBA}} .$$

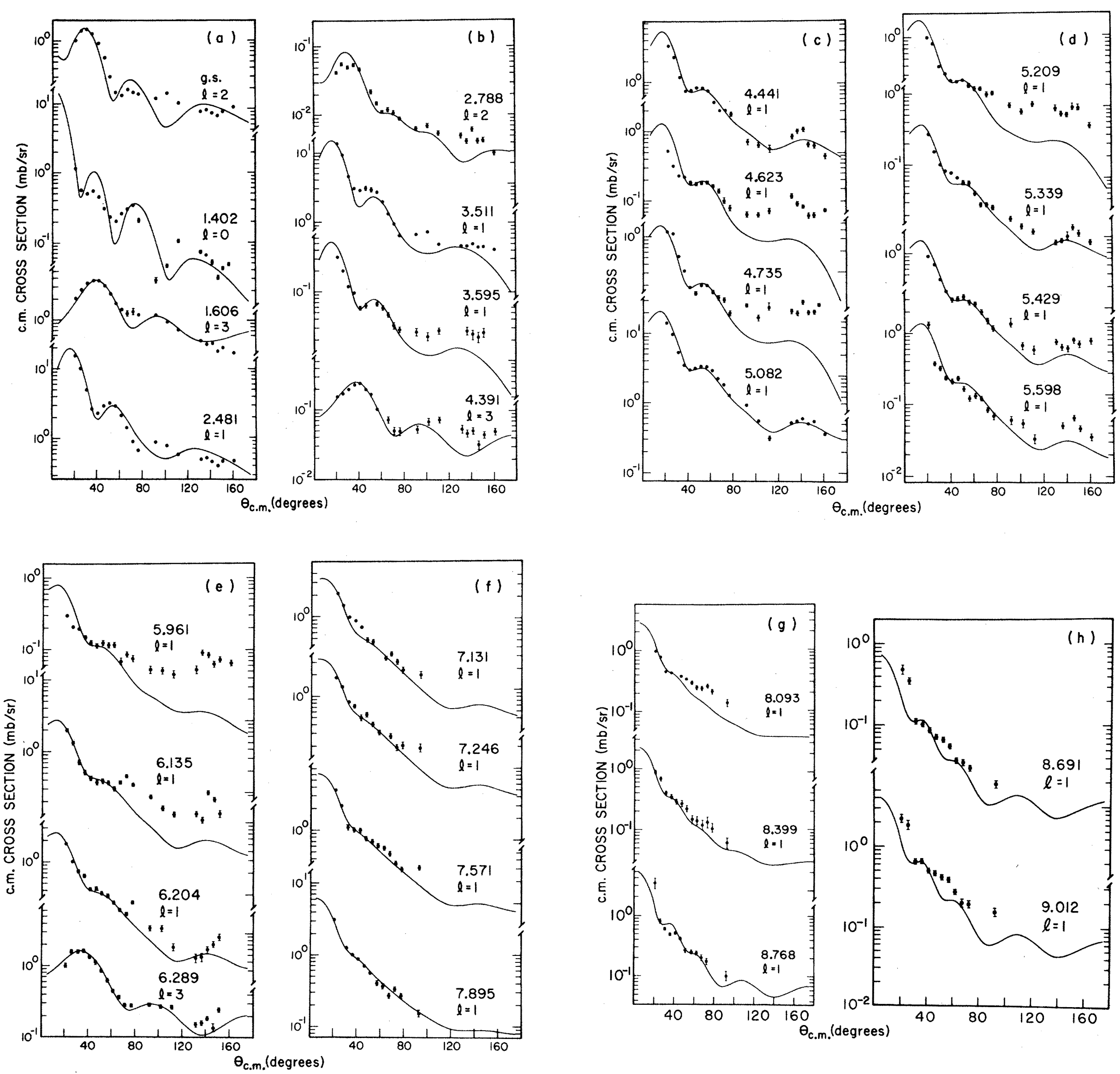

FIG. 4. DWBA fits to the $^{36}Ar(d,p)^{37}Ar$ angular-distribution data. The l values and the excitation energies are indicated. Where error bars are not used, the size of the data point indicates the approximate statistical error in the cross sections.

