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Low-Lying Levels in ^{42}Ca Excited by the ^{43}Ca(d,t) Reaction

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Angular distributions of triton groups corresponding to (d,t) transitions to five states in ^{42}Ca have been observed at a bombarding energy of 8.522 MeV. The tritons were recorded in a multigap broad-range spectrograph. The elastic scattering of deuterons from ^{43}Ca was also measured and fitted with an optical-model potential, which was then used in a distorted-wave analysis of the (d,t) cross sections. The results are in good agreement with the predictions for an $(f_{7/2})^3$ configuration for ^{43}Ca and $(f_{7/2})^2$ for ^{42}Ca, except that the 2^+ parentage is split approximately equally between the 1.53- and 2.44-MeV states of ^{42}Ca. The data do not allow $l=1$ pickup with more than a few percent of the single-particle strength. Transitions to the second 0^+ state at 1.84 MeV are not observed. The results are discussed in terms of the seniority coupling scheme and in terms of the shell model with residual interactions.

I. INTRODUCTION

In the past few years a large number of inelastic scattering experiments and one-nucleon-transfer experiments has been carried out on the Ca isotopes.[1–3] Owing to their low isotopic abundance, however, the data from ^{43}Ca and ^{48}Ca are not very extensive, and no results from bombardments of ^{46}Ca have been reported.

The present report on the ^{43}Ca(d,t) reaction is the first of a series dealing with the results from (d,t), (d,d'), and (d,p) reactions on isotopically separated targets of ^{43}Ca, ^{46}Ca, and ^{48}Ca. In these experiments bombarding energies between 7 and 11 MeV were used and the reaction products were recorded with energy resolutions of ≈ 15 keV. Angular distributions were measured by means of the multigap spectrograph[4] of the tandem accelerator laboratory at Atomic Weapons Research Establishment, (AWRE), Aldermaston, England. The results have been analyzed using the distorted-wave method and are discussed in terms of current nuclear models.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The ^{43}Ca targets were made by isotope separation of $CaCl_2$ enriched[5] to 24.4% in ^{43}Ca. The ion-source techniques and the isotope collection arrangements employed during the separations were identical to those described elsewhere.[6,7] Targets of greater than 99% isotopic purity and approximately 20 μg/cm^2 thickness resulted. C foils of 50 μg/cm^2 were used as backings.

Measurements of elastic deuteron scattering cross sections were undertaken with the purpose of providing information on the optical model parameters. The measurements on ^{43}Ca were made using the Copenhagen tandem Van de Graaff at bombarding energies of 7 and 8.5 MeV. At each of these energies the angular distributions of the elastically scattered deuterons were recorded by means of a 3750 Ω-cm n-type silicon surface-barrier counter in connection with a 512-channel pulse height analyzer. The resulting crosssections are shown in Fig. 1 in comparison with optical-model predictions. The absolute values of the cross sections were established by making further measurements at 4 MeV at angles from 60 to 70°. Optical-model studies at this energy indicated that at 65° (lab) the cross section is 0.78 ± 0.02 times the Rutherford cross section, and the value 0.78 was adopted. This figure is quite close to that deduced from comparison with measurements on Ti at 4 MeV.[8] Its use is further supported by the fact that it leads to a normalization of the 7- and 8.5-MeV data which allows the closest optical-model fits.

The ^{43}Ca(d,t)^{42}Ca angular distributions were measured at the Aldermaston AWRE tandem Van de Graaff laboratory, by employing the 24-gap broad-range heavy-particle spectrograph of Middleton and Hinds.[4] The input energy, 8.522 MeV, was the maximum energy that would allow the recording of the triton group corresponding to the ground-state transition. The reaction products (protons, deuterons, tritons, and α

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† Operated for the U. S. Atomic Energy Commission by Union Carbide Corporation.

