PHYSICAL REVIEW VOLUME 164, NUMBER 4 20 DECEMBER 1967

Levels of ^{42}Ca and ^{46}Ca as Observed in the ^{40}Ca(t,p) and ^{44}Ca(t,p) Reactions*

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(Received 3 August 1967)

The reactions ^{40}Ca(t,p) and ^{44}Ca(t,p) have been studied at a bombarding energy of 7.5 MeV using an E-ΔE solid-state detector telescope with an over-all energy resolution of about 50 keV. A cross-section fluctuation analysis was carried out on the ^{40}Ca(t,p) reaction; it showed that the compound-nucleus process did not contribute significantly to the observed transitions. Twenty-seven excited states in ^{42}Ca and 24 in ^{46}Ca have been identified. The principal maxima in the angular distributions of the stronger ^{40}Ca(t,p) transitions have been fitted with the predictions of a relatively simple distorted-wave Born-approximation stripping code, and L values have been assigned for 16 transitions. These values are in agreement with previously assigned spins and parities in all cases where the latter have been reported. L values were assigned to 12 ^{44}Ca(t,p) transitions. The ratios of cross sections for certain corresponding transitions in the ^{40}Ca(t,p) and ^{44}Ca(t,p) reactions have been compared with the theoretical predictions assuming pure $(f_{7/2}{}^n)$ configurations for these states; agreement was found for the ground and the 4+ states, but not for the 2+ states. The strongly excited levels of ^{42}Ca and ^{46}Ca are discussed in terms of shell-model configurations. Evidence is presented for the hypothesis that neutron configurations of the type $(f_{7/2}{}^{n-1}\,p_{3/2})$ are not the major components of the wave functions of states in ^{42,44,46}Ca at excitation energies below 4 MeV, in contrast with a number of theoretical treatments of these isotopes which have placed such configurations at energies $\lesssim 3$ MeV. States involving excitation of the ^{40}Ca core appear to be important.

I. INTRODUCTION

FOR a number of years, stripping reactions involving the transfer of a single nucleon have been one of the more powerful tools of nuclear spectroscopy. More recently, there has been a growing interest in reactions that involve the transfer of more than one nucleon. One of the most interesting of these is the (t,p) reaction.

The (t,p) reaction is attractive for a number of reasons. It permits study of certain neutron-rich nuclei not readily accessible by other means. Since it is generally exoergic, it can be carried out at the relatively low bombarding energies available with high-resolution electrostatic accelerators. When the target is an even-even nucleus, the selection rules are especially simple if the reaction proceeds by a stripping mechanism: The total orbital angular momentum L of the transferred neutron pair is equal to the spin J of the final state, and the final-state parity must be equal to $(-1)^L$; hence, no "unnatural" parity states should be excited. These selection rules are valid insofar as the triton wave function contains only pure singlet s-state components for the relative motion of the two neutrons, and thus they should be found to hold for final states that are strongly excited. Violations may occur with reactions involving other components of the triton wave function, and since the latter are very weak, the resultant states should be weakly excited.

Along with these features, however, there are others that make the analysis considerably more difficult than that for single-particle stripping. By analogy with the single-nucleon stripping model, one may construct a "single-pair" stripping model, in which the two neutrons are captured into two single-particle orbitals coupled to a particular spin and parity without alteration of the core configuration, and the resulting state may be expected to mix with others involving core excitation and having the same spin and parity, so that the "single pair strength" is distributed over several levels. If such a model were valid, the development of an adequate double stripping theory would permit determination of two-particle spectroscopic factors in a manner analogous to the (d,p) case. However, this simple model does not take into account a key difference between the (d,p) and (t,p) cases. For the former, only one single-particle configuration can be involved in the excitation of a level of a given spin and parity, assuming an even-even target nucleus. For the (t,p) case, a level of given spin and parity can be made from any of several two-particle configurations; for example, a 2+ state in ^{42}Ca could be constructed from the configurations $(f_{7/2}{}^2)$, $(f_{7/2}p_{3/2})$, $(p_{3/2}{}^2)$, $(p_{3/2}p_{1/2})$, etc. In general, we must expect these to mix, with each term contributing coherently to the (t,p) reaction amplitude. This coherent addition of several terms does not arise in the single-nucleon stripping reaction.

Some states generally described as "collective" can be expressed as a sum of many two-particle terms, no one of which constitutes a large part of the total wave

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
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function, and a number of these may each make a coherent contribution to the (t,p) reaction amplitude. When these terms add in phase, the resulting (t,p) cross section may be larger than that expected for a pure "single-pair" state. Thus, the (t,p) reaction may show collective enhancement in much the same fashion as do electromagnetic transition rates, although the degree of enhancement is expected to be less.[1] Such effects have been predicted theoretically[1] and appear to have been observed experimentally[2–4], especially for the ground-state transition in "superconducting" nuclei, although some of the data can be partially explained without resorting to collective effects.[5] In any case, the presence of a large (t,p) reaction cross section cannot be taken as proof that the final state has a structure that can be simply described in terms of the shell model.

