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Study of ^{48}Sc by the Reaction ^{46}Ca(α, d)^{48}Sc†

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Angular distributions in the range 10–60° have been measured for the reaction ^{46}Ca(α, d)-^{48}Sc at $E_\alpha = 25$ MeV. The lowest final states populated are those of odd angular momentum $J^\pi = 1^+$, 3^+, 5^+, and 7^+ belonging to the configuration ($\nu f_{7/2}{}^{-1} \pi f_{7/2}$). As expected, the even-J states $J^\pi = 2^+$, 4^+, and 6^+ of this configuration are only very weakly excited. Angular distributions for several additional states up to 4.2-MeV excitation in ^{48}Sc were also measured. The cross sections for these higher states are an order of magnitude lower than would be estimated from normalizing the microscopic distorted-wave calculations to the low-lying states.

I. INTRODUCTION

That ^{48}Sc states belonging to the particle-hole configuration ($\nu f_{7/2}{}^{-1} \pi f_{7/2}$) are preferentially populated in the charge-exchange reaction ^{48}Ca(^{3}He, t)-^{48}Sc suggests that they are of reasonably pure configuration.[1-3] For a further exploration of these $(f_{7/2})^2$ states in ^{48}Sc, we employ the reaction ^{46}Ca-(α, d)^{48}Sc. States to be excited in this two-nucleon-transfer reaction on a spin-zero target are of the form $(j_n j_p)_J$, where j_n and j_p are the angular momenta of the transferred neutron and proton, respectively, which couple to a total angular momentum J. Since the transferred nucleon pair in the (α, d) reaction will have spin 1 (and isospin 0), one obtains the condition that only odd-J states may be populated for configurations in which the transferred neutron and proton are in the same orbit. In ^{48}Sc, only the odd-J states (1^+, 3^+, 5^+, and 7^+) should be populated in the $(f_{7/2})^2$ configuration. The degree of suppression of the even-J states ($J^\pi = 2^+$, 4^+, and 6^+) is then a measure of the amount of configuration mixing within the $(f_{7/2})^2$ multiplet, provided second-order processes are unimportant.

The second objective of the present investigation concerns the structure of states in ^{48}Sc other than the ones belonging to the $(f_{7/2})^2$ configuration. The reaction ^{48}Ca(^{3}He, t)^{48}Sc, studied earlier and discussed in the article[4] immediately following the present one, revealed several strong states which could arise from such excitations as ($d_{3/2}{}^{-1} f_{7/2}$), ($s_{1/2}{}^{-1} f_{7/2}$), ($f_{7/2}{}^{-1} p_{3/2}$), and ($f_{7/2}{}^{-1} f_{5/2}$). The ^{46}Ca-(α, d)^{48}Sc reaction should excite only states of even parity, and the present experiment (which covers excitations up to about 4.2 MeV) should allow us to locate components of the f-p and f-f multiplets. From the relevant single-hole and single-particle spectra of nuclides adjacent to ^{48}Sc, we may estimate that these configurations should be contained in states around 3-MeV excitation.

II. EXPERIMENTAL APPARATUS

A Ca target enriched to 43.4% ^{46}Ca and determined to be 100 μg/cm^2 of Ca on a 30-μg/cm^2 carbon backing was bombarded with 25-MeV α particles from the Argonne tandem accelerator. Deuterons were recorded on photographic plates placed in the focal plane of an Enge split-pole spectrograph and covered with 15 mil of vinyl acetate foil to stop the He ions and tritons. The plates were scanned by the automatic plate scanner developed by Erskine and Vonderohe.[5] A typical spectrum, taken at $\theta_{\text{lab}} = 15°$, is shown in Fig. 1. The resolution width was approximately 25 keV. The spectra were fitted by the computer code AUTOFIT,[6] and both intensities and accurate excitation energies of the residual states have been obtained. Since the ground-state transition was very weak, excitation energies were determined with reference to the 3^+, 5^+, and 7^+ states of the $(f_{7/2})^2$ configuration, whose excitation energies had been determined in an earlier precision experiment by Ohnuma *et al.*[1] These values are also consistent with several other experiments.[7]

The states at excitation energies higher than 2 MeV were observed with considerable difficulty. The analysis was complicated considerably by a large number of impurity peaks due to (α, p) and other reactions and, at forward angles, to knock-on protons produced in the acetate foils by elastically scattered ^{4}He. It is estimated that the uncertainty in the excitation energies of these states is ±15 keV.

