Levels in ^{38}K from the ^{40}Ca(d,α) reaction at 22.8 MeV

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Twenty levels in ^{38}K up to an excitation energy of 10.26 MeV have been identified in a study of the ^{40}Ca(d,α)^{38}K reaction at an incident deuteron energy of 22.8 MeV. Differential cross sections were measured at forty-four angles in an angular range $11° \leq \theta \leq 165°$. Distorted-wave Born approximation analysis has been performed for eight transitions using two-nucleon spectroscopic amplitudes derived from a full *sd* shell-model calculation. For other levels, distorted-wave Born approximation calculations were performed assuming simple two-nucleon configurations. The 7.32-MeV level is found to be populated by $L=0+2$ transfer and hence has $J^\pi=1^+$. A newly identified level at 9.88 MeV is found to be excited by $L=2$ transfer and hence has $J^\pi=1^+$, 2^+, or 3^+.

[NUCLEAR REACTIONS ^{40}Ca(d,α)^{38}K, $E_d=22.8$ MeV, measured E_α and $\sigma(\theta,E_\alpha)$, DWBA analysis, deduced levels, L transfer.]

I. INTRODUCTION

There has been a great deal of interest in the (d,α) reaction, especially on even-even nuclei[1-7] because of its highly selective nature in populating the levels in the residual nuclei.[8,9] Some states which are weakly populated in single-nucleon transfer reactions can be very strongly excited in this reaction. The angular distributions are characteristic of the transferred orbital angular momenta and can be reproduced with distorted-wave Born approximation (DWBA) calculations. The (d,α) reaction has therefore become an important tool in the elucidation of nuclear structure.

In a simple shell-model picture for the low-lying positive-parity levels of ^{38}K, the $(1d_{3/2}{}^{-1})_p(1d_{3/2}{}^{-1})_n$ configuration is expected to be the dominant one. Pickup reactions, such as (d,α) and ($p,^3$He) on ^{40}Ca, are expected to populate levels with such configurations and ought to give direct information on proton-neutron hole states in ^{38}K. Higher levels are necessarily excited by pickup of nucleons from deeper subshells. Spectroscopic amplitudes derived from a full *sd*-shell—model calculation[10,11] can be used in a DWBA prediction of the cross section and the results can then be compared with experiments. Excitation of some odd-parity levels of ^{38}K can also be expected because the ground state of ^{40}Ca is known to contain *fp*-shell admixtures.[12,13]

The levels of ^{38}K have been investigated previously by single as well as multinucleon transfer reactions.[12] Abou-Zeid *et al.*[14] and Sens and de Meijer[15] have studied the low-lying levels via the ($p,^3$He) reaction at $E_p=42.5$ MeV and 30 MeV, respectively. Frascaria *et al.*[14] have investigated the ^{40}Ca(d,α) reaction at $E_d=80$ MeV with emphasis on excitation of the $(1f_{7/2}{}^{-1})_p(1f_{7/2}{}^{-1})_n$, $J^\pi=7^+$ configuration in ^{38}K. Recently, a study of the dependence of vector analyzing power (VAP) on the orbital angular momentum L and on the total angular momentum J transferred in the reaction has been made for the ground state and for the 0.46-MeV level of ^{38}K via the ^{40}Ca($\vec{d},\alpha$) reaction at $E_d=16.5$ MeV,[16] and the data have been analyzed assuming a proton-neutron cluster pickup. A study of the levels at 0.0, 0.46, and 1.69 MeV has been made by Merzet *et al.*[17] at $E_d=23$ MeV with a view to understanding the mechanism of ($\vec{d},\alpha$) reactions. No levels beyond an excitation energy of 7.35 MeV have been reported in any of the above experiments.

In the present investigation of the ^{40}Ca(d,α)^{38}K reaction at $E_d=22.8$ MeV, the levels up to an excitation energy of 10.26 MeV in ^{38}K have been studied. The angular distributions have been measured over a wide angular range. DWBA analyses have been performed for ten out of twenty transitions observed; orbital angular moment L transferred and J^π values are deduced.

TABLE I. Optical-model potential parameters used in the analysis of ^{40}Ca$(d,\alpha)^{38}$K reaction at 22.8 MeV.

