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^{40}Ca(d,^{3}He)^{39}K reaction at 76 MeV

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The differential cross sections of the ^{3}He groups emitted in the ^{40}Ca(d,^{3}He)^{39}K reaction have been measured at a bombarding energy of 76 MeV. The ^{3}He particles were measured with an energy resolution of 55 keV. Differential cross sections were fitted using a distorted wave program and spectroscopic factors were deduced for several proton hole states of ^{39}K. The single hole final states essentially exhaust the sum rule for the $1d_{3/2}$, $2s_{1/2}$, and $1d_{5/2}$ subshells. Because of the strong absorption of ^{3}He particles in nuclear matter, this reaction is a surface reaction, and as such populates only the outer shells. By contrast, the ^{40}Ca(p,2p) reaction is able to populate all proton hole states, including those of the 1p and 1s shells. The population of the quartet of odd parity states, which from a nuclear structure point of view consist of a $1d_{3/2}$ hole coupled to the 3^- state of ^{40}Ca, was observed. The differential cross sections for the ^{3}He groups populating those states were calculated using a coupled channels program and these calculations are in satisfactory agreement with the experimental results.

[NUCLEAR REACTIONS ^{40}Ca(d, ^{3}He), E=76 MeV; measured $\sigma(\theta)$, enriched target. DWBA and CCBA analysis, deduced spectroscopic factors.]

I. INTRODUCTION

Several one-nucleon pickup experiments on s-d shell nuclei[1,2] have noted the existence of deep-lying hole states which have been identified as resulting from 1p-nucleon removal. Such deep-lying hole states have been seen only in reactions on targets at the low mass end of the s-d shell, in which the 1p-shell nucleons are expected to be near the nuclear surface and where absorption in the nuclear interior is not expected to be a dominant factor. No such states in ^{39}K or ^{39}Ca resulting from single nucleon removal from ^{40}Ca have been reported in the literature.

Recent work on the ^{40}Ca(p, 2p)^{39}K reaction at 150 MeV (Ref. 3) has indicated structure in the summed energy spectra corresponding to excitation energy in ^{39}K of at least 60 MeV. States spread over such a range of excitation energies must surely include 1p-hole states. This study of the ^{40}Ca(d, ^{3}He)^{39}K reaction was initiated for the purpose of comparing this proton pickup reaction with the (p, 2p) proton knockout reaction.

In contrast to the (p, 2p) reaction, the (d, ^{3}He) reaction should be less sensitive to the nuclear interior because of the strong absorption of the ^{3}He particles in the nuclear surface. As a consequence, the excitation of states of low spin and high excitation energy may be deemphasized.

Another consequence of the strong absorption of the ^{3}He particles is the sensitivity of the angular distributions of (d, ^{3}He) reactions to the ^{3}He optical model parameters. There has been some uncertainty in the establishment of these parameters by elastic scattering,[4] with several potential sets from "shallow" to "deep" giving equivalent fits. One-nucleon transfer data may resolve this question since the ^{3}He particle occupies only the exit channel and, for particular nuclear final states, can interact with the residual nucleus in a limited fashion.

Furthermore, the ^{40}Ca(d, ^{3}He)^{39}K reaction is interesting in its own right. Earlier measurements[5,6] with lower bombarding energies and poorer resolution than the current experiment observed only about 70% of the $1d_{5/2}$ proton hole strength. Typically, states were observed in ^{39}K up to about 10 MeV of excitation. The $1d_{5/2}$ proton hole strength was found to be very fragmented, its distribution showing a pronounced peak; this was interpreted in terms of "quasiholes". This distribution of $1d_{5/2}$ strength was postulated to occur from decay of the quasihole via doorway states in which the quasihole is coupled to a 2^+ state of the target nucleus. The missing $1d_{5/2}$ strength was thought to occur at higher excitations. It is important to identify the nuclear states contributing to this missing strength. If, for example, it is found below about 9 MeV excitation, the interpretation of the quasihole and its decay may need to be modified. The higher resolution at the Indiana University Cyclotron Facility (IUCF) should enable the identification of weaker states, and use of a higher bombarding energy may enable the excitation of higher-lying heretofore unobserved $1d_{5/2}$ hole states.

For other final states, more complex coupling may occur, giving rise to multistep processes. Such processes have not been considered in the analysis of previous ^{40}Ca(d, ^{3}He)^{39}K measurements. There is some evidence that two-step processes may be difficult to distinguish from single-step direct reactions on the basis of the angular distributions above.[8] In the ^{40}Ca(d, ^{3}He)^{39}K reaction there are several final states which should be excited only by multistep processes. These transitions should make it possible to "calibrate" the extent of multistep processes at this energy. It may then be possible to determine whether the appropriate analysis of multistep reactions can be used to extract spectroscopic information which would otherwise not be obtainable.

Finally, although the spectroscopy of both ^{40}Ca and ^{39}K have been extensively studied,[9] additional work may prove fruitful in understanding the weak-coupling model.[10,11] In particular, while the $\{1d_{3/2}\times 3^-\}$ multiplet in ^{39}K has been well established,[12] the corresponding $\{1d_{3/2}\times 5^-\}$ multiplet has not.

Experimental procedures employed in this work will be described in Sec. II, the experimental results in Sec. III, and the discussions of the interpretation of those results in terms of distorted wave Born approximation (DWBA) and coupled channels Born approximation (CCBA) calculations in Sec. IV.

II. EXPERIMENTAL PROCEDURE

The data were obtained using a 76.4 MeV deuteron beam from the Indiana University multistage cyclotron facility. The incident deuteron beam was momentum analyzed to about 0.02% and dispersion matched at the target location. The beam current was variable from 10 to 100 nA, depending on dead time considerations. Data were taken in two runs. For the initial run[13] the target thickness was 1.5 mg/cm^2 and the overall resolution 140 keV. For the second run[14] the target thickness was 0.5 mg/cm^2, resulting in an overall resolution of 55 keV. The targets were self-supporting 99.9% enriched ^{40}Ca foils. The reaction products were observed using a quadrupole-dipole-dipole-multipole (QDDM) magnetic spectrograph[15] with the acceptance angle set to ± 4 mr horizontally and ± 8 mr vertically for laboratory scattering angles less than 26° and ± 17 mr horizontally and ± 17 mr vertically for angles equal to or greater than 26°.

