(^{6}Li, d) reaction on ^{40}Ca

U. Strohbusch,* C. L. Fink, and B. Zeidman
Argonne National Laboratory, Argonne, Illinois 60439†

R. G. Markham,‡ H. W. Fulbright, and R. N. Horoshko
Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627§
(Received 3 October 1973)

The ^{40}Ca(^{6}Li,d)^{44}Ti reaction was studied at $E(^6\text{Li}) = 32$ MeV. Angular distributions for ^{44}Ti levels up to 9-MeV excitation energy have been measured. They are compared with α-transfer distorted-wave Born-approximation calculations to determine angular momentum transfers and relative strengths.

[NUCLEAR REACTIONS ^{40}Ca(^{6}Li,d), $E = 32$ MeV measured $\sigma(\theta)$, levels. ^{44}Ti levels, ZR DWBA deduced l, J_f, π, S.]

I. INTRODUCTION

Considerable interest has been focused on the investigation of four-nucleon $2p2n$ correlations in fp-shell nuclei. This interest has been stimulated by experimental results on the (^{16}O, ^{12}C) reaction on Ca and Ni isotopes[1-5] and by the interpretation of these results in terms of α-transfer and quartet structures.[2,3,5] However, difficulties in the interpretation of the experimental data arise from the fact that the (^{16}O, ^{12}C) reaction (like other heavy-ion-induced reactions) is strongly governed by kinematic and absorption effects that obscure structure information. Moreover, the reaction mechanism is not well understood; doubts about its α-transfer nature have been expressed recently.[6]

An alternative tool for $2p2n$-correlation studies is provided by the (^{6}Li, d) reaction, which is fairly well established[7] to proceed via α-particle transfer. This reaction has been extensively applied to the study of light nuclei,[7] but few data exist for medium-mass targets.[8-10] The aim of our current work is to extend (^{6}Li, d) measurements to these heavier nuclei.

Here we report on the ^{40}Ca(^{6}Li, d)^{44}Ti reaction, which is of special interest since the transferred four-nucleon group occupies the very beginning of the fp shell. In terms of a conventional shell model, ^{44}Ti consists of two valence neutrons and two valence protons and, in this respect, represents the fp-shell analog of ^{20}Ne. Partly because of this analogy, ^{44}Ti has attracted particular theoretical interest.[11-16]

Several other four-nucleon transfer reactions on ^{40}Ca have been studied in the past. The ^{40}Ca(^{16}O, ^{12}C) reaction is reported in Refs. 1, 2, and 4. Siemssen *et al.*[17,18] have studied the (^{18}O, ^{14}C) and (^{20}Ne, ^{16}O) reactions. Goldberg *et al.*[8] presented the first ^{40}Ca(^{6}Li, d) and (^{7}Li, t) spectra, and recently the ^{40}Ca(^{7}Li, t) reaction has been further investigated by Cunsolo *et al.*[19] In the present work the ^{40}Ca(^{6}Li, d) reaction is studied with improved energy resolution and is discussed in more detail than in previous work. First results of this experiment were presented in Ref. 10.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experiment, begun concurrently at Argonne and at Rochester, was finished at Rochester where the MP tandem accelerator provided a beam current up to 800 nA of ^{6}Li^{3+}.

The targets were prepared by evaporating Ca of natural isotopic abundance (97.0% ^{40}Ca) onto gold foils. A spectrochemical analysis[20] revealed negligible impurities of nuclides with $A \geq 28$. In the experimental data, the lighter impurities (of which only C and O were important) could readily be identified from the kinematic shift of spectral lines with angle of observation. Isotopically enriched (99.9%) ^{40}Ca targets have been used to check the assignment of levels to ^{44}Ti.

The outgoing particles were analyzed in a split-pole magnetic spectrograph and were detected by use of a spark-counter system[21] allowing mass separation of the detected particles. The spectra were analyzed and plotted by means of the code AUTOFIT.[22] A Q plot of two representative deuteron spectra is presented in Fig. 1. The ^{44}Ti levels observed in the present and in previous experiments are surveyed in detail in Sec. IV.

Figure 2 displays angular distributions obtained at $E_{\text{lab}} = 32$ MeV. As opposed to reported (^{16}O, ^{12}C) angular distributions,[4] the (^{6}Li, d) angular distributions are clearly structured, with shapes characteristic of the transferred orbital momentum. The solid curves represent results of α-transfer distorted-wave Born-approximation (DWBA) calculations normalized to the experimental data.

III. DWBA CALCULATIONS

The characteristic shapes of the angular distributions indicate dominance of a direct-reaction mechanism. In the following, this mechanism is assumed to consist of one-body transfer of the $2p2n$ group in its intrinsic ground state, i.e., with the quantum number of an α particle.

