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Structure of ^{42}Ti from the ^{40}Ca(^{3}He, n)^{42}Ti reaction

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The structure of ^{42}Ti has been investigated using the ^{40}Ca(^{3}He, n)^{42}Ti reaction at a beam energy of 15 MeV. Comparisons between measured angular distributions and distorted wave Born approximation (DWBA) calculations provide a number of new spin assignments. The DWBA analysis also provides an estimate of p state admixtures in the low-lying states of the $(f_{7/2})^2$ configuration. A comparison with the results of the ^{40}Ca(t, p)^{42}Ca reaction demonstrates the analog character of many levels in ^{42}Ti and ^{42}Ca up to about 6.5 MeV. Above 3 MeV, in states involving large p^2 or fp components in the wave function, transition strengths are comparable in both two-proton and two-neutron transfers. The states in ^{42}Ca generally occur at an excitation energy several hundred keV above the corresponding analog in ^{42}Ti, suggesting that the $f_{7/2}$-$p_{3/2}$ single particle splitting is slightly greater in ^{42}Ca.

[NUCLEAR REACTIONS, STRUCTURE ^{40}Ca(^{3}He,n) $E=15$ MeV; measured angular distributions, DWBA deduced J, π. Comparison ^{42}Ti, ^{42}Ca analog states.]

I. INTRODUCTION

The nuclide ^{42}Ti is one of the interesting examples of the "closed core plus two particle" structures which have been extensively investigated theoretically.[1-5] The mirror levels in ^{42}Ca and ^{42}Sc have also been studied experimentally in considerable detail.[6] ^{42}Ti has received relatively little study since it is reached only via the ^{40}Ca(^{3}He,n) reaction or compound-nucleus reactions with heavy particles. Only the first reaction provides relatively direct information about the structure of the states excited.

An early attempt to study this reaction was reported[7] by Bryant *et al.* A later measurement by Shapiro[8] had identified many levels up to an excitation energy of about 5.5 MeV, but the beam energy was so low that little information about the angular momentum transfers involved could be extracted from the neutron angular distributions. A later study[9] of the (^{3}He,$n\gamma$) reaction has established the γ decay of several low-lying states. The lifetimes of a few states have also been measured.[10]

The present measurements provide clear spin assignments for a number of low-lying states in ^{42}Ti. In addition, the measured cross sections provide some interesting comparisons with results of studies of the ^{40}Ca(t,p)^{42}Ca reaction.[11]

II. EXPERIMENTAL PROCEDURE

The (^{3}He,n) measurements were carried out using the University of Rochester pulsed beam facility. The system provided average ^{3}He currents of about 150 nA, with an over-all time resolution of about 0.75 nsec in routine operation. A flight path of 4 m was available for the measurements. In the present measurements the energy resolution for the ground state group was about 300 keV [full width at half-maximum (FWHM)], with comparable contributions from target thickness and from the pulsing system time resolution.

The detector system is shown in Fig. 1. Counter 1 consisted of a 1 cm cube of plastic scintillator mounted on a 56 AVP photomultiplier, and was used to record γ rays from the target. The data acquisition program monitored the time location of the γ peak from counter 1 and shifted all time spectra, if necessary, to maintain this peak in a fixed location. This feature was necessary to maintain a time resolution better than 1 nsec during the long running times required. Counter 2 used a 10.2 cm diameter×2.5 cm thick NE213 scintillator mounted on a 58 AVP photomultiplier. Counters 3 and 4 were similar to 2, with a scintillator thickness of 3.8 cm. For each of these three counters the time spectrum, recoil proton spectrum, and n-γ discriminator output were recorded in the PDP6 computer. Time-of-flight spectra were gated by the neutron signals from the n-γ discriminator, and the recoil spectra by a selected group in the time spectra. The gated recoil spectra displayed both spectrum end point and discriminator cutoff for a neutron group of known energy and thus provided a measurement of discriminator bias level, which together with the results of Drosg[12] determine the counter efficiency.

Targets were prepared by evaporating natural calcium metal onto backings of gold or tantalum, and then evaporating a thin layer of gold over the calcium. Targets could be made and handled in vacuum except for the transfer from a vacuum lock to the target chamber. Target thickness was measured by observing the energy loss of a ^{3}He beam backscattered from the gold backing through the target material. The uncertainty in the thickness measurement is estimated to be no more than 25%.

Carbon and oxygen contamination on the targets was a fairly serious problem, since the cross section for the (^{3}He,n) reaction on ^{12}C and ^{16}O is very large. For the best targets, the ground states from ^{12}C and ^{16}O contaminants were resolved and had an intensity of only about 5% of the ground state group from ^{40}Ca. The transition to the first excited state in ^{18}Ne could not be resolved from that to the 2.68 MeV state in ^{42}Ti, and a subtraction was made for this level. For the other strongly excited states in ^{42}Ti, known contaminant groups could be resolved, or else gave a negligible contribution to measured cross sections.