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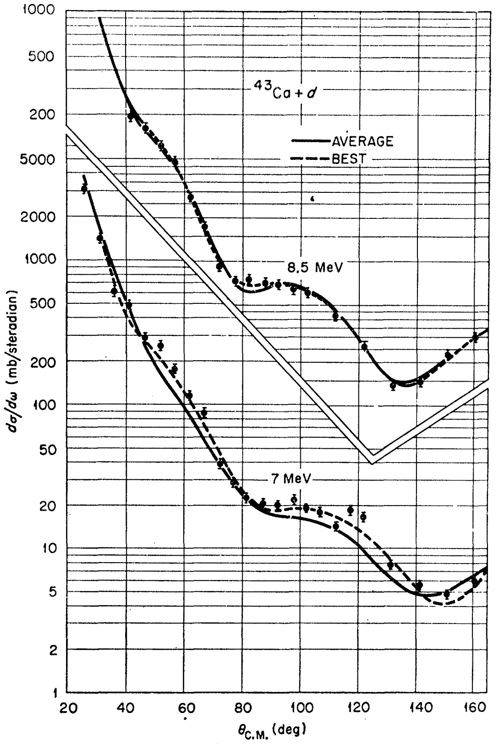

FIG. 1. Elastic scattering of deuterons from ^{43}Ca. The full curves are optical-model predictions using the "Average" parameters for 8.5 MeV (see Table II); the dashed curves are the optimum "Best" fits at each energy.

particles) were detected by 50-μ photographic emulsions. The triton tracks were selected in the scanning according to their length and grain density. At the three most forward scattering angles (5, 12.5, and 20°) part of the plates were obscured by a heavy deuteron background, originating from deuteron elastic scattering. No data for (d,t) transitions to excited states in ^{42}Ca was obtained at these angles. Several rescannings showed that when triton groups contained more than about 100 tracks, scanning errors were less than the statistical errors; but for groups of less than about 10 tracks scanning errors could be as high as 50%.

The triton spectrum observed at 35° laboratory scattering angle is shown in Fig. 2. Triton energies corresponding to ^{42}Ca excitation energies from 0 to 4.6 MeV were recorded, but only five groups belonging to mass 42 were identified.

The triton angular distributions are shown in Fig. 3. (The curves are the distorted-wave predictions, obtained as discussed in Sec. IV.) As the spectra mostly are free from background (see, for example, Fig. 2), the errors are principally statistical errors and scanning errors. The experimental cross-section scale was established by normalizing the elastic scattering yields, as observed at back angles in the multigap spectrograph run, to the previously measured elastic-scattering cross sections shown in Fig. 1.

TABLE I. States in ^{42}Ca (energies in keV).

$Q(d,t)$	Excitation		J_f, π	$S(f_{7/2})$
Present exp.	Present exp.	Ref. 9	Ref. 10	Theory
-1672 ± 10	0	0	0, +	9/12
-3204 ± 10	1532	1523	2, +	5/12
		1836	0, +	
-4107 ± 10	2435	2423	2, +	
-4436 ± 10	2764	2750	4, +	9/12
-4867 ± 10	3195	3191	6, +	13/12

The Q values obtained in the present experiment are given in Table I together with the excitation energies from the present experiment and those from Ref. 9, and spin-parity assignments from Ref. 10.

A special search for triton groups corresponding to ^{42}Ca excitation energies around 4-5 MeV was performed at a bombarding energy of 11 MeV, employing the deuteron beam and the single-gap heavy-particle spectrograph[11] of the Copenhagen tandem accelerator laboratory. No new groups were detected. Groups with intensities of about 10% of the intensity of the ground-state group would have been seen.

