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Vector analyzing power and cross section for the reaction $^{36}Ar(\vec{d}, p)^{37}Ar$

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Cross section and vector analyzing power for the reaction $^{36}Ar(\vec{d}, p)^{37}Ar$ have been measured for an incident deuteron energy of 10.02 MeV. The data have been analyzed in the framework of the distorted-wave Born approximation. The J dependence of the vector analyzing power permits unambiguous spin-parity assignments to be made for 19 states in ^{37}Ar with excitation energies up to 8.40 MeV. Tentative spin assignments are made to the states with excitation energies 8.093 and 8.399 MeV. Most probable spin-parity values for the constituents of the unresolved (5.880 + 5.961) MeV and (7.246 + 7.282) MeV groups in the spectra are suggested from an analysis of the data. Spectroscopic factors are extracted using deuteron optical model potential parameters obtained from a simultaneous analysis of the elastic cross section and vector analyzing power data. Results of the analysis for the 2.217 and 7.131 MeV states indicate the possible importance of reaction processes other than the one-step stripping mechanism.

[NUCLEAR REACTIONS $^{36}Ar(\vec{d},d)$, $(\vec{d},p)$, $E = 10.02$ MeV; measured $\sigma(\theta)$, $iT_{11}(\theta)$; deduced J, π, S by DWBA analysis. Enriched target.]

I. INTRODUCTION

In recent years, the level structure of the nucleus ^{37}Ar has received considerable attention from both experimental[1-9] and theoretical[10,11] points of view. One of the simplest ways of reaching the states with $T=\frac{1}{2}$ in ^{37}Ar is through the deuteron stripping reaction on ^{36}Ar, and this reaction has been utilized in experimental investigations by various groups. In particular the authors of Ref. 3 have reported the results of a distorted-wave Born-approximation (DWBA) analysis of the cross-section angular distribution data for proton groups corresponding to 29 states in ^{37}Ar with excitation energies up to 9.01 MeV. An incident deuteron energy of 9.16 MeV was used. Mermaz *et al.*[4] have reported the results of a similar investigation for 22 states with excitation energies up to 7.9 MeV at an incident deuteron energy of 18.0 MeV. As is well known, such data and analyses provide unambiguous orbital angular momentum assignments to the states in most cases. The low-lying states of ^{37}Ar have also been investigated through lifetime measurements[5,9] and γ-ray angular distribution and linear polarization measurements[8] via the reactions $^{34}S(\alpha, n)$ and $^{37}Cl(p, n)$. In addition, the level structure of the mirror nucleus ^{37}K has been investigated extensively through various reactions.[12,13] As a result of the large number of distinct investigations, a cross-check of consistency in the conclusions is possible, which permits definitive spin assignments to most of the states in ^{37}Ar with excitation energy ≤ 3.5 MeV. The latest tabulation by Endt and Van Der Leun[14] summarizes these results.

On the other hand, for states with higher excitation energies few measurements involving the (d,p) stripping reaction alone have been reported. The spin assignments have been made on the basis of (1) the conventional shell model ordering of states, and (2) the observation of the Lee-Schiffer effect[15] in the (d,p) cross sections. Although such arguments are plausible, the spin assignments made on these bases are not always convincing and reliable, particularly for states with relatively low spectroscopic factors (<0.1). Besides, disagreements exist between the results of Refs. 3 and 4 even in the orbital angular momentum values for some of the excited states of ^{37}Ar. Additional measurements are, therefore, in order.

It has been shown that for even-even target nuclei, particularly in the s-d and f-p shells, the J dependence of the vector analyzing power (VAP) for the (d,p) reactions can be used conveniently for definitive spin assignments.[16-21] The observed data can be reproduced fairly well by the DWBA calculations. The present work concerns the measurement of cross section and VAP for the reaction $^{36}Ar(d,p)^{37}Ar$ initiated by a vector polarized deuteron beam, together with an analysis of the data in the framework of the DWBA. It is expected that the VAP data will provide additional constraints in the determination of both the l and J values corresponding to a given transition and will thus resolve the points of disagreement in the results of Refs. 3 and 4.

II. EXPERIMENTAL PROCEDURE

A. Data acquisition

In the present measurements, a vector-polarized deuteron beam from the polarized ion source accelerated to 10.02 MeV was used to bombard a gas target of ^{36}Ar isotopically enriched to 99%. The ^{36}Ar was enclosed in a 2.5 cm diam gas cell with 4 μm thick stainless steel foil walls. A gas pressure of approximately 1 atm was used. The majority of the observed states in ^{37}Ar correspond to $l=1$ transitions.[3,4] The beam energy was chosen as ~10 MeV since at such incident energy the angular momentum match[22] for $l=1$ transitions in ^{37}Ar is rather good over the range of excitation energies of interest. Outgoing particles were detected by an array of 2 mm thick Si(Li) detectors. The pulses were analyzed, stored, and displayed as single parameter spectra by means of an on-line PDP-9 computer. A representative pulse-height spectrum taken at the lab angle of 45° is shown in Fig. 1. The excitation energies of the prominent states up to 5.6 MeV shown in Fig. 1 have been taken from the latest data compilation.[14] For the states with higher excitation energies, the energy values have been taken from Ref. 3. The best experimental proton resolution was approximately 70 keV but in general varied between 70 and 90 keV. Groups with excitation energies of 5.88 and 5.96 MeV, which are shown as a single group in Fig. 1, could be partially resolved in the spectra corresponding to most of the other angles of observation. Groups of 7.25 and 7.28 MeV excitation could not be resolved and appear as a single peak in the spectrum.

The VAP data were taken at 14 lab angles between 15 and 80° with the beam polarized alternately in directions parallel and antiparallel to the normal to the scattering plane. The reversal of the direction of polarization was achieved by switching the direction of precession of the spin-symmetry axis in the Wien filter located at the ion source. Further experimental details have been discussed in a previous publication.[23] The beam polarization was measured at regular intervals, separately for the two spin directions using the known value of analyzing power for the reaction ^{4}He($\vec{d}$, d)^{4}He at $\theta_{lab}=82.5°$, $E_d=10.0$ MeV.[24] The magnitude of the beam polarization, it_{11}, was typically 0.37± 0.01 ($p_y=0.43$) and was found to be reasonably constant (within error limits) in the two modes of polariza-