III. RESULTS

Angular distributions over the angular range 0°–55° were measured at an incident energy of 15 MeV. Typical spectra are shown in Fig. 2. The time resolution in these spectra was approximately 0.44 nsec per channel. Angular distributions for the strongly excited states are shown in Figs. 3 and 4, along with the results of zero-range distorted wave Born approximation (DWBA) calculations. These calculations were carried out using a version of the code DWUCK, modified[13] for the calculations of two-nucleon transfer cross sections using the Bayman-Kallio[14] method. Optical parameters used in the calculation are shown in Table I. The ^{3}He parameters were taken from the results of Urone *et al.*[15] and the neutron parameters from Becchetti and Greenless.[16] The bound state radius is slightly larger than the value of about 1.25 fm, often used in calculations of single-particle transfer cross sections, but the value of 1.3 fm was required with these optical parameters in order to fit the shape of the $L=0$ angular distributions at forward angles.

Levels which could be clearly identified in these measurements are listed in Table II along with L

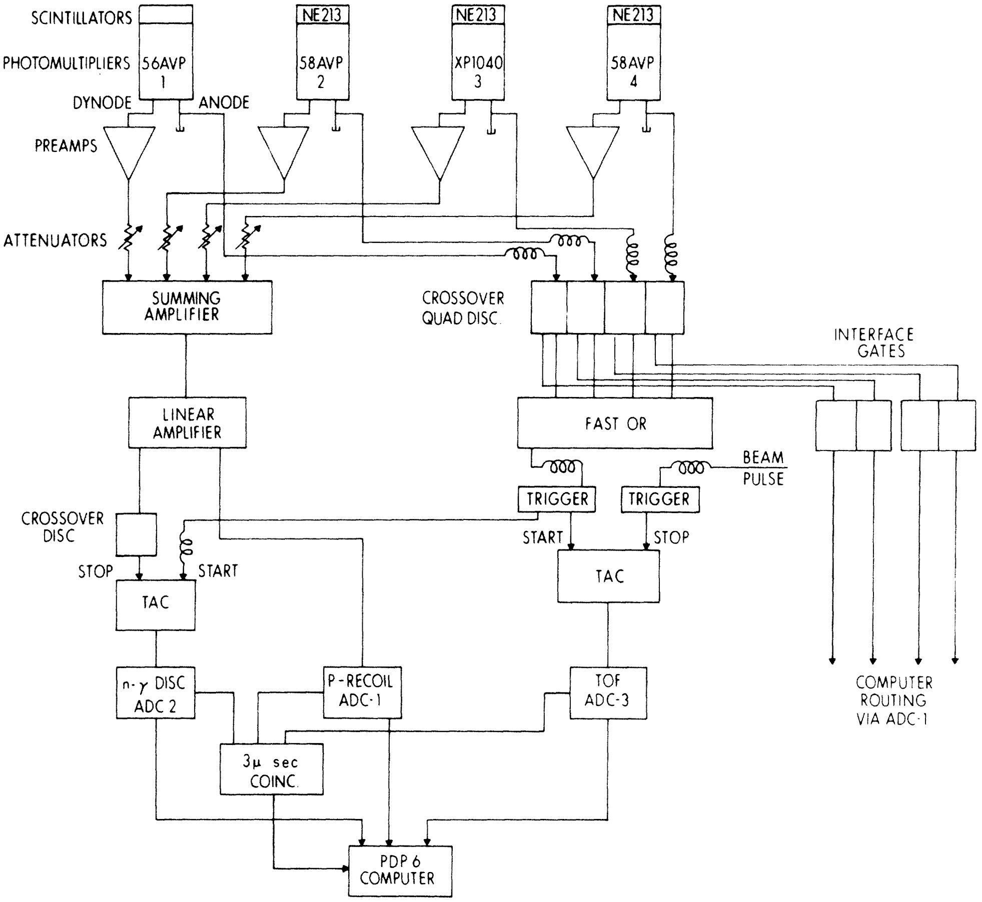

FIG. 1. Block diagram of detector system.