III. OPTICAL-MODEL ANALYSIS

The first requirements for a distorted-wave analysis are optical-model potentials which give a good account of the elastic scattering of the particles involved, at the appropriate energies. Data for deuteron scattering from ^{43}Ca were obtained in the present experiment, but very little data or analysis is available for triton scattering. Measurements have been made[12] for the elastic scattering of 7.2-MeV tritons from ^{40}Ca. This is reasonably close to the energies (3.5-6.9 MeV) of the tritons emitted in the present experiment. This data has been analyzed[12] using a Woods-Saxon optical potential in which the radius and diffuseness of the imaginary well are the same as for the real. However, it is reasonable to suppose that the optical potential for tritons is closely related to that for ^{3}He ions, and it is known that elastic scattering of ^{3}He favors a potential with an imaginary part extending to considerably larger radii than the real part.[13] (This is also similar to the behavior of the optical potential for deuterons, and reflects the importance of surface direct interactions for the absorption of these particles). Hence we chose a potential known to give a good account of ^{3}He scattering from nuclei in this mass region[13]; however, in order to fit the observed triton scattering from ^{40}Ca it was found necessary to increase the strength of the absorptive potential. A comparison between theory and experiment is shown in Fig. 4.

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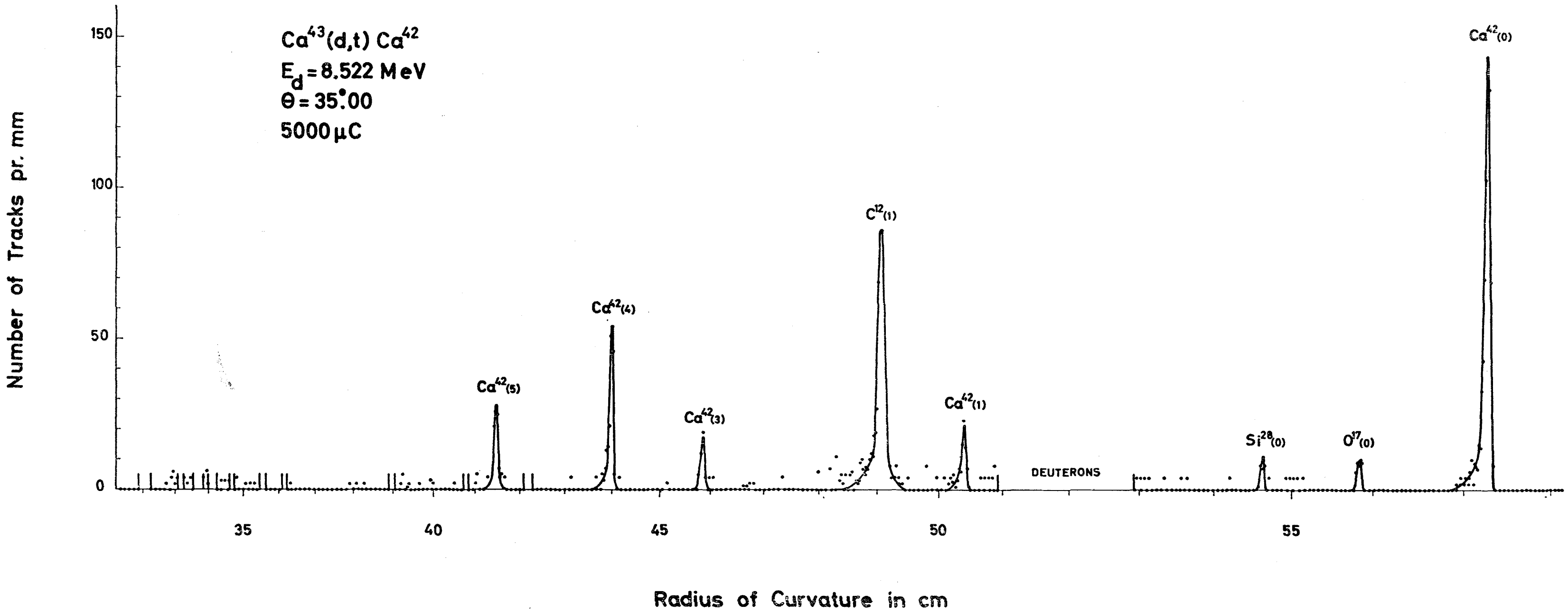

FIG. 2. Triton spectrum from the ^{43}Ca(d,t) reaction. The vertical bars in the bottom of the figure indicate ranges of the plates which could not be scanned because of dense peaks of proton, alpha, or deuteron tracks.