There is no *a priori* justification for this assumption.[23] In a representation in which the state of the four nucleons is described in terms of center-of-mass and intrinsic coordinates, the matrix element of the transfer process generally is a coherent sum of elements corresponding to different states of intrinsic and related center-of-mass motion. Because of this interference, the cross section cannot be factored into spectroscopic and dynamic factors. The derivation of spectroscopic information therefore is complicated and requires detailed knowledge of the relevant wave functions. It is usually argued, however, that in a surface reaction the transfer of the group in its intrinsic ground state is favored inasmuch as it corresponds to the maximum surface amplitude for the c.m. motion. The particularly high energy gap to excited states of the $2p2n$ system supports this effect.[24] In the (^{6}Li, d) reaction, the large α-d parentage[23,25] of ^{6}Li additionally suppresses transfer through states differing from that of an α particle.[26] Thus, to a good approximation the reaction can be described as α stripping. As in single-nucleon stripping, the cross section may be factored into dynamic and spectroscopic factors, the latter in our case representing the α-^{40}Ca$_{g.s.}$ strength in ^{44}Ti and the α-d strength in ^{6}Li$_{g.s.}$.

The dynamic factor was calculated by use of the single-nucleon transfer DWBA code DWUCK[27] where for the "nucleon" the charge, mass, and spin of an α particle were inserted. Because of the predominant S state of mutual α-d motion[25,28] in ^{6}Li$_{g.s.}$, the calculations may be performed in zero-range approximation.[29-31] The differential cross section then is given by

$$\frac{d\sigma}{d\Omega}=S(^6\mathrm{Li}\,|\,d,\alpha)S(^{44}\mathrm{Ti}\,|\,^{40}\mathrm{Ca},\alpha)D^2\sigma^{\mathrm{DWUCK}}, \qquad (1)$$

where the constant D^2 contains a factor $D_0^{\,2}$ arising from the zero-range approximation for the effective stripping interaction.

The bound-state wave function of the transferred α cluster was generated with a real Woods-Saxon potential whose geometric parameters were $R=1.25(40^{1/3}+4^{1/3})$ fm, $a=0.65$ fm, and whose depth was adjusted to reproduce the α-separation energy. It was found necessary to use this large radius (increased by $4^{1/3}$) in order to fit the angular distributions with zero-range DWBA. The number of nodes of the bound-state radial wave function was fixed by the relation

$$2(N-1)+L+\sum_{i(\alpha)=1}^{4}[2(\nu_i-1)+\lambda_i] = \sum_{i(\mathrm{Ti})=1}^{4}[2(n_i-1)+l_i], \qquad (2)$$

which expresses the energy conservation in the

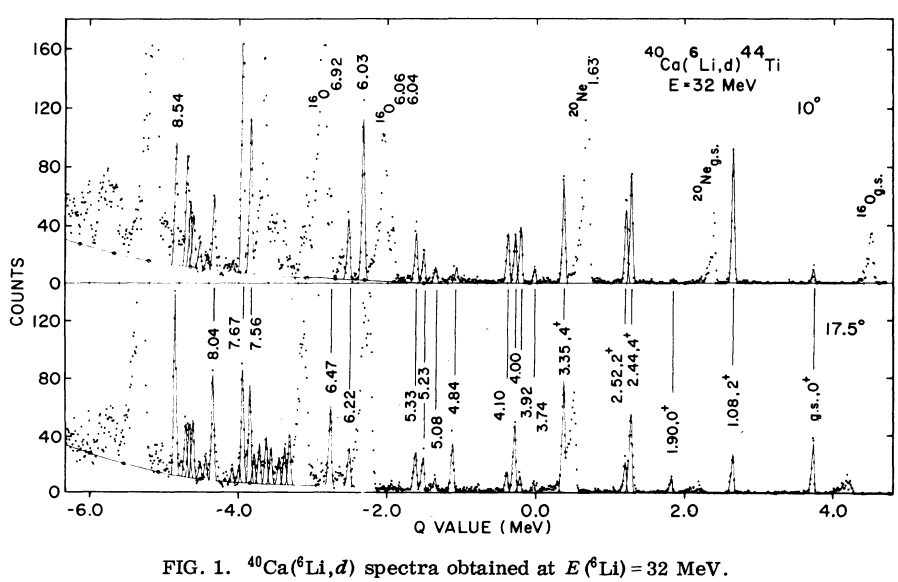

FIG. 1. ^{40}Ca(^{6}Li,d) spectra obtained at E(^{6}Li) = 32 MeV.