The spectroscopic factor S_J is then defined by the ratio

$$S_J = \sigma_{\text{expt}}/\sigma_{\text{Theory}}.$$

The magnitude of the spectroscopic factor was obtained by normalizing the calculated cross sections at forward angles to the experimental data.

The results of our investigation are listed in Tables I and II. Table I compares the excitation energies of the states of ^{37}Ar deduced from the present work with those observed by Rosner *et al.*,[4] by Holbrow *et al.*,[5] and by McNally.[27] There is reasonable agreement between the results of the present work and those of Refs. 5 and 27. In some cases, however, there is observable disagreement between the present work and that of Holbrow *et al.* A partial explanation for this disagreement is the following: We have assumed the ^{36}Ar$(d,p)^{37}$Ar ground-state Q value to be 6.566 MeV in agreement with the value determined experimentally by Yamamoto and Steigert[3] and also with the value predicted by Everling *et al.*'s[28] mass tables. Holbrow *et al.*, on the other hand, obtained a ground-state Q value of 6.62 ± 0.03 MeV. It is to be noted that in the present work, the states with excitation energies between 6.289 and 6.921 MeV are masked by the deuteron elastic scattering peak in the spectrum.

Table II lists the values of the orbital angular momentum transfer, the value of the assigned

TABLE I. Excitation energies E_x of the states of ^{37}Ar.

Level No.	E_x (MeV) Present work ±0.020	McNally (Ref. 27) ±0.025	Holbrow *et al.* (Ref. 5) ±0.010	Rosner and Schneid (Ref. 4) ±0.06	Level No.	E_x (MeV) Present work ±0.020	Holbrow *et al.* (Ref. 5) ±0.015
1	1.402	1.408	1.417	1.40	40		6.416
2	1.606	1.617	1.618	1.60	41		6.452
3	2.211	2.217			42		6.472
4	2.481	2.498	2.501	2.50	43		6.540
5	2.788	2.797	2.807	2.80	44		6.588
6	3.168	3.173			45		6.604
7	3.262	3.273			46		6.680
8	3.511	3.525	3.528	3.55	47		6.752
9	3.595	3.614			48		6.824
10	3.693	3.711	3.717	3.74	49		6.852
11	3.934	3.937	3.994		50		6.875
12	4.016	4.020	4.047	4.04	51	6.921	6.952
13	4.192	4.215	4.213	4.18	52	7.003	7.026
14	4.282	4.282	4.284		53	7.068	7.085
15		4.320			54		7.107
16	4.391	4.402	4.421		55	7.131	7.162
17	4.441	4.451	4.466	4.49	56	7.246	7.255
18	4.563	4.582			57		7.263
19	4.623	4.634	4.657	4.68	58	7.282	7.286
20	4.735	4.750	4.764	4.81	59	7.351	7.316
21	4.874	4.894	4.909	4.90	60		7.440
22	4.986	4.991	5.010		61		7.478
23		5.055	5.070		62	7.571	7.571
24	5.082	5.110	5.110	5.18	63		7.612
25		5.140	5.158		64	7.789	7.813
26	5.209	5.221	5.241	5.30	65	7.895	7.906
27	5.264				66	7.950	7.991
28	5.339	5.354	5.376	5.43	67		8.045
29	5.429	5.417	5.439		68	8.093	8.126
30	5.541	5.460	5.467		69		8.247
31	5.598	5.568	5.565		70	8.295	8.319
32	5.672	5.664	5.701		71	8.399	8.433
33	5.770	5.762	5.802		72		8.598
34	5.880	5.840	5.870		73		8.721
35	5.961		5.979		74	8.768	8.781
36	6.079		6.100		75		8.865
37	6.135		6.164		76	8.891	8.903
38	6.204		6.233		77	9.012	9.031
39	6.289		6.314				

spins, the maximum absolute cross sections, and the deduced spectroscopic factors. A comparison of the present work with that of Rosner and Schneid[4] is also shown.