TABLE I. Optical parameters used in DWBA analysis:

$$V=-V_R f(r,R_R,a_R)-W_V f(r,R_I,a_I)+4W_S\frac{d}{dr}f(r,R_I,a_I)+V_{\rm so}\vec{\sigma}\cdot\vec{1}\,\lambda_\pi{}^2\frac{1}{r}f(r,R_{\rm so},a_{\rm so})+V_{\rm Coul}\,,$$

$$f(r,R_i,a_i)=\left[1+\exp\left(\frac{r-R_i}{a_i}\right)\right]^{-1},\quad R_i=r_iA^{1/3}\,.$$

	V_R (MeV)	r_R (fm)	a_R (fm)	W_V (MeV)	W_S (MeV)	r_I (fm)	a_I (fm)	$V_{\rm so}$ (MeV)	$r_{\rm so}$ (fm)	$a_{\rm so}$ (fm)
^{3}He	175.4	1.14	0.71	19.9	0	1.53	0.85	0		
n	51.6	1.17	0.75	0.93	9.6	1.26	0.58	24.8	1.01	0.75
Bound state	a	1.30	0.65							

[a] Adjusted to reproduce observed binding energy.

values obtained from DWBA analysis of the stronger transitions. Maximum cross sections and the angles of the maxima are also shown. The uncertainties in excitation energies have been taken as the standard deviation of excitation energies determined at different angles. For the low-lying states, agreement with excitation energies found from γ ray measurements is quite good.

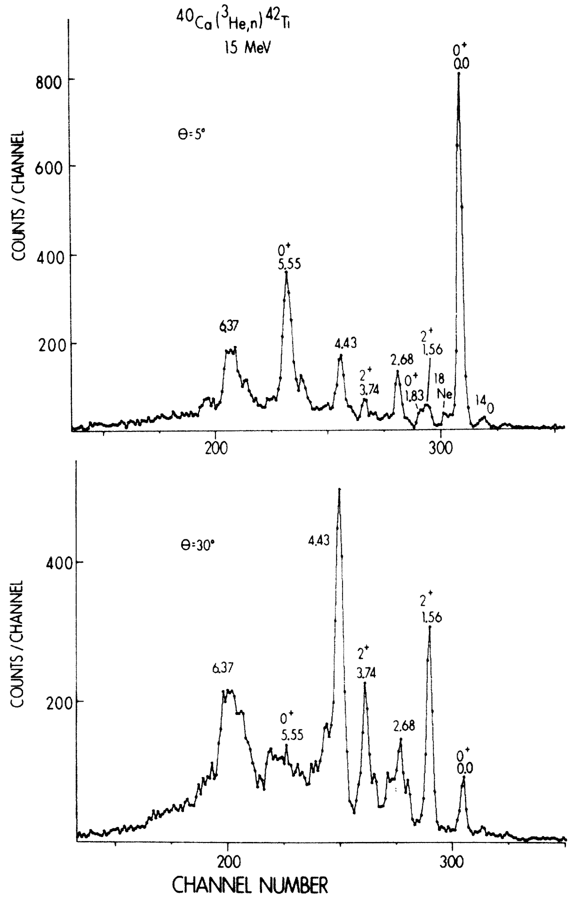

FIG. 2. Typical time-of-flight spectra. The time resolution is approximately 0.44 nsec/channel.

IV. DISCUSSION

A. Structure of ^{42}Ti

The interpretation of the two-nucleon transfer cross sections in terms of the structure of the states involved is complicated by the fact that the magnitude of the cross section predicted by DWBA calculations generally depends strongly on the form factor assumed for the transferred pair. In some cases this may also be true of the angular distribution for a given L transfer. In the present case, however, it is expected that the predominant configurations involved in low-lying states will be $(f_{7/2})^2$, $(p_{3/2})^2$, and $f_{7/2}p_{3/2}$. DWBA calculations have been carried out for form factors of the form $\alpha f^2 \pm (1-\alpha^2)^{1/2}p^2$ and $\alpha f^2 \pm (1-\alpha^2)^{1/2}fp$, as a function of the mixing parameter α. Resultant angular distributions for $L=0$ and $L=2$ are shown in Fig.

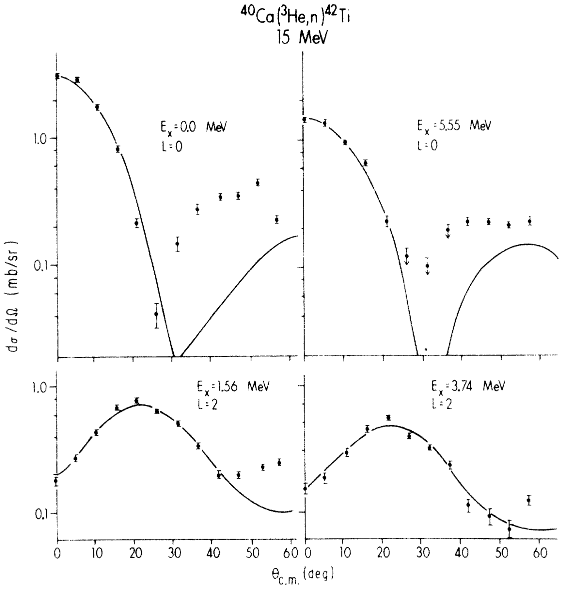

FIG. 3. Angular distributions for pure $L=0$ and $L=2$ transitions.