Channel	V_R (MeV)	r_0 (fm)	a_0 (fm)	W_S (MeV)	$4W_D$ (MeV)	r_I (fm)	a_I (fm)	$2V_{LS}$ (MeV)	r_{LS} (fm)	a_{LS} (fm)	r_C (fm)	β_{NL} (fm)
d	87.7	1.17	0.748	0.7	48.4	1.325	0.729	13.4	1.07	0.66	1.3	0.54
α_1	183.7	1.4	0.564	26.6		1.4	0.564				1.4	0.2
α_2	215.8	1.111	0.785	22.6		1.111	0.785				1.34	0.2
p,n[a]		1.18	0.68					$\lambda=25$			1.25	0.85

[a]The proton and neutron Woods-Saxon well depths are adjusted to reproduce the proper separation energy.

II. EXPERIMENTAL PROCEDURE

The experiment was carried out with a 22.8-MeV deuteron beam from the Argonne National Laboratory cyclotron. The ^{40}Ca target was prepared by evaporating the enriched isotope onto a thin carbon film. The target was always kept in vacuum in order to avoid oxidation. The outgoing α particles were simultaneously detected using a set of four dE/dX-E counter telescopes which were separated by 7.5° from each other. An energy resolution (FWHM) of about 135 keV was obtained. The spectra were recorded at 44 angles in an angular range from 11° to 165°. Other details of the experimental setup and procedure have been discussed previously.[18]

The target thickness was determined to be 60±15 μg/cm^2 by comparing the experimental deuteron elastic-scattering cross section around the maximum at $\theta=55°$ with that obtained by using optical-model potential parameters for deuterons listed in Table I.

The spectra were analyzed with a peak-fitting computer program MALIK.[19] A typical α-particle spectrum at a laboratory angle of 45° is shown in Fig. 1. A consistent energy calibration has been obtained using the levels of ^{38}K at 0.0, 0.459, 1.698, 3.431, and 3.978 MeV,[12] and the levels of ^{10}B at 0.0, 0.718, and 2.155 MeV.[20] The excitation energies of the ^{38}K levels determined in the present experiment are indicated in Fig. 1 and are also listed in Table II. The accuracy of the excitation energies is expected to be ±30 keV for the levels below 4 MeV excitation and about ±50 keV for levels above 4 MeV.

The angular distributions of α particles corresponding to various transitions have been determined and are displayed in Figs. 4–7. The error bars, where shown, contain statistical errors and errors due to background subtraction. The integrated cross sections for some of the levels have been determined using

$$\sigma_{\text{int}}=2\pi\int_0^{\pi}\left[\frac{d\sigma}{d\Omega}\right]_{\text{expt}}\sin\theta\,d\theta$$

and are listed in Table II. The $(d\sigma/d\Omega)_{\text{expt}}$ is the measured differential cross section in the center of mass system, and θ is the center of mass angle.

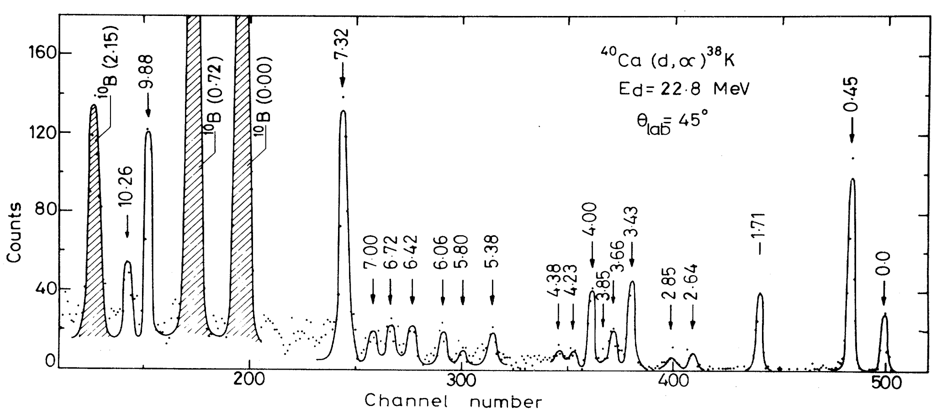

FIG. 1. The spectrum of α particles from the ^{40}Ca$(d,\alpha)^{38}$K reaction at $E_d=22.8$ MeV and $\theta_{\text{lab}}=45°$. The excitation energy (in MeV) shown on the peaks has been determined from the present experiment. Transitions from the ^{12}C$(d,\alpha)^{10}$B reaction are shown by hatched peaks.

TABLE II. Comparison of the excitation energies of the levels in ^{38}K.