Particle momenta were deduced by position measurements in a helical delay line focal-plane mounted counter.[16] Two plastic scintillators were placed downstream of the helix; signals from a 0.32 cm scintillator which stopped all ^{3}He particles of interest were used in conjunction with signals from the helix to form a two-dimensional array on a display generated by the on-line computer. A two-dimensional window was drawn around events in this array to serve as a means of particle identification. The following 1.3 cm scintillator was used to veto unwanted events coming from either the target or from the general room background. Data were taken with the program DERIVE[17] using one of the Harris Corporation 6024/4 on-line computers. Angular distributions were obtained from 6° to 42° in the laboratory system at about 2° intervals. At forward angles (6° to 26°) a cone-shaped Faraday cup was mounted inside the scattering chamber; for angles greater than 24° an external Faraday cup mounted in a beam dump about 6.4 m downstream of the target was used. Since the momentum acceptance of the QDDM is only 3%, three field settings were required to cover excitation energies in ^{39}K up to about 12 MeV.

Dead time corrections were made by using elastic deuterons detected in a solid state counter mounted inside the scattering chamber at about 18° to trigger a pulser which was both scaled directly and fed into the detector outputs for display in the experimental spectrum. Beam intensities were adjusted during runs to maintain the overall dead time measured in this way at 10% or less.

Experimental spectra were analyzed off line

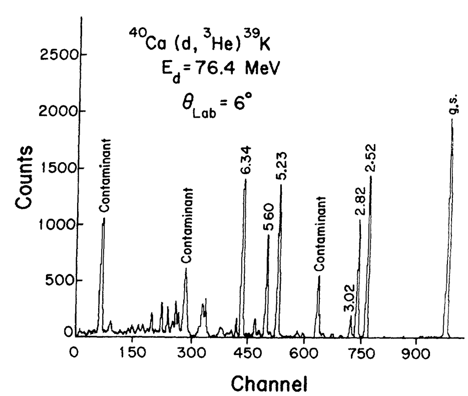

FIG. 1. Spectrum of ^{3}He particles emitted in the ^{40}Ca(d, ^{3}He)^{39}K reaction at a laboratory angle of 6° for an incident deuteron energy of 76 MeV.

using the fitting capability of the program GENFIT,[18] which can use a resolved peak to match an exponential tail to a Gaussian and then use this shape to fit up to five overlapping peaks with variable centroids, peak heights, and widths. Only peaks which were stable in location and width as a function of scattering angle were included in the analysis. For resolved peaks at low excitation, relative cross sections are considered accurate to ± 5%; this was confirmed by the reproducibility of overlapping runs taken on the two different running dates. Absolute cross sections for these peaks are believed to be accurate to ± 15%. Somewhat larger absolute errors exist for overlapping peaks and peaks at higher excitations due to uncertainties in the uniqueness of the fitting procedure.

III. EXPERIMENTAL RESULTS

The spectrum shown in Fig. 1 is for a 6° lab angle and is a composite of the three spectra for differing magnetic field settings, with each of the three spectra normalized for equal charge and adjusted for equal MeV/c per channel. Table I lists the excitation energies of states observed in the present experiment along with those observed in previous ^{40}Ca(d, ^{3}He)^{39}K experiments.[5,6] Above about 9 MeV of excitation for scattering angles larger than about 10°, there were no sharp peaks having essentially the experimental resolution and no peaks of height significantly above background. The binding energy for a single proton in ^{39}K is 6.38 MeV, and the height of the Coulomb barrier opposing emission of a proton from the residual ^{39}K is about 6 MeV. If the probability for a proton to penetrate the Coulomb barrier is significant only for protons having energy greater than half the barrier height, then it follows that sharply resolved states will be seen only up to about 9.5 MeV excitation. States of higher excitation than this will have a significant proton escape width, and therefore a relatively large total width. If the major part of the $1d_{5/2}$-hole strength falls below this excitation, as indeed it does, then the $1d_{5/2}$-hole states will not be so broadened by this increased escape width and their peak heights may be above the background. The structure above 9 MeV excitation, attributable to ^{39}K, is thus much broader and weaker. At laboratory angles greater than about 16° it became impossible to separate this structure from the background. We were able to extract excitation energies for these structures based on the 6° spectrum; we include these along with the other excitation energies in Table I.

Doll $et\ al.$[5] reported states up to 9.75 MeV, but their energy resolution of about 120 keV was insufficient to resolve many of the weaker states above 5.26 MeV. The data of Hiebert $et\ al.$[6] with 34.2 MeV incident deuterons also had an energy resolution between 90 and 150 keV and was unable to resolve many peaks; they report states only up to 8.09 MeV. Calibration of the two lower excitation regions (0 to 4 MeV and 3.5 to 8 MeV) was achieved by using the known lower lying levels of ^{39}K. Consequently, the excitation energies quoted for the strong states in this region are believed to be correct to ±10 keV. For the weak states and/or overlapping peaks, the fitting is less certain and as a consequence the errors quoted for the excitation energies are larger.

For the highest excitation region (7 to 12 MeV), calibrations were extrapolated from the 3.5 to 8 MeV region and the energies obtained for the stronger states compared to the values obtained for the $d_{5/2}$ states by Doll $et\ al.$[5] and Maripuu.[19] The agreement was generally to within ± 20 keV, although lower statistics, higher background, and overlapping peaks all contribute to making the quoted energies less certain for this region than for the other two.

Mention should be made of the partially resolved

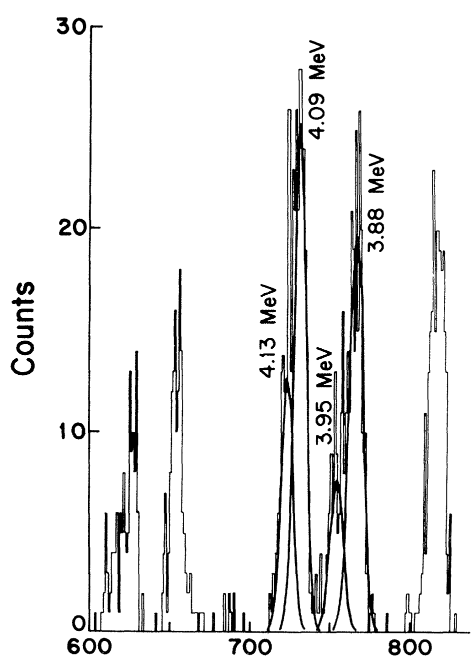

FIG. 2. The ^{3}He spectrum leading to final states in the doublets near 3900 and 4100 keV excitation in ^{39}K, showing the incomplete experimental resolution of the two ^{3}He groups leading to each doublet. The cont 'bution of each final state, as given by the peak-fitting program, is also shown.