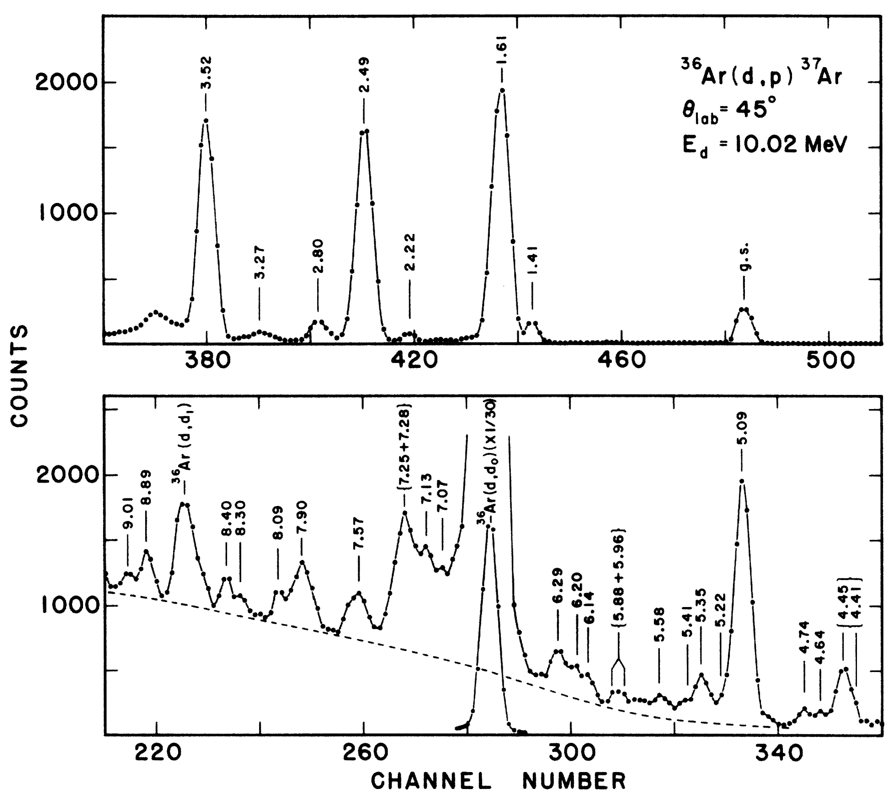

FIG. 1. ^{36}Ar($\vec{d}$,p)^{37}Ar pulse height spectrum at a lab deuteron energy of 10.02 MeV and a lab angle of 45.0°. Excitation energies are given in MeV. The counts shown correspond to a charge collection of 5 μC. In extracting the yields, spectra corresponding to charge collections of 15 μC or more were used.

tion. A small tensor polarization ($|p_{yy}| \leq 0.02$) is present in the vector-polarized beam but the effect of this is small compared with the uncertainties in the measurements and was considered negligible. The intensity of the polarized beam on the target was typically 3 nA. Cross-section data were obtained from the VAP data and are discussed in the next subsection.

B. Determination of VAP and cross section

A comparison of Fig. 1 in the present work and Fig. 1 of Ref. 3 shows a strong similarity in the two spectra. One observes a continuously increasing background in the region of the spectra above 5.1 MeV in excitation. This complicates the determination of the yields for the groups with excitation energy >5.1 MeV. The exact cause of this background is unknown and in all probability results from slit scattering, multiple scattering and/or pileup problems, although care was taken to keep the counting rate rather low. Since the actual shape of the background spectrum is not known, it was defined by drawing a smooth curve through points in the spectra far removed from the region of interest and which joins smoothly with the background for the states with excitation energy <5.1 MeV. One such curve is shown by the dotted line in Fig. 1. For the first few states with negative Q values, the low energy tail of the deuteron elastic group also contributes to the total background. In subtracting the background counts, the utmost care was taken to achieve consistency between the two modes of polarization in the definition of the background in the spectra for a given angle, as well as for spectra corresponding to different scattering angles.

Besides the complications introduced through the presence of a large background, additional uncertainties arise from the limited resolution in the present experiment. An example is provided by the three partially overlapping groups in the spectra in the neighborhood of 6.2 MeV excitation (Fig. 1), although the situation is not this complex at every angle. Since one has a fair idea of the cross sections corresponding to these groups from the better resolution (≈30 KeV) data of Ref. 3, the total yield under each group was extracted assuming that (1) the groups have a symmetrical line shape, (2) the positions of the centroids are known, (3) the full width at half-maximum (FWHM) are determined by the detector resolution, and (4) the individual yields add up to the total yield in the region.

Since the incident deuteron beam is essentially purely vector-polarized (see Subsec. II. A), the spin-up and spin-down differential cross sections $\sigma_+(\theta)$ and $\sigma_-(\theta)$ are related to the unpolarized cross section $\sigma(\theta)$ through

$$\sigma_\pm(\theta) = \sigma(\theta)[1 \pm 2it_{11\pm} iT_{11}(\theta)], \qquad (1)$$

where $it_{11\pm}$ describe the vector polarization of the incident beam for spin-up and spin-down modes and $iT_{11}(\theta)$ is the vector analyzing power for the reaction.[25] Thus,

$$iT_{11}(\theta) = \frac{\sigma_+(\theta) - \sigma_-(\theta)}{2[it_{11+}\sigma_-(\theta) + it_{11-}\sigma_+(\theta)]}, \qquad (2)$$
$$\sigma(\theta) = \tfrac{1}{2}[\sigma_+(\theta) + \sigma_-(\theta)] - (\Delta/2it_{11})[\sigma_+(\theta) - \sigma_-(\theta)],$$

where

$$it_{11} = \tfrac{1}{2}(it_{11+} + it_{11-}), \quad \Delta = \tfrac{1}{2}(it_{11+} - it_{11-}). \qquad (3)$$

In the present experiment, $it_{11+} \simeq it_{11-}$, i.e. $\Delta \simeq 0$. Hence,

$$iT_{11}(\theta) \simeq \frac{\sigma_+(\theta) - \sigma_-(\theta)}{2it_{11}[\sigma_+(\theta) + \sigma_-(\theta)]}, \qquad (4)$$
$$\sigma(\theta) \simeq \tfrac{1}{2}[\sigma_+(\theta) + \sigma_-(\theta)].$$

For a given detector, when equal amounts of charge are collected in the two modes of polarization,

$$iT_{11}(\theta) = \frac{1}{2it_{11}} \frac{Y_+(\theta) - Y_-(\theta)}{Y_+(\theta) + Y_-(\theta)} \qquad (5)$$

and

$$\sigma(\theta) = \frac{G(\theta)}{2}[Y_+(\theta) + Y_-(\theta)], \qquad (6)$$

where $Y_\pm(\theta)$ are the spin-up and spin-down yields for a particular group under consideration and $G(\theta)$ is a normalization constant. Expression (5) was used to obtain the VAP data.

Since the tensor polarization of the incident beam is ≃0, the cross-section data for the (d,p) states were obtained employing expression (6). Relative cross sections for deuteron elastic scattering and for the relatively strong (d,p) groups at 1.61, 2.49, 3.52, and 5.09 MeV excitations were obtained using an unpolarized beam and one detector of fixed geometry. Absolute cross sections for these groups were obtained by comparison of the relative cross sections with those for $^{16}O(p,p)$ obtained under identical experimental conditions. $^{16}O(p,p)$ cross section data of Skwiersky, Baglin, and Parker[26] at $E_p = 14.0$ MeV and $\theta_{lab} = 20$ to 70° in steps of 10° were used for this purpose. The absolute cross sections provide the necessary normalization constants $G(\theta)$. These constants were also checked for consistency by comparison with the 9.16 MeV (d, d) cross section data of Ref. 3. The data of Ref. 26 have a maximum uncertainty of 10%. The over-all uncertainty in the measured cross sections reported here is of the order ±15%.

The deuteron elastic cross-section and VAP data are shown in Fig. 2. It is to be noted that for the

TABLE I. Optical model potential parameters used in the calculations ($E = E_{lab}$).

Particle type	V (MeV)	W_D (MeV)	V_{so} (MeV)	a_0 (fm)	a_i (fm)	a_{so} (fm)	r_0 (fm)	r_i (fm)	r_{so} (fm)	r_c (fm)
d	105.0	10.45	8.0	0.85	0.62	0.50	1.073	1.563	0.86	1.30
p	56.18 $-0.32E$	11.80 $-0.25E$	5.9	0.75	0.67	0.40	1.17	1.28	0.92	1.25

elastic scattering the cross-section data were collected for 26 angles between 15 and 150° and the VAP data were taken for 24 angles between 15 and 130°. The data for the (d,p) states are displayed in Figs. 3 through 12. The errors shown are statistical, including the uncertainty in the background as well as that arising from error in the beam polarization measurements. Where error bars are not used, the size of the data point indicates the approximate statistical error.