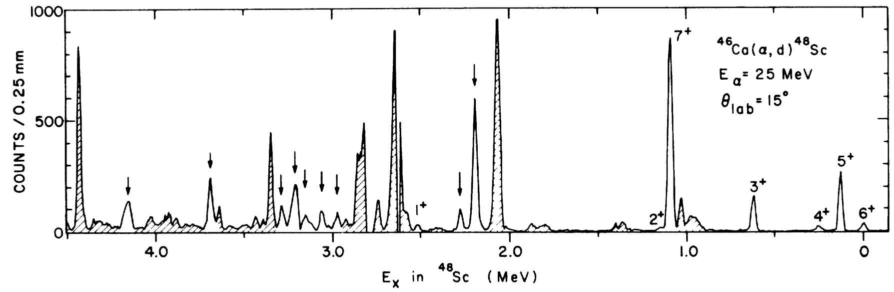

FIG. 1. Spectrum of particles from the reaction ^{46}Ca(α,d)^{48}Sc. The peaks due to impurities are shaded. The states belonging to the $(f_{7/2})^2$ configuration are shown with corresponding spins; the remaining states that have been analyzed are indicated by arrows.

Angular distributions for the states belonging to the $(f_{7/2})^2$ multiplet are displayed in Figs. 2 and 3. Those for the other states are shown in Figs. 4–6. The uncertainties in the absolute cross sections are ±20%. The errors in the relative cross sections are generally statistical and are represented by bars if they exceed the size of the points drawn. Uncertainties due to contaminants are more difficult to estimate and may be substantial for a few points.

III. RESULTS AND DISCUSSION

A. States of the $(\nu f_{7/2}{}^{-1}\pi f_{7/2})$ Configuration

As noted in Sec. I, the captured deuteron is in the spatially symmetric state so that when the transferred proton and neutron go into the same orbit, only odd-J states are populated. It is apparent from the spectrum shown in Fig. 1 and the angular distributions in Figs. 2 and 3 that the 7^+ state at $E_x = 1.096$ MeV has the highest cross section. An enhanced cross section is to be expected for the transfer of the two nucleons into the stretched $(j)^2{}_{2j}$ configuration.[8] This is readily obtained from an inspection of the jj-LS transformation brackets. The strength of excitation gradually decreases in the 5^+ ($E_x = 0.131$ MeV) and 3^+ ($E_x = 0.622$ MeV) states to a cross section of about 20 μb/sr for the 1^+ level ($E_x = 2.521$ MeV). The even-spin states (the 2^+ at 1.143 MeV, the 4^+ at 0.252 MeV, and the 6^+ ground state), though forbidden, are weakly excited.

Distorted-wave (DW) calculations for the allowed transitions into odd-J final states were performed with the code TWOPAR of Bayman.[9] Several optical-model potentials taken from the literature have been used for calculating the distorted waves in the α and d channels, but only the combination of