Adopted energy levels[a]		^{40}Ca(d,α)^{38}K Present study		Ref. 4[b]
E_x (MeV)	J^{π}	E_x[c] (MeV)	σ_{int} (mb)	E_x (MeV)
0.0	3^+	0.0	0.99	0.0
0.459	1^+	0.45	1.46	0.45
1.698	1^+	1.71	0.74	1.70
2.649	$(2,4)^-$	2.64	0.14	2.63
2.870	2^-	2.85	0.26	2.85
3.431	2^+	3.43	1.06	3.42
3.668	3^+	3.66	0.37	3.60
3.857	1^+	3.85		
3.978	1^+	4.00	0.52	3.97
		4.23		4.28
		4.38		
		5.38		5.28
		5.80		
		6.06		
		6.42		6.35
		6.72		6.60
		7.00		6.90
		7.32	5.51	7.35
		9.88	3.16	
		10.26		

[a]Reference 12.
[b]E_x values are taken from Fig. 4 of Ref. 4.
[c]The errors in E_x are estimated to be ±30 keV for the levels below 4 MeV and about ±50 keV for higher levels.

III. ANALYSIS

A. Optical-model parameters

Previous studies of (d,α) reactions[2,4,21] indicated that the shapes of the DWBA angular distributions are not very sensitive to the choice of the deuteron optical-model (OM) parameters, while they are quite sensitive to the choice of α-particle parameters. Therefore, we have compared the DWBA angular distributions calculated using different sets of α-particle OM parameters with the experimental angular distributions for the 0.0-MeV (3^+) and 3.43-MeV (2^+) transitions. In particular the 3.43-MeV level can be expected to be populated by pure $L=2$ transfer.

The deuteron OM parameters are taken from the global fits (potential set L) of Daehnick *et al.*[22] For α particles, two different sets from the compilation of Perey and Perey[23] have been tried. The OM parameter sets are listed in Table I. The set α_1 is the average parameter set used by Bock *et al.*[24] to fit elastic scattering of 19.47-MeV α particles on nuclei near ^{40}Ca. The set α_2 is derived from an analysis of elastic scattering of 27-MeV particles on ^{39}K. The fits corresponding to these α-particle OM parameters are shown in Fig. 2. (The shell-model spectroscopic amplitudes for the DWBA calculations are taken from Table III.) The set d-α_1 seems to give better fits at forward angles and hence the DWBA analyses for all other transitions have been performed using this set.

B. Form factors

The two-nucleon form factors were calculated from a microscopic model using the method of Bayman and Kallio.[25] The single-particle wave functions of the transferred proton and neutron were generated in a real potential of Woods-Saxon shape with the values of $r_0=1.18$ fm and $a_0=0.68$ fm for the radius and diffuseness parameters, respectively. These bound-state parameters have been derived from an extrapolation to zero energy of the parameters obtained in a proton elastic scattering experiment.[26] For comparison, the set $r_0=1.25$ fm and $a_0=0.65$ fm commonly used for the calculation of form factors has also been tried for a few transitions. The shapes of the DWBA curves are very similar and σ_{DW} for the latter case is about 1.3 times

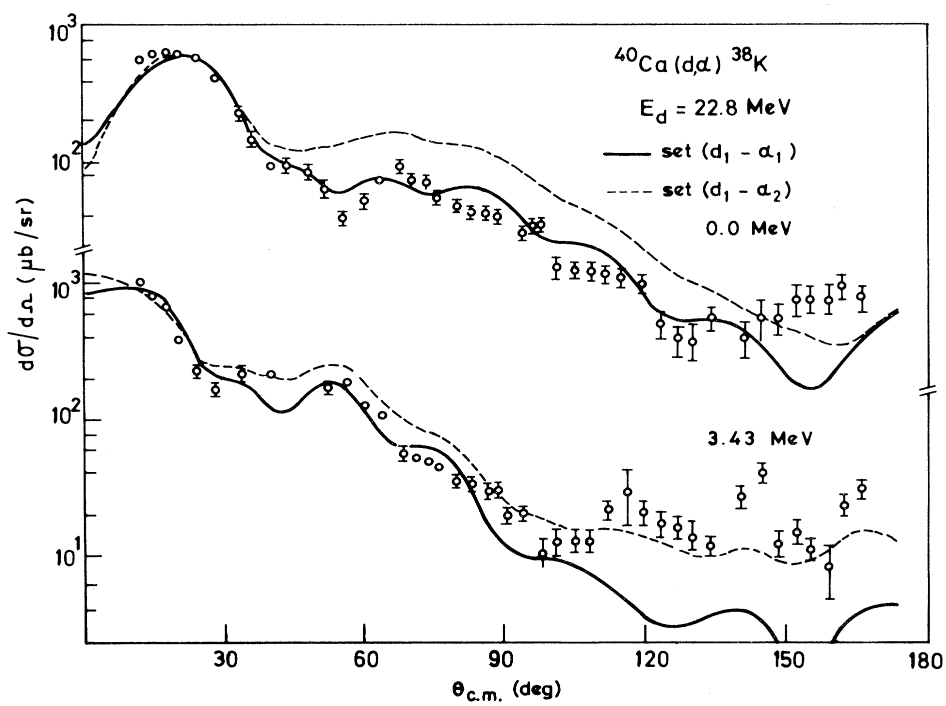

FIG. 2. Comparison of the experimental angular distributions with the DWBA curves obtained using different sets of the optical model parameters listed in Table I.