III. DWBA ANALYSIS

A. Elastic scattering and choice of optical model potential

The deuteron optical model potential parameters were obtained from a simultaneous fit to the elastic cross-section and VAP data. A conventional form for the potential[27] with a surface absorptive term and a real spin-orbit term was used. A grid search was performed, starting with the average parameters for ^{40}Ca(d, d) given by Schwandt and Haeberli,[28] in order to reproduce the ^{36}Ar(d, d) elastic cross-section and VAP data. Additional constraints were introduced through the requirement that the data for the relatively strong (d,p) states at 1.61, 2.49, 3.52, and 5.09 MeV excitation also be reasonably well described with the same parameters. The set of potential parameters obtained is listed in Table I. The elastic cross-section and VAP data along with the optical model predictions are shown in Fig. 2. Proton potentials were obtained from the work of Becchetti and Greenlees,[29] except for the spin-orbit part, which was chosen from the work of Lombardi *et al.*[30] The proton parameters were varied slightly in order to improve the degree of agreement with the stripping data. The potential set used is listed in Table I.

B. Analysis of the stripping data

The (d,p) cross-section and VAP data for the states in ^{37}Ar have been analyzed using the zero-range code DWUCK,[31] including corrections for nonlocality of the optical potentials.[32] Bound-state neutron wave functions were calculated using a Woods-Saxon well of standard geometry, with $r_0 = 1.25$ fm and $a_0 = 0.65$ fm. The spin-orbit depth was chosen as 6.25 MeV. The real central well depth was searched to reproduce the experimental separation energy of each level.

Cross-section and VAP data together with the DWBA predictions are shown in Figs. 3 to 12. All DWBA calculations were performed without radial cutoff and using the normalization constant

$$D_0^2 = 1.58 \times 10^4 \text{ MeV}^2 \text{fm}^3 .$$

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

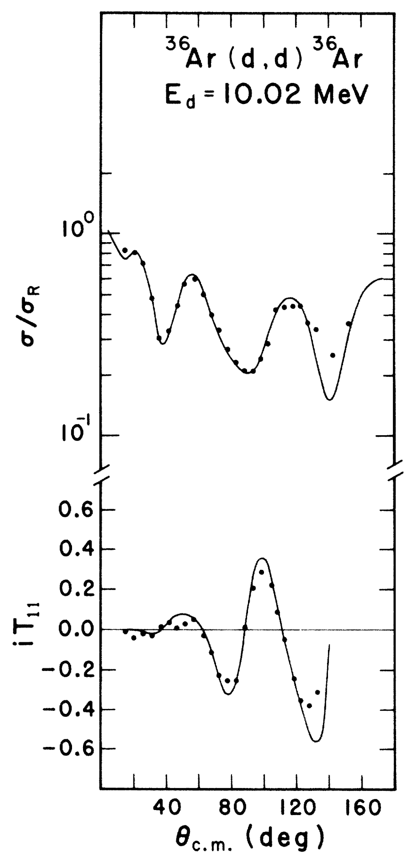

FIG. 2. Optical model fits to the ^{36}Ar(d,d) cross-section and vector analyzing power data. The cross section is shown as a ratio to the corresponding Rutherford cross section.

IV. RESULTS AND DISCUSSION

The results of the analyses discussed in this section are summarized in Table II. The excitation energies up to 5.58 MeV have been taken from Ref. 14. For states with higher excitation energy, the values are taken from Ref. 3. The (d,p) cross-section data and extensive analyses of such data have been reported in previous studies.[3,4] In the present analysis, apart from extracting the spectroscopic factors, the cross-section data have been included primarily for the sake of completeness. Except for the cases where disagreement exists between the results of Refs. 3 and 4, the discussions will be concentrated mainly on the VAP data.

The $^{36}Ar(d,p)^{37}Ar$ ground state data are reasonably well reproduced through DWBA calculations (Fig. 3). For the cross-section data, the quality of agreement is similar to that in Ref. 3. The VAP data confirm the $\frac{3}{2}^+$ spin-parity assignment.

The quality of reproduction of the cross-section data for the 1.41 MeV state (Fig. 3) through DWBA calculations is similar to that in Ref. 3. Since

TABLE II. Summary of the results of DWBA analysis of the $^{36}Ar(d,p)$ cross-section and vector analyzing power data.

Excitation energy	Present work			Previous studies (Refs. 3 and 4)					
				l		J^π		S_J	
E_x (MeV) [a]	l	J^π	S_J	Ref. 3	Ref. 4	Ref. 3	Ref. 4	Ref. 3	Ref. 4
g.s.	2	$\frac{3}{2}^+$	0.56 ± 0.04	2	2	$\frac{3}{2}^+$	$\frac{3}{2}^+$	0.49	0.52
1.410	0	$\frac{1}{2}^+$	0.22 ± 0.07	0	0	$\frac{1}{2}^+$	$\frac{1}{2}^+$	0.22	0.10
1.611	3	$\frac{7}{2}^-$	0.76 ± 0.06	3	3	$\frac{7}{2}^-$	$\frac{7}{2}^-$	0.51	0.77
2.217	(2)	$(\frac{5}{2}^+)$	(0.02 ± 0.003)						
2.490	1	$\frac{3}{2}^-$	0.44 ± 0.02	1	1	$\frac{3}{2}^-$	$\frac{3}{2}^-$	0.35	0.42
2.796	2	$\frac{5}{2}^+$	0.04 ± 0.008	2	2	$\frac{5}{2}^+$	$\frac{5}{2}^+$	0.06	0.04
3.517	1	$\frac{3}{2}^-$	0.35 ± 0.02	1	1	$\frac{3}{2}^-$	$\frac{3}{2}^-$	0.23	0.33
4.449	1	$\frac{1}{2}^-$	0.14 ± 0.01	1	1	$\frac{1}{2}^-$	$\frac{1}{2}^-$	0.14	0.14
4.638	1	$\frac{3}{2}^-$	0.012 ± 0.003	1	(3)	$\frac{3}{2}^-$	$(\frac{5}{2}^-)$	0.02	(0.02)
4.744	1	$\frac{3}{2}^-$	0.010 ± 0.003	1	(3)	$\frac{3}{2}^-$	$(\frac{5}{2}^-)$	0.02	(0.01)
5.090	1	$\frac{1}{2}^-$	0.60 ± 0.05	1	1	$\frac{1}{2}^-$	$\frac{1}{2}^-$	0.49	0.51
5.346	1	$\frac{3}{2}^-$	0.042 ± 0.004	1	1	$(\frac{1}{2}^-)$	$(\frac{1}{2}^-; \frac{3}{2}^-)$	0.08	(0.08, 0.04)
5.409	1	$\frac{3}{2}^-$	0.011 ± 0.003	1	(3)	$\frac{1}{2}^-$	$(\frac{5}{2}^-)$	0.03	(0.03)
5.580	1	$\frac{3}{2}^-$	0.010 ± 0.002	1		$\frac{1}{2}^-$		0.02	
{5.880	(1)	$(\frac{1}{2}^-)$	(0.008 ± 0.003)}						
{5.961	(3)	$(\frac{7}{2}^-)$	(0.016 ± 0.006)}	1		$(\frac{3}{2}^-)$		0.01	
6.135	1	$\frac{1}{2}^-$	0.035 ± 0.009	1	1	$(\frac{1}{2}^-)$	$(\frac{1}{2}^-, \frac{3}{2}^-)$	0.05	0.03, 0.01
6.204	1	$\frac{1}{2}^-$	0.055 ± 0.015	1		$\frac{1}{2}^-$		0.05	
6.289	3	$\frac{5}{2}^-$	0.14 ± 0.03	3	3	$\frac{7}{2}^-$	$(\frac{5}{2}^-, \frac{7}{2}^-)$	0.11	0.11, 0.06
7.131	(3)	$(\frac{7}{2}^-)$	(0.090 ± 0.030)	1	3	$\frac{1}{2}^-$	$(\frac{5}{2}^-, \frac{7}{2}^-)$	0.05	0.04, 0.02
{7.246	1 +	$(\frac{1}{2}^-)$	(0.063 ± 0.015)}	1		$\frac{1}{2}^-$		0.05	
{7.282	3	$(\frac{7}{2}^-)$	(0.070 ± 0.017)}		3		$(\frac{5}{2}^-, \frac{7}{2}^-)$		0.17, 0.09
7.571	1	$\frac{1}{2}^-$	0.095 ± 0.020	1	1	$\frac{1}{2}^-$	$(\frac{1}{2}^-, \frac{3}{2}^-)$	0.08	0.10, 0.05
7.895	1	$\frac{1}{2}^-$	0.15 ± 0.02	1	1	$\frac{1}{2}^-$	$(\frac{1}{2}^-, \frac{3}{2}^-)$	0.07	0.20, 0.10
8.093	(3)	$(\frac{7}{2}^-)$	(0.035 ± 0.009)	1		$\frac{1}{2}^-$		0.03	
8.295	3	$\frac{7}{2}^-$	0.018 ± 0.005						
8.399	(3)	$(\frac{7}{2}^-)$	(0.035 ± 0.008)	1		$\frac{1}{2}^-$		0.02	