The ground state, the 1.61-MeV state, and the 2.48-MeV state are, respectively, populated through $l=2$, $l=3$, and $l=1$ transitions, as shown in Fig. 4. The J^π assignments of $\frac{3}{2}^+$ for the ground state and $\frac{3}{2}^-$ for the 2.48-MeV state are based on arguments similar to those given in Ref. 4. A γ-decay half-life measurement[29] favors the assignment of $J^\pi=\frac{7}{2}^-$ for the 1.61-MeV state, in agreement with Ref. 4. The state with an excitation energy of 1.40 MeV corresponds to an $l=0$ transition and is consequently an $s_{1/2}$ state. The same J^π assignments for these four states have been re-

TABLE II. Summary of the results of DWBA analysis of the states of ^{37}Ar via the reaction $^{36}Ar(d,p)^{37}Ar$. E_x is the excitation energy of the analyzed levels (numbered according to Table I) in ^{37}Ar, l is the orbital angular momentum transfer, J and π are the spin and parity of the observed levels, $(d\sigma/d\Omega)_{max}$ is the maximum experimental c.m. differential cross section, and S_J is the spectroscopic factor as defined in the text.

Level No.	Present work E_x (MeV)	l	J^π	$(d\sigma/d\Omega)_{max}$ (mb/sr)	S_J	Rosner and Schneid (Ref. 4) E_x (MeV)	l	J^π	$(d\sigma/d\Omega)_{max}$ (mb/sr)	S_J
0	g.s.	2	$\frac{3}{2}^+$	1.58	0.49	g.s.	2	$\frac{3}{2}^+$	2.10	0.43
1	1.402	0	$\frac{1}{2}^+$	1.12 [a]	0.22	1.40	0	$\frac{1}{2}^+$	0.82	0.14
2	1.606	3	$\frac{7}{2}^-$	3.71	0.51	1.60	3	$\frac{7}{2}^-$	6.75	0.82
4	2.481	1	$\frac{3}{2}^-$	15.2 [a]	0.35	2.50	1	$\frac{3}{2}^-$	14.3 [a]	0.45
5	2.788	2	$\frac{5}{2}^+$	0.52	0.06	2.80	(1, 2)			
8	3.511	1	$\frac{3}{2}^-$	13.8 [a]	0.23	3.55	1	$\frac{3}{2}^-$	12.3 [a]	0.36
9	3.595	1	$\frac{3}{2}^-$	0.31 [a]	0.01					
16	4.391	3	$\frac{7}{2}^-$	0.24	0.03					
17	4.441	1	$\frac{1}{2}^-$	3.23 [a]	0.14	4.49	1	$\frac{1}{2}^-$	2.74 [a]	0.16
19	4.623	1	$\frac{3}{2}^-$	5.13 [a]	0.02	4.68				
20	4.735	1	$\frac{3}{2}^-$	1.17 [a]	0.02	4.81				
24	5.082	1	$\frac{1}{2}^-$	14.0 [a]	0.49	5.18	1	$\frac{1}{2}^-$	1.07 [a]	0.59
26	5.209	1	$\frac{3}{2}^-$	0.99 [a]	0.02					
28	5.339	1	$(\frac{1}{2}^-)$	2.71 [a]	0.08	5.43				
29	5.429	1	$\frac{1}{2}^-$	0.90 [a]	0.03					
31	5.598	1	$\frac{1}{2}^-$	1.32 [a]	0.02					
35	5.961	1	$(\frac{3}{2}^-)$	0.31 [a]	0.01					
37	6.135	1	$(\frac{1}{2}^-)$	1.98 [a]	0.05					
38	6.204	1	$\frac{1}{2}^-$	1.75 [a]	0.05					
39	6.289	3	$\frac{7}{2}^-$	1.59	0.11					
55	7.131	1	$\frac{1}{2}^-$	2.14 [a]	0.05					
56	7.246	1	$\frac{1}{2}^-$	1.82 [a]	0.05					
62	7.571	1	$\frac{1}{2}^-$	3.62 [a]	0.08					
65	7.895	1	$\frac{1}{2}^-$	3.14 [a]	0.07					
68	8.093	1	$\frac{1}{2}^-$	0.96 [a]	0.03					
71	8.399	1	$\frac{1}{2}^-$	0.84 [a]	0.02					
74	8.768	1	$\frac{1}{2}^-$	3.25 [a]	0.04					
76	8.891	(1)	$(\frac{1}{2}^-)$	4.83 [a]	(0.07)					
77	9.012	(1)	$(\frac{1}{2}^-)$	2.23 [a]	(0.05)					