that for the former case. The nucleon binding energy has been taken to be $S_d/2$, where S_d is the deuteron separation energy of levels under consideration; a relative *s* state has been assumed for the transferred pair of nucleons.

Mixed configurations in the *sd*-shell—model space[11] have been used in the calculation of form factors for most of the levels. The two-nucleon spectroscopic amplitudes used in the analyses are listed in Table III. For negative-parity levels, pure two-particle configurations from an *sdf*-shell—model space have been tried.

C. DWBA cross sections

The DWBA analyses have been made using the code DWUCK (Ref. 27) by including a finite-range correction of 0.4 fm and nonlocality correction given in Table I. The contribution from different *L* transfers for a transition is determined by the shell-model spectroscopic amplitudes (listed in Table III).

TABLE III. Two-nucleon spectroscopic amplitudes for the ^{40}Ca(d,α)^{38}K reaction and the results of the DWBA analysis. The DWBA angular distributions for these transitions are shown in Figs. 4 and 5.

E_x			Two-nucleon spectroscopic amplitudes[a]						
(MeV)	L	J^{π}[a]	($D5,D5$)	($D5,S1$)	($D5,D3$)	($S1,S1$)	($S1,D3$)	($D3,D3$)	N[b]
0.0	2,4	3_1^+	−0.0193	0.0421	−0.5684			2.5836	1.00
0.45	0,2	1_1^+	0.1137		−0.9324	0.4773	−1.2344	0.6052	1.17
1.71	0,2	1_2^+	−0.3501		0.7336	−0.3344	0.0160	1.4924	1.26
3.43	2	2_1^+		0.6228	0.9889		1.9064		0.53
3.66	2,4	3_2^+	−0.7077	−1.7597	−1.7964			0.4186	0.14
4.00	0,2	1_3^+	−0.1855		0.7270	−0.8470	−1.1771	−0.5781	0.61
7.32	0,2	1_4^+	0.1930		−0.9477	−1.3935	0.2908	0.1957	15.8
9.88	2,4	3_3^+	0.0861	−1.9293	−1.7726			−0.3579	7.00

[a]Reference 11. The notation ($D5,D5$) implies a $(1d_{5/2}^{-1})(1d_{5/2}^{-1})_n$ configuration.

[b]Normalized relative to the ground state value of $N = 0.30 \times 10^4$.

TABLE IV. Two-nucleon configurations assumed for odd-parity levels in ^{38}K and the results of the DWBA analysis. The resulting DWBA angular distributions are shown in Fig. 6.

E_x (MeV)	L	Assumed J^π	Two-nucleon configurations[a]	N[b]
2.64	1,3	2^-	$(D3,F7)$	1.06
2.85	1,3	2^-	$(D3,F7)$	2.44

[a]The notation $(D3,F7)$ implies a $(1d_{3/2}{}^{-1})_p(1f_{7/2}{}^{-1})_n$ configuration.
[b]Normalized relative to the ground state value of $N=2.08\times10^4$.

For odd J-even parity transitions, the contributions for two different L transfers have been added together incoherently and the summed curves are represented by solid lines in Figs. 4 and 5. Each of them has been independently normalized for each state according to

$$\left[\frac{d\sigma}{d\Omega}\right]_{\text{expt}}=\frac{N}{2J+1}\left[\frac{d\sigma}{d\Omega}\right]_{\text{DW}}.$$

The resulting normalization factors N have also been listed in Table III. In the case of negative-parity levels the values of N are listed in Table IV.