[a] $E_x \leq 5.580$ MeV from Ref. 14.
≥ 5.5880 MeV from Ref. 3.

this state corresponds to an $l=0$ transition, the $J^{\pi}=\frac{1}{2}^{+}$ assignment is unambiguous. However, the VAP data are not reproduced even qualitatively, except at very forward angles. The spin-orbit potential parameters in the entrance and exit channels were varied systematically in an attempt to improve the agreement but without success. It has been shown that finite-range effects are small[33] and that deuteron D-state effects on the VAP are least important in the case of $l=0$ transitions.[34] It is probable that reaction mechanisms other than simple stripping are important in populating this state.

Data for the 1.61 MeV state are rather well reproduced by DWBA calculations (Fig. 3). The VAP data confirm the $J^{\pi}=\frac{7}{2}^{-}$ assignment made in earlier studies.

The state with excitation energy 2.22 MeV is relatively weakly populated in the (d,p) reactions and no reliable data could be extracted in earlier studies.[3] Ericson fluctuation analyses of the excitation functions in the reaction ^{39}K$(d,\alpha)^{37}$Ar by Naude, Bottega, and McMurray[2] indicate a spin of $\frac{5}{2}$ for this state. Champlin, Howard, and Olness,[6] through lifetime and angular correlation measurements concluded that this state has a spin of either $\frac{5}{2}$ or $\frac{7}{2}$. γ-ray angular distribution and lifetime measurements of Ragan *et al.*[7] yield a most probable spin-parity assignment of $\frac{7}{2}^{+}$ for this state. Taras, Turcotle, and Vaillancourt[8] make a definitive $J^{\pi}=\frac{7}{2}^{+}$ assignment to this state on the basis of

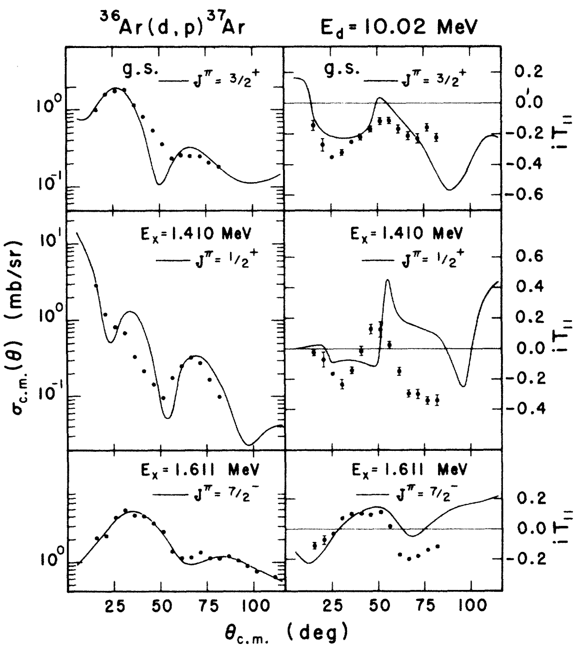

FIG. 3. Cross-section and vector analyzing power data for the ground state, 1.410 MeV, and 1.611 MeV states in ^{37}Ar along with the DWBA predictions.

angular distribution measurements of the decay γ rays via the reactions ^{37}Cl$(p,n)^{37}$Ar and ^{34}S(α,n)-^{37}Ar. Recent shell model calculations[10] predict a $\frac{7}{2}^{+}$ state in this energy region. On these bases, the latest compilation[14] shows a definite $\frac{7}{2}^{+}$ assignment to this state.

In agreement with earlier studies,[3,4] this state is rather weakly excited in the present experiment. Calculations were performed for $J^{\pi}=\frac{5}{2}^{+}$, $\frac{7}{2}^{+}$, and $\frac{7}{2}^{-}$ (Fig. 4), but none of these calculations reproduce the data well. Although no definitive assignments can be made from the present work, a simultaneous consideration of both cross-section and VAP data favors a possible J^{π} value of $\frac{5}{2}^{+}$ for the state. A definitive $J^{\pi}=\frac{7}{2}^{+}$ assignment would seem to imply that a one-step stripping process is not the dominant mode through which this state is populated in a (d,p) reaction.

The spin-parity assignment of $\frac{3}{2}^{-}$ for the 2.49 MeV state in ^{37}Ar is clearly consistent with the present data (Fig. 4), which are well reproduced by the DWBA calculations.

The state with excitation energy 2.80 MeV corresponds to an $l=2$ transition (Fig. 4). The reproducibility of the cross-section data through DWBA calculations compares to that in Ref. 3. The VAP data lead to an unambiguous J^{π} value of $\frac{5}{2}^{+}$, confirming earlier conjectures.

Data for the 3.52 MeV state are well reproduced by the calculations (Fig. 5). A definitive J^{π} assignment of $\frac{3}{2}^{-}$ is in agreement with the results of earlier studies. The low-energy end of this peak in the spectra masks the peak corresponding to the 3.61 MeV state in ^{37}Ar. The data of Ref. 3 show that the peak cross section for the 3.61 MeV state is approximately 3% of that of the 3.52 MeV state, so that no significant error is introduced by the presence of this state.

In the present experiment, the 4.45 MeV state could not be resolved from the 4.41 MeV state which was observed and analyzed in Ref. 3. However, the data of Ref. 3 show that the peak cross section for the 4.41 MeV state is almost an order of magnitude smaller than that of the 4.45 MeV state. The observed group was therefore analyzed as a single group at 4.45 MeV excitation. The cross-section data are fairly well reproduced through an $l=1$ transition (Fig. 5). The VAP data, although reproduced only qualitatively, lead to a definitive $J^{\pi}=\frac{1}{2}^{-}$ assignment. The data show a peak at ~75°, whereas the calculation shows a dip around this angle. Part of this possibly results from the admixture of the 4.41 MeV state.