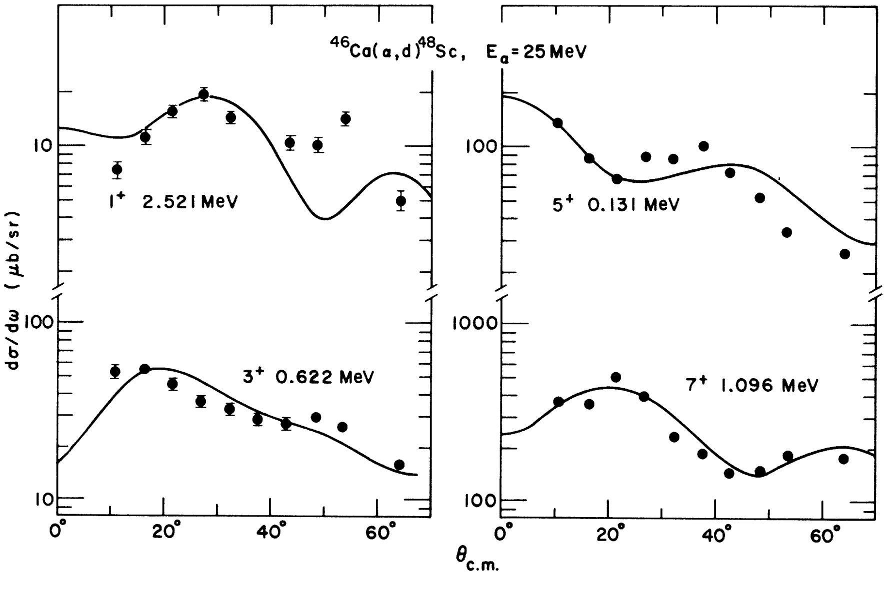

FIG. 2. Angular distributions for the allowed (odd-J)$(f_{7/2})^2$ states together with the DWBA calculations described in the text.

the one by Stock *et al.*[10] for α particles (determined from α scattering from ^{50}Ti at 30.5 MeV) and by Rawitscher and Mukherjee[11] for deuterons (from the scattering of 11-MeV deuterons from ^{40}Ca) described the angular distributions reasonably well (as seen in Fig. 2). This α-particle potential contained a volume-absorption term and the deuteron potential was of the surface-absorption type; the potential parameters are listed in Table I. The bound-state form factors were calculated by taking the binding energy of the single-neutron and single-proton states outside ^{48}Ca. An rms radius of 1.63 F was used for the α particle. No corrections were made for nonlocality or finite range. The fractional-parentage coefficient for placing two nucleons outside the ^{48}Ca core into the different odd-J $(f_{7/2})^2$ states is 0.5 for all four states. The ratios of the observed to the calculated cross section are given in Table II. They are normalized to unity for the 7^+ state and are remarkably constant for all but the 1^+ state. Since admixtures are very unlikely for the 7^+ state, the constancy of the ratio implies very small admixtures in the 5^+ and 3^+ states and some possible admixtures in the 1^+ state.

As has already been mentioned, the even-spin states of the $(f_{7/2})^2$ configuration are forbidden in the (α, d) reaction. That they are weakly seen may be attributed either to higher-order reaction mechanisms or to configuration admixtures. We can estimate the order of magnitude of the admixtures that would be implied by comparing the observed cross sections with those for the $(f_{7/2}{}^7 p_{3/2})$ and $(f_{7/2}{}^7 f_{5/2})$ configurations. Because of the large uncertainty in distorted-wave Born-approximation (DWBA) calculations and the possibility of two-step processes, these estimates of admixtures can only be qualitative guides.

B. States of Configuration Other Than $(\nu f_{7/2}{}^{-1}\pi f_{7/2})$

In addition to the $(f_{7/2})^2$ multiplet states discussed in Sec. III A, we see nine additional excited states. Their angular distributions are shown in Figs. 4–6 and the excitation energies are listed in column 1 of Table III.

The simplest shell-model expectation would be to assume good seniority and that these states have the configurations $(f_{7/2}{}^7 p_{3/2})$ and $(f_{7/2}{}^7 f_{5/2})$. We will

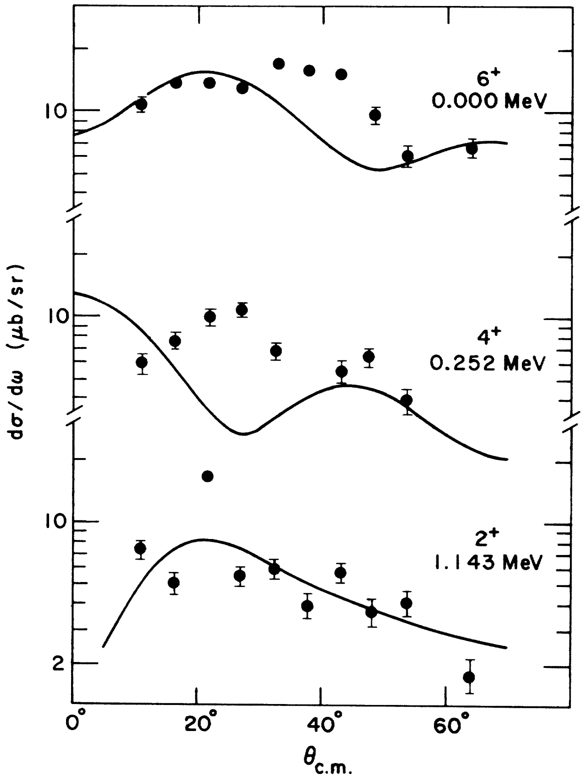

FIG. 3. Angular distributions for the forbidden (even-J) $(f_{7/2})^2$ states together with DWBA calculations for states of the same J, but for different configurations.