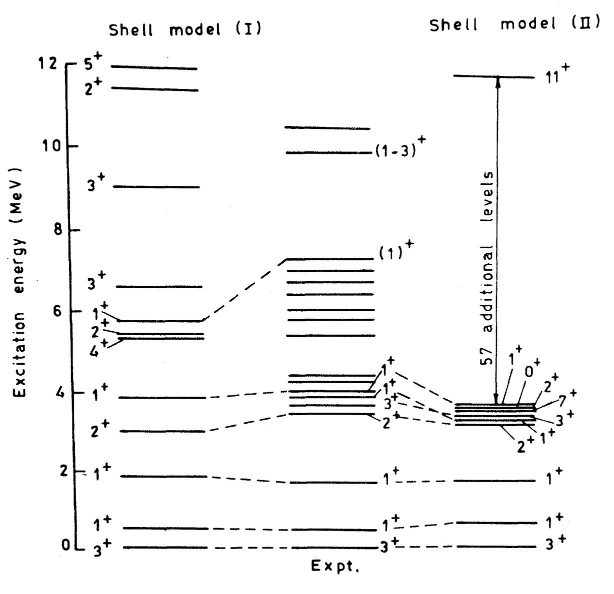

FIG. 3. The positive-parity levels in ^{38}K excited in the ^{40}Ca(d,α) reaction at $E_d=22.8$ MeV and a comparison with shell-model calculations. Shell model (I) refers to the full sd-shell—model calculation (Ref. 11) and shell model (II) refers to the $sdfp$-model calculation (Ref. 28).

IV. RESULTS AND DISCUSSION

A. Excitation energies

The excitation energies of the levels in ^{38}K deduced from the present experiment are compared in Table II with those adopted by Endt and van der Leun,[12] and with the results of the 80-MeV study of the ^{40}Ca(d,α) reaction by Frascaria *et al.*[4] A one-to-one correspondence of our results with the various levels of ^{38}K could be made only for levels up to an excitation energy of 4 MeV. Our results compare well with those obtained by Frascaria *et al.*[4] except for the 5.28-MeV level ($J^\pi=7^+$), which is weakly excited in our experiment.

The excitation energies of positive-parity levels of ^{38}K deduced here are shown in Fig. 3 along with the theoretical predictions of $1d_{5/2}$-$2s_{1/2}$-$1d_{3/2}$-shell—model[11] and $2s_{1/2}$-$1d_{3/2}$-$1f_{7/2}$-$2p_{3/2}$-shell—model[28] calculations.

B. Even-parity levels

The experimental angular distributions to eight even-parity transitions studied in the present ^{40}Ca(d,α)^{38}K reaction are shown in Figs. 4 and 5. The DWBA curves calculated using the spectroscopic amplitudes of Wildenthal and Chung[11] are also shown in the figures. The ground state and the 3.66-MeV level show dominant $L=4$ and 2 transfers, respectively. Previous studies by Frascaria *et al.*[4] and VAP measurements in the ($\vec{d},\alpha$) experiment[16] had strongly suggested the ground-state angular distribution to be $L=4$. The level at 3.43 MeV is found to show a characteristic $L=2$ shape; a pure $L=J=2$ is expected on the basis of the selection rules for this level.

The newly identified level at 9.88 MeV was excited with a total cross section of 3.16 mb, which is three times that for the ground-state transition (see, e.g., Table II). The DWBA calculation was made initially with all possible pure two-nucleon configurations in the sdf-shell—model space. This suggests a dominant $L=2$ shape for the experimental angular distribution for the 9.88-MeV level. Hence $J^\pi=1^+$, 2^+, or 3^+ is expected. A DWBA calculation was performed with mixed configurations corresponding to the theoretically predicted 3_3^+ level at 9.06 MeV and the spectroscopic amplitudes listed in Table III. The predicted shape fits the experimental data quite well (see Fig. 4) and hence the 9.88-MeV level is most likely to have the assignment 3^+, $T=0$.

The levels at 0.45, 1.71, and 4.00 MeV are known[12] to have $J^\pi=1^+$. Therefore an $L=0+2$ transfer is expected. The experimental angular dis-