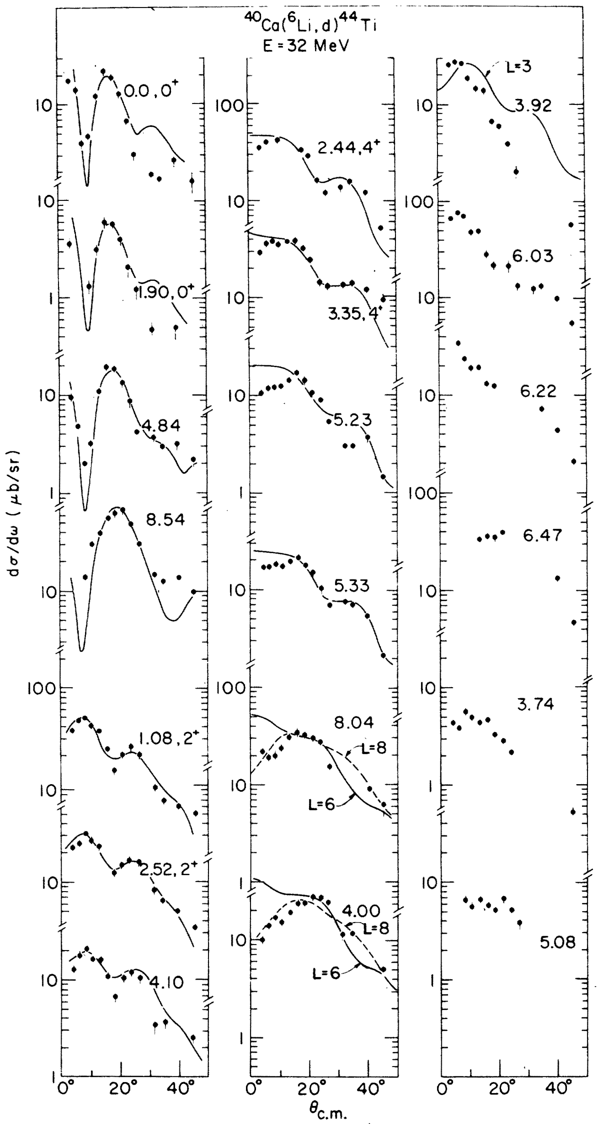

FIG. 2. Experimental angular distributions and DWBA results for the ^{40}Ca(^{6}Li,d) reaction.

Talmi-Moshinsky transformation from single-nucleon coordinates to intrinsic and c.m. coordinates of the four-nucleon group. This leads to $2(N-1)+L=12$ for the transfer of an α particle into the $1f2p$ shell. N is thus uniquely determined for given final spin ($I_i=0$, $L=I_f$).

The distorted waves in both channels were generated using optical potentials (Table I) that were obtained from the analysis of elastic scattering data[32,33] except for the imaginary potential depth W(^{6}Li), which was increased to 8 MeV due to the higher ^{6}Li energy in our experiment. No lower cutoff radius was introduced. The DWBA results normalized to the experimental angular distributions are displayed in Fig. 2.

Spectroscopic factors can be obtained from Eq. (1) by comparing the DWBA cross sections with the experimental results. Absolute values cannot be given without knowledge of the constant D^2. However, both this constant and the spectroscopic factor S(^{6}Li), cancel in deriving *relative* spectroscopic factors for different ^{44}Ti states. The last column of Table II lists the ratios of spectroscopic factors to that of the ^{44}Ti ground state.

Recently, DeVries[34] performed finite-range calculations for three of the ^{40}Ca(^{6}Li,d) angular distributions, which were chosen for comparison with available (^{16}O, ^{12}C) data. The finite-range calculations and the present zero-range calculations yield similar shapes of the angular distributions and almost the same relative spectroscopic factors. The absolute spectroscopic factors[34] extracted [e.g., $S(^{44}\mathrm{Ti}_{\mathrm{g.s.}})=0.063$] may serve to normalize our results, although they are subject to large uncertainties, particularly due to the sensitivity of the calculated cross section to small changes of the form-factor radius.

IV. ^{44}Ti LEVELS

The levels observed in this experiment, their assigned spins, and their relative spectroscopic factors S/S(g.s.) are summarized in Table II, which also lists the results of previous four-nucleon transfer experiments[1,2,19] and of recent ^{40}Ca(α,γ)[35] and ^{46}Ti(p,t) studies.[36,37] In this section we comment briefly on levels of particular interest.

1.90 MeV. The spin of this state has been determined by Rapaport *et al.*[36] from ^{46}Ti(p,t)^{44}Ti to be 0^+. In the present work this is confirmed by the similarity between the corresponding (^{6}Li,d) angular distribution and the one for the 0^+ ground state and by evidence from the DWBA curve for $L=0$ transfer. This state is assumed to be based on core deformations.[15] In contrast to earlier

TABLE I. Optical potentials.