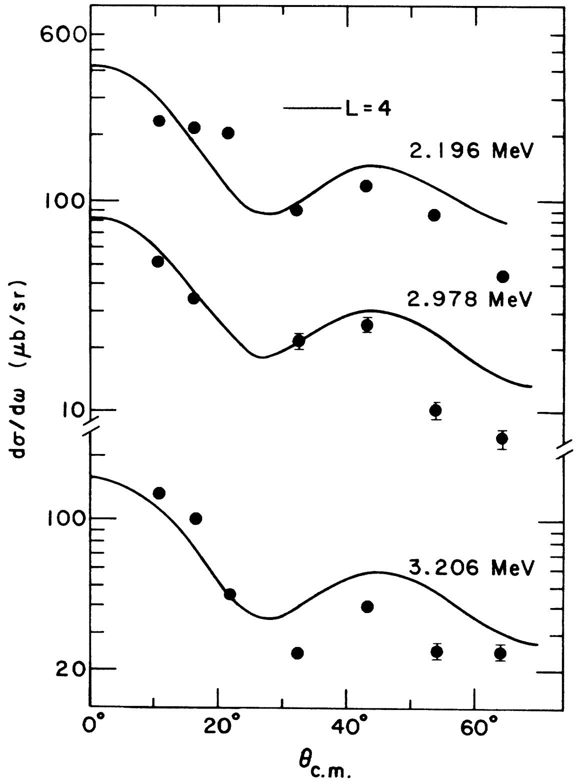

FIG. 4. Angular distributions for states showing an $L = 4$ pattern in their angular distributions. The lines represent DWBA calculations.

TABLE I. Optical-model parameters used for the α and d channels in the reaction ^{46}Ca$(\alpha, d)^{48}$Sc. The optical potential used was of the standard type:

$$V=-V_0\frac{1}{1+e^x}-iW\frac{1}{1+e^{x'}}+4iW_D\frac{d}{dx''}\frac{1}{e^{x''}+1}+V_{\mathrm{Coul}},$$

with $x=(r-r_0A^{1/3})/a$, $x'=(r-r_0'A^{1/3})/a'$, and $x''=(r-r_0''A^{1/3})/a''$. The bound-particle Woods-Saxon potential had the parameters $r_0=1.25$ F, $a=0.65$ F, and $\lambda=25.0$.

	V_0 (MeV)	r_0 (F)	a (F)	W (MeV)	r_0' (F)	a' (F)	W_D (MeV)	r_0'' (F)	a'' (F)	Reference
α	183.7	1.4	0.56	26.0	1.48	0.56	...	...	...	10
d	115.38	1.006	0.878	...	...	...	18.766	1.517	0.482	11

discuss the f-p states first. Their calculated excitation energies are about 3 MeV. Only the components having isospin $T=3$ can be excited in ^{46}Ca$(\alpha,d)^{48}$Sc. Two sets of such states should occur,[12] each containing four levels with $J^\pi=2^+$, 3^+, 4^+, and 5^+. They will be distinguished by the partial isospin of the $f_{7/2}$ particles. One may think of a $p_{3/2}$ particle coupled either to the ground state of ^{47}Sc ($T'=\frac{5}{2}$) so the resulting configuration is $[(f_{7/2})^7{}_{7/2,5/2}(p_{3/2})_{3/2,1/2}]_{J,T=3}$, or to the ground state of ^{47}Ca ($T'=\frac{7}{2}$) (and partially to its analog in ^{47}Sc) so the result is $[(f_{7/2})^7{}_{7/2,7/2}(p_{3/2})_{3/2,1/2}]_{J,T=3}$.[13] The cross sections to the two sets of states should be in the ratio of the squares of the isospin parts of the fractional-parentage coefficients.[14] This ratio is $\frac{27}{8}$ in favor of the $T'=\frac{5}{2}$ states. A similar separation should occur for the $(f_{7/2}{}^7f_{5/2})$ states, of which two sets of six states with $J^\pi=1^+,\ldots,6^+$ are expected. These should be centered around 4-MeV excitation. The $T'=\frac{5}{2}$ states should occur at ~1-MeV-lower excitation energy than the $T'=\frac{7}{2}$ states.