In the 18.0 MeV data of Ref. 4, it was concluded that the 4.64 MeV state in ^{37}Ar corresponds to an $l=3$ transition, whereas the 9.16 MeV data and analysis of Ref. 3 lead to an $l=1$ transition for this state. A simultaneous analysis of the cross-section and VAP data in the present work conclusively establishes $J^\pi = \frac{3}{2}^-$ for this state (Fig. 5). The data are fairly well reproduced by the DWBA calculations. Predictions for $J^\pi = \frac{7}{2}^-$ and $\frac{5}{2}^-$ have been included for comparison.

A similar discrepancy between the results of Refs. 3 and 4 exists in the case of the 4.74 MeV state. The DWBA calculations are shown for $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$ spin-parity assignments (Fig. 6). The present work unambiguously establishes a $\frac{3}{2}^-$ spin-parity value for this state, in agreement with the results of Ref. 3.

Cross-section data for the 5.09 MeV state are well reproduced assuming an $l = 1$ transition (Fig. 6). The VAP data establishes $J^\pi = \frac{1}{2}^-$ for this state, in agreement with the results of previous studies. The VAP data for this strong state are qualitatively reproduced by the calculations. The data show a small maximum at ~75° relative to the valley predicted by the calculations. The situation is similar to that for the $\frac{1}{2}^-$ state at 4.45 MeV, though the effects are much more pronounced in that case. Kocher and Haeberli[35] observed a similar behavior for the reaction ^{40}Ca(d,p) leading to the $\frac{1}{2}^-$ state in ^{41}Ca at 3.95 MeV. An improved DWBA fit to the VAP data could be obtained using a deuteron potential with a deeper real well. However, such

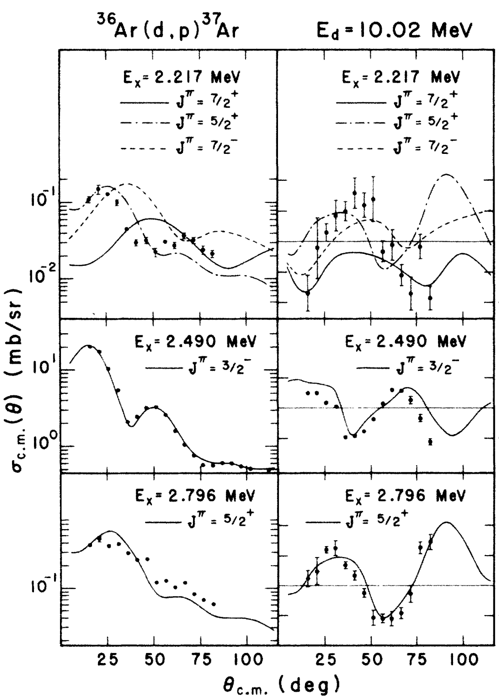

FIG. 4. Cross-section and vector analyzing power data for the 2.217 MeV, 2.490 MeV, and 2.796 MeV states in ^{37}Ar. The J^π values and the corresponding DWBA calculations are shown.

parameter variation leads to a deterioration in the quality of the fits to the deuteron elastic scattering data and in the (d,p) data involving other l values, particularly $l = 2$.

Disagreement exists between the results of Refs. 3 and 4 concerning the l value of the 5.22 MeV state. Data for this state could not be extracted reliably in the present work, primarily because of the proximity of the low-energy end of the 5.09 MeV state (Fig. 1). Hence no analysis is reported for this state.

The state with excitation energy 5.35 MeV has previously been tentatively assigned[3] as $J^\pi = \frac{1}{2}^-$. The present VAP data show clearly that the spin-parity assignment should be $\frac{3}{2}^-$ (Fig. 6). The data are well reproduced by the calculations.

The results of Refs. 3 and 4 disagree on the l vlaues for the state with excitation energy 5.41 MeV. Calculations corresponding to both $l = 1$ and $l = 3$ transitions are shown in Fig. 7. A consideration of both cross-section and VAP data lead to a spin-parity assignment of $\frac{3}{2}^-$ for this state. The agreement between the calculated and measured cross sections is only fair. The quality of agreement is, however, influenced by the presence of the 5.44 MeV state which could not be resolved in the spectra. Although the l value is in agreement with the results of Ref. 3, the VAP data show that the spin value for the state is $\frac{3}{2}$ instead of $\frac{1}{2}$ as assigned in Ref. 3.

The 5.58 MeV state of ^{37}Ar has previously been

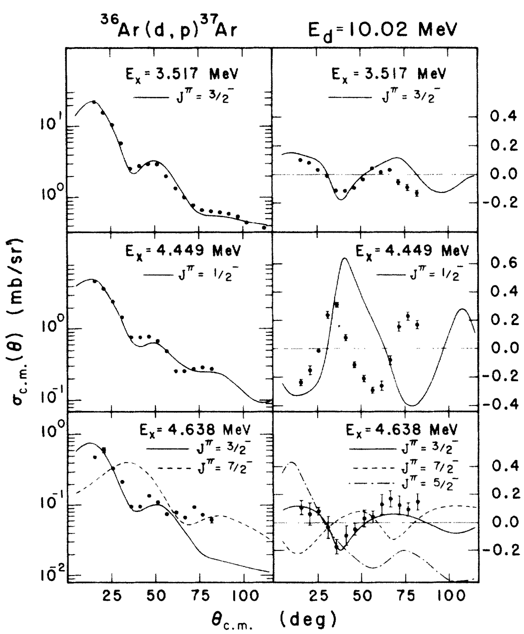

FIG. 5. Comparison of the DWBA calculations with the cross-section and vector analyzing power data for the 3.517 MeV, 4.449 MeV, and 4.638 MeV states in ^{37}Ar.

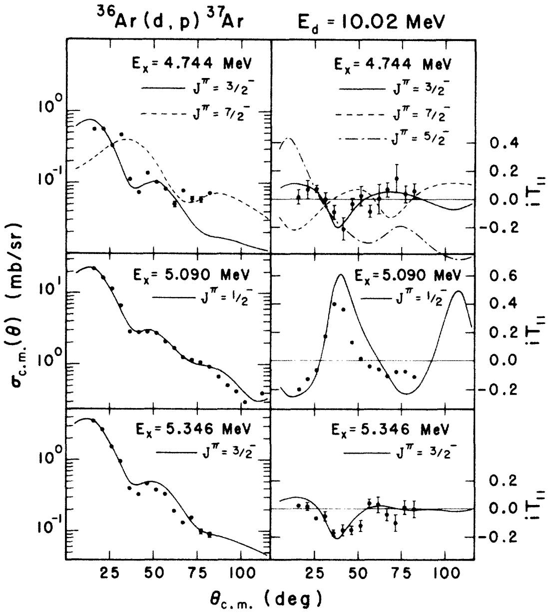

FIG. 6. Cross-section and vector analyzing power data for the states with excitation energies 4.744, 5.090, and 5.346 MeV. The J^π values and the corresponding DWBA predictions are shown.

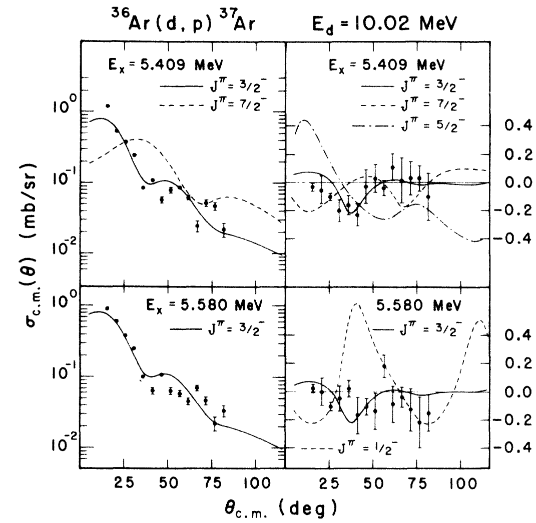

FIG. 7. Cross-section and vector analyzing power data for the 5.409 and 5.580 MeV states in ^{37}Ar. The J^π values and the results of the DWBA calculations are shown.