TABLE I. Summary of the known excited states of ^{39}K and comparison with results obtained in this experiment.

Current assignment[a]		Present experiment		New
E_c	J^π	E_x	l transfer	assignment
0	$\frac{3}{2}^+$	0	2	
2552.4 ± 0.2	$\frac{1}{2}^+$	2 550 ± 10	0	
2814.3 ± 0.2	$\frac{7}{2}^-$	2 813 ± 10	3	
3019.3 ± 0.2	$\frac{3}{2}^-$	3 020 ± 10	c	
3597.6 ± 0.2	$\frac{9}{2}^-$	3 600 ± 10	c	
3883.1 ± 0.5	$\frac{5}{2}^{-\,b}$	3 880 ± 20	c	
3938.9 ± 0.5	$\frac{3}{2}^+$			
3944.3 ± 0.2	$\frac{11}{2}^-$	3 941 ± 20	d	
4082.8 ± 0.3	$\frac{3}{2}^-$			
4095.0 ± 0.5	$\frac{1}{2}^+$	4 090 ± 30	0	
4125.9 ± 0.5	$\frac{7}{2}^{-\,b}$	4 124 ± 30	c	
4475.2 ± 0.5	$(\frac{1}{2},\frac{3}{2})^-$			
4514.1 ± 1.0	$(\frac{1}{2},\frac{7}{2}^+)$	4 509 ± 15	(3)	$(\frac{5}{2})^-$
4520.6 ± 0.6	$\frac{9}{2}^-$			
4679.1 ± 0.5	$(\frac{5}{2},\frac{7}{2})^-$	4 677 ± 15	(3)	$(\frac{7}{2}^-)$
4738.9 ± 0.7	$(\frac{3}{2}^- - \frac{7}{2}^+)$	4 737 ± 20	d	
4929.4 ± 1.0	$\frac{3}{2}^+$	4 941 ± 20	d	
5008.7 ± 0.5	$(\frac{5}{2} - \frac{9}{2})$			
5009.0 ± 1.0	$(\frac{1}{2} - \frac{5}{2})$			
5157 ± 2	$(\frac{3}{2} - \frac{11}{2}^-)$			
5163.0 ± 1.0	$(\frac{7}{2}^- - \frac{11}{2}^-)$			
5173.2 ± 1.0	$(\frac{1}{2} - \frac{7}{2}^+)$	5 171 ± 15	d	
5261.7 ± 1.0	$\frac{5}{2}^+$	5 258 ± 10	2	
5316.8 × 1.0	$\frac{3}{2}^+$			
5354.0 ± 0.2	$\frac{11}{2}^-$			
5501.3 ± 1.0	$(\frac{5}{2} - \frac{9}{2}^-)$	5 499 ± 15	(3)	$(\frac{5}{2},\frac{7}{2})^-$
5596.3 ± 1.0	$\frac{5}{2}^+$	5 595 ± 10	2	
5644.1 ± 0.5	$(\frac{5}{2},\frac{7}{2})^-$			
5710.6 ± 1.0	$\frac{3}{2}^+$			
5718.4 ± 0.2	$\frac{13}{2}^-$			
5787.6 ± 1.0	$(\frac{1}{2} - \frac{7}{2}^+)$			
5803.4 ± 0.7	$(\frac{5}{2} - \frac{11}{2}^-)$	5 800 ± 25	d	
5826.3 ± 0.7	$(\frac{1}{2},\frac{3}{2})^-$	5 829 ± 15	d	
5891	$(\frac{7}{2},\frac{9}{2})^-$			
5936.9 ± 1.0	$(\frac{1}{2},\frac{3}{2})^-$	5 943 ± 10	2	$(\frac{3}{2}^+)$
6041.0 ± 1.0	$(\frac{1}{2} - \frac{7}{2}^+)$			
6093.0	$(\frac{3}{2} - \frac{11}{2}^-)$	6 099 ± 15	3	$(\frac{5}{2}^-)$
6110.5 ± 1.0	$(\frac{1}{2},\frac{3}{2})^-$			
6186	$(\frac{1}{2} - \frac{7}{2}^+)$			

TABLE I. (*Continued.*)

Current assignment[a]		Present experiment		New assignment
E_c	J^π	E_x	l transfer	
6192	$(\frac{7}{2}^- - \frac{13}{2}^-)$	6192 ± 25	d	
6244.0 ± 1.0	$(\frac{5}{2},\frac{7}{2})^+$			
		6263 ± 25	0	$\frac{1}{2}^+$
6330.7 ± 1.0	$\frac{3}{2}^+$	6328 ± 15	2	$(\frac{5}{2}^+)$
6356 ± 2	$\frac{5}{2}^+$			
6396 ± 2	$(\frac{1}{2}^- - \frac{5}{2}^+)$			
6433 ± 2	$(\frac{7}{2}^- - \frac{15}{2}^-)$			
6465 ± 2	$(\frac{1}{2} - \frac{7}{2})^+$			
6475.3 ± 0.2	$\frac{15}{2}^+$			
6502 ± 2	$(\frac{3}{2},\frac{5}{2})^+$	6503 ± 20	d	
6527 ± 2	$(\frac{1}{2} - \frac{7}{2}^+)$			
6546 ± 2	$\frac{7}{2}^-;\frac{3}{2}$			
		6653 ± 20	2	$(\frac{5}{2}^+)$
6770[e]	$\frac{5}{2}^+$	6736 ± 25	(2)	$(\frac{3}{2},\frac{5}{2})^+$
		6795 ± 25	2	$(\frac{3}{2},\frac{5}{2})^+$
6960[e]	$\frac{5}{2}^+$	6930 ± 25	2	$(\frac{3}{2},\frac{5}{2})^+$
		6987 ± 25	2	$(\frac{3}{2},\frac{5}{2})^+$
7141.7 ± 0.2	$\frac{15}{2}^-$			
7200[e]	$\frac{5}{2}^+$	7191 ± 25	(3)	
		7341 ± 25	d	
7430[e]	$\frac{5}{2}^+$	7423 ± 20	2	$(\frac{3}{2},\frac{5}{2})$
		7502 ± 20	2	$(\frac{3}{2}^+)$
		7606 ± 25	2	$(\frac{3}{2}^+)$
7739.1 ± 0.5[f]	$\frac{3}{2}^-$			
7776.4 ± 0.2[g]	$\frac{17}{2}^+$			
		8017 ± 30	3	$(\frac{5}{2})$
8028.4 ± 0.2[g]	$\frac{19}{2}^-$			
		8204 ± 30	2	$(\frac{3}{2},\frac{5}{2})^+$
8295[f]		8292 ± 30	2	$(\frac{3}{2},\frac{5}{2})^+$
8392[f]		8391 ± 30	2	$(\frac{3}{2},\frac{5}{2})^+$
8529[f]		8518 ± 30	2	$(\frac{3}{2},\frac{5}{2})^+$
		8703 ± 30	2	$(\frac{3}{2},\frac{5}{2})^+$
8900[e]		8880 ± 40	d	
		9012 ± 50	2	$(\frac{3}{2},\frac{5}{2})^+$
9100[e]	$(\frac{3}{2},\frac{5}{2})^+$	9127 ± 50	h	
		9265 ± 50	h	
		9405 ± 50	h	
		9586 ± 50	h	
		9699 ± 50	h	