One might hope to take advantage of the fact that selection rules from other reactions would help to make configuration assignments. For instance, the reaction ^{48}Ca$(^3$He$,t)^{48}$Sc should populate only the $T'=\frac{7}{2}$ states in ^{48}Sc. The states seen strongly in pickup reactions – ^{49}Ti$(d,{}^3$He$)^{48}$Sc and ^{50}Ti(d,α)-^{48}Sc – should either be even-parity members of the low-lying $(f_{7/2})^2$ multiplet, or odd-parity states involving the pickup of a $d_{3/2}$ or $s_{1/2}$ particle. The states seen in pickup around 3–4-MeV excitation should have odd parity, while the states seen in the (α,d) reaction should have even parity. The $(^3$He$,t)$ reaction should populate both types but only if $T'=\frac{7}{2}$. Unfortunately, the density of levels is so high that for many of the states seen in the (α,d) reaction, there is one within 20 keV in the $(^3$He$,t)$ and the (d,α) reactions. Since we can have no assurance that the states seen in the different reactions are in fact the same ones, it is not possible to make much use of all these data.

TABLE II. Comparison of the measured and calculated cross sections for the reaction ^{46}Ca$(\alpha, d)^{48}$Sc leading to the *odd*-spin states of the $(f_{7/2})^2$ multiplet, normalized to the 7^+ state.

J^π	$\left(\frac{d\sigma}{d\omega}\right)_{\mathrm{EXP}}\Big/\left(\frac{d\sigma}{d\omega}\right)_{\mathrm{DW}}$
1^+	0.51
3^+	0.80
5^+	0.83
7^+	1.00

The calculated DW curves are displayed in Fig. 7. The calculations are for the $T'=\frac{5}{2}$ states and include the coefficient of fractional parentage, which has the same value $\sqrt{27/56}$ for all these states. Of the $(f_{7/2}{}^7p_{3/2})$ states, the one with $J=5$ is far stronger than the others; and similarly the $J=6$ state in expected to be the strongest in the $(f_{7/2}{}^7f_{5/2})$ multiplet. The angular distributions are not easily distinguished. The $L=2$ and $L=6$ shapes are quite similar, and the shapes of the mixed-L, $J=3$, and $J=5$ angular distributions depend very much on the configuration.

The nine experimental angular distributions fall into three groups. The data in Fig. 4 fit $L=4$ curves. The strongest state, the one at 2.196 MeV, is very weakly excited in $(^3$He$,t)$; it is most likely the $(f_{7/2}{}^7p_{3/2})$ state with $J=5$, $T'=\frac{5}{2}$. The 2.978-MeV state is possibly present in $(^3$He$,t)$, and is weaker in the (α,d) reaction by just about the required factor of 3.4 so that it may be the $T'=\frac{7}{2}$, $J=5$ state. The 3.206-MeV state may well be $J=4$, $(f_{7/2}{}^7f_{5/2})$; it is somewhat too strong to allow its assignment to be interchanged with that of the 2.978-MeV state.

The three states in Fig. 5 could be $J=1$, 2, or 6 states of the $(f_{7/2}{}^7f_{5/2})$ configuration or $J=2$ or 3 states of $(f_{7/2}{}^7p_{3/2})$. The 42° point in the angular distribution of the 3.151-MeV state is confused by an unresolved impurity. This uncertainty allows us to leave this as $J=2$ or 3 in the $(f_{7/2}{}^7p_{3/2})$ configuration and the 3.061-MeV state is best fitted with the 1^+ angular distribution.