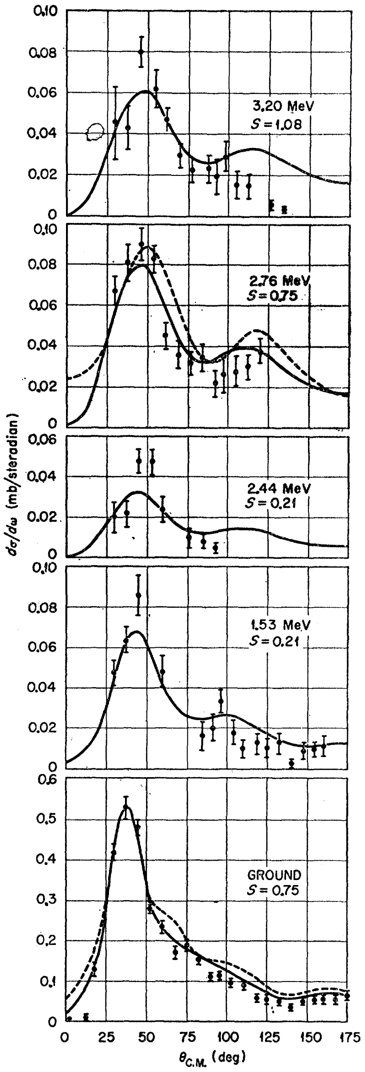

FIG. 3. Differential cross sections for the ^{43}Ca(d,t) ^{42}Ca reaction at 8.522 MeV. The curves are distorted-wave predictions for neutron pickup from the $1f$ orbit. The full curves were calculated with the "Average" deuteron parameters, the dashed curves with the "Best" deuteron parameters.

Note added in proof. The experimental points for the ground-state transition at the three most forward angles as shown in the figure should be multiplied by factors of 3.96, 2.00, and 1.33, respectively.

The optical potential used has the form

$$U(r) = -V(e^{x}+1)^{-1} - i(W - 4W_D d/dx')(e^{x'}+1)^{-1}$$

where (1)

$$x = (r - r_0 A^{1/3})/a, \quad x' = (r - r'_0 A^{1/3})/a'.$$

The Coulomb potential from a uniform charge of radius $r_c A^{1/3}$ is also included. The triton parameters used are given in Table II.

Fits to the deuteron scattering from ^{43}Ca were obtained using an automatic search code[14] based on a least-squares criterion. Because it shows less scatter, more attention was given to the 8.5-MeV data. The searches were started with parameters suggested by a potential (called *Average Z*) which gave a good over-all fit to deuteron scattering from ^{40}Ca in the 7–12-MeV energy range.[3] This potential uses surface absorption only ($W=0$). Optimum fits, obtained by varying V and W_D only, are called "Average," while optimum fits obtained by varying all parameters are called "Best." The curves labelled "average" in Fig. 1 were both calculated using the "Average" parameters for the 8.5-MeV data; the "best" use the "Best" parameters at each energy. These various parameter values are presented in Table II, together with the predicted reaction cross sections σ_R. To study the effects of errors in normalization of the data, other normalizations were chosen and refitted; for example, the main effect of an increase in the magnitude of the cross sections is to increase the absorptive potential and slightly decrease the real potential.

It will be seen that there is a tendency for the radius of the imaginary potential to increase as the energy is lowered. The same tendency was seen[3] for deuterons on ^{40}Ca; however, it was also found that in a distorted-wave calculation of the (d,p) stripping cross sections that better fits were obtained by fixing this radius at the "Average" value rather than using the optimum "Best" value. The same result is obtained in the present analysis of the (d,t) reaction.

