Nuclear Spectroscopy of ^{42}Ca via the (d, t), $(^3$He$, d)$, and (α, α') Reactions

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Measurements of the ^{43}Ca(d,t) and ^{41}K$(^3$He$,d)$ reactions have been carried out at incident energies of 20 and 23 MeV, respectively, with an energy resolution of 9–14 keV full width at half maximum. Single-particle strength distributions have been studied up to an excitation energy of 6.24 MeV in ^{42}Ca. About 75% of the total $l = 3$ pickup strength is observed in the even-parity states up to the 6^+ state at 3.188 MeV. The other 25% is distributed over 10 states between 3.2 and 6.2 MeV. The $l = 2$ pickup transitions should populate four $T = 1$ states of the $[(1f_{7/2})^3 \times 1d_{3/2}^{-1}]$ multiplet with $J^\pi = (2, 3, 4, 5)^-$. The strength is found to be spread over at least 20 states, however, and many transitions show considerable $l = 0$ admixture. The stripping measurements also show extensive fragmentation of the $l = 3$ strength leading to the negative-parity states of ^{42}Ca, and large differences are observed between the strength distributions observed in stripping and pickup to these states. The particle transfer measurements were supplemented by high-resolution measurements of the ^{42}Ca(α, α') reaction at 28.5 MeV which provided definite spin-parity assignments to many natural parity states in ^{42}Ca.

1. INTRODUCTION

A great deal of experimental and theoretical effort has gone into the study of the structure of ^{42}Ca. Single-particle structure has been investigated in the ^{43}Ca$(d, t)^{42}$Ca, ^{43}Ca$(^3$He$, \alpha)^{42}$Ca, and ^{41}K$(^3$He$, d)^{42}$Ca reactions.[1–5] Collective states have been studied via inelastic scattering of protons,[6] deuterons,[7] and α particles.[8,9] Measurements of the ^{40}Ca$(t, p)^{42}$Ca reaction[10,11] and the ^{44}Ca$(p, t)^{42}$Ca reaction[12,13] have also been reported. Particle-γ coincidence[14–17] and β-decay[18,19] studies have resulted in measurements of spins and lifetimes for most states of ^{42}Ca up to about 4.2 MeV. The ^{41}Ca$(d, p)^{42}$Ca reaction has also been studied recently.[20]

Several theoretical calculations have been performed using different models. Extensive work, with some success, has been directed toward the study of positive-parity states by making use of different interactions and the $1f$-$2p$ space[21–28] or a more expanded space.[29,30] Somewhat more successful calculations using both spherical and deformed basis states have been performed.[31–34] In an attempt to explain the high density of negative-parity states, a shell-model calculation with the $[(1f_{7/2})^3 \times 1d_{3/2}^{-1}]$ configuration[35] has had little success. A core-particle-coupling calculation with random-phase approximation (RPA) core states[36] succeeds in explaining the position and density of the low-lying odd-parity states, but cannot produce the observed spectroscopic factors for the ^{41}K$(^3$He$, d)$ reaction. Recently the Padova group has repeated the (3p-1h) shell-model calculation[5] using different sets of $(1f_{7/2} \times 1d_{3/2}^{-1})$ interaction parameters, but their stripping strengths do not agree with the experimental values.

The present measurements were undertaken initially to study the negative-parity states ascribed to the $[(1f_{7/2})^3 \times 1d_{3/2}^{-1}]_{T=1}$ configuration in ^{42}Ca. One earlier (d, t) measurement[1] went only to an excitation of 3.19 MeV. Although it gave the distribution of $1f_{7/2}$ strength among low-lying states, it provided no information on the $l = 0$, 1, and 2 strengths. A later (d, t) measurement[2] extended to higher energies, but with a limited energy resolution (of about 100 keV). A measurement of the ^{43}Ca$(^3$He$, \alpha)$ reaction[3] was reported up to an excitation energy of about 10 MeV in ^{42}Ca. This permitted identification of the $[(1f_{7/2})^3 \times 1d_{3/2}^{-1}]_{T=2}$ states, but the angular distributions in $(^3$He$, \alpha)$ did not allow clear l assignments for many low-lying states.

The present pickup results provide a clear measurement of transfer l values and spectroscopic strengths for states up to about 6 MeV in ^{42}Ca. An immediate conclusion from these results is that the expected states of the $(f_{7/2})^3 \times d_{3/2}^{-1}$ multiplet are extensively fragmented, and the measurements provide little information on the $f_{7/2}$-$d_{3/2}$ effective interaction.

The $l = 3$ transitions showed a strength distribution in good agreement with earlier results for states up to the 6^+ state at 3.188 MeV. About 25% of the total $l = 3$ strength was observed in higher states. Weak $l = 1$ admixtures were observed in many $l = 3$ transitions, but the total $l = 1$ strength indicated very slight excitation of $2p$ particles in the target ground state. If it is assumed that $1f_{5/2}$ excitations are correspondingly small, then the observed $l = 3$ strength must be essentially all assigned to $1f_{7/2}$ pickup. As a result, the centroids of the $(f_{7/2})^2{}_{T=1}$ states are shifted appreciably from the values based only on the even-parity states up to the 3.188-MeV 6^+ state.

Measurements of the ^{41}K(^{3}He, d) reaction have been reported[4] at 11.0 MeV, going up to an excitation energy of 5.79 MeV. At this incident energy, it was difficult to measure mixing of $l=1$ and $l=3$ strengths in transitions to the negative-parity states. There also appeared to be some inconsistencies between the results of the previous (^{3}He, d) measurements[4] and the present (d,t) results. For these reasons, measurements of the (^{3}He, d) reaction were repeated, at a few angles, at an incident energy of 23.0 MeV. These show a strength distribution for $l=3$ transitions to the negative-parity states in ^{42}Ca which is quite different from that observed in the $l=2$ pickup. This is a further indication of the extent of fragmentation of the $[(f_{7/2})^3 \times d_{3/2}{}^{-1}]$ states.

2. EXPERIMENTAL PROCEDURES

The ^{43}Ca(d,t) measurements were carried out at an incident energy of 20 MeV. Line targets of ^{43}Ca 1 mm in width were prepared by simultaneous decomposition of $CaCO_3$ and evaporation of the Ca