TABLE II. Levels observed in ^{42}Ti.

Present results				Other work	
E_x (MeV)	$\sigma_{\max}$ (mb/sr)	$\theta_{\max}$	L	E_x [a] (MeV)	E_x [b]
0.00	3.2	0	0	0.0	0.0
1.56 ± 0.03	0.78	20	2	1.55	1.555
1.83 ± 0.04	0.2	0	0	1.89	1.851
2.45 ± 0.1	<0.2	~20		2.35	2.394
				(2.60)	
2.68 ± 0.05	0.28	0	(0	2.75	2.674
	0.26	>30	4)	2.94	
3.06 ± 0.07	~0.1	30	6	3.06	
3.4 ± 0.1	~0.1	<15		3.42	(3.334)
3.74 ± 0.05	0.55	20	2		3.739
4.43 ± 0.02	0.35	20	(2		
	0.40	40	4)		
5.55	1.5	0	0	5.49	
6.37	1.4	5	0 + ?		

[a] See Ref. 7. Above 3 MeV many levels are reported which cannot be clearly correlated with present results.

[b] See Ref. 8.

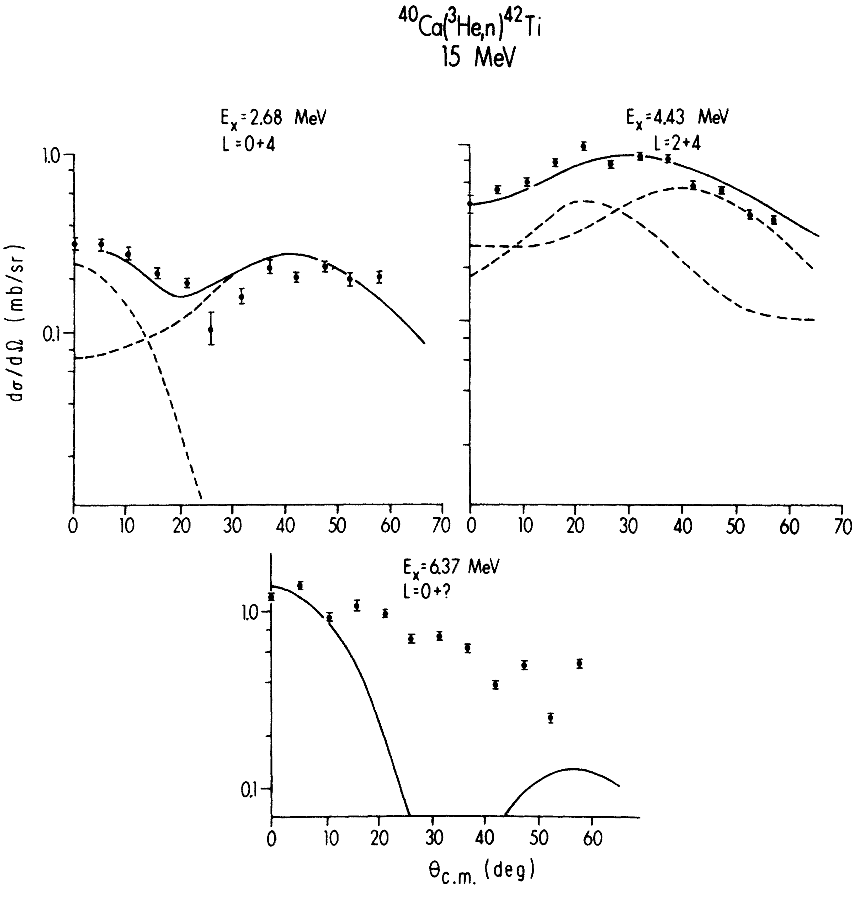

FIG. 4. Angular distributions of selected unresolved groups.

5. In this calculation the optical model parameters were those listed in Table I. Calculations with other sets of parameters which provide reasonable fits to the shape of the $L=0$ ground state angular distribution show the same general behavior: The magnitude of the DWBA cross section increases by about an order of magnitude in going from f^2 to p^2 or fp form factors, and the shape of the angular distribution is almost independent of mixing. This last statement is true except for cases in which destructive interference between different components in the form factor leads to a very small cross section.