IV. DISTORTED-WAVE ANALYSES

The potentials obtained as described in the last section were then used in distorted-wave calculations[15]

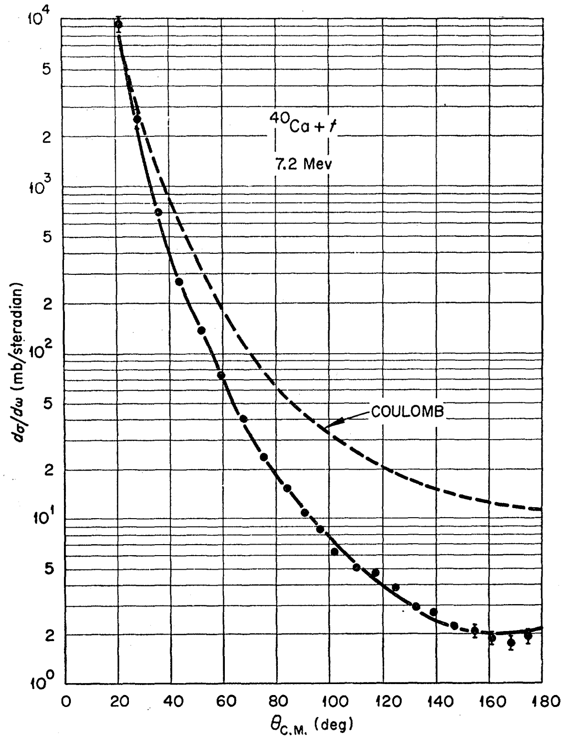

FIG. 4. Elastic scattering of 7.2-MeV tritons from ^{40}Ca compared to the predictions of the optical potential used in the present analysis. The data were normalized to the theory at 44°.

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TABLE II. Optical-model potential parameters.

Particle	Energy (MeV)	Potential	V (MeV)	r_0 (F)	a (F)	W (MeV)	W_D (MeV)	r_0' (F)	a' (F)	r_c (F)	σ_R (mb)	χ^{2} [a]
Deuteron	8.5	Average	115.5	1.0	0.9	0	17.5	1.55	0.47	1.3	1116	0.72
		Best	109.3	0.991	0.986	0	13.3	1.686	0.535	1.3	1343	0.28
	7	Average	110.6	1.0	0.9	0	20.0	1.55	0.47	1.3	981	3.88
		Best	129.0	0.883	0.864	0	6.3	1.816	0.691	1.3	1342	1.58
Triton	all	···	107.0	1.07	0.854	12.0	0	1.81	0.592	1.4	···	···

[a] The mean-square deviation χ^2 between experiment and theory was calculated assuming 10% errors for all cross sections.

of the (d,t) reaction, assuming simple neutron pickup. The bound neutron is assumed to be moving in a Saxon potential of radius 1.25 $A^{1/3}$ F and diffuseness 0.65 F. The binding energy to be used is discussed below. Differential cross sections were obtained with both the "Average" and the "Best" 8.5-MeV deuteron potentials. Over-all, the "Average" potential gives a better fit to the observed angular distributions; two examples are shown in Fig. 3.

The absolute normalization of the predicted cross sections is not well known at present. The differential cross section may be written in the form[15]

$$d\sigma/d\omega = N_t S(l_j,J_f)\sigma_{lj}(\theta)\,\text{mb/sr}, \tag{2}$$

where σ_{lj} is a "reduced" cross section calculated by the distorted-wave theory for pickup from an orbit with quantum numbers l and j, and $S(l_j,J_f)$ is the spectroscopic factor[16] for the transition to a final state with spin J_f. N_t is a normalization constant of order unity; besides physical constants it includes the overlap for dissociation of a triton into a deuteron and a neutron. It should not differ much from the corresponding constant for $(d,{}^3\mathrm{He})$ reactions, and experience with these[17] suggests that N_t should be somewhat larger than 2. The shell model suggests the configurations $(f_{7/2})^3$ for the $\frac{7}{2}^-$ ground state of ^{43}Ca, and $(f_{7/2})^2$ for the 0^+, 2^+, 4^+ and 6^+ states of ^{42}Ca. This implies[16,18] spectroscopic factors for $1f_{7/2}$ pick up of 0.75, 0.42, 0.75, and 1.08, respectively. If we normalize the theoretical $l=3$ cross section to the observed cross section for the ground-state group, using this spectroscopic factor and assuming that the neutron binding is equal to its separation energy, we obtain $N_t=2.96$ when using the "Average" deuteron potential, and $N_t=4.25$ when using the "Best" potential. The curves shown in Fig. 3 were drawn using this normalization and the theoretical spectroscopic factors, except it was assumed that the strength for the 2^+ parent was equally split between the two observed 2^+ levels. This procedure leads to good agreement with experiment.