Channel	V (MeV)	W_{vol} (MeV)	W_S (MeV)	R (fm)	a (fm)	R_I (fm)	a_I (fm)	Ref.
^{6}Li + ^{40}Ca	72.6	8.		4.69	0.87	7.87	0.81	33
d + ^{44}Ti	95.7		12.2	3.78	0.81	4.66	0.76	32

suggestions,[11,38] it is also seen via the ^{40}Ca-(^{16}O, ^{12}C) reaction.[39]

2.52 MeV. This 2_2^+ state and the 0_2^+ state at 1.90 MeV are assumed to form the beginning of a quasirotational band. This is suggested by the strongly enhanced transition strength $B(E2, 2_2^+ \rightarrow 0_2^+)/B(E2, 2_2^+ \rightarrow 0_1^+) \approx 160$ deduced by Simpson, Dixon, and Storey.[35] The 2_2^+ state had not been resolved from the 2.44-MeV 4^+ state in previous four-nucleon transfer experiments.[1,2,8,17–19] In the present experiment its strength is found to be equal to that of the 0_2^+ state. It is tempting to assume that the 4_2^+ state at *3.35 MeV* represents the third member of this band.

3.92 MeV. This state has spin 3^- if it is identical with the level at 3.942 MeV identified previously.[23] A state of negative parity cannot be excited by transfer of all four nucleons into one main shell. A possible configuration of this state may thus be $(sd)^{-1}(fp)^5$, populated via the $(sd)^{-2}$-$(fp)^2$ component in ^{40}Ca. The mixed-shell transfer is still consistent with α-particle transfer; the above nucleon configuration corresponds to a $5f$ bound state of the α particle $[2(N-1)+L=11]$. However, in striking contrast to its success in reproducing neighboring 2^+ and 4^+ angular distri-

TABLE II. Levels in ^{44}Ti.

^{40}Ca(α,γ)^{44}Ti (Ref. 35)		^{46}Ti(p,t)^{44}Ti (Ref. 36)		(Ref. 37)		^{40}Ca(^{7}Li,t) (Ref. 19)	^{40}Ca(^{16}O, ^{12}C) (Ref. 2)	(Ref. 1)	^{40}Ca(^{6}Li,d)^{44}Ti Present work		
E_x (MeV)	I^π	E_x (MeV)	I^π	E_x (MeV)	I^π	E_x (MeV)	E_x (MeV)	E_x (MeV)	E_x (MeV)	I^π	S/S(g.s.)
g.s.	0^+	g.s.	0^+	g.s.	0^+	g.s.	g.s.	g.s.	g.s.	0^+	1
1.083	2^+	1.0822	2^+	1.08	2^+	1.08	1.08	1.09	1.08	2^+	0.33
1.905	$0^{(+)}, 2$	1.903	0^+	1.90		1.90			1.90	0^+	0.25
2.454	$(3), 4^{(+)}$	2.450	(4^+)	2.46	4^+				2.44	4^+	0.16
						2.50	2.51	2.50			
2.531	2^+	2.535	(2^+)	2.55	2^+				2.52	2^+	0.25
2.886	2^+	2.885	2^+	2.89	(3^-)						
3.175		3.175	(2^+)	3.18	2^+						
						3.29					
		3.365	4^+	3.37	4^+			3.35	3.35	4^+	0.12
3.415	2,3						3.44				
3.645											
				3.76		3.74			(3.74)		
3.942		3.942	3^-	3.97		3.93			3.92		
		3.980	4^+								
		4.015	$(5^-, 6^+)$				4.01	4.01	4.00	>4	(0.11)[a]
		4.060	4^+	4.08		4.13			4.10	2^+	0.2
		4.605	0^+	4.61	0^+	4.62					
		4.792	(2^+)	4.80	(4^+)	4.83	4.80	4.82	4.84	0^+	1.35
		5.055	(4^+)	5.06	(4^+)	5.07			5.08		
									5.23		
		5.315		5.35		5.31	5.3	(5.28)	5.33	(4^+)	0.09
		5.415	(2^+)								
		6.030	(4^+)	6.04		6.05	6.10	6.01	6.03		
						6.25			6.22		
						6.49		6.45	6.47		
		6.535									
		6.600	$2^+, T=1$	6.62	$2^+, T=1$		6.6				
		6.965	$(4^+), T=1$	6.98			7.03	(6.90)			
						7.35					
								(7.49)	7.56		
		7.67		7.70		7.67	7.75		7.67		
						8.05			8.04	≥6	0.16[a]
						8.40			8.38		
8.565						8.55	8.55		8.54	(0^+)	(8)
Many									(8.96)		
resonances						9.00			(9.03)		
9.227		9.33		9.38	$0^+, T=2$						
									(10.70)		
									(11.00)		

[a] If $I^\pi = 6^+$.

butions, the DWBA calculation fails in the 3^- case. This may indicate the need for a more microscopic computation of the form factor at least in such mixed-shell cases and/or it may indicate a more complicated mechanism.