As a result of these characteristics it is reasonable to utilize DWBA calculations for a simple f^2 form factor in order to extract L values. At the same time, the ratio $R = d\sigma_{\mathrm{exp}}/d\sigma_{\mathrm{DW}}(f^2)$ will provide an estimate of the intrinsic strength of a given transition, with the relatively uninteresting L dependence and Q dependence removed. This intrinsic strength can then be interpreted in terms of the magnitude of the mixing parameter α.

Table III lists the intrinsic strengths obtained in these measurements, with the ratio R normalized to unity for the ground state transition. DWBA calculations could not be carried out for states above 4 MeV since the proton pair was unbound. The energy dependence of the peak section at energies below 4 MeV was simply extrapolated to higher excitation energies when necessary. The

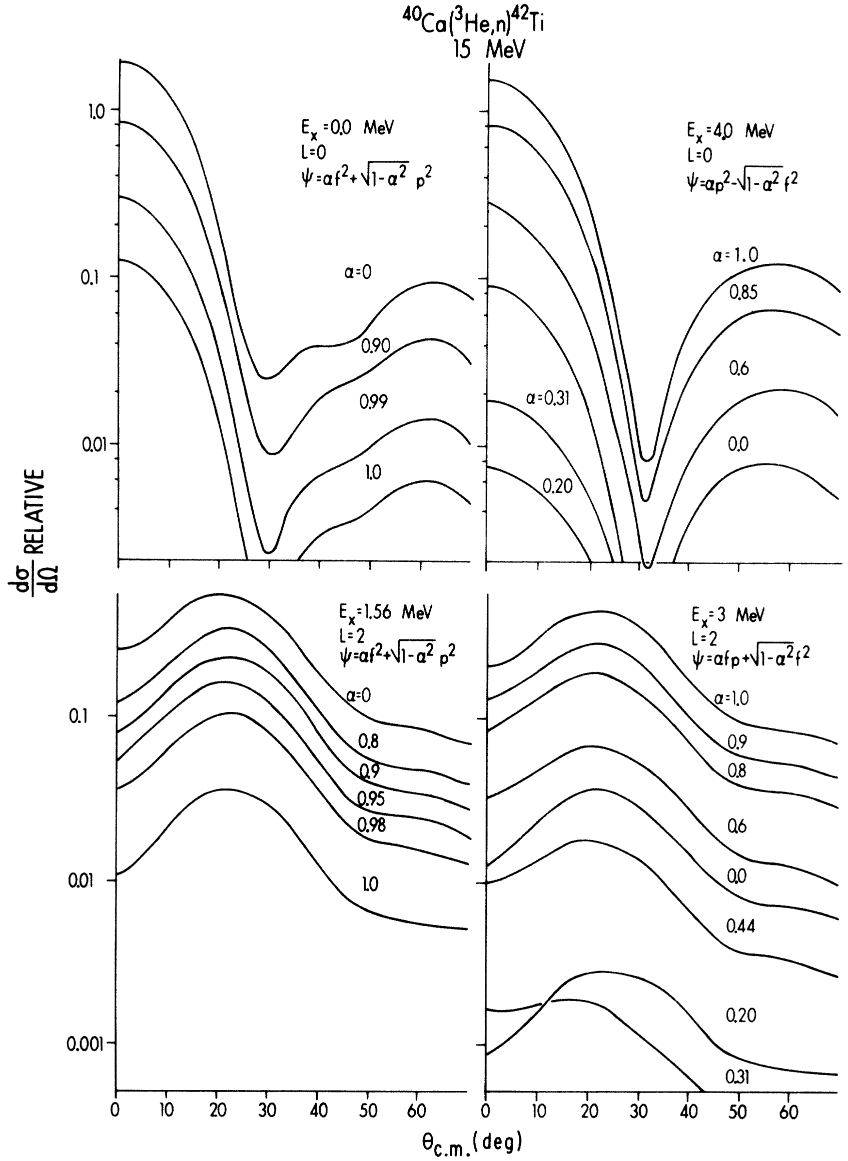

FIG. 5. DWBA cross section for $L=0$ and $L=2$ transitions assuming $f_{7/2}$ and $p_{3/2}$ components in the form factor.

shapes of angular distributions were assumed to be those for an excitation energy of 4 MeV. Also listed in Table III is the same information for states in ^{42}Ca observed in the ^{40}Ca$(t,p)^{42}$Ca reaction.

In the following discussion, these results are interpreted in terms of the form factors for the strongly excited states in ^{42}Ti. In addition, a comparison of the intrinsic strengths of analog states observed in ^{40}Ca$(^3$He$,n)^{42}$Ti and ^{40}Ca$(t,p)^{42}$Ca reveals some differences which should be investigated in theoretical studies of the $A=42$ system.