In the calculations just described, the wave function for the picked-up neutron is taken to be the eigenfunction of a Saxon well with a binding energy equal to the separation energy, 6.26-Q MeV, for each final state. This at least gives the correct form for the tail of the wave function. However, it has been suggested[19,20] that one should use the same effective binding energy for all the final states when generating this wave function, namely the zero-order single-particle binding energy. In the present case, calculations were also made using the same neutron wave function (with 7.93-MeV binding) for transitions to the excited states of ^{42}Ca as to the ground state. The effects on the angular distributions are negligible, but the magnitudes of the excited state cross sections are increased considerably (by factors of 1.27, 1.65, 1.79, and 1.95 for the levels at 1.53, 2.44, 2.76, and 3.20 MeV, respectively). The spectroscopic factors inferred from experiment would then have to be reduced correspondingly. Alternatively, if one assumed that the 6^+ level was most likely to be pure $(f_{7/2})^2$, and normalized the theoretical cross sections correspondingly, then the spectroscopic factors for the lower levels become unreasonably large. The ground state, for example, then requires $S(f_{7/2})\approx 1.5$. Assuming the ^{40}Ca ground state to be mainly a double closed-shell state, we may expect an $f_{7/2}$ neutron pick-up strength from the ^{43}Ca ground state of three particles. Using eigenfunctions of binding energy equal to 6.26-Q MeV we obtain good agreement with the experimentally observed strength, whereas use of 7.93-MeV binding for all states leads to an experimental strength of either two particles (normalizing to the ^{42}Ca ground-state group) or of four particles (normalizing to the ^{42}Ca 6^+ group).

A total strength of two $f_{7/2}$ particles would imply an admixture in the ^{43}Ca ground state of one particle from other shell-model states, most likely from the $p_{3/2}$ orbital (see, for example, the neutron pick-up data from Ti isotopes[21]); no such transitions were observed in the present experiment. Thus we see that the prescription of using the same neutron wave function for all transitions is not satisfactory in the present instance, whereas assuming motion in a potential well with a binding

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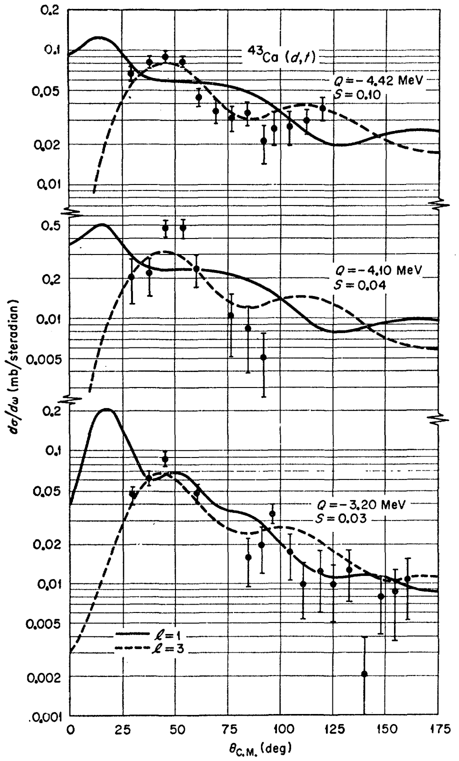

Fig. 5.

FIG. 5. Comparison of $l=1$ and $l=3$ predictions for the (d,t) reaction to the 2^+ and 4^+ states, using the "Average" deuteron potential. The $l=1$ spectroscopic factors used are displayed, while those for $l=3$ are given in Table I.

equal to the respective separation energies does give a good account of the observed cross sections.