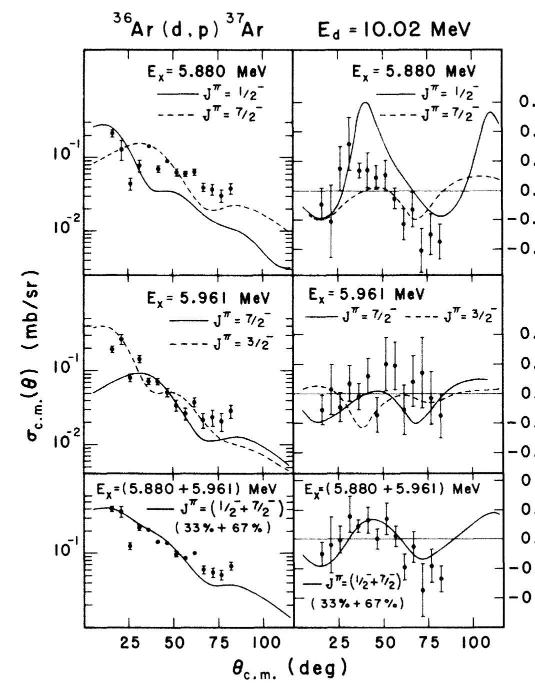

FIG. 8. Analysis of the (5.880 +5.961) MeV composite group in the spectra. The cross-section and vector analyzing power data for the 5.880 MeV and 5.961 states obtained by using the peak-unfolding procedure described in the text is shown in the top and the middle parts of the figure. DWBA analysis of the unresolved group treated as an admixture of a $J^\pi = \frac{1}{2}^-$ and a $J^\pi = \frac{7}{2}^-$ state is shown in the lowest part of the figure.

assigned[3] $J^\pi = \frac{1}{2}^-$. The present analysis of both cross-section and VAP data is in conformity with the spin-parity assignment of $\frac{3}{2}^-$ (Fig. 7). Since the spectra of Ref. 3 indicate that the 5.54 MeV state is rather weakly populated compared to the 5.58 MeV state, the present conclusions are not expected to be affected by the unresolved 5.54 MeV group.

Two proton groups corresponding to excitation energies of 5.88 and 5.96 MeV could be resolved only partially for most of the angles of observation. Unfolding of the peaks was approximately achieved following the approach outlined in Subsec. II B in order to obtain some idea of the spins of the two states. In Ref. 3, even though the 5.88 MeV state was well resolved, no reliable cross-section data could be obtained for this state. The cross-section data for the 5.96 MeV state were analyzed in Ref. 3 assuming an $l=1$ transition. The reproducibility of the data, however, shows that such an assumption cannot be definitive. In the present analysis, the unfolded cross-section and VAP data for the 5.88 and 5.96 MeV states were first analyzed individually. Uncertainties introduced through the peak-unfolding procedure, together with uncertainties from the large background are reflected in the large error bars in the data shown in Fig. 8. Calculations corresponding to $l=1$ and $l=3$ transitions are shown. Although the quality of the data does not permit any definitive conclusions to be drawn, an $l=1$ and an $l=3$ transition with the J^π values of $\frac{1}{2}^-$ and $\frac{7}{2}^-$ for the 5.88 and 5.96 MeV states, respectively, seemed to be a possibility from the VAP data. The overlapping groups were next analyzed as a single composite group with an excitation energy of 5.92 MeV. The composite cross sections $\overline{\sigma}(\theta)$ and VAP's $\overline{iT_{11}}$ were calculated using the expressions:

$$\overline{\sigma}(\theta) = C^1\sigma^1(\theta) + C^3\sigma^3(\theta) \qquad (7)$$

and

$$\overline{iT_{11}}(\theta) = \frac{C^1\sigma^1(\theta)iT_{11}^1(\theta) + C^3\sigma^3(\theta)iT_{11}^3(\theta)}{\overline{\sigma}(\theta)}, \qquad (8)$$

where the superscripts 1 and 3 refer to $l=1$ and $l=3$; $\sigma^{1,3}(\theta)$ are the calculated single-particle cross sections; $iT_{11}^{1,3}(\theta)$ are the corresponding calculated VAP's. The ratio of the coefficients C^1 and C^3 was varied in order to obtain reasonable agreement between calculated $\overline{\sigma}(\theta)$ and $\overline{iT_{11}}(\theta)$ and the composite experimental data. The data together with the calculations corresponding to an admixture of 33% $p_{1/2}$ and 67% $f_{7/2}$ are shown in Fig. 8. This percentage admixture corresponds to an incoherent superposition of a $p_{1/2}$ state of spectroscopic factor 0.008 and an $f_{7/2}$ state of spectroscopic factor 0.016. The reasonable agreement between the data and the calculations lends credence to the assumption that the 5.88 and 5.96 MeV states are $p_{1/2}$ and $f_{7/2}$ states, respectively. It is emphasized, however, that no definitive assignments are possible on the basis of the present data. The J^π values should be regarded as tentative and are shown in parentheses in Table II.

Two proton groups with excitation energies 6.14 and 6.20 MeV appear as partially overlapping groups in the spectra corresponding to some angles of observation. However, the data-extraction procedure was considerably aided by a knowledge of the relative cross sections of these states from the data of Ref. 3. Results of Refs. 3 and 4 show that both of these states correspond to an $l=1$ transition. The data were extracted using the peak-unfolding procedure described in Subsec. II B. The data are fairly well reproduced by DWBA calculations (Fig. 9). The VAP data lead to a $J^\pi = \frac{1}{2}^-$ assignment for both of the states.

The state with excitation energy 6.29 MeV corresponds to an $l=3$ transition.[3,4] Its proton group partially overlaps the 6.20 MeV proton group in the spectra for some angles. The procedure outlined above was used for data extraction. Agreement between the present cross-section data and DWBA calculations for an $l=3$ transition for the 6.29 MeV state (Fig. 9) is only fair. The VAP data lead to a $J^\pi = \frac{5}{2}^-$ assignment for this state.

States with excitation energies between 6.3 and

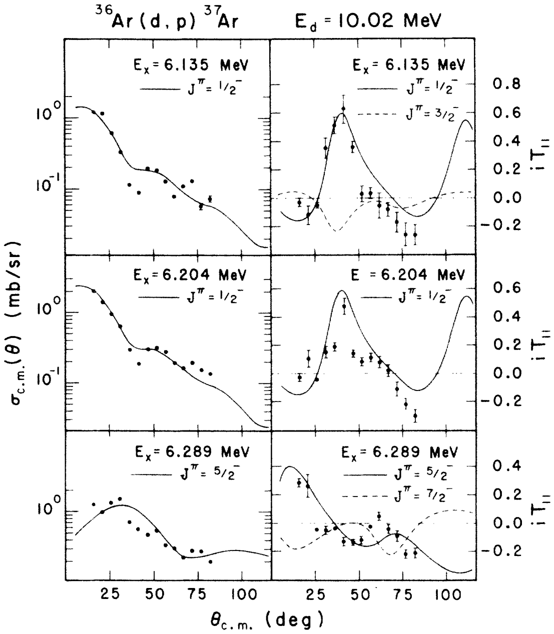

FIG. 9. Comparison of the DWBA calculations with the cross-section and the vector analyzing power data for the 6.135 MeV, 6.204 MeV, and 6.289 MeV states.