1. 0^+ states

Strong $L=0$ transitions are observed to the ground state and a state at 5.55 MeV. In addition there is a broad group centered at 6.37 MeV. The width of the group suggests that it is at least a doublet, and the shape can be fitted well as a superposition of two groups centered at 6.47 and 6.27 MeV. This broad group shows a definite forward peaking in its angular distribution, which has been interpreted as indicating some $L=0$ transition strength in the group. Table III lists the intrinsic strength of this $L=0$ component.

In the simplest model of ^{42}Ti, the ground state would be described as a proton pair in the $f_{7/2}$ shell coupled to the ^{40}Ca ground state, with the state at 5.55 MeV arising from a proton pair in the $p_{3/2}$ shell. In this model, the ratio of the cross sections is calculated to be

$$r=\frac{\sigma(p^2)5.55}{\sigma(f^2)\text{g.s.}}=10.2\,,$$

compared with an experimental value $r=0.48$. If it is assumed that the $L=0$ strength at 6.37 MeV should be considered as part of the p^2 strength, the experimental ratio is increased to a value $r=0.91$. However, mixing between f^2 and p^2 states would result in a wave function of the form $\psi_{\text{g.s.}}=\alpha f^2+(1-\alpha^2)^{1/2}p^2$ and $\psi_{\text{exc}}=(1-\alpha^2)^{1/2}f^2-\alpha^2p^2$. The ratio of the predicted cross sections as a function of α, for form factors assuming these wave functions, is shown in Fig. 6, and it is seen that the experimental result $r=0.91$ would require a value of $\alpha=0.89$. The predicted ground state cross section is increased over the value of pure $(f_{7/2})^2$ by a factor of about 7 by this p state component in the wave function. Thus in Table III, with the relative strength normalized to unity for the ground state, a relative strength close to unity for other low-lying states of the ${f_{7/2}}^2$ configuration would imply a p state component in the wave function comparable with that of the ground state. A transition to a state with a pure f^2 configuration would be expected to have a relative strength of $\frac{1}{7}$.

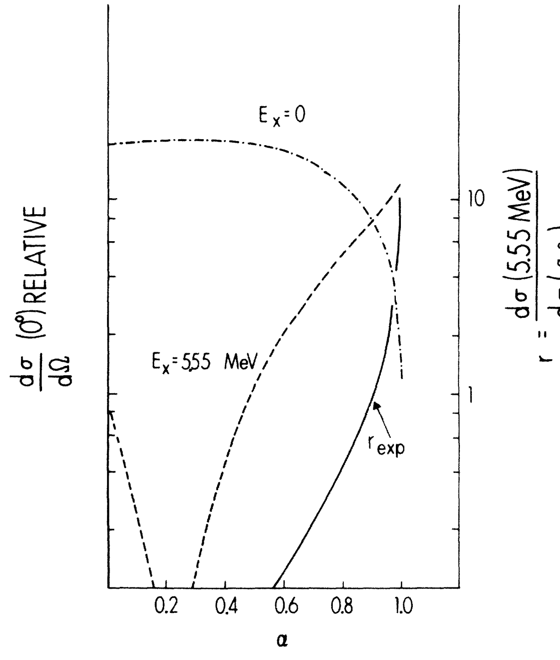

FIG. 6. The ratio of cross sections for $L=0$ transitions to ground and excited states as a function of p state excitation in the ground state is shown as the solid line. Cross sections for the two states are shown by the broken curves. The experimental value $r=0.91$ is consistent with a value $\alpha=0.89$.

In ^{40}Ca$(t,p)^{42}$Ca, strong $L=0$ transitions are observed to the ground state, and to levels at 5.85, 6.01, 6.51, and 6.70 MeV. The relative strengths of these transitions, assuming f^2 form factor and optical parameters taken from Baer *et al.*[17] are listed in Table III. If it is assumed that the structure of these states is similar to that of the strongly excited $L=0$ states in ^{42}Ti, then the ground state wave function for ^{42}Ca can be characterized by a value $\alpha=0.93$, in good agreement with the estimate obtained for the ^{42}Ti ground state.

A level at 1.87 ± 0.05 MeV has been reported as the analog of the deformed 0^+ state at 1.836 MeV in ^{42}Ca. In the present measurements a poorly resolved state was seen at forward angles only (0°–10°), at an excitation of 1.83 ± 0.05 MeV. The relative strength of this transition was about 0.07, which is close to the value 0.10 found in the (t,p) reaction leading to the analog state in ^{42}Ca.

One other candidate for 0^+ assignment is seen from the angular distribution to a level at 2.68 MeV. Since this transition is relatively strong, the angular distribution would be expected to be characteristic of the L transfer. The peaking at forward angles is consistent only with $L=0$ or $L=1$, but the cross section at large angles indicates that another component is probably present. Since a strong $L=4$ transition is expected near this energy, the angular distribution has been fitted with a superposition of $L=0$ and $L=4$ angular distributions. The resultant relative strength of the $L=0$ component is 0.1.