TABLE I. (*Continued.*)

Current assignment[a] E_c	J^π	Present experiment E_x	l transfer	New assignment
9750[e]	$(\frac{3}{2},\frac{5}{2})^+$	9 808 ± 50	h	
		9 935 ± 50	h	
		10 704 ± 50	h	
		10 864 ± 50	h	
		11 034 ± 50	h	
		11 156 ± 50	h	

[a]Reference 9.
[b]Assignment from Ref. 12.
[c]Not a one-step single particle transfer; see coupled channels calculation.
[d]Not a one-step single particle transfer; coupled channels calculations not made.
[e]Reference 5.
[f]Reference 19.
[g]Reference 34.
[h]Angular distribution not extracted.

doublets near 3900 and 4100 keV. Four peaks were extracted from the region by peakfitting, as shown in Fig. 2. The 3880 and 3941 keV peaks are consistently better resolved than the 4090 and 4124 peaks. This fact is reflected in the errors quoted for these peaks in Table I. In the fitting procedure the peak widths were allowed to vary one channel (~7 keV), and the peak positions varied without constraints. The peak shapes were assumed to be Gaussian; finer peak shape details are irrelevant when there are so few counts per channel. Quite reasonable consistency was obtained in both position and width for each of the four peaks and the continuity of the angular distributions obtained (see Sec. IV) encourages confidence in the peak extraction procedure.

IV. DISCUSSION OF RESULTS

A. DWBA calculations

The ^{40}Ca ground state has been known to be incorrectly described by doubly closed shells for some time. A random-phase approximation (RPA) calculation[20] gave significant occupation numbers for $1f_{7/2}$ (0.102) and $2p_{3/2}$ (0.035) protons as well as the occupation deficiencies for $1d_{3/2}$ (0.170), $2s_{1/2}$ (0.112), and $1d_{5/2}$ (0.037) protons. This being the case, it should be possible to describe transitions to many of the states of ^{39}K as proceeding by means of a single proton pickup. In such situations the DWBA has proved to be very useful in determining the l value of the transferred proton.[21]

Many of the 43 angular distributions extracted from the data were analyzed using a local zero-range DWBA calculation by means of the code DWUCK4 (Ref. 22); nonlocality corrections were not applied. Since the ground state ($\frac{3}{2}^+$) of ^{39}K and the first excited state (2.52 MeV, $\frac{1}{2}^+$) are believed very nearly to exhaust the sum rule for $1d_{3/2}$ and $2s_{1/2}$ proton transfer, respectively, we believed fitting the angular distributions for these states would unambiguously determine the optical model parameters for the ^{3}He particles.

The optical potential parameters used to obtain

TABLE II. Optical model parameters.

Projectile	V_R (MeV)	R_R (fm)	A_R (fm)	W_{vol} (MeV)	W_{surf} (MeV)	R_I (fm)	A_I (fm)	R_C
d[a]	76.95	1.15	0.79		9.62	1.33	0.685	1.30
^{3}He	160.0	1.22	0.63	11.0		1.75	0.33	1.40
p[c]	~60.0[b]	1.25	0.70					1.30

[a]Reference 23.
[b]Adjusted to reproduce measured binding energy.
[c]VSOR adjusted with $\lambda = 25$.

these fits are given in Table II. The deuteron parameters were taken from the preliminary analysis of the elastic scattering of 80 MeV deuterons from ^{40}Ca, an experiment recently performed at IUCF by Foster *et al.*[23] These parameters differ somewhat from those of Duhammel *et al.*[24] for the elastic scattering of 80 MeV deuterons, but it was found that the DWBA fits to the $(d, {}^3He)$ data were insensitive to this difference in the deuteron optical potentials.

The optical potentials for the ^3He particle, however, differ markedly from the elastic scattering results observed at 70 MeV on ^{40}Ca by Chang *et al.*[25] in that much deeper real wells are required to fit the $(d, {}^3He)$ data. Our result is similar to those observed by Didelez *et al.*[26] in an 80 MeV $^{12}C(d, {}^3He)^{11}B$ experiment, in which deep well, zero-range DWBA calculations were used. The inclusion of finite-range effects has only about a 20% effect on the resulting spectroscopic factors in this work. Doll *et al.*[5] used similar potentials to fit the $^{40}Ca(d, {}^3He)^{39}K$ data at 50 MeV and a similar set was used by Roaf *et al.*[27] analysis of 20 MeV $^{41}Ca(d, {}^3He)^{40}K$. It appears that, in general, deep wells give better fits to the one- or two-nucleon transfer reactions than do shallow wells.