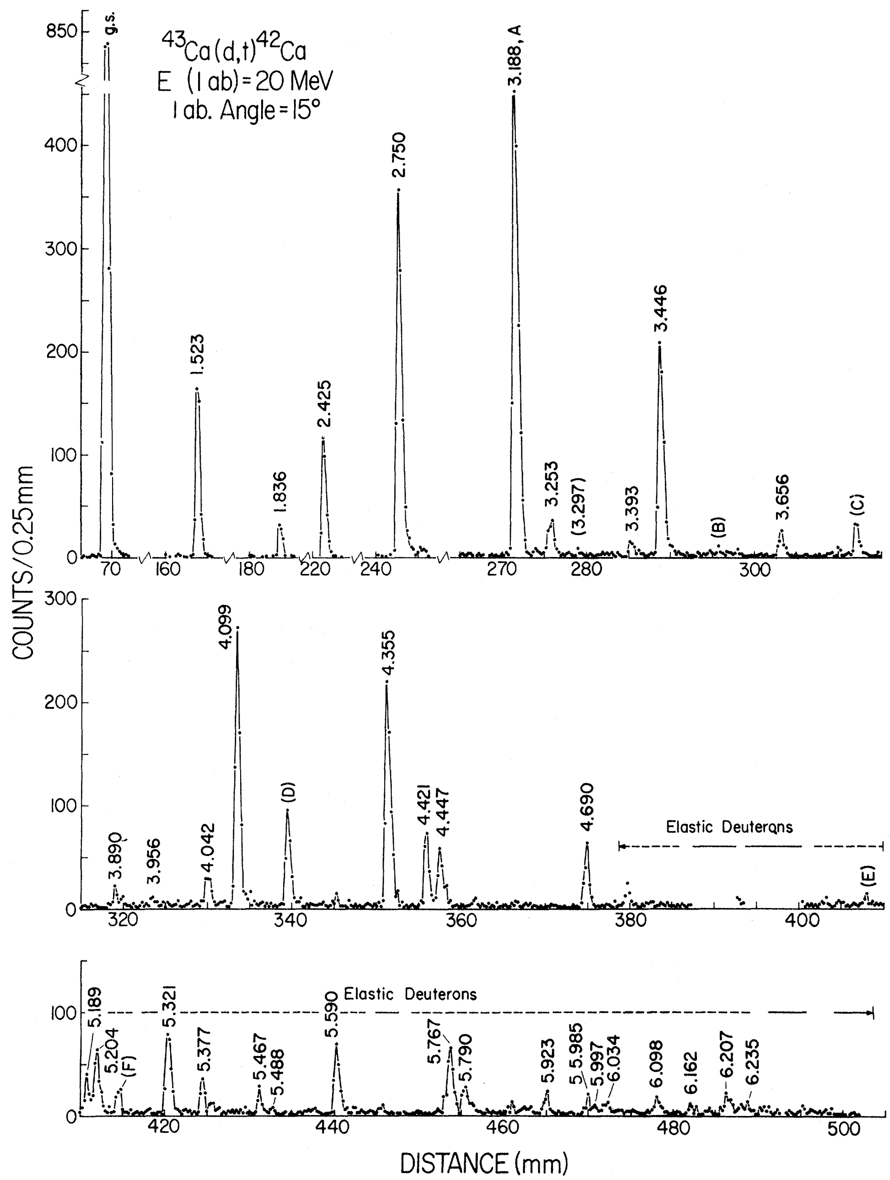

FIG. 1. The spectrum of tritons from the ^{43}Ca$(d,t)^{42}$Ca reaction at laboratory angle of 15°. The letters A, (C), (D), (E), and (F) stand for the ground state and the 0.59-, 0.99-, 1.96-, and 2.05-MeV excited states of ^{43}Ca. These groups are due to the 5.4% of the ^{44}Ca impurity in the target. (B) indicates the location of the ground state of ^{41}Ca, arising from a 0.65% of ^{42}Ca impurity in the target.

as metal from a tantalum boat. Targets were evaporated on carbon foils 20 $\mu g/cm^2$ in thickness. The enriched material contained 81% ^{43}Ca, with about 5% ^{44}Ca and 14% ^{40}Ca. Target thickness was about 60 $\mu g/cm^2$, giving an energy resolution in the (d, t) measurement of 10 to 14 keV. Reaction products were detected in nuclear emulsions by using an Enge broad-range spectrograph. Angular distributions were measured in steps of 2.5 or 5° over the range from 7.5 to 60° lab.

The $^{41}K(^3He, d)$ measurements were carried out with 23-MeV ^3He. Line targets 1 mm in width were prepared by evaporating KI enriched to 99% in ^{41}K on 20-$\mu g/cm^2$ carbon foils. Target thickness was about 70 $\mu g/cm^2$, yielding an energy resolution of 12 to 14 keV. In these measurements, it was intended merely to obtain a comparison of the relative excitation in stripping of the states in ^{42}Ca seen in pickup. For this reason, data were taken only at angles of 10, 20, 30, and 45°. These angles were chosen on the basis of distorted-wave Born-approximation (DWBA) calculations which indicated that transfer l values could be clearly determined from measurements at these angles. If the parity of the final state is known from (d, t) measurements, then mixtures of $l = 0 + l = 2$ or $l = 1 + l = 3$ can also be determined.

Since many of the states seen at high excitation

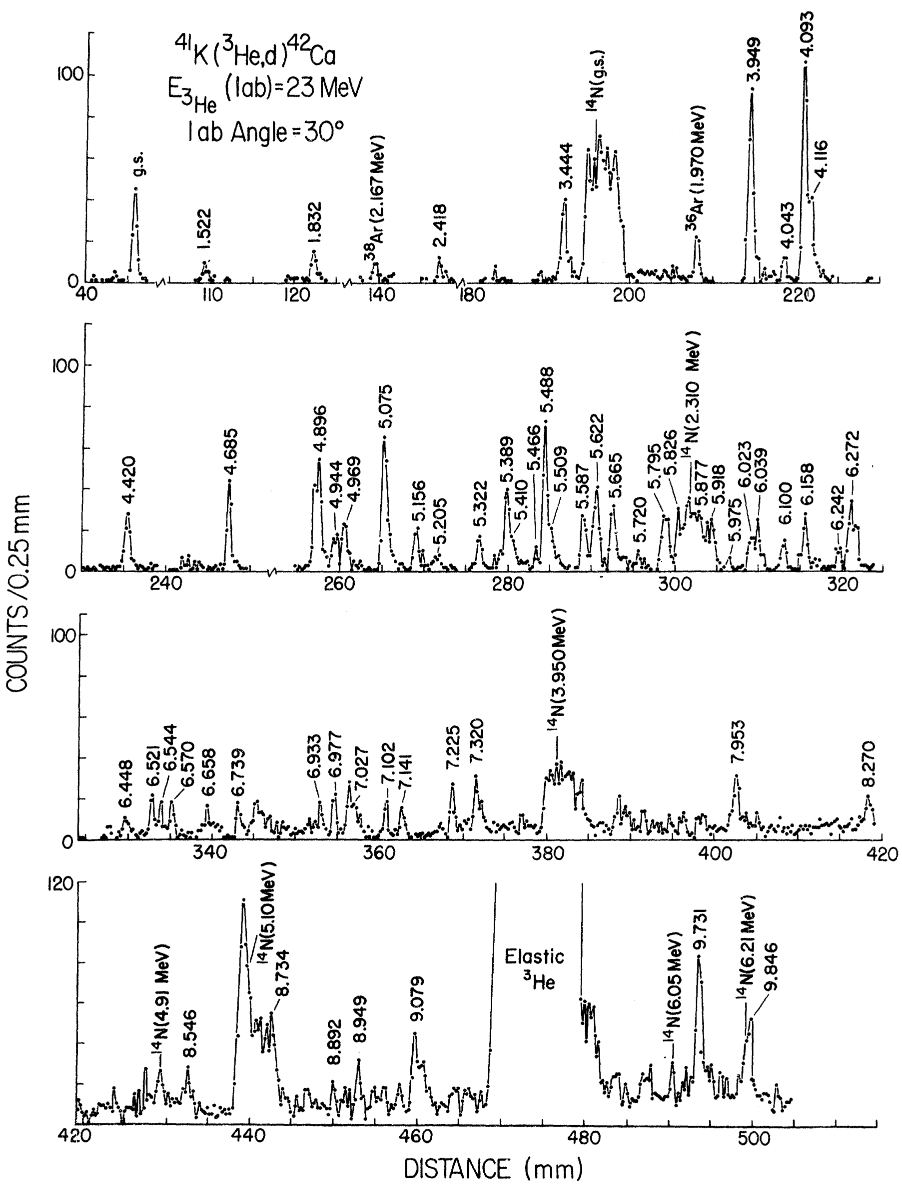

FIG. 2. Spectrum of deuterons from the $^{41}K(^3He, d)^{42}Ca$ reaction.

in the particle-transfer reactions lacked spin and parity assignments, measurements of inelastic α scattering were carried out at 28.5 MeV to identify some of the natural parity states. For these measurements, targets of enriched ^{42}Ca (94% ^{42}Ca) were prepared in the same fashion as the ^{43}Ca target. Target thickness was about 90 μg/cm^2, and the energy resolution was about 25 keV. Measurements were carried out for the angular range 14 to 43° in steps of 2 or 3° at forward and 5° at large angles. Since the spins of all low-lying states are known, measurements were carried out only for states above 3 MeV excitation.

Reaction cross sections were determined by comparison with the elastic scattering cross section. The elastic scattering was monitored by a counter fixed in the scattering chamber at 60° for the (^{3}He, d) and (d, t) measurements and at 45° for the (α, α'). Elastic cross sections were calculated using the same optical-model parameters as used in the DWBA reaction analysis. The over-all uncertainty in absolute reaction cross sections is estimated to be about 25%. Relative uncertainties for measurements at different angles are given by the counting statistics which were between 3 and 10%, except for very weak or very intense groups.