Conservation of angular momentum allows pick up with $l=1$ to the $J_f=2^+$ and 4^+ states. Pure $(f_{7/2})^n$ configurations for ^{42}Ca and ^{43}Ca would exclude $l=1$, and examination of the data for $l=1$ contributions would provide a sensitive measure of the amount of these admixtures. Figure 5 shows a comparison of the $l=1$ and $l=3$ predictions for these states, using the "Average" deuteron potential. The $l=1$ spectroscopic factors used in drawing the curves are displayed in the figure, while the $l=3$ curves use the predicted $S(f_{7/2})$ of Table I as in Fig. 3. [The normalizing constant N_t of Eq. (2) is, of course, the same for $l=1$ as for $l=3$]. Only for the lower 2^+ level does $l=1$ give anything like an acceptable fit to the observed angular distribution, and even here a predominantly $l=1$ transition would be ruled out if sufficient weight were given to the measured cross section at 30°. Data at more forward angles would be decisive in distinguishing between $l=1$ and $l=3$ in this case. The other states are clearly fed mainly by $l=3$ pick up. We may then conclude that the spectroscopic actors for $l=1$ are no larger than 0.01, and may be less.

The calculations as described so far have been made using the so-called "zero-range" approximation,[15] in which the product of the interaction binding neutron and "deuteron" to form a triton, and the internal wave function of the triton, is assumed to be proportional to a delta function in the neutron-deuteron separation. Calculational techniques have been proposed[22] for avoiding this approximation. The results of such "finite-range" computations for two of the groups seen in the present experiment are shown in Fig. 6. The "average" deuteron potential was used, and the neutron binding energy taken to be equal to its separation energy. The delta function of the zero-range approximation is replaced by a Gaussian of range 1.5 F. Contrary to the results obtained[23] for $(d,{}^3\text{He})$ reactions at 21 MeV, rather little effect is seen at the much lower energy involved here. Indeed, the introduction of a finite range produces a small *increase* in the cross section. The cause of this effect may be traced to the importance at low energy of the contributions to the reaction from the nuclear surface and beyond. The neutron wave function is essentially exponential, and hence concave, in this region, while the distorted waves are rather slowly varying. The averaging implied by the finite range then produces a small enhancement. A calculation was also performed for the $Q=-4.87$-MeV group using the same neutron wave function as for the ground state. This gave a 12% increase in peak cross section compared to the corresponding zero-range prediction, and a slight change in shape similar to that shown in Fig. 6.

It has also been suggested that, for a variety of reasons, improved fits to experiment would be obtained

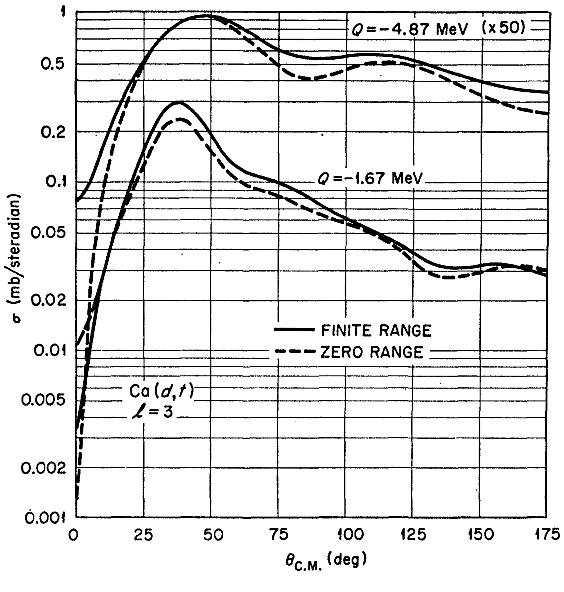

FIG. 6. Comparison of zero-range and finite-range distorted-wave predictions for the reduced cross section of Eq. (2) at 8.522-MeV deuteron energy.

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if the contributions to the reaction from the nuclear interior were excluded.[24] In the present case, however, where the use of such a radial cutoff produces any significant change at all, it also worsens the agreement between the theoretical and experimental angular distributions.