It is noteworthy in this context that strong excitation of negative-parity states (particularly 3^- states) has been observed[40] also in the ^{16}O-(^{7}Li, t) reaction, the ^{54}Fe(^{6}Li, d) reaction,[41] and the (^{16}O, ^{12}C) reactions.[4,42,43]

4.00 MeV. From the angular distributions, this level can be assigned $L > 4$. Figure 2 shows DWBA results for $L = 6$ and $L = 8$. Though $L = 8$ is seen to give the better fit at small angles, uncertainties in the DWBA for these larger L values do not allow $L = 6$ to be precluded. A discrepancy between DWBA and experiment at small angles is already observed for 4^+ angular distributions.

4.10 MeV. The angular distribution clearly indicates $L = 2$. No 2^+ level has been reported previously at this energy, but a 4^+ state has been identified at 4.060 MeV from the (p, t) reaction.[36] In the (^{7}Li, t) reaction,[19] levels at 3.94 and 4.10 MeV are observed. The resolution in this experiment is not sufficient to resolve levels in between. The (^{16}O, ^{12}C) experiments did not resolve the levels around 4 MeV.

4.84 MeV. The present experiment indicates $L = 0$ for this level. In (p, t) studies[36,37] a state close to 4.80 MeV is reported with the tentative spin assignments 2^+ (Ref. 36) and 4^+ (Ref. 37), respectively.

5.23 and 5.33 MeV. The angular distributions of these two levels are similar to those corresponding to known 4^+ levels, although significant deviations from DWBA predictions occur at small angles. The 5.23-MeV state has not been reported previously. These states are unbound (threshold for α decay = 5.12 MeV). However, the form factor used in the DWBA calculations for these and higher states corresponds to weak binding ($E_B = -50$ keV). Because of the small α penetrability this approximation should cause no serious difficulty at least as far as the prediction of the shape of the angular distribution is concerned.

6.03 and 6.22 MeV. The angular distributions for these levels resemble that for the 3.92-MeV state. Although (p, t) work led to a tentative (4^+) spin assignment for the 6.03-MeV level,[36] a comparison between the angular distribution seen in the present work and those known to be $L = 4$ seems to preclude this assignment.

8.04 MeV. For reasons analogous to those mentioned in connection with the 4.00-MeV level, all we can conclude is that $L > 4$.

8.54 MeV. The level seen at this energy is strongly populated, and the shape of its angular distribution suggests spin 0^+. Although this state is unbound against α-particle emission, the form factor used in calculating the DWBA corresponds to weak binding ($E_B = -50$ keV). It is hoped that this approximation does not strongly affect the shape of the predicted angular distribution. However, the assumed boundness implies an underestimation of the surface amplitude of the radial wave function and hence an underestimation of the DWBA cross section. At least part of the remarkably large relative strength $S(8.54)/S(\text{g.s.}) = 8$ is thus due to the relative underestimation of σ^{DW} (8.54 MeV).

It should be noted in this context that the Wigner limit corresponding to the α penetrability

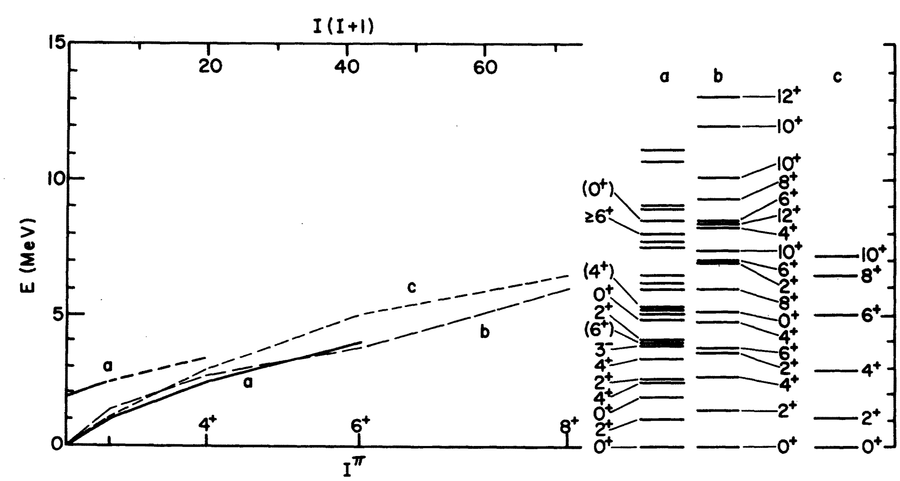

FIG. 3. ^{44}Ti level schemes obtained (a) from this experiment, (b) from $(fp)^4$ shell-model calculations (Ref. 16), and (c) from $(f_{7/2})^4$ stretch-scheme calculations (Ref. 13).

($P_{L=0}=kR(F_0{}^2+G_0{}^2)^{-1}<10^{-4}$) is much smaller than the experimental resolution width, i.e., no peak broadening is expected to be observed.