3. EXPERIMENTAL RESULTS AND DWBA ANALYSIS

Typical spectra for the three reactions studied are shown in Figs. 1–3. The excitation energies of the observed levels are listed in Tables I and II. Except for very weak states, the excitation energy measured at different angles did not deviate from the mean by more than 5 keV, and the mean excitation energies reported are believed to be accu-

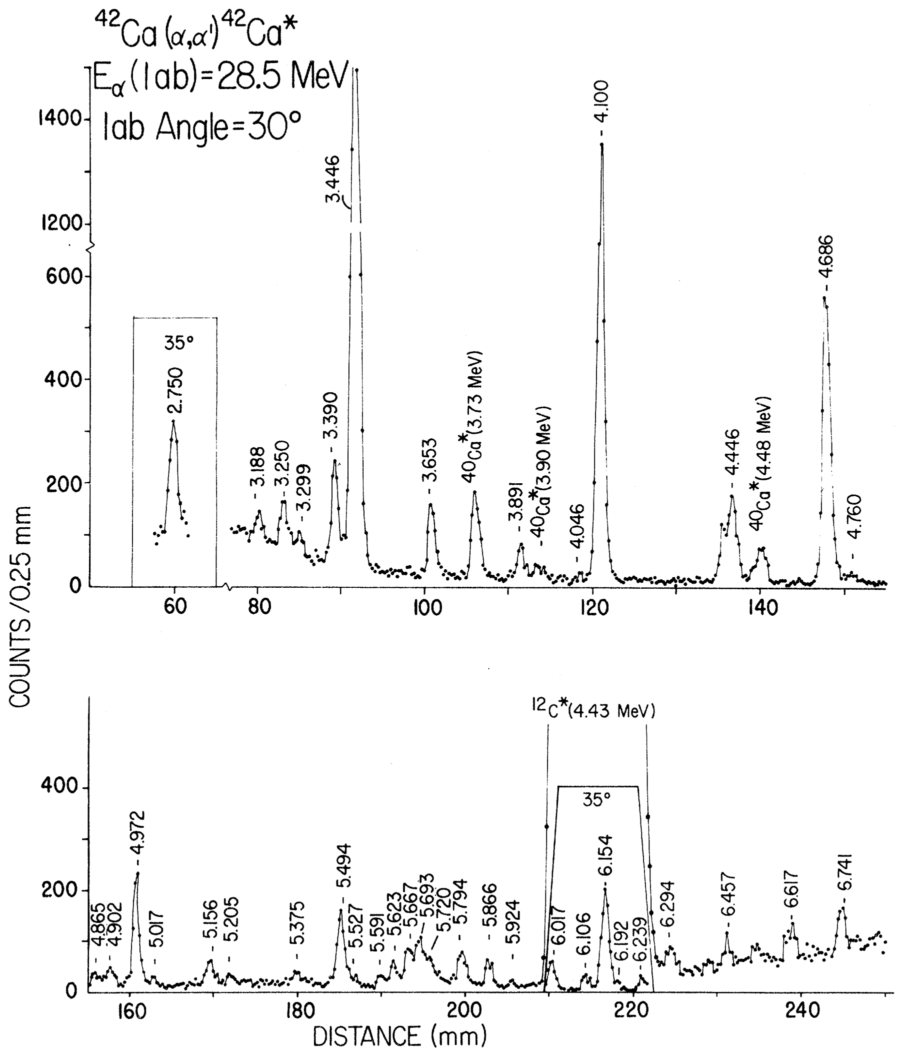

FIG. 3. Spectrum of α particles from the ^{42}Ca(α,α')^{42}Ca reaction at 28.5 MeV. Only states above the 4^+, 2.750-MeV state were observed in these measurements.

TABLE I. Results of the present ^{43}Ca$(d,t)^{42}$Ca and ^{41}K$(^3$He$,d)^{42}$Ca reactions.

Pickup reaction				Stripping reaction			
E_x (MeV)	l_1+l_2 [a]	$C^2[S(l_1)\pm\Delta S(l_1)]$ [b]	$C^2[S(l_2)\pm\Delta S(l_2)]$	E_x (MeV)	l_1+l_2	$(2J_f+1)\times C^2[S(l_1)\pm\Delta S(l_1)]$	$(2J_f+1)\times C^2[S(l_2)\pm\Delta S(l_2)]$
g.s.	3		0.46 ± 0.01	g.s.	2	2.22 ± 0.21	
1.523	3		0.19 ± 0.01	1.522	2	0.25 ± 0.06	
1.836	3		0.04	1.832	2	0.39 ± 0.07	
2.425	(1) + 3	(0.004)	0.16 ± 0.01	2.418	2	0.37 ± 0.06	
2.750	(1) + 3	(0.01)	0.59 ± 0.02				
3.188	3		(0.87 ± 0.03) [c]				
3.253	(1) + 3	(0.001)	0.08 ± 0.01				
(3.297)		Very weakly excited		(3.297)		Very weakly excited	
3.393	1 + (3)	0.003	(0.01 ± 0.01)				
3.446	0 + 2	0.09 ± 0.01	0.14 ± 0.02	3.444	1 + 3	0.06 ± 0.02	1.06 ± 0.12
3.656	3		0.06 ± 0.01				
				3.880	1 + (3)	0.02	(0.06 ± 0.01)
3.890	(0) + 2	(0.002)	0.02				
3.956	0 + (2)	0.002	(0.01)	3.949	3		2.77 ± 0.28
4.043	0 + 2	0.01	0.01	4.044	1 + 3	0.03 ± 0.01	0.27 ± 0.04
4.099	2		0.30 ± 0.01	4.093	3		3.03 ± 0.31
				4.116	(1)	(0.18)	
				4.225	(1)	(0.02)	
4.355	2		0.29 ± 0.02				
4.421	2		0.09 ± 0.01	4.420	1 + 3	0.03 ± 0.01	0.71 ± 0.07
4.447	1 + 3	0.02	0.04 ± 0.01				
4.690	0 + 2	0.04	0.06 ± 0.01	4.685	1 + (3)	0.14 ± 0.02	(0.11 ± 0.03)
				4.710			
4.895	(0) + 2	(0.02 ± 0.01)	0.16 ± 0.03	4.896	1 + 3	0.18 ± 0.03	0.40 ± 0.06
				4.944	1 + (3)	0.06	(0.07 ± 0.01)
4.966	(2)		(0.18 ± 0.01) [d]	4.969	1 + 3	0.09 ± 0.01	0.23 ± 0.05
5.012	(1 + 3)	(0.003)	(0.08 ± 0.02)				
				5.075	1 + (3)	0.26 ± 0.03	(0.32 ± 0.08)
				5.156	1 + 3	0.07	0.12 ± 0.03
5.189	3		0.13 ± 0.01				
5.204	1 + 3	0.01	0.08 ± 0.02	5.205			
5.321	0 + 2	0.02	0.12 ± 0.02	5.322	3		0.32 ± 0.05
5.377	2		0.05 ± 0.01				
				5.389	1 + (3)	0.10 ± 0.01	(0.12 ± 0.03)
5.403	(0) + 2	(0.004)	0.05 ± 0.01	5.410	1 + 3	0.06 ± 0.01	0.15 ± 0.02
5.436	0 + (2)	0.01	(0.02 ± 0.01)				
5.467	1 + 3	0.01	0.04	5.466	3		0.34 ± 0.07
5.488	(1) + 3	(0.001)	0.03	5.488	1 + 3	0.11 ± 0.02	0.49 ± 0.09
				5.509	1 + 3	0.07 ± 0.02	0.37 ± 0.07
5.590	0 + 2	0.08 ± 0.01	0.10 ± 0.02	5.587	1 + 3	0.06 ± 0.01	0.27 ± 0.03
				5.622	1 + (3)	0.16 ± 0.01	(0.16 ± 0.06)
				5.665	1 + 3	0.07 ± 0.01	0.30 ± 0.06
				5.720	(1 + 3), (2)		
5.767	2	0.17 ± 0.02					
5.790	3	0.16 ± 0.02					
				5.795	1	0.12 ± 0.01	
				5.826	1	0.04 ± 0.01	
				5.877	(1 + 3), (2)		
5.923	2		0.06 ± 0.01	5.918	(1 + 3)	(0.02)	(0.07 ± 0.01)
				5.975	1	0.02 ± 0.01	
5.985	0 + (2)	0.02	(0.03 ± 0.01)				
5.997	0 + (2)	0.03	(0.02 ± 0.01)				
				6.023	2	0.27 ± 0.04	
6.034	(0) + 2	(0.004)	0.04 ± 0.01	6.039	(1 + 3)	(0.03 ± 0.01)	(0.13 ± 0.05)
6.098	2		0.06 ± 0.01	6.100	(1 + 3)	(0.01 ± 0.01)	(0.24 ± 0.06)
6.162	(0 + 2)	(0.01)	(0.02 ± 0.01)	6.158	1 + 3	0.07	0.23 ± 0.02
				6.191			

TABLE I (*Continued*)

Pickup reaction				Stripping reaction			
E_x (MeV)	l_1+l_2 [a]	$C^2[S(l_1)\pm\Delta S(l_1)]$ [b]	$C^2[S(l_2)\pm\Delta S(l_2)]$	E_x (MeV)	l_1+l_2	$(2J_f+1)\times C^2[S(l_1)\pm\Delta S(l_1)]$	$(2J_f+1)\times C^2[S(l_2)\pm\Delta S(l_2)]$
6.207	0 + (2)	0.05	(0.04 ± 0.01)				
6.235	0 + 2	0.002	0.05 ± 0.01	6.242	(1 + 3)	(0.05 ± 0.01)	(0.19 ± 0.04)

[a] Values of l in parentheses indicate uncertain fits due to missing experimental points or poor statistics. For mixed transitions, parentheses on one component only indicate that the data permit, but do not require, a small admixture. The corresponding spectroscopic factor represents an upper limit for that component.