2. 2^+ states

The level at 1.56 MeV shows good agreement with the distorted wave (DW) angular distribution for $L=2$, and is clearly the analog of the 1.523 MeV 2^+ state in ^{42}Ca. The relative strength of the transition to this state is close to unity, indicating that the p state component in the wave function of the 2^+ state is similar to that in the ground state. In fact, if the DWBA calculation using a value of $\alpha=0.89$ is normalized to yield the measured ground state cross section, then the present results will be consistent with a wave function of the same form,

$$\psi=[\alpha f^2+(1-\alpha^2)^{1/2}p^2]_{(2^+)},$$

with a value of $\alpha=0.91$.

A weak group at an excitation of about 2.4 MeV is seen at angles between 15 and 35°. This may be the analog of the second 2^+ state seen in ^{42}Ca at 2.423 MeV. If it is a 2^+ state, the relative strength cannot be more than half that for the corresponding transition excited in the ^{40}Ca(t, p)^{42}Ca reaction. Weakly excited 2^+ states in ^{42}Ca are also seen at 3.389 and 3.651 MeV. In the present results there is some indication of a weak group 3.4 MeV excitation, but no reliable cross section could be measured.

A strong $L=2$ transition leads to a state at 3.74 MeV with relative strength of 0.65. This probably represents part of the strength expected in this region from 2^+ states with a large $(f_{7/2}p_{3/2})$ component.

The only other strongly excited state seen in ^{42}Ti is one at 4.43 MeV. The angular distribution shown in Fig. 4 suggests that this is a doublet and at several angles the group is slightly broader than expected for a single level. The measured angular distribution can be fairly well fitted with a superposition of DW calculations for $L=2$ and $L=4$, with a relative strength of 0.66 for the $L=2$ component.

3. 4^+ states

As noted above, the group at 2.68 MeV appears to involve a superposition of $L=0$ and $L=4$ transitions. The 4^+ state involved must be the analog of the 2.750 MeV 4^+ state in ^{42}Ca. The relative strength of 0.42 indicates little p state component in the wave function. If a wave function of the form $\psi(4^+)=\alpha f^2+(1-\alpha^2)^{1/2}fp$ is assumed, then the measured cross section is consistent with a value $\alpha=0.98$.

TABLE III. Comparison of relative strengths for two-nucleon transfer to states in ^{42}Ca and ^{42}Ti.

^{40}Ca(^{3}He,n)^{42}Ti				^{40}Ca(t,p)^{42}Ca		
E_x (MeV)	J^π	$r=\frac{d\sigma_{\rm exp}}{d\sigma_{\rm DW}}$ [a]	Level No.	E_x (MeV)	J^π	$r=\frac{d\sigma_{\rm exp}}{d\sigma_{\rm DW}}$ [b]
0	0^+	1	0	0	0^+	1
1.56	2^+	0.85	1	1.523	2^+	0.59
1.83	(0^+)	0.07	2	1.836	0^+	0.10
2.45			3	2.423	2^+	0.16
2.68	(4^+)	0.42	4	2.750	4^+	0.37
3.06	(6^+)	≤ 0.2	5	3.191	6^+	0.13
2.68	(0^+)	0.1	7	3.297	0^+	~0.01
			8	3.389	2^+	0.05
3.4	(2^+)		9	3.442	3^-	
			10	3.651	2^+	0.14
3.74	2^+	0.65	18	4.45	2^+	0.35
4.43	(2^+)	0.66				
			23	4.75	2^+	0.53
			24	4.86	2^+	0.34
4.43	(4^+)	0.97	27	5.01	4^+	0.24
5.55	0^+	0.85	43	5.85	0^+	0.80
			46	6.01	0^+	0.21
6.37	(0^+)	~0.75	55	6.51	(0^+)	0.22
			58	6.70	0^+	0.21

[a] Present results. J^π assignments in parentheses are deduced from angular distributions of incompletely resolved states.

[b] See Ref. 10. Only strongly excited states, or those which can be plausibly correlated with states observed in ^{42}Ti, are listed.

A possible $L=4$ component in the group at 4.43 MeV has also been noted, with relative strength of 0.97. As with the 2^+ component, this 4^+ state probably has a large $(f_{7/2}p_{3/2})$ component in its wave function.