Additional states observed at 8.93, 10.7, and 11.0 MeV indicate the possibility of finding even higher ^{44}Ti states by means of the (^{6}Li, d) reaction. This reaction therefore may provide the tool to search for members of the "α rotator" band discussed by Stock *et al.*[44] The beginning of this band is expected at ~10 MeV. The 0^+ state at 8.54 MeV could be regarded as a possible candidate for the head of this band.

V. COMPARISON WITH SHELL-MODEL CALCULATIONS

Figure 3 compares the levels observed in the present experiment with those predicted by shell-model calculations.[13,16] The left-hand side of Fig. 3 illustrates the departure of the ground-state band from the $I(I+1)$ rule. This contrasts with the case of ^{20}Ne and has been stressed previously.[15,35,36]

Jaffrin[13] has calculated excitation energies on the truncated basis of the stretch scheme for $1f_{7/2}$ nucleons. Bhatt and McGrory[15] have performed an extended shell-model calculation including all fp orbits in the active space and have also calculated[16] the strength for $(\lambda,\mu)=(12,0)$ configuration, which corresponds to the α spectroscopic factor. (Figure 3 displays only those states for which this strength is $\geq$10%.)

It has been suggested that some of the observed states—e.g., the 0^+ state at 1.90 MeV, the 2_2^+ at 2.52 MeV, and the 3^- at 3.92 MeV are based on core excitations and hence are not accounted for in the shell-model calculations. Arima, Gillet, and Ginocchio[45] predict a quartet excited $[(sd)^{-4}$-$(fp)^8]$ 0^+ state at 2.3 MeV. If the recently corrected mass of ^{44}Ti is used,[35,36] this energy shifts to 2.0 MeV—very close to the observed 1.90 MeV. In a one-step α-transfer reaction, such a state would have to be populated via the very weak (~1%) $4p4h$ component[46] of ^{40}Ca$_{\text{g.s.}}$. From the strength with which the state in question is seen in the (^{6}Li, d), (^{7}Li, t) (Ref. 19), and the (^{16}O, ^{12}C) reactions[39] one would therefore suggest that it contains 4p-0h and/or 6p-2h admixtures, the latter populated via the relatively strong 2p2h component[46] in the ^{40}Ca target nucleus. On the other hand, a large α strength in the 8p-4h state could compensate for the weakness of its 4p-4h parent. At present we cannot argue more quantitatively. If the state in question has 8p-4h configuration, it should be appreciably populated by the reaction ^{36}A(^{12}C, α)^{44}Ca. This experiment is being performed.[47]

The 0_2^+ state at 1.90 MeV and 2_2^+ at 2.52 MeV are supposed to form the head of a quasirotational band.[15,35,38] The strong relationship between these states is reflected in the enhanced $B(E2, 2_2^+\to 0_2^+)$ value.[35] It is interesting to note that in the (^{6}Li, d) reaction the two states are populated with equal strengths: $S(2_2^+)/S(0_2^+)=1$. This may be considered as another indication of the rotational character of these states as opposed to the "ground-state band" members for which $S(2_1^+)/S(0_1^+)\approx 0.3$ (Table II). In Fig. 3, the 4_2^+ state at 3.35 MeV has tentatively been associated with the 2_2^+ and 0_2^+ levels. However, its relative spectroscopic factor is smaller than the 1 for these states.

The strong decrease in the relative spectroscopic factors of the first "g.s.-band" members with increasing spin contrasts with corresponding results[11] for ^{20}Ne. This decrease appears to be predicted by $(f_{7/2})^4$ stretch-scheme results,[14] whereas according to the $(fp)^4$ shell-model calculations[16] the spectroscopic factors should be nearly constant. The latter calculations predict a 0^+ state at ~5 MeV with about twice the (12, 0) strength of the ground state. The level at 4.84 MeV with S/S(g.s.) = 1.35 is a possible candidate for this state.

Kurath[48] calculated α strengths associated with different subspaces $[(1f)^{4-n}(2p)^n](n\leq 4)$. He shows that the $2p$ contribution is much more important than the $1f$ contribution; the α strength concentrates strongly on configurations with two or more $2p$ nucleons. In the cross section, further enhancement of $2p$ dominance is expected[49,50] from the larger radial extension of the corresponding wave functions. (The situation is similar, but less pronounced for two-nucleon transfer.[49])

Here, a major deficiency in the present analysis becomes evident. The cluster form factor, calculated according to the standard recipe as outlined in Sec. II, does not appropriately account for differences in $2p$ and $1f$ radial wave functions. This certainly limits the significance of the above comparison of calculated and derived relative strengths. One would, for example, expect that the present form factor seriously underestimates the surface amplitude of $(2p)^4$ with respect to $(1f)^4$ configuration. This results in an overestimation of the corresponding relative spectroscopic factor.