[b] The quoted uncertainties in the spectroscopic factors are due to statistical errors only. For weak states for which no error is given, it is generally about 25% of the quoted strength.

[c] 20% of the observed strength of this group has been subtracted to account for the g.s. of the ^{44}Ca$(d,t)^{43}$Ca impurity group.

[d] Observed only at backward angles.

rate to within 5 keV. In a number of experiments with the Enge spectrograph, measured excitation energies consistently show agreement with accurate values obtained from γ-decay work to within a few keV.

Some angular distributions measured in the ^{43}Ca$(d,t)^{42}$Ca reaction are shown in Figs. 4–7. In this reaction, the target has nonzero spin so that the transition to a given final state can generally involve admixtures of different l and j values. Since the present measurements were undertaken to provide a determination of the strength distributions for different single-particle states in ^{42}Ca, the problem of l discrimination is a major concern. In the distorted-wave (DW) analysis of the results, fits to the observed angular distributions have been obtained with the assumption of transitions involving a single l value, or admixtures of two different l values. Because of the experimental uncertainties in the data and theoretical uncertainties in the DW calculations, no attempt was made to look for admixtures with more than two components, although these are allowed by angular-momentum selection rules in some transitions.

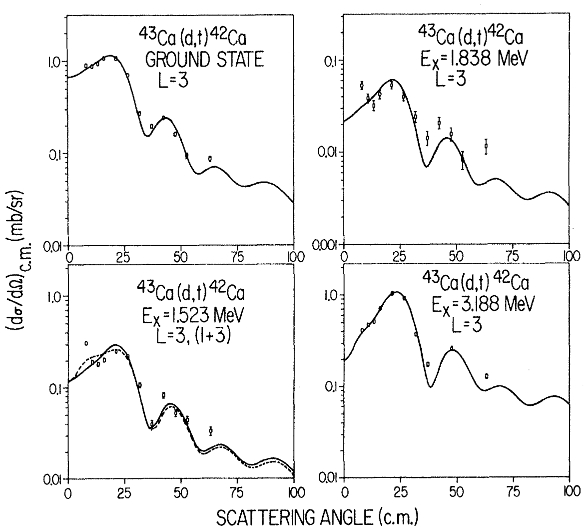

FIG. 4. Typical pure $l=3$ angular distributions from the ^{43}Ca$(d,t)^{42}$Ca reaction. The statistical error is indicated by error bars only when the error exceeds the size of the circles. The curves are the least-squares DWBA fits to the observed angular distributions. When two values of $L=3$, $(1+3)$ are indicated, the solid curve represents the first and dashed curve the second value. Unless stated in the text, the solid curve is always preferred, and the dashed curve is drawn only for comparison.

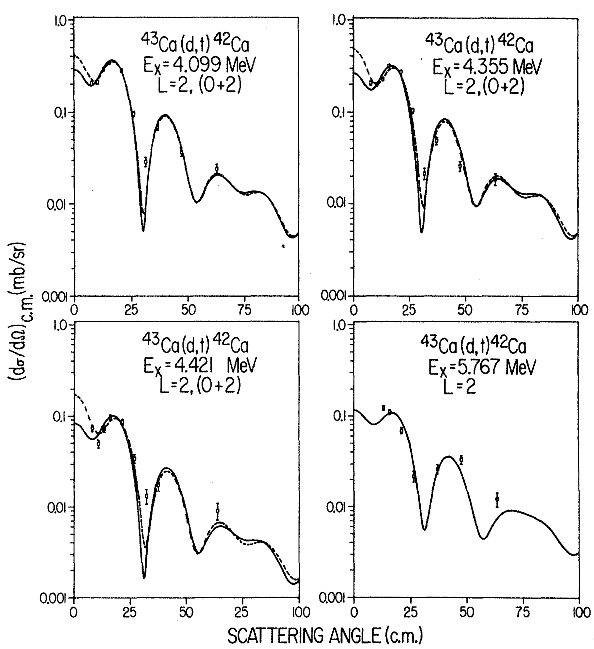

FIG. 5. Typical pure $L=2$ angular distributions from ^{43}Ca$(d,t)^{42}$Ca. See caption to Fig. 4.

TABLE II. Summary of assignments for levels in ^{42}Ca.

Published results E_x (MeV)	Ref.	J^π	Present (d,t) E_x (MeV)	J^π	Present $(^3\text{He},d)$ E_x (MeV)	J^π	Present (α,α') E_x (MeV)	ΔL	Final J^π
g.s.		0^+	g.s.	$(0-6)^+$	g.s.	$(0-3)^+$			0^+
1.523	a	2^+	1.523	$(0-6)^+$	1.522	$(0-3)^+$			2^+
1.836	a	0^+	1.836	$(0-6)^+$	1.832	$(0-3)^+$			0^+
2.422	a	2^+	2.425	$(0-6)^+$	2.418	$(0-3)^+$			2^+
2.750	a	4^+	2.750	$(0-6)^+$			2.750	4	4^+
3.191	a	6^+	3.188	$(0-6)^+$			3.188	6	6^+
3.250	a, b	4^+	3.253	$(0-6)^+$			3.250	4	4^+
3.297	a, b	(0^+)	(3.297)		(3.297)		3.299	(0?)	(0^+)
3.389	a	2^+	3.393	$(2,4)^+$			3.390	2	2^+
3.442	a	3^-	3.446	$(3,4)^-$	3.444	$(2,3)^-$	3.446	3	3^-
3.651	a	2^+	3.656	$(0-6)^+$			3.653	2	2^+
3.883	a, b	1^-			3.880	$(0-3)^-$			1^-
			3.890	$(2-5)^-$			3.891	3	3^-
3.95	b	4^-	3.956	$(3,4)^-$	3.949	$(2-5)^-$			$(4)^-$
4.043	a, b	$(2,3)^-$	4.042	$(3,4)^-$	4.044	$(2,3)^-$	4.046		3^-
4.09	b	5^-	4.099	$(2-5)^-$	4.093	$(2-5)^-$	4.100	5	5^-
					4.116				
4.23	c				4.225				
4.35			4.355	$(2-5)^-$					$(2-5)^-$
4.41		2^-	4.421	$(2-5)^-$	4.420	$(2,3)^-$			$(2)^-$
4.45		2^+	4.447	$(2-4)^+$			4.446	4	$2^+, 4^+$
4.68		3^-	4.690	$(3,4)^-$	4.685	$(0-3)^-$	4.686	3	3^-
4.71					4.710				
4.75		2^+					4.760	(2)	2^+
4.86		2^+					4.865	2	2^+
4.90			4.895	$(2-5)^-$	4.896	$(2,3)^-$	4.902	3	3^-
					4.944	$(0-3)^-$			$(0-3)^-$
4.96		$2^+, 3^-$	4.966		4.969	$(2,3)^-$	4.972	3	3^-
5.01		4^+	5.012				5.017	(3, 4)	4^+
5.07					5.075	$(0-3)^-$			$(0-3)^-$
5.15					5.156	$(2,3)^-$	5.156	3	3^-
			5.189	$(0-6)^+$					$(0-6)^+$
5.20		2^+	5.204	$(2,4)^+$	5.205		5.205	2	2^+
5.32			5.321	$(3,4)^-$	5.322	$(2-5)^-$			$(3,4)^-$
5.37			5.377	$(2-5)^-$			5.375	(?)	$(2-5)^-$
					5.389	$(2,3)^-$			$(2,3)^-$
5.41			5.403	$(2-5)^-$	5.410	$(2,3)^-$			$(2,3)^-$
			5.436	$(3,4)^-$					$(3,4)^-$
5.46			5.467	$(2-4)^+$	5.466	$(2-5)^-$			$(2-4)^+, (2-5)^-$
			5.488	$(0-6)^+$	5.488	$(2,3)^-$	5.494	3	$(0-6)^+, 3^-$
					5.509	$(2,3)^-$			$(2,3)^-$
5.52		3^-					5.527		3^-
5.58			5.590	$(3,4)^-$	5.587	$(2,3)^-$	5.591	(3)	3^-
5.61					5.622	$(0-3)^-$	5.623	(3)	$(3)^-$
5.66		3^-			5.665	$(2,3)^-$	5.667	3	3^-
5.70							5.693	(4, 5)	(4, 5)
					5.720		5.720	(4)	(4^+)
5.76			5.767	$(2-5)^-$					$(2-5)^-$
5.79			5.790	$(0-6)^+$					$(0-6)^+$
					5.795	$(0-3)^-$	5.794	3	3^-
					5.826	$(0-3)^-$			$(0-3)^-$
							5.866	2	2^+
					5.877				
5.92			5.923	$(2-5)^-$	5.918		5.924		$(2-5)^-$
					5.975	$(0-3)^-$			$(0-3)^-$
5.98			5.985	$(3,4)^-$					$(3,4)^-$
			5.997	$(3,4)^-$					$(3,4)^-$
					6.023	$(0-3)^+$	6.017	2	2^+