4. *Other states*

At angles greater than 20° a weak group appears at an energy of 3.06 MeV. The angular distribution is consistent with the DWBA prediction for $L=6$, and the state is probably the analog of the 3.191 MeV 6^+ state in ^{42}Ca. The upper limit of 0.2 on the relative strength is somewhat greater than the value of 0.14 expected for a pure $(f_{7/2})^2$ state, but the difference may be due to other unresolved states contributing to the measured cross section.

A broad group appears at about 5.3 MeV, but the relatively high background and overlap with the strong group at 5.55 MeV prevented any quantitative analysis. There is also some indication of a weak group near 4.8 MeV. It is noteworthy that in the (t,p) reaction strong $L=2$ transitions are seen to states in ^{42}Ca at 4.75 and 4.86 MeV with combined cross sections almost twice that of the 1.523 MeV state. In the present results, any $L=2$ transition in this energy region would be at least an order of magnitude weaker than that to the 1.56 MeV level.

B. Analog states in ^{42}Ca

The comparison of ground state and excited state $L=0$ transitions in $^{40}\mathrm{Ca}(t,p)^{42}\mathrm{Ca}$ was discussed earlier, and it was noted that these implied a degree of p state excitation in the ^{42}Ca ground state that was comparable with, but probably significantly less than, that in ^{42}Ti. Table III lists the levels in ^{42}Ca which are strongly excited in the (t,p) reaction, along with the relative strengths, again normalized to unity for the ground state transition. In this case the ground state cross section is increased by a factor of about 3.7 over that for pure f^2 by the p state excitations, so that transitions to pure f^2 states should show a relative strength of $1/3.7=0.27$.

The first 2^+ state at 1.523 MeV has a relative strength of 0.59. This implies a value $\alpha=0.97$, which represents significantly less p state excitation than the analog state in ^{42}Ti. Additional information on the structure of this state is provided by the results of measurements of the $^{41}\mathrm{Ca}(d,p)^{42}\mathrm{Ca}$ reaction,[18] which show an $l=1$ component in the cross section to this state with a spectroscopic factor $S=0.05$. The result implies a wave function $\psi(2^+)=\alpha f^2+(1-\alpha^2)^{1/2}fp$ with $\alpha=0.98$.

The 2.750, 4^+ state also appears to have almost pure $(\alpha=0.99)$ f^2 form factor. The relative strength of the 3.191 MeV 6^+ state is less than half the value expected for a pure f^2 state. Since this state is expected to be very close to pure f^2, this result brings into question the capability of the DWBA calculation to reproduce the L dependence of the cross section. This in itself would not affect the estimate of p state components in the ground state wave function. It could imply that the relative strengths for higher L transitions should be increased, thus increasing the estimate of p state components in the wave functions of these states.

Above 3 MeV, the total relative strength in $L=2$ transitions in ^{42}Ca is comparable with that in ^{42}Ti, but the distribution of strength is somewhat different, and the centroid of the strength lies at 4.70 MeV in ^{42}Ca compared with 4.1 MeV in ^{42}Ti. It is interesting to note that the three states between 4 and 5 MeV are also excited relatively strongly by $l=1$ transfer in the $^{41}\mathrm{Ca}(d,p)^{42}\mathrm{Ca}$ reaction,[19] indicating important fp components in their wave functions. Presumably similar components are important in the 3.74 and 4.43 MeV levels in ^{42}Ti.

For the strong $L=0$ transitions near 6 MeV, the distribution of strength is similar in ^{42}Ca and ^{42}Ti, with about half the total going to the lowest state of the group. The centroid of the strength lies at 6.1 MeV in ^{42}Ca and 5.9 MeV in ^{42}Ti.

The other possible analog correspondence is between the 4^+ state at 5.01 MeV in ^{42}Ca and the presumed 4^+ state at 4.43 MeV in ^{42}Ti. The relative strength appears to be higher for the state in ^{42}Ti, but this may be the result of contributions to the measured cross section by other unresolved states.

V. CONCLUSIONS

The present results provide spin assignments for a number of known levels in ^{42}Ti, and permit the identification of several new levels. The magnitude of p state admixtures in the low-lying $f_{7/2}$ states is estimated, and found to be greatest for the ground state. Some information on the structure of higher excited states is also obtained by a comparison of these results with measurements of one or two particle transfers leading to ^{42}Ca.

A comparison with results of measurements of the $^{40}\mathrm{Ca}(t,p)^{42}\mathrm{Ca}$ reaction demonstrates the analog character of the states excited in two-neutron and two-proton transfer reactions. Below 3 MeV excitation, both relative strengths and excitation energies show close agreement. Above 3 MeV levels in ^{42}Ca lie several hundred keV above the location of corresponding levels in ^{42}Ti, possibly indicating that the $p_{3/2}$-$f_{7/2}$ splitting is greater in ^{42}Ca than in ^{42}Ti.

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