1. $l=0$ transitions

In Fig. 3 we show measured angular distributions and DWBA fits to them for the known $\frac{1}{2}^+$ $l=0$ transitions at 2552.4 and 4095.0 keV, and one presumed $l=0$ transition at 6263 ± 25 keV. This state is weak and not completely separated from neighboring states. The existence of additional unresolved states in this excitation region cannot be ruled out, but the dominant strength seems to follow an $l=0$ shape. A state of ^{39}K is known at 6244.0 ± 1.0 keV and believed to be $\frac{5}{2}^+$ or $\frac{7}{2}^+$ on the basis of gamma-ray lifetime measurements.[12] Calculations by Durell[12] using 2p-3h and 4p-5h configurations with deformation do not indicate a $\frac{1}{2}^+$ state this high in excitation, although such calculations do not reproduce the known positive-parity structure of ^{39}K very well. The spectroscopic factors for the measured states are shown for these three states in Fig. 3. The state at 2550 keV contains most of the single particle strength, while that of the 4090 keV state about 10%. The other presumed $\frac{1}{2}^+$ state had a very small percentage of this strength.

2. $l=1$ transitions

The rather small $2p$-proton strength in the ^{40}Ca ground state wave function[20] militates against a significant contribution to the $(d, {}^3He)$ reaction

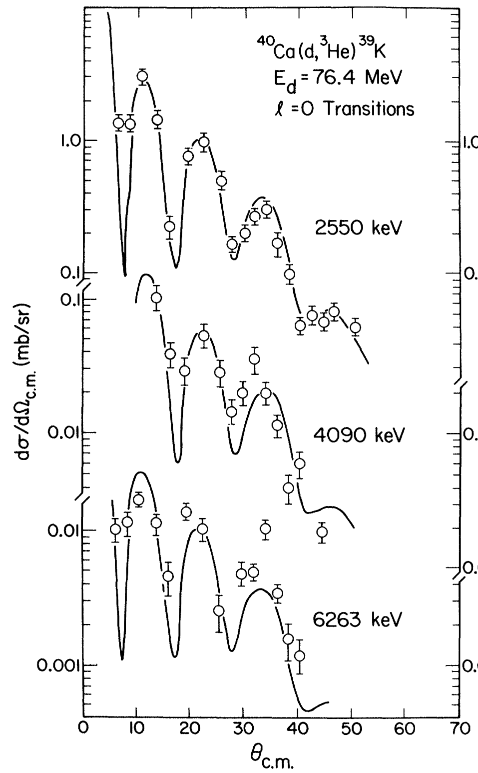

FIG. 3. Measured differential cross sections for the transitions identified as proceeding by $l=0$ pickup, and the DWBA fits to them. The spectroscopic factors for these states are 1.66, 0.2, and 0.01, respectively.

strength to $\frac{1}{2}^-$ or $\frac{3}{2}^-$ states. This is borne out by the coupled channels calculations discussed in Sec. III B. A shell model calculation[28] assuming an inert ^{32}S core and interactions within $1d^n_{3/2}$, $1f_{7/2}$ and $1d^n_{3/2}$, $2p_{3/2}$ configurations (with $n=2$, 4, or 6) predicts several $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states between 5.3 and 7.6 MeV. Such states may be observable in this excitation range, but better energy resolution and statistics will be required. A number of $\frac{1}{2}^-$ and $\frac{3}{2}^-$ resonances have been observed above 7265 keV in the reaction $^{38}Ar(p, \gamma)^{39}K$,[28,29] but the Q value for this reaction prohibits observation of lower-lying states.

3. $l=2$ transitions

A large number of $l=2$ transitions were observed in the experiment to previously identified $\frac{3}{2}^+$ or $\frac{5}{2}^+$ states and to several not previously known. The angular distribution for these are shown in Fig. 4, with spectroscopic factors in Table III. The $1d_{5/2}$ single-particle strength in ^{40}Ca is known to be considerably fragmented.[7] This is apparent from the large number of $l=2$ transitions. The sum of the spectroscopic factors for the presumed $1d_{3/2}$ transitions approaches the shell

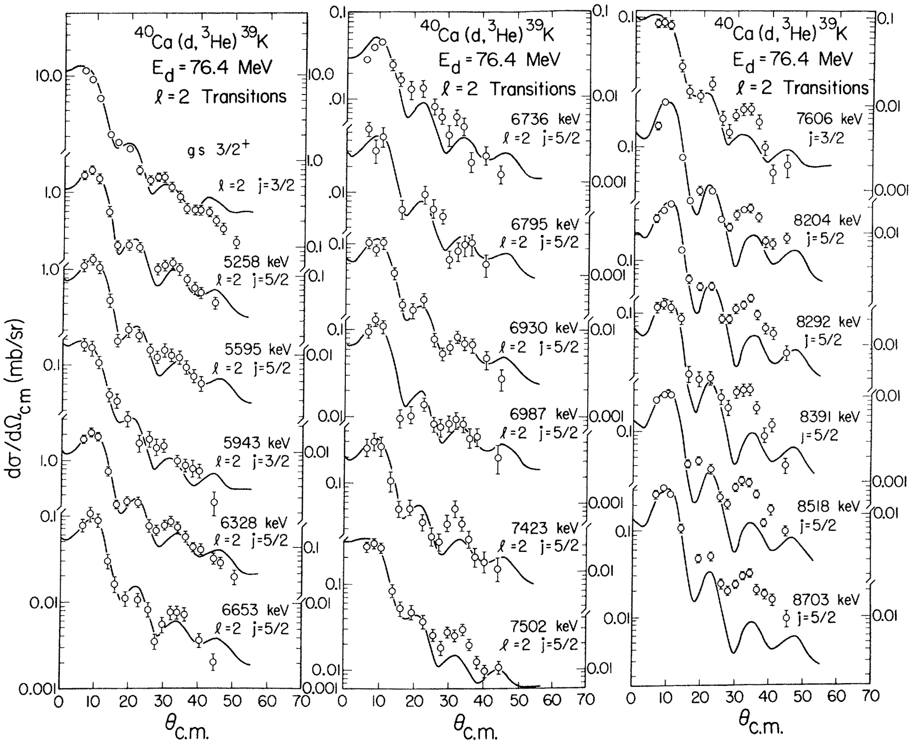

FIG. 4. Measured differential cross sections for the transitions identified as proceeding by $l = 2$ pickup, and the DWBA fits to them.

model limit and is in good agreement with Doll *et al.*[5] However, Doll *et al.* identified only one $1d_{3/2}$ transition, to the ground state, and the spectroscopic factor we obtain to that state is considerably smaller. We note that the spectroscopic factor deduced for this state at an even lower bombarding energy, 34.4 MeV, is even larger.[6] It is likely that a correction for the size of the ^{3}He should be applied similar to that used in the deduction of $B(E2)$ values from alpha-particle scattering.[30]

The sum of the spectroscopic factors for the presumed $1d_{5/2}$ transitions is 94% of the shell model limit, and also disagrees with earlier measurements. In this case, however, there is reasonable agreement for individual transitions. In the region between 5 and 9MeV, we find 18 $l = 2$ transitions, compared to 13 for Doll *et al.*[5] Even though we tentatively identify three of these as $1d_{3/2}$ transitions, the remaining 15 are sufficient to account for most of the $1d_{5/2}$ strength. We believe the high resolution of this measurement has made a more unambiguous determination of spectroscopic factors possible.