VI. SUMMARY

We have studied the ^{40}Ca(^{6}Li, d)^{44}Ti reaction at 32 MeV. The improved energy resolution enabled us to separate states that were unobserved or unresolved in previous four-nucleon transfer experiments. In contrast to heavy-ion-induced reactions such as (^{16}O, ^{12}C), (^{18}O, ^{14}C), and (^{20}Ne, ^{16}O), this reaction yields structured angular distributions with shapes characteristic of the transferred orbital momentum.

The angular distributions, generally, are remarkably well described by DWBA calculations performed under the assumption that the (^{6}Li, d) reaction proceeds via one-step transfer of an α particle. Relative spectroscopic factors have been extracted on the basis of this picture and used for comparative discussion of ^{44}Ti levels.

The (^{6}Li, d) reaction has proved a promising spectroscopic tool in the $A \approx 40$ region. It appears desirable to extend the measurements to further Ca isotopes and to even heavier target nuclei. Such work is in progress.[43,51,52]

ACKNOWLEDGMENTS

We want to thank D. Hodges, J. Kulaga, and E. A. Sutter for their aid in analyzing the data and S. Omiecinski for preparing targets. We are grateful to J. B. McGrory for sending us results of his shell-model calculations. One of us (U.S.) especially thanks L. M. Bollinger and J. P. Schiffer for the opportunity to work at Argonne and W. P. Alford for his hospitality at Rochester; and he gratefully acknowledges the financial support by the Bundesministerium für Wissenschaft und Forschung, Germany.

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*Present address: Fakultät für Physik, Freiburg, Germany.

†Work performed under the auspices of the U. S. Atomic Energy Commission.

‡Present address: Cyclotron Laboratory, Michigan State University.

§Work supported by the National Science Foundation.

[1]A. M. Friedman, H. T. Fortune, G. C. Morrison, and R. H. Siemssen, in *Proceedings of the International Conference on Nuclear Reactions Induced by Heavy Ions, Heidelberg, Germany, 1969,* edited by R. Bock and W. R. Hering (North-Holland, Amsterdam, 1970), p. 171.

[2]H. Faraggi, M. -C. Lemaire, J. -M. Loiseaux, M. C. Mermaz, and A. Papineau, Phys. Rev. C 4, 1375 (1971).

[3]J. -C. Faivre, J. Gastebois, B. G. Harvey, J. -M. Loiseaux, and A. Papineau, Ann. Phys. (N.Y.) 66, 905 (1971), and references therein.

[4]G. C. Morrison, J. Phys. (Paris) Colloq. 32, C6 (1971).

[5]H. Faraggi, Comments Nucl. Part. Phys. 5, 79 (1972).

[6]D. Robson, Comments Nucl. Part. Phys. 5, 16 (1972).

[7]K. Bethge, Annu. Rev. Nucl. Sci. 20, 255 (1970), and references therein.

[8]V. Z. Goldberg, V. V. Davydov, A. A. Oglobin, S. B. Sakuta, and V. I. Chuev, Izv. Akad. Nauk. SSSR, Ser. Fiz. 33, 586 (1969) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 33, 542 (1970)].

[9]H. H. Gutbrod and R. G. Markham, Phys. Rev. Lett. 29, 808 (1972).

[10]U. Strohbusch, C. L. Fink, B. Zeidman, R. N. Horoshko, H. W. Fulbright, and R. G. Markham, Phys. Rev. Lett. 29, 735 (1972).

[11]A. Arima, J. Phys. (Paris) Colloq. 32, C6 (1971); A. Arima, H. Horiuchi, K. Kubodera, and N. Takigawa, Advan. Nucl. Phys. 5, 345 (1972), and references therein.

[12]V. Gilet, J. Phys. (Paris) Colloq. 32, C6 (1971), and references therein.

[13]A. Jaffrin, Nucl. Phys. A196, 577 (1972).

[14]J. N. Ginocchio, in *The Structure of $1f_{7/2}$ Nuclei, Proceedings of the Topical Conference, Legnaro (Padova), 15–21 April 1971,* edited by R. A. Ricci (Editrice Compositori, Bologna, 1971), p. 163.

[15]K. H. Bhatt and J. B. McGrory, Phys. Rev. C 3, 2293 (1971).

[16]J. B. McGrory, private communication.

[17]R. H. Siemssen, C. L. Fink, L. R. Greenwood, and H. J. Körner, Phys. Rev. Lett. 28, 626 (1971).

[18]R. H. Siemssen, M. L. Halbert, M. Saltmarsh, and A. van der Woude, Phys. Rev. C 4, 1004 (1971).

[19]A. Cunsolo, M. -C. Lemaire, M. C. Mermaz, J. L. Quebert, and H. Sztark, Centre d'Etudes Nucléaires de Saclay, CEN Report No. 1600, Saclay, 1972 (unpublished).

[20]Performed in the Chemistry Division of Argonne National Laboratory.