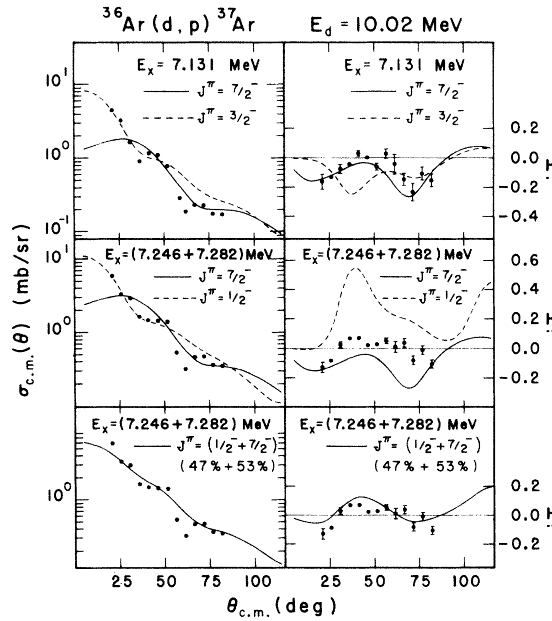

FIG. 10. DWBA analysis of the 7.131 MeV state and of the unresolved (7.246 + 7.282) MeV group. The bottom third of the figure shows the comparison of the cross-section and vector analyzing power data for the unresolved group with a calculation assuming an incoherent mixture of two states with $J^\pi = \frac{1}{2}^-$ and $\frac{7}{2}^-$ as discussed in the text.

7.0 MeV were masked in the spectra by the deuteron elastic group. This is true for the 7.07 MeV state also, for most angles. Hence, these groups could not be analyzed in the present work.

The 18.0 MeV data of Ref. 4 show an $l=3$ transition for the 7.13 MeV state whereas the data of Ref. 3 lead to an $l=1$ transition for this state. The present data together with calculations for both $l=1$ and $l=3$ transfers are shown in Fig. 10. The cross-section data are not well reproduced by any of these calculations, although an $l=1$ transition seems more probable. The VAP data, on the other hand, lead to a $J^\pi=\frac{7}{2}^-$ value for this state. This inconsistency between the cross-section and VAP data is puzzling. It is conceivable that multistep processes may be the primary modes through which this state is populated. A contribution from the unresolved 7.10 MeV group observed in the spectrograph data of Ref. 1 might also influence the cross-section data. But the effect should be observable in the VAP data as well as in the 18.0 MeV cross-section data of Ref. 4. Part of the problem arises from contributions from the low-energy tail of the deuteron elastic group. Consequently, no definitive conclusions can be drawn from the present data. Assuming that the l value obtained in Ref. 4 is correct, a tentative assignment of $J^\pi=(\frac{7}{2}^-)$ could be made to this state.

Two proton groups corresponding to states having excitation energies 7.25 and 7.28 MeV could not be resolved in the spectra and were treated as a single group in the present analysis. The calculations shown in Fig. 10 indicate that neither the cross-section nor the VAP data are reproduced through the assumption of a single spin value. In the work of Ref. 3, the 7.25 MeV state was resolved and was assigned $J^\pi=\frac{1}{2}^-$, whereas the data for the composite group was reproduced in Ref. 4 by the DWBA calculations assuming an $l=3$ transition. Assuming that the composite group is due to an incoherent mixture of a $p_{1/2}$ and an $f_{7/2}$ state, cross sections and VAP were calculated utilizing expressions (7) and (8) discussed earlier. The data are fairly well reproduced by a calculation using an admixture of 47% $p_{1/2}$ and 53% $f_{7/2}$ which is shown in Fig. 10. This percentage admixture corresponds to an incoherent superposition of a $p_{1/2}$ state of spectroscopic factor 0.063 and an $f_{7/2}$ state of spectroscopic factor 0.07. The disagreement between the results of Refs. 3 and 4 is thus reconciled in this particular case. A third state with excitation energy of 7.26 MeV has been identified in the spectrograph data of Ref. 1.

The 7.57 MeV state in ^{37}Ar corresponds to an $l=1$ transition (Fig. 11) in agreement with the results of earlier studies.[3,4] Although the agreement between calculated and measured VAP is only qualitative, it appears that a definite $J^\pi=\frac{1}{2}^-$ assignment can be made.

The cross-section data for the state with excitation energy 7.90 MeV have been analyzed assuming an $l=1$ transition in agreement with the results of Refs. 3 and 4. The agreement between the data and the calculations is only fair. The VAP data are reproduced qualitatively indicating a spin-parity assignment of $\frac{1}{2}^-$. The quality of the fits is influenced partly by the unresolved weak groups at 7.79 and 7.95 MeV excitation observed in the work of Ref. 3.

In Ref. 3, the state with excitation energy 8.09 MeV has been analyzed assuming an $l=1$ transition. The agreement between the calculation and the data is only fair. In the present analysis, calculations were performed assuming an $l=1$ as well as an $l=3$ transition. The cross-section data are not well reproduced by either of these calculations (Fig. 11). The VAP data show a small preference for a spin-parity assignment of $\frac{7}{2}^-$. The cross-section and the VAP data show a peak at ~70°, probably resulting from an unidentified contamination in the spectra. Although the data on the whole indicate a tentative $J^\pi=\frac{7}{2}^-$ assignment, no definitive conclusions can be drawn from these data.

The state with excitation energy 8.30 MeV has been identified in earlier studies,[1,3] but no analysis of the data has been reported. Although the error bars are relatively large, the present data are

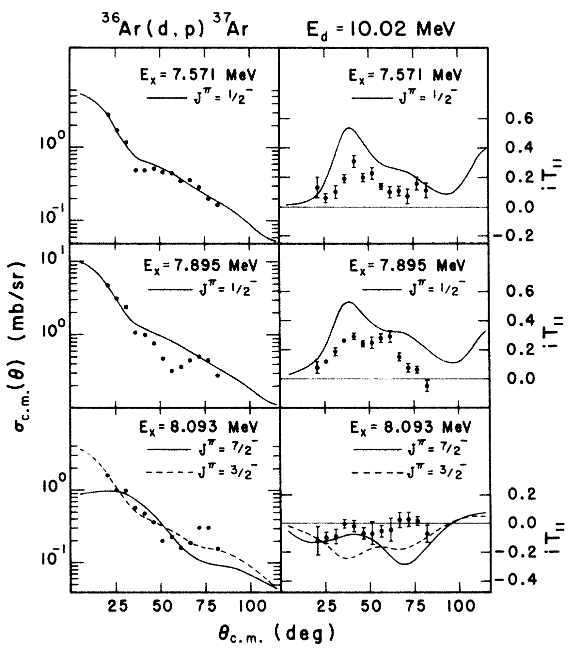

FIG. 11. Cross-section and vector analyzing power data for the states with excitation energies 7.571 MeV, 7.895 MeV, and 8.093 MeV. The J^π values and the corresponding DWBA calculations are shown.