TABLE III. Spectroscopic factors for $l = 2$ transitions.

E_x (keV)	J	C^2S	E_x (MeV)	J	C^2S
0000	$(\frac{3}{2})$	2.20	7423	$(\frac{5}{2})$	0.23
5258	$(\frac{5}{2})$	1.38	7502	$(\frac{3}{2})$	0.63
5595	$(\frac{5}{2})$	0.98	7606	$(\frac{3}{2})$	0.18
5943	$(\frac{3}{2})$	0.30	8204	$(\frac{5}{2})$	0.23
6328	$(\frac{5}{2})$	1.57	8292	$(\frac{5}{2})$	0.32
6653	$(\frac{5}{2})$	0.07	8391	$(\frac{5}{2})$	0.04
6736	$(\frac{5}{2})$	0.03	8518	$(\frac{5}{2})$	0.17
6795	$(\frac{5}{2})$	0.03	8703	$(\frac{5}{2})$	0.20
6930	$(\frac{5}{2})$	0.08	9012	$(\frac{5}{2})$	0.24
6987	$(\frac{5}{2})$	0.10			
			$\sum C^2S 1d_{3/2}$		3.31
			$\sum C^2S 1d_{5/2}$		5.67

4. $l = 3$ transitions

The 2814 keV $(\frac{7}{2}^-)$ level is known to be essentially a pure $1f_{7/2}$ proton hole with only small collective admixtures.[31] The DWBA fit is shown in Fig. 5. There is evidence[12] for substantial mixing between this 1p – 2h state and the core coupled $\frac{7}{2}^-$ state at 4126 MeV. This mixing may account for the rather

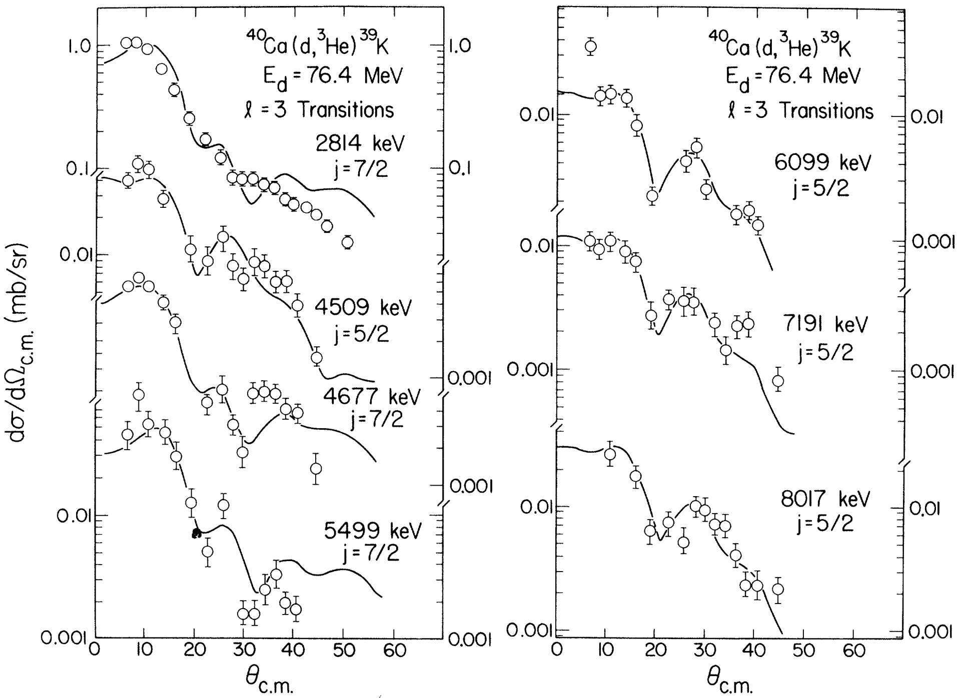

FIG. 5. Measured differential cross sections for the transitions identified as proceeding by $l=3$ pickup, and the DWBA fits to them.

poor DWBA fit. An additional three states had angular distributions which were surprisingly well fitted by $1f$-proton pickup ($l=3$): states at 4509, 4677, and 5499 keV. This transferred l value does not contradict previous studies, and allows the range of acceptable j values for two of these states to be decreased. For the 4509 keV state, a $1f_{5/2}$ fit is significantly better than that for $1f_{7/2}$. It is noteworthy that the j-dependent difference in angular distribution shapes has shifted well into the forward quadrant because of the higher bombarding energy used here, compared to previous experiments, and become more marked for the $l=3$ transfers than for $l=2$. For the other two states, the $j^\pi=\frac{7}{2}^-$ fit is marginally better, so for them no conclusion beyond $l=3$ transfer is drawn. The spectroscopic factors for these four states are given in Table IV.

TABLE IV. Spectroscopic factors for $l=3$ transitions.