TABLE II (*Continued*)

Published results E_x (MeV)	Ref,	J^π	Present (d,t) E_x (MeV)	J^π	Present (^{3}He,d) E_x (MeV)	J^π	Present (α,α') E_x (MeV)	ΔL	Final J^π
			6.034	$(2-5)^-$	6.039				$(2-5)^-$
6.10		4^+	6.098	$(2-5)^-$	6.100		6.106	(4)	$4^+,(2-5)^-$
6.17		3^-	6.162		6.158	$(2,3)^-$	6.154	3	3^-
					6.191		6.192		
6.20			6.207	$(3,4)^-$					$(3,4)^-$
			6.235	$(3,4)^-$	6.242		6.239	3	3^-

[a] See Ref. 14.
[b] See Ref. 17.
[c] All higher levels Ref. 10, except 4.41 MeV from Ref. 5.

In order to obtain reliable spectroscopic factors for the components of admixed transitions, the DW calculations must provide good fits for the known transitions involving a single l value. For this reason, a search was made for optical parameters which could provide fits to the pure $l=3$ (assumed to be $1f_{7/2}$) and $l=2$ (assumed to be $1d_{3/2}$) pickup transitions leading to the known 0^+ ground state and the 4.10-MeV 5^- state of ^{42}Ca, respectively.

Zero-range DW calculations using local potentials were carried out using the code DWUCK.[37] The optical-model parameters used in the DW analysis of the present (d,t) and (^{3}He, d) reactions are listed in Table III. The deuteron parameters are the same as those used by Yntema[2] in the analysis of a series of (d,t) and (d, ^{3}He) reactions on Ca and Ti isotopes at 21.4-MeV incident energy. The triton parameters are similar to those used by Gaillard *et al.*[38] in an analysis of (d,t) and (d, ^{3}He) reactions on ^{40}Ca at 28.0 MeV. It was found that best fits to the ground state and 5^- state of ^{42}Ca were obtained by some adjustment in the triton parameters and by introducing a lower radial cutoff of 4.5 fm. The effect of varying the cutoff radius out to 8 fm is shown in Fig. 8. Out to 6 fm changes in shape and magnitude were not very large, but they were important in producing the detailed fits to the data shown in Figs. 4–7.

In the present analysis, it has been assumed that all the observed $l=0$, 1, 2, and 3 pickup transitions correspond to the $2s_{1/2}$, $2p_{3/2}$, $1d_{3/2}$, and $1f_{7/2}$ orbitals, respectively. The weakness of the $l=1$ transitions indicates that there is little excitation of particles into the $2p$ state in the ^{43}Ca ground

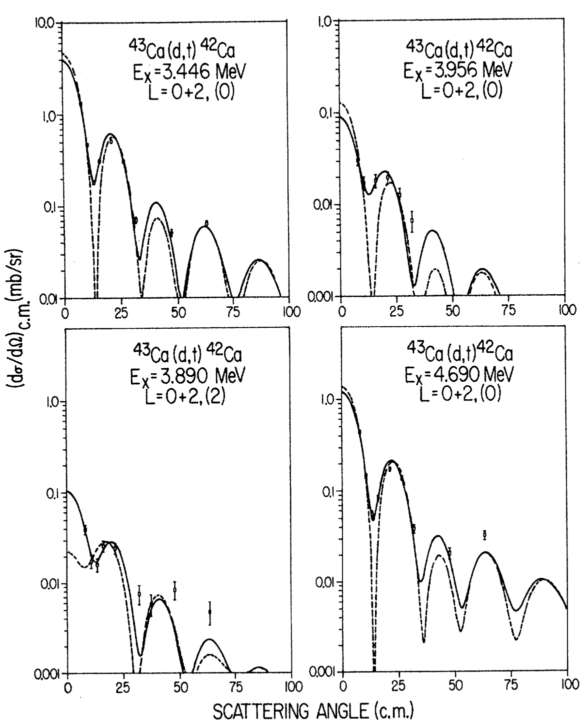

FIG. 6. Typical mixed $l=0+2$ angular distributions from ^{43}Ca$(d,t)^{42}$Ca. See caption to Fig. 4.

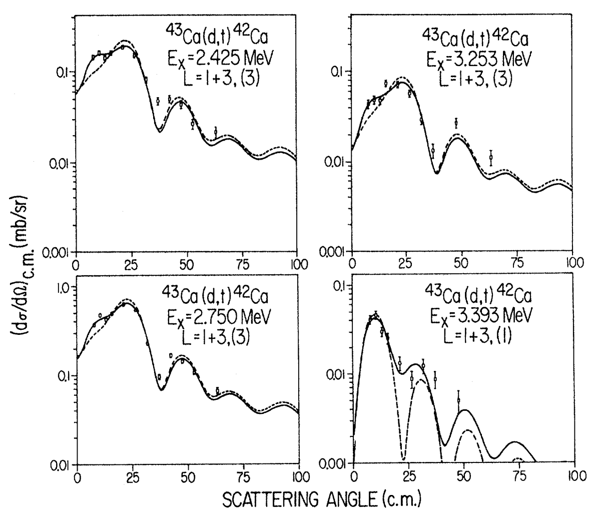

FIG. 7. Typical mixed $l=1+3$ angular distributions from ^{43}Ca$(d,t)^{42}$Ca. See caption to Fig. 4.

state. Excitation to the $1f_{5/2}$ orbit should be comparable to that of $2p$ so that neglect of $1f_{5/2}$ pickup is probably justified. Neglect of $1d_{5/2}$ pickup is based on the observation that the $1d_{3/2}$-$1d_{5/2}$ splitting is about 5 MeV at A = 39 so that states involving substantial $1d_{5/2}$ strength should lie at excitation energies above the limit of the present measurements. It is quite probable that some $p_{1/2}$ strength is included in the $l=1$ transitions, but this cannot be discriminated in the present measurements.