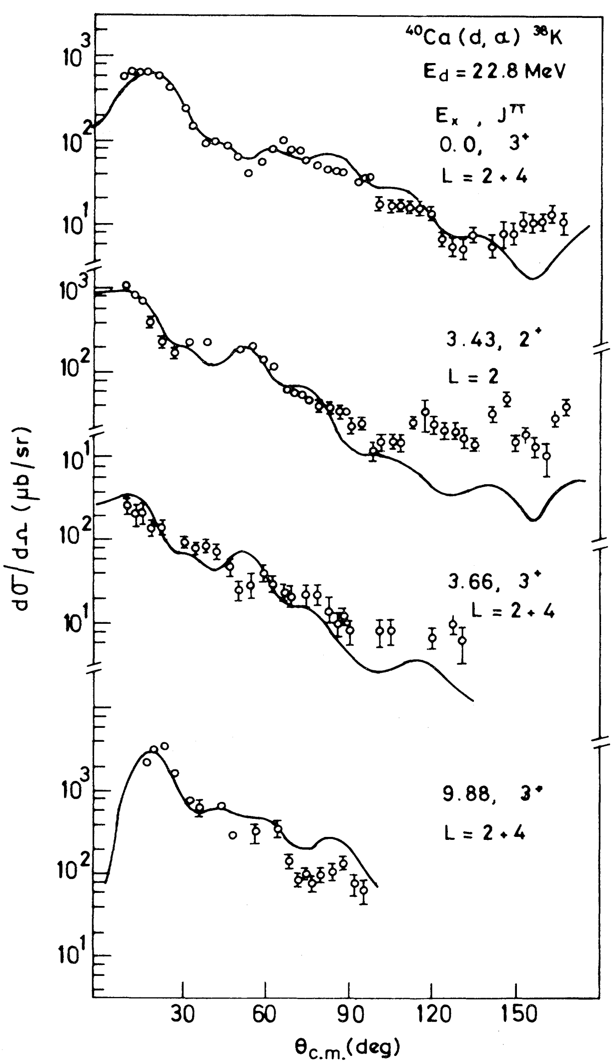

FIG. 4. Angular distributions for the levels excited in the ^{40}Ca(d,α) reaction at E_d=22.8 MeV. The curves are the results of the DWBA analysis. The two-nucleon spectroscopic amplitudes of Wildenthal and Chung used here are listed in Table III.

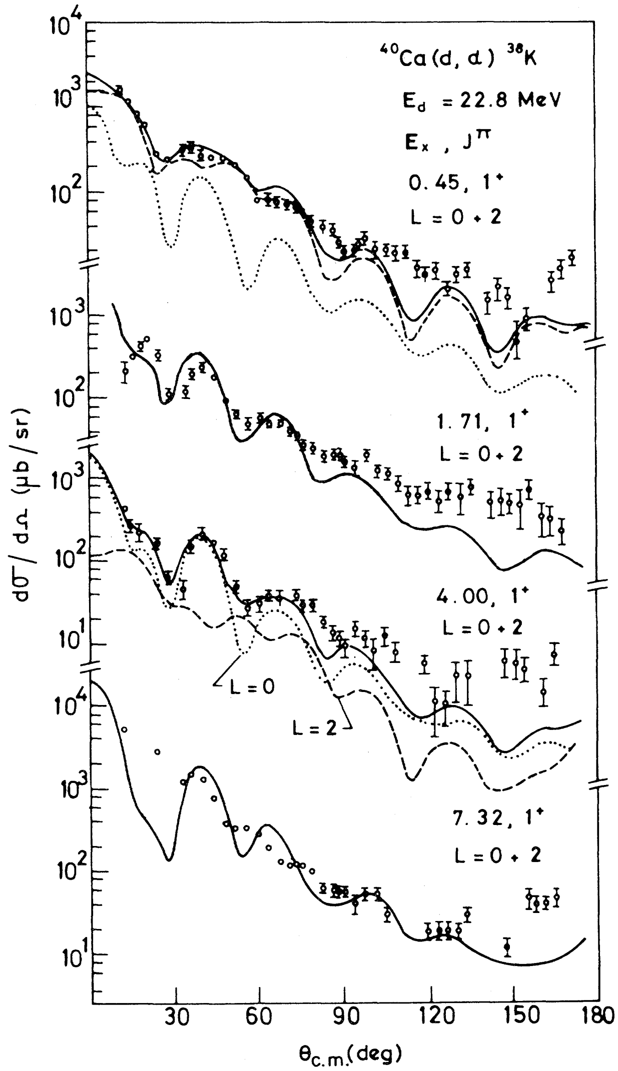

FIG. 5. Angular distributions for the 1^+ levels in ^{38}K. The curves are the DWBA fits for the L =0+2 transfer.

tributions and the curves calculated using sd-shell—model wave functions[11] are shown in Fig. 5. The shapes of the experimental angular distributions for all these transitions indicate dominance by a single L transfer. The partial contributions due to L =0 and 2 in the case of the 0.45- and 4.00-MeV levels are indicated in Fig. 5 along with their incoherent sums. It can be seen that the 0.45-MeV level has largely an L =2 shape, which supports the VAP measurements by Ludwig *et al.*[16] The 1.71- and 4.00-MeV levels show dominant L =0 shapes.