State	J^π	C^2S
2814 MeV	$\frac{7}{2}^-$	0.32
4509 MeV	$(\frac{5}{2}^-)$	0.01
4677 MeV	$(\frac{7}{2}^-)$	0.01
5499 MeV	$(\frac{7}{2}^-)$	0.01
6094 MeV	$(\frac{5}{2}^-)$	0.01
7191 MeV	$(\frac{5}{2}^-)$	0.01
8017 MeV	$(\frac{5}{2}^-)$	0.01
	$\sum\frac{7}{2}^-$	0.34
	$\sum\frac{5}{2}^-$	0.04

B. CCBA calculations

In addition to the single-step transitions described in the preceding section, other states can be reached by two-step transitions involving coupling of the proton hole to excitation of the ^{40}Ca

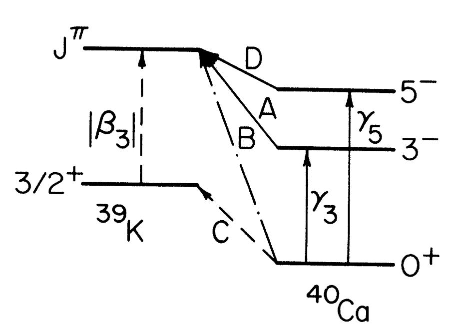

FIG. 6. Illustration of the three possible two-step reaction couplings for the quartet of final states whose structure is that of a $1d_{3/2}$ hole coupled to the octupole vibration state of ^{40}Ca.

core, as illustrated in Fig. 6. Three paths are indicated: excitation of the 3^- octupole vibration state in ^{40}Ca at 3737 keV followed by $1d_{3/2}$-proton pickup to a state indicated as J^π, direct proton pickup from the ^{40}Ca ground state to J^π, and $1d_{3/2}$-proton pickup up to the ^{39}K ground state followed by inelastic scattering of the ^{3}He to the state J^π. Reverse coupling of the $0^+ \to 3^-$ and $0^+ \to \frac{3}{2}^+$ transitions must be included when elastic scattering cross sections are being considered, but in the case of transfer reactions this process (which is effectively third order) cannot affect the results significantly. On a more pragmatic level, the inclusion of reverse coupling requires about four times as much computer time and is prohibitively expensive.

These calculations were done on the University of Melbourne CYBER computer using the program CHUCK4,[32] for the quoted states at 3019, 3597, 3883, and 4126 keV excitation, which have been identified as the weak coupling multiplet having the configuration[12]

$$[\pi^{-1}(1d_{3/2}\times{}^{40}\mathrm{Ca}^*(3^-))]\ \tfrac{3}{2}^- \le J^\pi \le \tfrac{9}{2}^- . \qquad (1)$$

The $0^+ \to 3^-$ coupling parameter $\gamma_3 = -0.23$. The $0^+ \to \frac{3}{2}^+$ coupling parameter was fixed at 420. In CHUCK for $(d, {}^3\mathrm{He})$, this number is related to the spectroscopic factor by

$$\left(\frac{V}{225}\right)^2 = S . \qquad (2)$$

The coupling parameters A and β_3 were varied to obtain the fits shown as full lines in Fig. 7; the deduced results are given in Table V.

The direct pickup, coupling B in Fig. 6, was found to be rather small for all transitions, as is expected, but is certainly not negligible for the transitions to the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ final states. In Fig. 8 we show the contribution of the three paths separately for the $\frac{3}{2}^-$ state.

Coupling A, shown in Fig. 6, refers to a two-step reaction in which the first step is excitation of the octupole vibrational state of the ^{40}Ca target, followed by pickup of a $1d_{3/2}$ proton. Given that the ground state of ^{39}K is well represented by a $1d_{3/2}$- proton hole coupled to the ^{40}Ca ground state, the expectation is that the two-step process described above will exhibit a $1d_{3/2}$- proton pickup strength, which is just that shown by the one-step transition to the ^{39}K ground state. That is, the sum of S_A for the quartet of states on the 3^- state of ^{40}Ca should be the same as the $0^+ \to \frac{3}{2}^+$ spectroscopic factor, independent of the purity of the $1d_{3/2}$ hole in ^{39}K. Table V shows that the sum of the S_A factors is less than the value 3.31 obtained for the $0^+ \to \frac{3}{2}^+$ proton pickup.

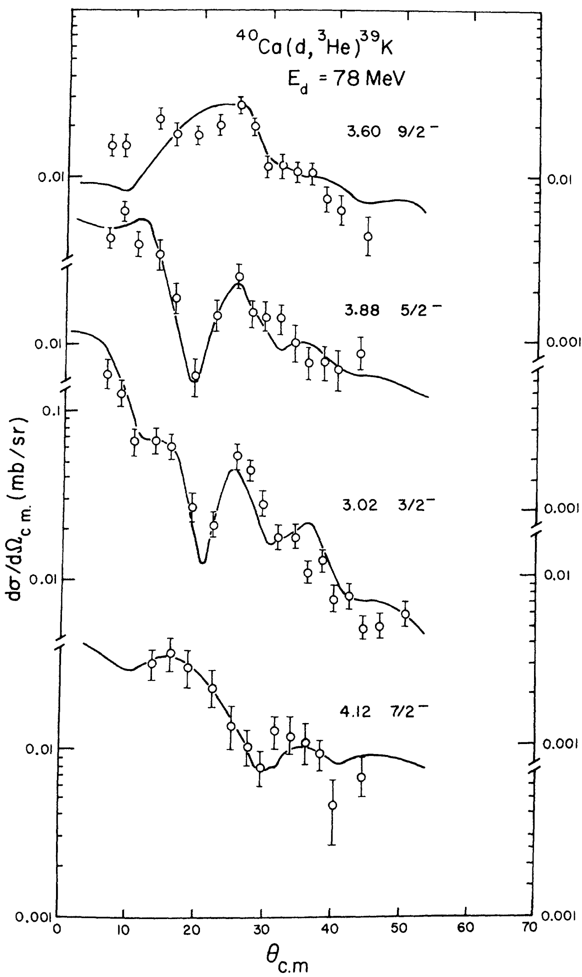

FIG. 7. Measured differential cross sections for the four states, referred to in Fig. 6, reach by two-step reaction processes, and the fits to them obtained in the coupled channels calculation.

TABLE V. Spectroscopic strengths for the core-coupled states by means of CCBA calculations.

J^π	Final state Excitation energy (keV)		S_A	S_B	S_C
$\frac{3}{2}^-$	3019		0.50	0.02	0.10
$\frac{9}{2}^-$	3597		0.68		0.06
$\frac{5}{2}^-$	3883		0.07	0.05	0.24
$\frac{7}{2}^-$	4126		0.84	0.01	0.28
		Sum	2.09[a]		0.68[b]

[a]To be compared with 3.31.
[b]To be compared with 1.00.