The DWBA fits to the angular distributions for transitions observed in the present (d, t) and $(^3He, d)$ reactions have been obtained using a computer program which adjusts the relative contributions from two specified l transfers in order to minimize the value of χ^2 for the DW fit to the data. DW calculations for different l transitions

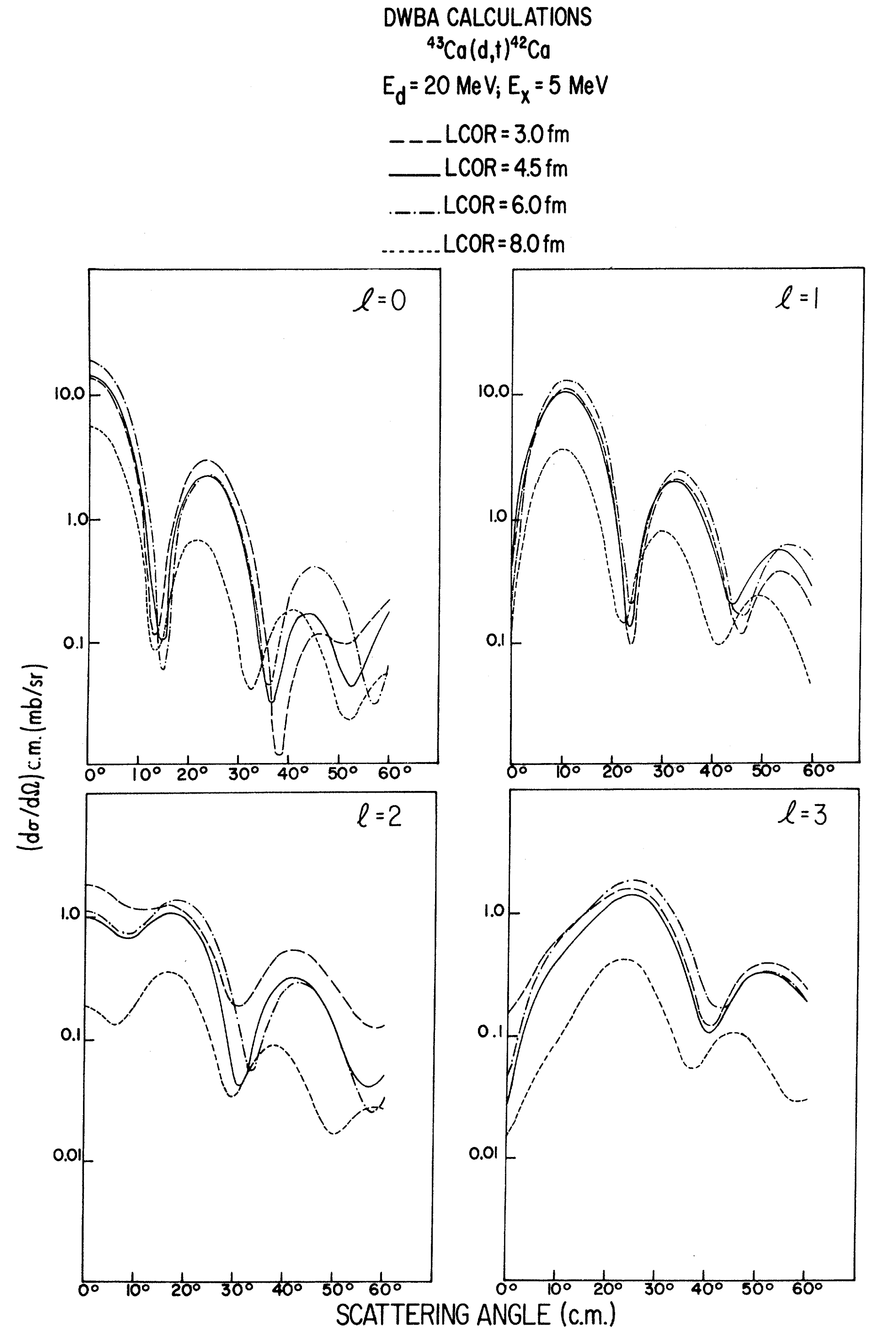

FIG. 8. Effect of a lower cutoff radius in DWBA calculations. A value of 4.5 fm was used in the analysis.

were performed in steps of 1–2 MeV of excitation energy. The program then calculated the DW differential cross sections for each specified l component of a given transition by interpolation. The best fit to the measured angular distribution for each state was then obtained by adjusting the relative strengths for the two specified components. A few typical χ^2 distributions for fits to some of the states in ^{42}Ca are shown in Fig. 9. The DWBA fits to some transitions, representative of all the (d,t) transitions observed here, are exhibited in Figs. 4–7. The measured spectroscopic factors are listed in Table I. The errors quoted are statistical uncertainties arising from the least-squares fit of the data to the DW calculations.

One of the problems contributing to the uncertainties in the spectroscopic factors of different components, in an admixed transition, is the difference in the magnitudes of DW cross sections for different l values. The DW cross sections for the $l=0$ and $l=1$ transitions are about 16 times larger than those for the $l=2$ and $l=3$, respectively. Small admixtures of up to a few percent of $l=0$ or $l=1$ in the predominantly $l=2$ or $l=3$ transitions can easily be detected. However, the sensitivity of separating the $l=2$ or $l=3$ components of even up to 50% from transitions with large contributions from $l=0$ or $l=1$ is much less. Therefore, spectroscopic factors for the $l=2$ or 3 transitions with less than a few percent of $l=0$ or 1 admixtures should be taken as lower limits and those with more than 50% of $l=0$ or 1 admixtures as upper limits.

For the ^{41}K(^{3}He, d)^{42}Ca reaction, the ^{3}He parameters were the same as those used by R. Bock *et al.*[39] and the deuteron parameters the same as those for the (d,t) reaction; the DW predictions

TABLE III. Optical-model parameters used in the DWBA calculations of pickup and stripping reactions.

Particle	U	W	r_0	a_0	W_D	a_0'	r_0'	V_{so}	r_c
d	105.0		1.02	0.86	60.0	0.65	1.42	12.0	1.3
t	153.0	10.8	1.188	0.703		0.813	1.43		1.4
^{3}He	165.0	20.2	1.14	0.723		0.81	1.6		1.3
Bound	U [a]		1.2	0.65				55.4	1.2

[a] U was chosen to give the observed separation energy for each energy level:

$$V(r)=U_C+U(1+e^{x})^{-1}+iW(1+e^{x'})^{-1}+iW_D\frac{d}{dx'}(1+e^{x'})^{-1}-V_{so}(\vec{L}\cdot\vec{S})\times\frac{1}{x}\frac{d}{dx}(1+e^{x})^{-1},$$

$x=(r-r_0A^{1/3})/a_0$; $x'=(r'-r_0'A^{1/3})/a_0'$;

U_C = Coulomb potential of a uniformly charged sphere of radius $R_c=r_cA^{1/3}$.

are shown in Fig. 10. It is seen that the relative cross sections at the four angles at which measurements were made provide clear discrimination of l values for unmixed transitions. It is less obvious from the figure, but a detailed analysis shows that the relative strengths of $l=1+l=3$ or $l=0+l=2$ are reasonably well determined provided that the parity of the final state is known from the (d,t) results. The present results were thus useful primarily as a means of identifying $l=1$ admixtures in the $l=3$ transitions to negative-parity states. These mixtures had not been reported in the earlier measurements of ^{41}K(^{3}He, d) at lower energies.[4,5]

The extraction of strengths was carried out as for the pickup measurements, and results are shown in Table I. For $l=2$ transitions, the strengths are in good agreement with those observed[4,5] at lower energies. For $l=3$, the measured strengths are definitely smaller than in the earlier measurements noted above. The most probable explanation of this discrepancy is that the DW calculations are failing to reproduce the energy dependence of the cross sections for transitions of different l and j.

Typical angular distributions observed in the inelastic α scattering measurements are shown in Fig. 11. The DWBA curves were calculated by using optical parameters taken from a similar study at 25.5 MeV.[9] The agreement with experimental results for states of known spin is seen

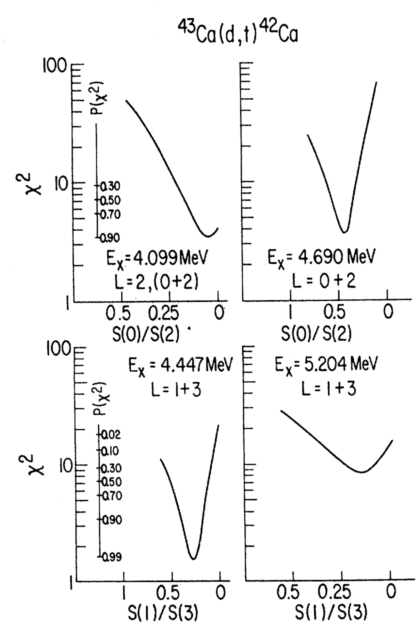

FIG. 9. Typical χ^2 distributions for DW fits to four states of ^{42}Ca excited in the present ^{43}Ca$(d,t)^{42}$Ca reaction. $S(l)$ is the strength corresponding to the l component of the angular distribution.

to provide a satisfactory determination of spin and parity for the natural parity states excited in this reaction. The results of the (α, α') measurements are also listed in Table II, which gives the final spin (or spin limits) determined by all three measurements.