In the 80-MeV study of ^{40}Ca(d,α) by Frascaria *et al.*,[4] a level at 7.35 MeV excitation was observed; no spectroscopic information was, however, deduced. In the present study, the level at 7.32 MeV was excited very strongly. The integrated cross section for the transition to this level is about five times that for the ground-state transition (see Table II). DWBA calculations were made initially with all possible pure two-nucleon configurations in the sdf-shell—model space; the DWBA angular distributions obtained by assuming $(2s_{1/2})_p(2s_{1/2})_n$ pick-up, and $J^\pi = 1^+$ and L =0 have been found to fit the experimental angular distribution fairly well. Calculations have therefore been made assuming the two-nucleon spectroscopic amplitudes (see Table III) for a predicted level at 5.75 MeV (1_4^+). The results of the DWBA analysis are shown in Fig. 5. The 7.32-

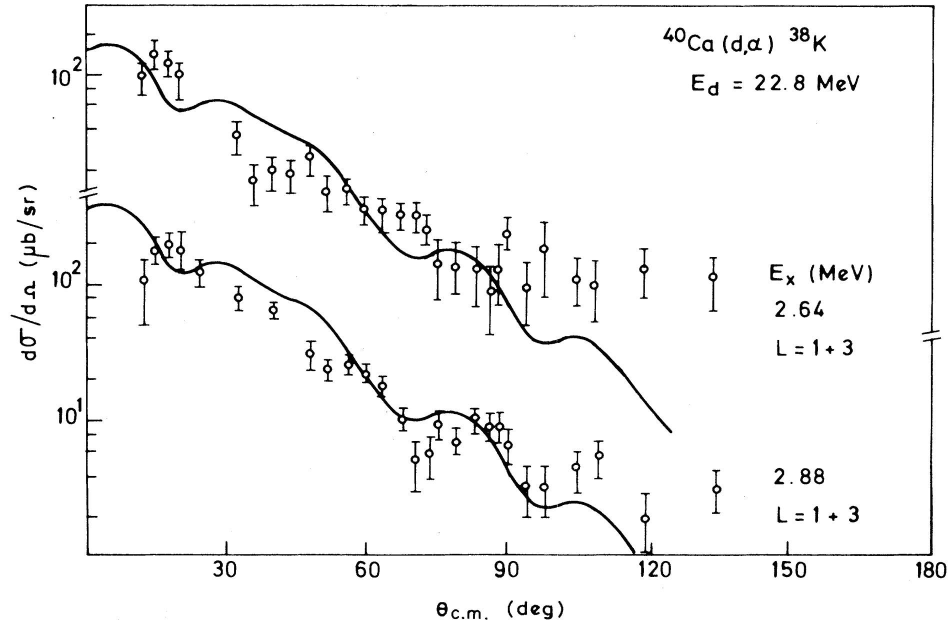

FIG. 6. Angular distributions for the odd-parity levels excited in the ^{40}Ca(d,α) reaction at E_d=22.8 MeV. The curves are the results of the DWBA analysis using the configurations indicated in Table IV.

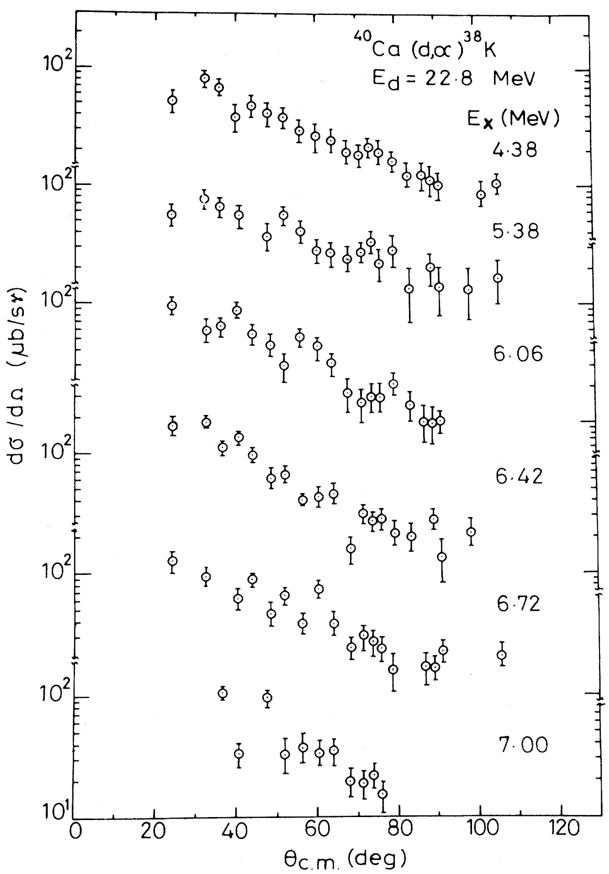

FIG. 7. Angular distributions for the levels in ^{38}K for which L-value assignments could not be made.