[a] Taken at 20°.

ported by Naude, Bottega, and McMurray[30] from analysis of the fluctuations in the ^{39}K(d, α)^{37}Ar excitation functions.

The spectroscopic factor for the ground state and for the state with excitation energy 2.48 MeV are in fair agreement with those of Ref. 4. For the $s_{1/2}$ state at 1.40-MeV excitation, we have normalized the theoretical cross sections to the 20° experimental data. As the theoretical fit to this state is only fair, data at further forward angles are essential for a meaningful comparison with the spectroscopic factor obtained in Ref. 4. The S_J value for the $l=3$, 1.61-MeV state was found to be 0.51 in the present work compared with 0.82 in Ref. 4. As was mentioned in Sec. III, a number of sets of deuteron parameters were found which gave equally good fits (nearly the same values of χ^2) to the deuteron elastic angular-distribution data. Spectroscopic factors and fits to the angular-distribution data for $l=2$ and $l=3$ transitions were, however, found to be very sensitive to the choice of the deuteron optical-potential parameters in the DWBA calculation. For the $l=0$ and $l=1$ states, this dependence of the fits to the choice of the optical potential was detectible, though not pronounced. Such behavior is to be expected because of larger angular momentum mismatch for higher-l-value transfers. The set of potentials chosen in the present work leads to reasonably good fits for all the states over the entire spectrum corresponding to all the observed l-value transfers. Hence the spectroscopic factors listed in Table II are believed to be consistent.

The state at 2.79-MeV excitation corresponds to an $l=2$ transition. Assuming, as seems quite certain from the excitation energies and the similarities of the γ decay, that the 2.79-MeV excited state of ^{37}Ar and 2.74-MeV excited state of ^{37}K are mirror states and then making a consistency argument in the theoretical fit to the angular distribution of the 2.74-MeV γ ray in ^{37}K, Kavanagh and Goosman[31] concluded that the J^π assignment for these mirror states should be $\frac{5}{2}^+$. We have, therefore, assigned the spin $\frac{5}{2}$ to the 2.79-MeV state in ^{37}Ar. The same spin assignment has been made to this state by Naude, Bottega, and McMurray.[30] The small value of $S_J=0.06$ is expected, because the $d_{5/2}$ shell in ^{37}Ar is expected to be full in a conventional shell-model description.

Goosman and Kavanagh,[10] from an extensive study of various reactions have made spin assignments to states of the mirror nucleus ^{37}K. In addition to the 2.74-MeV state in ^{37}K, the ground state and the first three excited states have the same J^π assignments as those of ^{37}Ar in the present work. Glaudemans, Brussaard, and Wildenthal[7] have reported detailed shell-model calculations for nuclei ranging from ^{29}Si to ^{40}Ca. In these calculations it was assumed that the two outer shells $2s_{1/2}$ and $1d_{3/2}$ are in the central field of the inert core of ^{28}Si (a closed $1d_{5/2}$ shell). The interaction matrix elements were expressed in terms of 17 parameters evaluated by the method of a least-squares fit, and the energies and wave functions of the states in the $2s_{1/2}$, $1d_{3/2}$ shell were calculated. Using the nuclear wave functions obtained, the spectroscopic factors for (d, p) reactions on ^{36}Ar were calculated wherever possible. The ground state $J^\pi=\frac{3}{2}^+$ and $S_J=0.46$ are in close agreement with our results. For the first excited state $J^\pi=\frac{1}{2}^+$, $S_J=0.069$ was predicted much smaller than the value of S_J of 0.22 obtained in the present work.