4. DISCUSSION

The final results for measured strengths and spin assignments or limitations are shown in Tables I and II. All of the known states of ^{42}Ca up to 4.10 MeV inclusive are excited in at least two of the present experiments, and their previously assigned spin-parities are consistent with the present observations. The known (0^+) level[17] at 3.297 MeV is very weakly populated in both the pickup and stripping reactions, and no definite ΔL value could be obtained for it in the present (α, α') work. The reported 1^- level at 3.883 MeV[17] may correspond to the present stripping state at 3.880 MeV if a pure $l=1$ is assumed for it. Since a definite $\Delta L = 3$ transition at 3.891 MeV in the (α, α') reaction and a weak $l = (0) + 2$ pickup at 3.890 MeV are consistent with a 3^- state at this energy, therefore the existence of a $(1^-, 3^-)$ doublet at 3.88-3.89 MeV is quite possible.

The strong $l=3$ stripping state at 3.949 MeV is seen in the pickup reaction as a weak $l = 0 + (2)$ transition at 3.956 MeV. The fact that no inelastic group is observed at this energy supports the previous 4^- assignment based on the stripping strength.[4] Also a group at 4.044 MeV, seen as

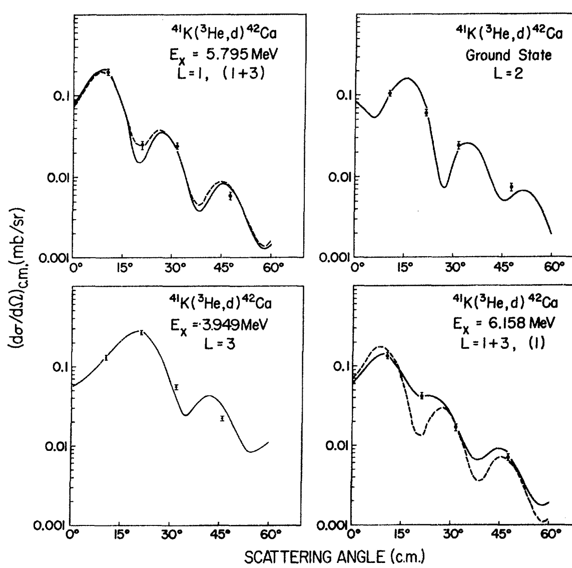

FIG. 10. Typical DW angular distributions for the ^{41}K-(^{3}He,d)^{42}Ca reaction. Data points are shown to indicate the discrimination possible with observations at angles of 10, 20, 30, and 45°.

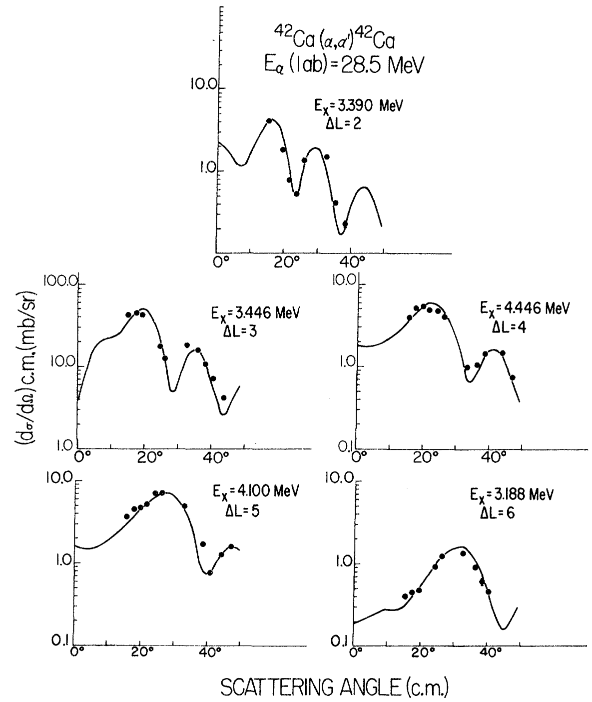

FIG. 11. Typical ΔL=2, 3, 4, 5, and 6 angular distributions for the ^{42}Ca$(\alpha, \alpha')^{42}$Ca reaction. Solid lines are DW calculations.

$l = 1 + 3$ transition in the stripping reaction, corresponds to the $l = 0 + 2$ pickup group at 4.043 MeV; therefore a 3^- assignment would be reasonable. As for the 5^- state at 4.10 MeV, all the present observations support this assignment. Finally, it should be noted that no transition corresponding to the reported 4.0-MeV state[10,17] has been observed in the present experiments.

At higher excitation energy, the only work which can be usefully compared with the present results is a measurement[10] of ^{40}Ca$(t, p)^{42}$Ca with a resolution of 20 keV. The (t, p) results assign spins and parities to levels at 4.68, 4.75, 4.86, 4.96, 5.01, 5.20, and 6.10 MeV which are in agreement with present results. A strong $\Delta L = 2$ transition is re-

TABLE IV. The observed and expected total strengths for the $T = 1$ states of ^{42}Ca excited via ^{41}K(^{3}He,d) and ^{43}Ca(d,t) reactions.

Reaction		Spectroscopic strength [a] $l=0$	$l=1$	$l=2$	$l=3$
(^{3}He,d)	Observed	···	0.49	0.88	3.11
	Expected	0.00	3.00	1.00	6.50
(d,t)	Observed	0.38	0.05	2.03	3.02
	Expected	1.50	0.00	3.00	3.00

[a] Spectroscopic strength equals $\sum C^2S$ for (d,t) and equals $\sum (2J_f+1)/(2J_i+1)C^2S$ for (^{3}He,d).

ported to a state at 4.45 MeV in the (t, p) results. The present (α, α') measurements indicate a 4^+ state at 4.446 MeV, suggesting a doublet near this energy. Finally, two 0^+ states are strongly excited in the (t, p) results at 5.85 and 6.01 MeV, but are not seen in any of the present measurements.

The total single-particle strengths seen in the present measurements are shown in Table IV. In taking the strength sums for pickup, it was assumed that all $l = 3$ transitions corresponded to the $1f_{7/2}$ orbit. In support of this, it has been noted that the $l = 1$ strength, presumably arising from $2p$ excitations in the ^{43}Ca ground state, is only a few percent of the sum-rule limit. It thus seems reasonable to assume negligible $1f_{5/2}$ excitations in the ground state. This is also supported by the observation[40] that pickup strengths to known $\frac{5}{2}^-$ states in ^{41}Ca and ^{43}Ca are very small. If this assumption is correct, it is then seen that the full sum-rule limit for $1f_{7/2}$ pickup strength has been observed in these measurements. The observed $l = 2$ strength is assumed to involve $1d_{3/2}$ neutrons. The justification for this lies in the fact that only about 25% of the total $2s_{1/2}$ strength is observed in these measurements, while the unperturbed $2s_{1/2}$ hole state is expected to lie 1 to 2 MeV below the $1d_{5/2}$ hole state. Convincing evidence for the importance of $1d_{5/2}$ transfers would be provided by the observation of significant $l = 2$ strength to a 1^- or 6^- state. Unfortunately no such states have been identified at high excitation in ^{42}Ca.

The uncertainty in the absolute normalization in the DWBA is large enough that the observation of the $1f_{7/2}$ sum-rule limit for $l = 3$ pickup is not very significant. It is noteworthy, however, that with the same normalization as for $1f_{7/2}$, these results indicate that no more than two thirds of the total $1d_{3/2}$ strength and one quarter of the $2s_{1/2}$ strength has been identified below 6.2 MeV excitation.