Finally, Fig. 6 shows three similar states that could be $J=2$, 3, 5, and 6. The 3.689-MeV state,

TABLE III. Ratios of observed to calculated cross sections, normalized with respect to the ratio for the 7^+ state of the $(f_{7/2})^2$ configuration.

Excitation energy (MeV)	σ_{peak} (μb/sr)	Configuration $f_{7/2}p_{3/2}$ $J^{\pi}=2^+$	3^+	4^+	5^+	$f_{7/2}f_{5/2}$ 1^+	2^+	3^+	4^+	5^+	6^+
2.196	220				$\underline{0.09}$						
2.281	40	$\underline{0.10}$	0.06				0.30	0.30		0.30	
2.978	50			0.42	$\underline{0.20}$ [a]				0.21		
3.061	55	0.16	0.10			$\underline{0.27}$					
3.151	40	0.12	$\underline{0.08}$			0.20	0.34				
3.206	140				(0.03)				$\underline{0.42}$		
3.289	50						0.40	0.37		$\underline{0.31}$	
3.689	130					0.56		0.79		0.86	$\underline{0.13}$
4.178	60					0.29	$\underline{0.51}$				0.08
g.s. (6^+)	16										0.02
1.143 (2^+)	8	0.02					0.06				
0.252 (4^+)	11			0.06					0.03		

[a] The calculated cross section here is for $T'=\frac{7}{2}$. In all the other cases, the calculated cross sections are for $T'=\frac{5}{2}$.

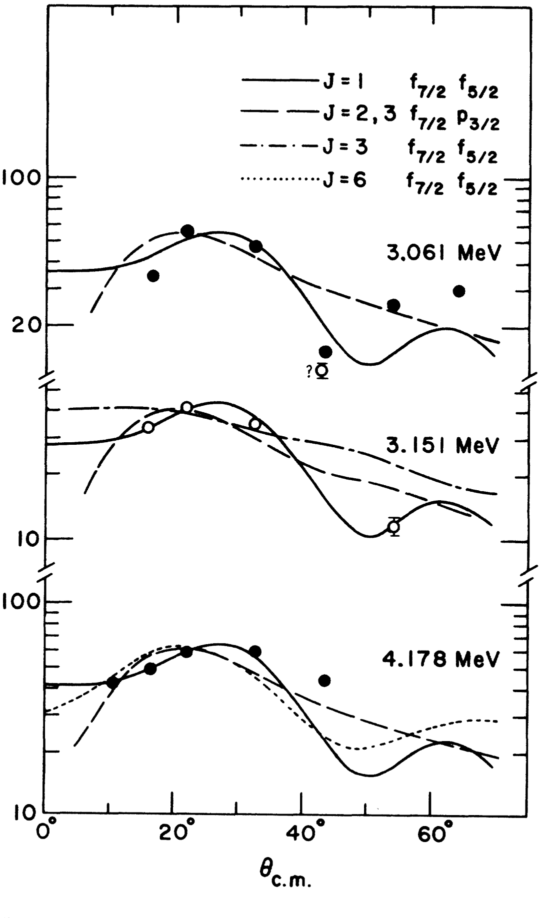

FIG. 5. States whose angular distributions peak at ~25°. Various DWBA curves are also shown.