Extensive shell-model calculations in the mass range $A=17-39$ have been reported by the Oak Ridge group.[9] For the mass range $A=34-39$ calculations have been performed using the full space of all possible $2s$-$1d$ wave functions. The effective interaction chosen was derived from a realistic potential that fits the nucleon-nucleon scattering data. This calculation predicts J^π for the ground state and J^π and the excitation energy of the first excited state in close agreement with experimental results. Two states with $J^\pi=\frac{5}{2}^+$ are predicted at excitation energies of 2.1 and 3.1 MeV. A $\frac{5}{2}^+$ state is experimentally observed at 2.79 MeV. A $\frac{7}{2}^+$ state is predicted at an excitation of 1.9 MeV, but has not been observed experimentally.

The states with excitation energies 1.61, 4.39, and 6.29 MeV, which are populated by $l=3$ transfer, have all been assigned spin value $\frac{7}{2}$; most of the $f_{7/2}$ single-particle strength is in the strong 1.61-MeV state. Since the spin-orbit splitting between the $f_{7/2}$ and $f_{5/2}$ states is about 6.5 MeV,[32] it is reasonable to assume a spin of $\frac{7}{2}$ for the 4.39-MeV state. Since $f_{7/2}$ single-particle strength is not yet exhausted and because of the remarkable similarity between the angular-distribution data for the three $l=3$ states, the 6.29-MeV state is also assigned a spin of $\frac{7}{2}$. However, since the j dependence is not strong for $l=3$ transitions, this spin assignment must be regarded as only tentative.

The spin assignments for the states with excitation energies 3.51, 3.60, 4.44, 4.62, 4.74, 5.08, 5.21, 5.34, 5.43, 5.60, 5.96, 6.14, and 6.20 MeV, all of which are populated by $l=1$ transitions, have been made on the basis of the observed Lee-Schiffer effect.[33] A comparison of the experimental data for the relatively strong $l=1$ states at 2.48 and 5.08 MeV [Figs. 4(a) and 4(c)] shows that, while the 5.08-MeV state has a distinct dip around 110°, the 2.48-MeV state indicates no such effect. In the case of the reaction ^{38}Ar(d, p)^{39}Ar at a deuteron energy of 11.6 MeV, the dip in the angular-distribution data for $p_{1/2}$ states occurs around 100°, whereas the data are smooth for $p_{3/2}$ states.[19] In the present work the incident deuteron energy is 9.162 MeV, and most of the states populated by $l=1$ transitions have $S_J<0.1$. Hence the effect is not expected to be pronounced.[33] The states with the excitation energies 4.44, 5.43, 5.60, and 6.20 MeV, whose angular-distribution data show trends similar to that of the 5.08-MeV state, have been assigned spin $\frac{1}{2}$. The 5.34- and 6.14-MeV states also tend to show a similar j dependence, although only weakly. Hence, the spin assignment of $\frac{1}{2}^-$ for these states should be regarded as tentative. The states with excitation energies 2.48, 3.51, 3.60, 4.62, 4.74, 5.21, and 5.96 MeV have been assigned spin $\frac{3}{2}$. The assignment for 5.96-MeV state is rather doubtful, and so is given in parentheses.

Angular-distribution data from 20 to 90° only could be obtained for states high enough in excitation to lie beyond the deuteron elastic peak. The states with excitation energies 7.13, 7.25, 7.57, 7.90, 8.09, and 8.77 MeV show essentially no structure in the angular-distribution data. The closest fit could be obtained by assuming an $l=1$ transition in each of these cases. Since these states lie at high excitation energy, we have assigned spin $\frac{1}{2}$ to each of these states in conformity with the conventional shell-model picture.

Two states with excitation energies 8.89 and 9.01 MeV observed in the present work are neutron unbound. As the states are rather strongly excited, these are probably sharp unbound states of ^{37}Ar, i.e., a scattering resonance of the system ^{36}Ar + neutron. If these states are sharp, the (d,p) reaction is effectively independent of the subsequent neutron emission, and the usual stripping analysis may be employed. We have assumed a small (10 keV) binding energy (= separation energy) for these states in the form-factor calculation. In both cases, equally good fits could be obtained by assuming either an $l=1$ or an $l=2$ transfer. On the basis of the conventional shell-model picture, we have tentatively assigned an $l=1$ transfer. Although the calculation has been done assuming a final-state spin of $\frac{1}{2}$, no attempt has been made towards definitive spin assignments for these two states, and the spectroscopic factors are not considered to be reliable.