MeV level is therefore most likely to have a value $J^\pi=1^+$. The large value of N and the large difference in energies, however, make it likely that the 7.32-MeV level is to be identified with a higher theoretical 1^+ state.

C. Odd-parity levels

Two levels in ^{38}K, one at 2.64 MeV and another at 2.85 MeV are weakly excited in the present (d,α) experiment. From a study of the ^{39}K(d,t)^{38}K reaction, Fortune *et al.*[18] found that the 2.64-MeV level has an $l=1$ angular distribution, while a high resolution study of the ^{39}K(p,d)^{38}K reaction by Wildenthal *et al.*,[29] suggests an $l=3$ pickup for the same level. However, the parity of the level is determined to be negative and the value $J^\pi=(2,4)^-$ is adopted for this level by Endt and van der Leun.[12] It may be that (p,d) favors somewhat higher l transfers than does (d,t). If the transfer results are correct, then $J^\pi=4^-$ is not allowed.

In the present experiment angular distribution patterns for the 2.64- and 2.85-MeV transitions (as shown in Fig. 6) are similar. A good DWBA fit is obtained with $L=1+3$ and $J^\pi=2^-$ transfers for both the transitions. The assumed two-nucleon configurations for these levels are given in Table IV. According to the $sdfp$-shell—model calculation[28] the lowest odd-parity level having a significant fp-shell configuration is at 2.52 MeV excitation and has $J^\pi=4^-$. We expect that the 2.64-MeV level is probably a 2^- state. Our spin assignment for the 2.85-

MeV level, however, is $J^\pi = 2^-$, in agreement with previous studies.[12]

D. Other levels

The experimental angular distributions for a few other weak levels in ^{38}K are displayed in Fig. 7 and they do not exhibit distinctive patterns. Therefore, not much spectroscopic information could be obtained for them. There is a clear indication for the presence of a level in ^{38}K at 10.26-MeV excitation energy. The present data, however, do not enable us to extract an angular distribution for this level.

V. CONCLUSIONS

The excitation energies of various levels in ^{38}K obtained in the present study are in good agreement with the previous results.[4,12]

In spite of the ambiguities in the detailed DWBA predictions for the (d,α) reactions,[6,30,31] additional spectroscopic information on ^{38}K has been obtained via the ^{40}Ca(d,α) reaction. The shapes of the angular distributions for most positive-parity levels below the 9.88-MeV excitation are rather well predicted by DWBA calculations performed using the two-nucleon spectroscopic amplitudes from the full *sd*-shell—model calculation.[11] Tentative J^π assignments made here are consistent with the previous assignments.

Our analysis indicates that the 7.32-MeV level has a large $(2s_{1/2}{}^{-1})_p(2s_{1/2}{}^{-1})_n$ component and hence has $J^\pi = 1^+$. Two new levels, one at 9.88 MeV and another at 10.26 MeV have been identified. The 9.88-MeV level exhibits a characteristic $L = 2+4$ transfer and probably corresponds to the predicted 3_3^+ level at 9.06 MeV.

The energies in ^{38}K deduced from a recent shell-model calculation[28] in the $2s_{1/2}$-$1d_{3/2}$-$1f_{7/2}$-$2p_{3/2}$—model space compare well with those obtained in the present work up to an excitation energy of 3.5 MeV. Since the spectroscopic amplitudes are not available from this *sdfp* calculation, it has not been possible to compare our experimental angular distributions with the theoretical predictions.

Values of the normalization constant N obtained for the levels in ^{38}K from the (d,α) reaction are quoted in the last columns of Tables III and IV. Large variations in the values of N have been found. Similar variations in the relative values of N have been observed in the study of the ^{58,60}Ni(d,α) reaction by Nann *et al.*[32]; these variations are attributed to the type of residual interaction used in evaluating the shell-model wave functions. In the present case the variation in the normalization constant (e.g., normalization constants calculated relative to the ground state) for the levels below the 4.00-MeV excitation is rather small. The variations in the values of the normalization constant could perhaps be further reduced with improvements in the shell-model calculations. The *sd*-shell—model calculation[11] assumes that ^{40}Ca is a good closed shell nucleus. Several experiments[12] have established that a small amount of 2p-2h and 4p-4h admixtures have to be included in the ground state of ^{40}Ca. Therefore, it is strongly felt that an elaborate *sdfp*-shell—model calculation of two-nucleon spectroscopic amplitudes for the levels in ^{38}K is highly desirable. Unfortunately the two-nucleon spectroscopic amplitudes for the levels in ^{38}K are not available from the *sdfp*-shell—model calculation of Hasper.[28]

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