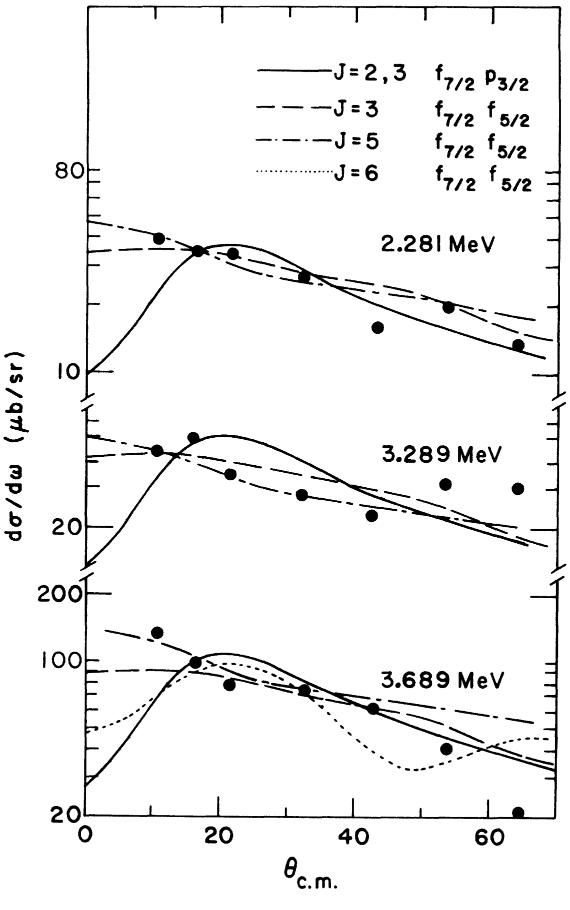

FIG. 6. States whose angular distributions show no clear structure. Various DWBA curves are also shown.

the one with the largest cross section, was assigned very tentatively $J=6$ in the $(f_{7/2}{}^7f_{5/2})$ configuration, through its cross section is still too low and its shape is fitted poorly. The 2.28-MeV state is lowest in excitation energy and could be $J=2$ or 3 in the $(f_{7/2}{}^7p_{3/2})$. Since its cross section is slightly lower than that of the 3.151-MeV state, we prefer $J=2$ for the 2.28-MeV state and $J=3$ for the 3.151-MeV one. This leaves the 3.289-MeV state as a possible candidate for the $J=5$ state of the configuration $(f_{7/2}{}^7f_{5/2})$.

It should be emphasized that all these assignments are very tentative and speculative. They are summarized in Table III. Only the 4^+ member of the $(f_{7/2}{}^7p_{3/2})$ multiplet and the 3^+ of the $(f_{7/2}{}^7f_{5/2})$ are missing, and these are expected to be lowest in cross section. Only one of the $T'=\frac{5}{2}$ states is identified, a fact which again is consistent with the expected low yield for these states. The cross sections are summarized in Table III, where the ratios to DWBA calculations are given as well, normalized to 1 for the 7^+ $(f_{7/2})^2$ state. For this state, the absolute normalization factor between the experimental cross section and the TWOPAR output would be 15 000. We note that for the higher configurations, a normalization factor about one tenth of this would be more appropriate.

The difference between the normalizations of the $(f_{7/2})^2$ and the $(f_{7/2}p_{3/2})$ states to DWBA calculations is very much of a mystery. The most clear-cut case is for 5^+ states. The microscopic DWBA calculations very firmly predict that a 5^+ state from $(f_{7/2}p_{3/2})_{T'=5/2}$ should be about twenty times as strong as the $(f_{7/2}f_{7/2})$ 5^+ state. This should be by far the strongest state below ~3-MeV excitation. The second strongest state we see (at 2.196 MeV – the 7^+ state is the strongest) indeed has the correct shape but is, in fact, only about twice as strong as the $(f_{7/2})^2$ 5^+ state. The obvious solution (namely large admixtures between the two 5^+ states) is contradicted by the fact that the relative cross sections for the 3^+, 5^+, and 7^+ $(f_{7/2})^2$ states are correctly predicted and admixtures to the 7^+ state are difficult to obtain. The other possibility (namely that the strong 5^+ state is fragmented into many components, as could occur if seniority were completely broken) also seems unlikely because the fragmentation would have to be very thorough to give only about 10% of the strength to the strongest component and <5% to the next strongest. The large cross-section ratio in the DW calculation is not sensitive to distorting parameters; instead it arises from the magnitude of the form factors and can be traced back to the transformation coefficients. Since the radial shapes of the form factors for the $(f_{7/2})^2$ and the $(f_{7/2}p_{3/2})$ cases are very similar, it seems also unlikely that one could account for this in terms of finite-range effects. The possibility of second-order processes dominating the reaction mechanism needs to be seriously examined.