The spectroscopic factor for the state with 5.08-MeV excitation is 0.49 in the present work, in reasonable agreement with the value 0.59 for a state with 5.18-MeV excitation energy in Ref. 4. It appears that at least two close states in this energy neighborhood are not resolved in the work of Ref. 4.

V. DISCUSSIONS AND CONCLUSION

Of the 53 states of ^{37}Ar with excitation energy up to 9.012 MeV observed via the (d,p) reaction, orbital-angular-momentum-transfer values were obtained for 29 states through DWBA calculations. One $l=0$, two $l=2$, three $l=3$, and twenty-three $l=1$ transfer values are assigned. The rest of the states had very small cross sections and reliable cross-section data could not be extracted. The spin assignment to the $l=0$ state is obvious; the spin assignments to $l=2$ and $l=3$ states were made using a combination of the following arguments:
(1) Conventional shell-model ordering of states;
(2) spin assignments for the states of the mirror nucleus ^{37}K, through studies of various reactions;
(3) information obtained from other reactions leading to states of ^{37}Ar.

The spin values for states with $l=1$ transitions were made on the basis of (1) the Lee-Schiffer effect and (2) conventional shell-model ordering of states. The Lee-Schiffer effect is not pronounced, however, as most of the states are rather weakly excited, with spectroscopic factors of less than 0.1. In addition, the incident deuteron energy is relatively small (9.162 MeV). At backward angles, where the cross sections are small, there is the possibility of predominance of compound-nuclear contributions, as indicated by poor fits at backward angles in a number of cases shown in Figs. 4(a)–4(e).

The spectroscopic factor $S_J=0.49$ for the $d_{3/2}$ ground state is quite reasonable and is in accord with the conventional shell-model, two-neutron-hole configuration of ^{36}Ar. The low value of $S_J=0.06$ for the $d_{5/2}$ state as well as $S_J=0.22$ for the $s_{1/2}$ state is also reasonable, and indicates that the $2s_{1/2}$ and $1d_{3/2}$ subshells are not completely full. There is, therefore, configuration mixing of the $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$ configurations in the shell-model wave function, which one has to remember when performing a realistic calculation. The S_J values of the $f_{7/2}$ and $p_{3/2}$ states, respectively, add up to 0.65 and 0.66 and are less than the value of $\sum_i S_i^{(J)}=1$ required by the sum rule. It is, however, to be expected that part of the $f_{7/2}$ and $p_{3/2}$ strengths are distributed in many of the very weak states that have been observed but could not be analyzed in the present work. Since the S_J values for the unbound states with excitations 8.89 and 9.01 MeV are unreliable, they are neglected in $\sum_i S_i^{(J)}$ for $J=\frac{1}{2}$. The sum of the spectroscopic factors is found to be 1.20, exceeding the stripping sum rule $\sum_i S_i^{(J)}=1$. The discrepancy is, however, within standard uncertainties in S_J values obtained from DWBA analysis.[34] The centroids of the single-particle states can be obtained from

$$\bar{E}(J)=\sum_i E_i S_i^{(J)} / \sum_i S_i^{(J)} .$$

We obtain $\bar{E}(f_{7/2})=2.527$ MeV, $\bar{E}(p_{3/2})=3.125$ MeV, and $\bar{E}(p_{1/2})=5.891$ MeV.

The spin, parity, excitation energies, and the spectroscopic factors predicted for the lowest few states through shell-model calculations are in fair agreement with our results. A comparison of the level structures of ^{37}Ar (present work) and those of ^{37}K obtained from the works of Refs. 10 and 11 indicate that for the first few low-lying states there is correspondence between the levels of the two mirror pairs. No correspondence between higher excited states could be established.

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