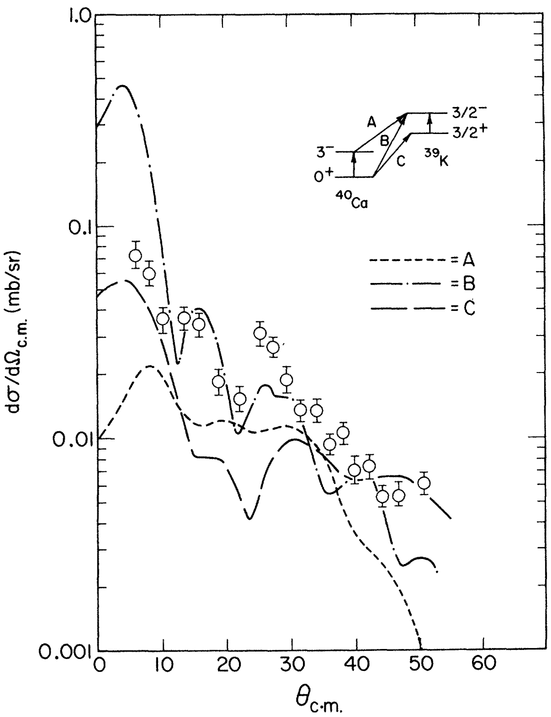

FIG. 8. Differential cross section of ^{3}He particles populating the $\frac{3}{2}^-$ state of ^{39}K, a member of the quartet of states in Fig. 6, showing the contributions of paths A, B, and C separately. When combined they add coherently.

One explanation of this deficiency is that it may result from the mixing of the $\frac{7}{2}^-$ and $\frac{9}{2}^-$ states based on the ^{40}Ca 3^- state with those based on the 5^- state. While the four states described by the coupling of a $1d_{3/2}$ proton hole to the 3^- excited state of ^{40}Ca have been identified with reasonable certainty ($\frac{3}{2}^-$ at 3019 keV excitation, $\frac{9}{2}^-$ at 3598 keV, $\frac{5}{2}^-$ at 3883 keV, and $\frac{7}{2}^-$ at 4126 keV), all four states formed by coupling a $1d_{3/2}$ proton hole to the 5^- excited state of ^{40}Ca have not been identified. They have J^π values of $\frac{7}{2}^-$, $\frac{9}{2}^-$, $\frac{11}{2}^-$, and $\frac{13}{2}^-$. The $\frac{11}{2}^-$ state at 3944 keV excitation is the obvious candidate for one of the states; a candidate for the $\frac{13}{2}^-$ state is the state at 4514 keV tentatively assigned that spin and parity by Nann[33] on the basis of a study of the ^{41}K(p,t)^{39}K reaction. The other two states are more difficult to specify and we have therefore not made coupled channels calculations for final states whose structure is described by a $1d_{3/2}$- hole coupled to the 5^- state of ^{40}Ca.

V. SUMMARY AND CONCLUSIONS

This study has examined the ^{40}Ca(d, ^{3}He)^{39}K reaction at 76 MeV bombarding energy with good resolution (55 keV). Differential cross sections were measured for 43 ^{3}He groups leading to excited states of ^{39}K, and the majority of these were fitted with DWBA calculations describing a single step proton pickup process. From these fits, the spectroscopic factor for each final state so fitted was deduced. The fits specified also the orbital angular momentum of the picked-up proton in ^{40}Ca. Indeed, it proved to be possible to specify the j transfer for some of the $l=2$ and $l=3$ transfers. This is possible because the higher momentum transfer in this present study means that the j-dependent effects reported earlier in lower energy single nucleon transfer reactions are brought into the forward quadrant.

The excitation energies deduced for the states of ^{39}K are in excellent agreement with those given by Endt and Van der Leun[9] up to 8 MeV in excitation energy, and with those given by Doll *et al.*[5] for the states given by the latter between 8 and 9 MeV. The spectroscopic factors deduced for the $2s_{1/2}$, $1d_{3/2}$, and $1d_{5/2}$ hole strength exhaust 90% of the sum rule limit for each of those single proton orbitals. In view of the uncertainties associated with the extraction of spectroscopic factors, it is unlikely that all of the proton hole strength for these orbitals has been observed in the present experiment.

No transitions having an angular distribution characteristic of $l=1$ were observed. The transitions to final states of spin-parity $\frac{3}{2}^-$ are evidently dominated by a two-step reaction mechanism; this situation reflects, as well, the smallness of $2p_{3/2}$ and $2p_{1/2}$ components in the ground state of ^{40}Ca.

Angular distributions were not extracted for ^{3}He groups which left ^{39}K in states greater than 9 MeV in excitation. Eleven such groups were observed, and these groups each had an energy width greater than that of the groups corresponding to population of states of lower excitation. This is attributed to the fact that these states have energy 3 to 5 MeV above the separation energy of a proton in ^{39}K. Such an energy excess will lead to a significant probability for the proton to penetrate the Coulomb barrier (height about 6 MeV), thus leading to an escape width the presence of which will make these states broader than those of excitation below, say, 7 MeV. The width of these states meant that it was much more difficult to determine the counts in the corresponding peaks with enough accuracy to warrant extraction of an angular distribution.

Differential cross sections were found for the four states which have been identified as having the structure of a $1d_{3/2}$-proton hole coupled to the lowest octupole vibration state of ^{40}Ca. This description of the structure also specifies one possible two-step reaction pathway to the population of these states. They are the states at 3019 keV ($\frac{3}{2}^-$), 3598 keV ($\frac{9}{2}^-$), 3883 keV ($\frac{5}{2}^-$), and 4126 keV ($\frac{7}{2}^-$). Coupled channels calculations were made of the differential cross sections of each of the four ^{3}He groups, the strength parameters S_A, S_B, and S_C being varied to give an optimum fit to the experimental data. Satisfactory fits were indeed possible; the sum of the parameters S_A is to be related to the $1d_{3/2}$-hole strength observed in the single step reaction processes. The S_B values reflect the purity of the ground state wave function since these direct pickup spectroscopic factors refer to pickup of $1f_{7/2}$, $1f_{5/2}$, and $2p_{3/2}$ protons from the ^{40}Ca ground state.

No pickup from the "inner" $1p$ and $1s$ shells has been found in this experiment; this is attributed to the strong absorption of ^{3}He, in particular, in the nuclear surface. As a consequence, the spectroscopy of the deep shells must be left to reactions involving particles less strongly absorbed in nuclear matter, for example, the ^{40}Ca(p, 2p)^{39}K reaction.

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