Perhaps the most interesting result of these measurements is the distribution of strength for the $1f_{7/2}$ and, to some extent, the $1d_{3/2}$ neutrons. Previous neutron-pickup measurements on ^{43}Ca have failed to identify the $l = 3$ strength above the 6^+ state at 3.188 MeV. Present results show that about 25% of the total $l = 3$ strength lies in states between 3.2 and 6.2 MeV excitation. Spins and parities are known for all these except states at

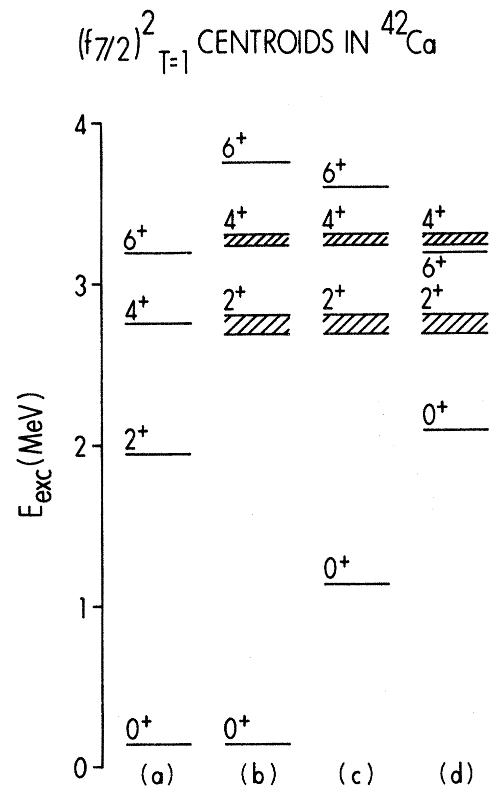

FIG. 12. Centroids of $(f_{7/2})^2{}_{T=1}$ strength in ^{42}Ca. Diagram (a) takes account of states below 3.2 MeV only. In (b), (c), and (d) the uncertainty in the 2^+ and 4^+ centroids arises from uncertainty in the spin of the 4.447-MeV state. Spins of the 5.189- and 5.790-MeV states are assumed to have the following values: (b) 6^+, 6^+; (c) 0^+, 6^+; (d) 0^+, 0^+. See text for further discussion of assignments.

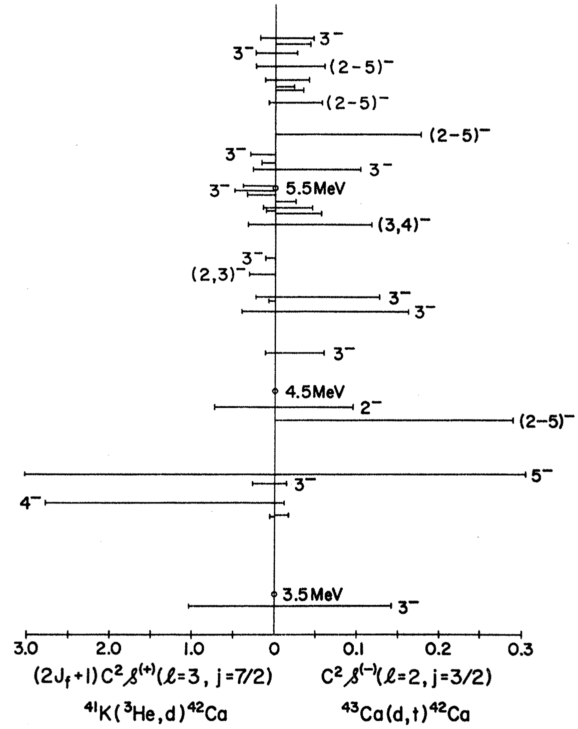

FIG. 13. The strength distributions for the presently observed $l = 3$ (presumably $1f_{7/2}$) stripping and $l = 2$ (presumably $1d_{3/2}$) pickup transitions as a function of excitation energy in ^{42}Ca.

5.189, 5.466, 5.488, and 5.790 MeV. The levels at 5.466 and 5.488 MeV involve $l=1+3$ transfer and so must have spins between 2^+ and 5^+. Levels are seen at 5.467 and 5.488 MeV in the (^{3}He, d) measurements, but show a clear indication of $l=3$ stripping strength. The inelastic α scattering results indicate a 3^- state at 5.494 MeV, but do not populate a level near 5.466 MeV. Thus the only conclusion from the present results is that in both cases these levels are actually close doublets.

The levels at 5.189 and 5.790 MeV carry more strength and, hence, are more interesting. These are populated apparently by pure $l=3$ pickup. Except for the 2^+, 3.656-MeV state, all known 2^+ and 4^+ states show a small $l=1$ contribution so that it is most probable that the two states in question have spin-parity either 0^+ or 6^+. An unsuccessful attempt was made to observe the γ decay of these levels in a ^{43}Ca(^{3}He, $\alpha\gamma$)^{42}Ca coincidence measurement. A search for transitions to these states was also made in the ^{41}Ca(d,p)^{42}Ca measurements.[41] From the observed strengths in the pickup reaction, it is expected that in stripping a 6^+ state would have a strength about 10 times that of a 0^+ state. The level at 5.189 MeV is apparently not excited in the (d,p) results. There is some indication of a state at 5.787 MeV, but it is not well resolved from a strong $l=1$ transition to a state at 5.774 MeV.

Indirect evidence on these levels is also provided by an analysis[42] of the mixing of spherical and deformed states in ^{42}Ca. The conclusion from this study is that the level at 5.790 MeV is most likely the 6^+ state arising primarily from the rotational band built on the deformed 0^+ state at 1.836 MeV. The available evidence is thus consistent with a 6^+ assignment for the 5.790-MeV state and 0^+ for the 5.189-MeV state, though a more direct determination would clearly be desirable.

The inclusion of the observed $l=3$ pickup transitions above the 3.188-MeV, 6^+ state of ^{42}Ca has a significant effect on the centroids of the $(1f_{7/2})^2{}_{T=1}$ states. This is shown in Fig. 12 for different assumptions about the spins of the levels at 4.447, 5.189, 5.466, 5.488, and 5.790 MeV. The levels at 5.189 and 5.790 MeV are assumed to have spin 0^+ or 6^+ as discussed earlier. The other three levels may have spin 2^+ or 4^+, and it has been assumed that the 5.466- and 5.488-MeV levels have spin 4^+. The uncertainty indicated in the centroids of the 2^+ and 4^+ states then arises from the uncertainty in the assignment of the 4.447-MeV state. If either of the 5.466- or 5.488-MeV states is assumed to be 2^+, then the 4^+ centroid lies only about 150 keV above the 2^+ centroid. If both states are assumed to be 2^+, then the 4^+ centroid lies below the 2^+. The 4^+ assignment to the two upper states is thus reasonable, but more direct evidence would again be desirable.

Figure 12 then indicates the $(f_{7/2})^2{}_{T=1}$ centroids for the possible 0^+ or 6^+ assignments of the 5.189- and 5.790-MeV states. If 0^+ is assumed for both states, then the level ordering is unreasonable. Either of the other possible assignments results in a spectrum quite different from previous results based only on states below 3.2 MeV.

If the negative-parity states are assumed to arise from the $[d_{3/2}{}^{-1}\times(f_{7/2})^3]$ configuration, then the $l=2$ strengths observed in the pickup reaction should be proportional to the $l=3$ strengths in stripping. A comparison of these strengths is shown in Fig. 13. There is reasonable proportionality for the states identified in stripping[4] as the main components of the 2^-, 3^-, and 5^- shell-model states, but the 4^- state is very weakly excited in pickup. A state at 4.355 MeV is excited in pickup, with a strength expected for the 4^- state, but is not seen in stripping. At higher excitation, many negative-parity states have been identified, but in many cases a state is excited in one reaction but not the other, indicating a complicated structure.

5. SUMMARY

The results of the present studies are summarized in Tables I, II, and IV. It appears that the total strength for the $l=3$ pickup transitions (assumed to be $1f_{7/2}$) have been observed. About 25% of the total $l=3$ strength lies in states between 3.2 and 6.2 MeV of excitation. Among these, two relatively strong $l=3$ pickup groups at 5.189 and 5.790 MeV could be candidates for 0^+ or 6^+ states of ^{42}Ca. It is observed that the centroids of the low-lying $(1f_{7/2})^2{}_{T=1}$ states are significantly shifted by the inclusion of these highly excited states. Only two thirds of the total $l=2$ (assumed to be $1d_{3/2}$) pickup strength and about one quarter of the $l=0$ ($2s_{1/2}$) pickup strength has been observed below 6.24 MeV of excitation. The $l=2$ pickup strength is found to be severely fragmented and many transitions show considerable $l=0$ admixtures. Therefore no information concerning the centroids of the $[(1f_{7/2})^3\times(1d_{3/2})^{-1}]_{T=1}$ multiplet and the corresponding particle-hole matrix elements could be obtained. Extensive fragmentation is observed for the $l=3$ stripping strength. The observation of large differences in the strength distributions of the $l=2$ pickup and $l=3$ stripping transitions indicate the complexity of the structure of the negative-parity states in ^{42}Ca.

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