The assignments regarded as slightly favored are underlined in Table III. It is worth mentioning that unpublished work[15] on the reaction ^{46}Ca$(^3\mathrm{He},p)^{48}$Sc assigns $J^\pi=1^+$ or 0^+ to a state at 3.230 MeV (possibly our 3.206-MeV state) and $J^\pi=1^+$ to

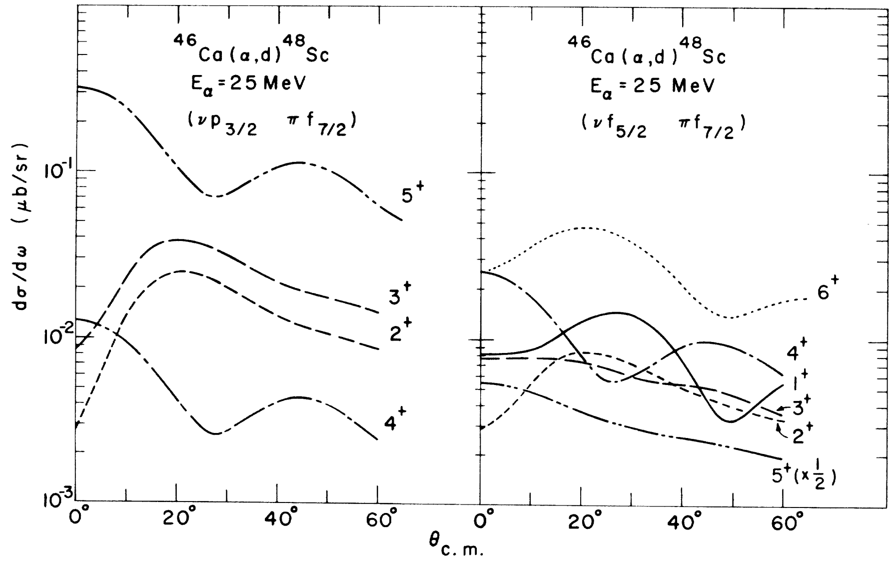

FIG. 7. Calculated DWBA curves (TWOPAR outputs) for the $(f_{7/2}p_{3/2})$ and $(f_{7/2}f_{5/2})$ multiplets. The coefficient of fractional parentage for $T'=\frac{5}{2}$ was used in the absolute cross-section scale.

states at 2.995 (2.978), 3.068 (3.061), 3.179 (3.151), 3.690 (3.689), and 4.175 (4.178) MeV, where the numbers in parentheses are our excitation energies. They also assign $J^{\pi}=(2,3)^{+}$ to states at 2.210 (2.196) and 2.295 (2.281) MeV. It is very difficult to reconcile these assignments with our data. These $(^{3}\mathrm{He},p)$ assignments are based on measurements of the forward peak of the angular distribution. The selection rules for $S=1$ (deuteron) transfer must, of course, be the same in $(^{3}\mathrm{He},p)$ as in (α,d); but in cases in which $S=0$ transfer is also possible, states could be populated with different relative cross sections.

IV. CONCLUSIONS

The results of this experiment leave matters in a rather unsatisfactory state. For the allowed transitions in the $(f_{7/2})^{2}$ multiplet, the DW fits to the angular distributions are reasonably good. The factor-of-2 variation in the normalization constant may be attributed to admixtures in these states; however, in view of the great sensitivity of the calculated curves to the distorting parameters, it may equally well be caused by an unsatisfactory representation of the reaction mechanism.

For the forbidden natural-parity $(f_{7/2})^{2}$ states, we can see from the lower part of Table III that the cross sections would suggest ~20% admixtures of higher configurations. The fits to angular distributions are very poor, especially for the 4^{+} state, and it seems very likely that second-order processes could be important for cross sections as small as these (a few microbarns).

For the states at higher excitation energy, the situation is again complicated. We have attempted to assign the observed states to the expected configurations. Because of the high level density, correlation of the present data with other reactions leading to the same nucleus did not seem to be of much help. Since the cross sections are low, the impurities numerous, and the reaction mechanism poorly understood, we cannot make unique assignments.

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[12] We thank Dr. R. D. Lawson for pointing this out to us.

[13] It is possible to construct a number of states of the $T'=\frac{5}{2}$ configuration. The (α,d) reaction will populate only the lowest-seniority component and, to the extent that seniority is a good quantum number in ^{48}Sc, only a single set of $T'=\frac{5}{2}$ states should be populated.

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