V. DISCUSSION

The present analysis has shown that the distorted-wave method is able to give a good account of the observed (d,t) angular distributions, and requires a reasonable value of the normalization factor N_t to fit the absolute values of the cross sections. The most consistent application of the theory is in very good agreement with the predictions of the shell model assuming $(f_{7/2})^n$ configurations, except that the strength for 2^+ excitation is shared roughly equally by the two 2^+ states at 1.53- and 2.44-MeV excitation in ^{42}Ca. This implies considerable interaction between these two states. Since there is only one 2^+ state for the $(f_{7/2})^2$ configuration, another configuration must be invoked. The most likely candidate is $(f_{7/2}p_{3/2})$ which, in the absence of residual interactions, would have an excitation energy of approximately 2 MeV.[3] This could be reached by $l=3$ pickup through an $(f_{7/2})^2p_{3/2}$ admixture in the ^{43}Ca ground state, or by $l=1$ through an $f_{7/2}(p_{3/2})^2$ admixture. However, the *sum* of the strengths to these two levels is just that predicted by $(f_{7/2})^n$ configurations, which suggests a strong coupling between the $(f_{7/2})^2$ and $(f_{7/2}p_{3/2})$ configurations in ^{42}Ca rather than admixtures in the ^{43}Ca ground state. It would be of considerable interest to have more precise information on the amount of $l=1$ pickup to these states.

The second 0^+ state at 1.84 MeV is not populated with measurable strength in the present experiment. The nature of this state is somewhat obscure; it is unlikely to arise from any simple configuration like $(p_{3/2})^2$. It is probably related to the low-lying 0^+ state at 3.35 MeV in ^{40}Ca, and the appearance of a second $\frac{3}{2}^-$ state at 2.47 MeV in ^{41}Ca; that is, it probably involves excitation of the closed shells in the ^{40}Ca core. It is known[25] to decay to the lower 2^+ state with an $E2$ strength some 12 times "single particle," and to the ground state with a strong $E0$ transition. The nonappearance of the second 0^+ state in the present experiment does not necessarily imply the absence of such core excitations in the ground state of ^{42}Ca; rather, it suggests only that the state of the core in the ^{42}Ca and ^{43}Ca ground states is essentially the same, and orthogonal to that in the 1.84-MeV level in ^{42}Ca. Further, the agreement between theory and the present experiment for the *relative* cross sections to the various states in ^{42}Ca suggests that the core state is closely the same for all of these.

Further light will be thrown upon the nature of these states when the measurements[26] of the ^{40}Ca$(t,p)^{42}$Ca reaction have been fully interpreted. In this reaction, the second 2^+ is excited with an intensity three times lower than that of the first 2^+ state. This would be consistent with the present experiment if the two 2^+ states were formed from roughly equal mixtures of $(f_{7/2})^2$ and $(f_{7/2}p_{3/2})$. If the ^{43}Ca ground state is fairly pure $(f_{7/2})^3$, as we have argued above, only the $(f_{7/2})^2$ components will contribute significantly to the (d,t) reaction. For the (t,p) however, the $(f_{7/2}p_{3/2})$ can also contribute, and since the relative sign of the two components will be opposite in the two states, reinforcement can occur for the lower state and cancellation for the higher.

The second 0^+ is observed in the (t,p) experiment, but with an intensity only one-tenth of that for the ground state. This again is consistent with the model for these two states in which two orthogonal core states are coupled to $(f_{7/2})^2$, and also suggests the core state in the ^{42}Ca ground is quite similar to that of the actual ^{40}Ca ground state.

The present work may be compared to an earlier distorted-wave analysis[27] of the ^{51}V$(n,d)^{50}$Ti reaction. Within the $f_{7/2}$ shell model, this reaction is the proton pickup analog of the ^{43}Ca(d,t) neutron pickup, involving $(f_{7/2})^3$ to $(f_{7/2})^2$ transitions. The results of that experiment were consistent with the shell-theory predictions, and also indicated very small p-state admixtures. Similar conclusions have been reached from a study of the ^{42}Ca$(d,p)^{43}$Ca reaction.[16,28]

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[24] See the discussion of this in, for example, Refs. 3 and 20.

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