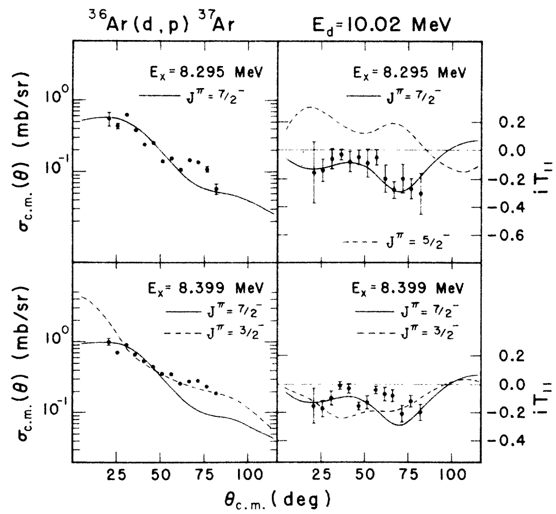

FIG. 12. Cross-section and vector analyzing power data for the 8.295 MeV and 8.399 MeV states in ^{37}Ar along with the DWBA predictions.

consistent with a definite $J^\pi = \frac{7}{2}^-$ assignment for this state (Fig 12).

Data for the 8.40 MeV state have been analyzed in Ref. 3 assuming an $l=1$ transition. At such high excitation energy, cross-section angular distribution data lose their characteristic structure. Comparison of the present data (Fig. 12) to that of Ref. 3 indicates that the selection of the l-value transfer hinges on the first two data points. Data at further forward angles will be required to obtain an unambiguous l value for this state. A consideration of both cross-section and VAP data suggest a $J^\pi = \frac{7}{2}^-$ assignment for this state. However, this spin-parity assignment should be regarded as tentative.

Two neutron-unbound states with excitation energies 8.89 and 9.01 MeV were observed in the present work. The 8.89 MeV group was masked by the 1.98 MeV deuteron inelastic peak at several angles. No reliable data could be extracted for either of these states and hence no analysis is being reported.

The spectroscopic factors obtained from the DWBA analysis are sensitive to the choice of the optical potentials, especially in cases where the angular momentum mismatch is large. In the present analysis, the match is rather good for most of the $l=1$ transitions. Since the VAP data provide additional constraints on the selection of the deuteron optical potential, it is expected that the spectroscopic factors for all l transfers should be more reliable than those obtained from an analysis of the cross-section data alone. However, the uncertainties arising from (1) large background in part of the spectra, (2) the quality of reproduction of the data by DWBA calculations, and (3) the selection of the data points at which the calculated cross sections are normalized to the experimental values, cannot be ruled out. Since the exact shapes of the background spectra are unknown, only rough estimates were made using possible alternative curves defining the background spectra. Uncertainties arising from normalization to alternative data points were also estimated. The spectroscopic factors obtained in the present work along with these estimated errors are shown in column 4 of Table II, and are in reasonable agreement with the results of Refs. 3 and 4. The differences are within the error limits usually assumed for spectrscopic factors obtained in DWBA analyses.[36]

The ground state spectroscopic factor $S_J = 0.56$ is quite reasonable and is in conformity with the conventional shell model two-neutron-hole configuration of ^{36}Ar. The S_J values for the states with definitive J^π assignments of $f_{7/2}$, $p_{3/2}$, and $p_{1/2}$ add up to 0.96, 0.90, and 1.07, respectively. The spectroscopic strength is thus almost exhausted for these states. The spectroscopic factors for the states for which J^π assignment is only tenta-

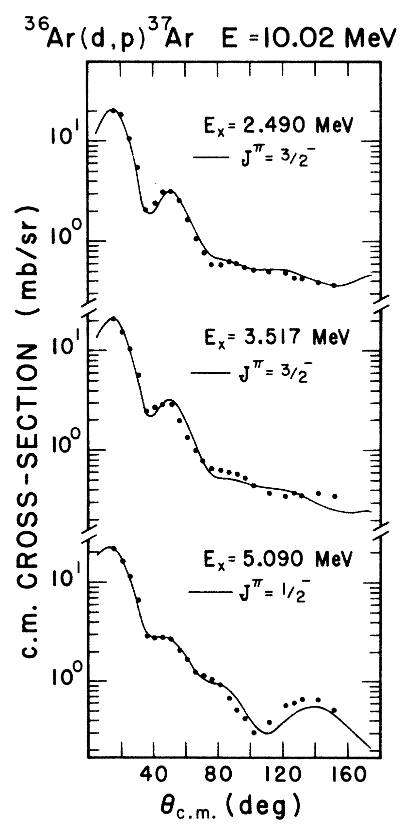

FIG. 13. The Lee-Schiffer effect for strong $l=1$ transitions. The solid lines are the predictions of conventional DWBA calculations including spin-orbit coupling.

tive, are relatively small and thus would not appreciably affect the values of $\sum_i S_J^i$. The calculated centroids for the single-particle states corresponding to these sums are found to be $\overline{E}(f_{7/2}) = 1.448$ MeV; $\overline{E}(p_{3/2}) = 3.147$ MeV; $\overline{E}(p_{1/2}) = 5.039$ MeV.

It is noted that several of the spin assignments for $l=1$ transitions made in Ref. 3 on the basis of the Lee-Schiffer effect[15] agree with the assignments made in the present work on the basis of the J dependence of the VAP. In earlier studies[37,38] of the reactions ^{40}Ca$(d,p)^{41}$Ca and ^{38}Ar(d,p)-^{39}Ar, strong Lee-Schiffer effects for $l=1$ transitions have been observed and could be reproduced provided the deuteron optical potential parameters, particularly the spin-orbit part, were chosen from fits to the polarization data. The cross-section data for the strong $l=1, J=\frac{3}{2}$ states at 2.49 and 3.52 MeV and for the $J^\pi = \frac{1}{2}^-$, 5.09 MeV state were obtained in the present work for scattering angles up to 150°. The data show (Fig. 13) the Lee-Schiffer effect at ~100° and are well reproduced by the DWBA calculations. It is believed that, at least for this mass neighborhood, spin assignments for the relatively strong $l=1$ states on the basis of this effect, should be considered quite reliable. However, as is well known, for states with low spectroscopic factors (<0.1), the Lee-Schiffer effect does not always lead to correct J^π assignments.

V. SUMMARY AND CONCLUSIONS

By a simultaneous analysis of the cross-section and VAP data for the reaction ^{36}Ar$(d,p)^{37}$Ar, definitive total angular momentum and parity values have been assigned to 19 states in ^{37}Ar with excitation energies up to 8.30 MeV. Ambiguities in the assignments in earlier studies have been removed in most cases. For states which are relatively weak (spectroscopic factor <0.1), the present J^π assignments are reliable and disagreements with the results of earlier studies based on (1) the Lee-Schiffer effect and (2) the conventional shell model ordering of states, is not surprising. The data and the analysis for the state with excitation energy 8.30 MeV have not been reported in earlier studies.

Tentative J^π assignments have been made to two states with excitation energies 8.09 and 8.40 MeV. The probable spin-parity vlaues of the constituents in the (5.88 + 5.96) MeV and (7.25 + 7.28) MeV composite groups in the spectra have been determined in the present analysis.

The l-value transfers for the states with excitation energies 4.64, 4.74, and 5.41 MeV obtained in the present study agree with those of Ref. 3 but disagree with the results of Ref. 4. Disagreement between the results of Refs. 3 and 4 in the case of the excited state at 7.25 MeV has been reconciled in this analysis.

Spectroscopic factors extracted from the present data agree reasonably well with those obtained in earlier studies.

The data for the $s_{1/2}$ state at 1.41 MeV could not be reproduced by the DWBA calculations. No definite spin or parity assignment could be made for the 2.22 MeV state. The present data for this state are in apparent conflict with definite J^π assignments obtained from γ-decay studies. In addition, in the case of the 7.13 MeV state, the conclusions from the cross-section data are found to be inconsistent with those from the VAP data. These observations seem to indicate that multistep processes in the ^{36}Ar$(d,p)^{37}$Ar reaction are of some importance.

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