[21]H. W. Fulbright and J. A. Robbins, Nucl. Instrum. Methods 71, 237 (1969); H. W. Fulbright, W. A. Lanford, and R. Markham, Bull. Am. Phys. Soc. 16, 57 (1971); H. W. Fulbright, R. G. Markham, and W. A. Lanford, Nucl. Instrum. Methods (to be published).

[22]J. R. Comfort, Argonne National Laboratory Physics Division Informal Report No. PHY-1970B (unpublished).

[23]I. Rotter, Nucl. Phys. A135, 378 (1969).

[24]A. Arima, Argonne National Laboratory, Argonne, Illinois, Physics Division Informal Report No. PHY-1972H, 1972 (unpublished), p. 304.

[25]For example, Yu. A. Kudeyarov, I. V. Kurdyumov, V. G. Neudatchin, and Yu. F. Smirnov, Nucl. Phys. A163, 316 (1971).

[26]This latter argument is based on the usual assumption (Ref. 23) that the internal state of the group does not change during the transfer.

[27]P. D. Kunz, University of Colorado, unpublished.

[28]K. -H. Passler, Verh. Dtsch. Phys. Ges. 1, D2.5 (1973). The D component in the mutual α-d motion of ^{6}Li is estimated at ~0.02%.

[29]R. M. Drisko, G. R. Satchler, and R. H. Bassel, in *Proceedings of the Third Conference on Reactions Between Complex Nuclei, Asilomar, California, 1963,* edited by A. Ghiorso, R. M. Diamond, and H. E. Conzett (Univ. of California Press, Berkeley, 1963), p. 85.

[30]L. J. Denes, W. W. Daehnick, and R. M. Drisko, Phys. Rev. 148, 1097 (1966).

[31]The wave function of mutual α-d motion in ^{6}Li is believed [see R. Middleton, B. Rosner, D. J. Pullen, and

L. Polsky, Phys. Rev. Lett. 20, 118 (1968)] to have a second maximum which may make finite-range effects important though the latter seem not to significantly affect the shape of the angular distributions (Refs. 29 and 30).

[32]E. Newman, L. C. Becker, B. M. Preedom, and J. C. Hiebert, Nucl. Phys. A100, 225 (1967); average potential, p. 234.

[33]K. Bethge, C. M. Fou, and R. W. Zürmuhle, Nucl. Phys. A123, 521 (1969), Table I, line 14; C. L. Fink, U. Strohbusch, and B. Zeidman, to be published.

[34]R. M. DeVries, Phys. Rev. Lett. 30, 666, 940 (1973).

[35]J. J. Simpson, W. R. Dixon, and R. S. Storey, Phys. Rev. C 4, 443 (1971).

[36]J. Rapaport, J. B. Ball, R. L. Auble, T. A. Belote, and W. E. Dorenbusch, Phys. Rev. C 5, 453 (1972).

[37]D. H. Kong-A-Siou, J. F. Bruandet, J. P. Longequeue, N. Longequeue, and B. Vignon, Nucl. Phys. A197, 568 (1972).

[38]W. R. Dixon, R. S. Storey, and J. J. Simpson, Nucl. Phys. A202, 579 (1973).

[39]G. C. Morrison, private communication.

[40]For example, Middleton, Rosner, Pullen, and Polsky (Ref. 31).

[41]R. A. Lindgren, R. G. Markham, H. W. Fulbright, and G. C. Morrison, to be published.

[42]G. Bruce, A. Chameaux, R. DeVries, and G. C. Morrison, Phys. Rev. Lett. 29, 295 (1972).

[43]G. C. Morrison, J. Phys. (Paris) Colloq. 33, C5 (1972).

[44]R. Stock, G. Gaul, R. Santo, M. Bernas, B. Harvey, D. Hendrie, J. Mahoney, J. Sherman, J. Steyaert, and M. Zisman, Phys. Rev. C 6, 1226 (1972).

[45]A. Arima, V. Gillet, and J. Ginocchio, Phys. Rev. Lett. 25, 1043 (1970).

[46]W. J. Gerace and A. M. Green, Nucl. Phys. A123, 241 (1969).

[47]H. T. Fortune, private communication.

[48]D. Kurath, Phys. Rev. C 7, 1390 (1973).

[49]R. N. Glover and A. M. McGregor, Phys. Lett. 24B, 97 (1967).

[50]P. Bonche, B. Giraud, A. Cunsolo, M. -C. Lemaire, M. C. Mermaz, and J. -L. Quêbert, Phys. Rev. C 6, 577 (1972).

[51]U. Strohbusch and J. P. Schiffer, Bull. Am. Phys. Soc. 17, 909 (1972).

[52]U. Strohbusch, H. W. Fulbright, R. N. Horoshko, R. Markham, C. L. Fink, B. Zeidman, and J. P. Schiffer, Verh. Dtsch. Phys. Ges. 1, 60 (1973).