In the (d,p) reaction, only one single-particle component of the product state wave function can contribute, and single-particle spectroscopic factors can, in principle, be extracted unambiguously. For the (t,p) reaction, the observed cross section can represent the result of the coherent addition of several two-particle contributions, and no unambiguous "two-particle spectroscopic factor" can be extracted or even defined. These features, together with the added complications inherent in a double stripping calculation, have presented formidable problems for the development of a quantitative theory. A number of treatments have been reported, first employing the plane-wave Borne approximation[6–9] and, more recently, the distorted-wave approximation.[10–14] One of the reactions chosen for analysis in the latter[11–13] was $^{40}Ca(t,p)^{42}Ca$, which involves addition of a neutron pair to a doubly magic target. The first experimental study of this reaction was made by Middleton and Pullen,[2] who (with an incident triton energy of 7.2 MeV) measured the absolute cross sections of the proton distributions leading to the ground state and the first four excited states of ^{42}Ca. Using plane-wave stripping theory, they obtained consistent fits to the lowest-angle peaks which led to the correct spin-parity assignments. Peak cross sections calculated by Glover, Jones, and Rook,[13] using a distorted-wave Born-approximation (DWBA) treatment and stripping into simple shell-model states, agreed surprisingly well with those observed. However, recent theoretical analyses[15–22] of the level structure of the calcium isotopes have shown that the simple shell-model description of ^{42}Ca, in terms of neutron-pair states on an undisturbed 20-20 core, is inadequate. Core states must be taken into account.

The present work was undertaken to extend the $^{40}Ca(t,p)^{42}Ca$ measurements to higher excited states and to obtain comparable information on the ^{46}Ca level structure via the reaction $^{44}Ca(t,p)^{46}Ca$.

II. EXPERIMENTAL PROCEDURES

Tritons were accelerated to an energy of 7.50 ± 0.01 MeV in the Los Alamos Vertical Van de Graaff Accelerator. The analyzing magnet used to determine the energy was calibrated by accelerating ^4He ions, scattering them from a thin (5–10-μg/cm^2) gold target, and determining their energy by comparing with a natural α source (^{238}Pu).

The calcium targets were prepared by vacuum deposition[23] onto carbon backings about 50 μg/cm^2 thick. For ^{40}Ca, calcium of natural isotopic composition was used and the targets were about 80–140 μg/cm^2 thick. The ^{44}Ca targets were prepared from calcium enriched[24] to 98.6% ^{44}Ca and were about 15–30 μg/cm^2 thick.

Protons were detected using an E-ΔE solid-state dee tector telescope and a particle identification circuit. Th- defining slit in front of the detector telescope subtended an angle of 0.9° as seen from the target. The spectra were analyzed and stored in 1024 channels of a Nuclear Data 4096-channel analyzer. In some of the later experiments, a Victoreen Model S16 ADC (analog-to-digital converter) was used in conjunction with a SDS 930 on-line computer. The optimum over-all energy resolution was about 50 keV.

The solid-state detectors employed were chosen to optimize the measurement of the proton spectra. However, the system did permit the simultaneous recording of α-particle spectra, and the results of these (t,α) reaction measurements will be reported elsewhere.

A conventional Faraday-cup current integration was used for total beam charge determination. For angles of 30° or more to the beam, the total bombardment was usually about 400–800 μC for the ^{40}Ca targets and 1200–1800 μC for the ^{44}Ca targets. The bombardments were also monitored by measuring elastically scattered tritons at a fixed angle of 30° to the beam direction.

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For the ^{40}Ca$(t,p)^{42}$Ca reaction, measurements were taken at 10°, 15°, 20°, and then at 10° intervals at angles up to 160°. For the ^{44}Ca$(t,p)^{46}$Ca reaction, measurements were taken at 5° intervals in the range 10°–60° and then at 10° intervals out to 160°. At angles of 20° and less, the intense elastic scattering required the use of very low beam intensities and the total beam exposure was consequently considerably less than for the larger angles. These measurements were supplemented with others carried out with the detectors covered by an aluminum foil thick enough to stop the scattered tritons. This method permitted the use of higher beam currents, but the resolution was then much poorer, about 200 keV, and generally only the higher-energy peaks could be so measured. Effective dead time (of the detector-analyzer system) was checked using a 60-Hz pulser, and bombardment rates were adjusted to keep the count loss tolerable.

Since the bombarding energy employed is relatively low, it was desired to determine whether there was a significant contribution from the compound-nucleus mechanism. A fluctuation analysis was therefore carried out at an angle of 50° to the beam for several of the proton groups observed in the ^{40}Ca$(t,p)^{42}$Ca reaction. The bombarding energy was varied in steps of 50 keV over an energy range of 7.00 to 8.00 MeV.

In order to obtain absolute differential cross sections, measurements were made of the elastic scattering of 5.00±.01-MeV ^{4}He ions at angles of 60° and 80°. An optical model calculation, using the code PEREY,[25] indicates that at this energy the scattering should deviate from the Rutherford cross section by less than 0.1% for all angles less than 100°. Hence, the scattering cross section may be taken as known, and a single factor including target thickness, solid angle, and any current integrator calibration error can be determined. As a check, the thickness of one of the ^{40}Ca targets was estimated by comparing the triton scattering with that from a relatively thick (1.59-mg/cm^2) target whose thickness had been measured by direct weighing. The results agreed to about 10%, which is probably as accurate as the determination of the thickness of the thicker calcium target.

III. DETERMINATION OF EXCITATION ENERGIES

When the same nucleus is studied in different ways, a question often arises as to whether the levels excited in different experiments are actually the same levels. Accurate determination of the excitation energies of these levels can be of considerable aid in resolving this question. For this and other reasons, some effort was expended in determining these excitation energies as accurately as possible.

The detectors used generally showed a slightly nonlinear response for the highest proton energies present. For this reason, the ground-state ^{40}Ca(t,p) and ^{44}Ca(t,p) transitions were not used as energy standards. Instead, the ^{42}Ca third excited state at 2.423 MeV and the ^{46}Ca first excited state at 1.347 MeV were employed. Other energy standards used were the ^{12}C(t,p) and ^{16}O(t,p) ground-state transitions and, for the ^{44}Ca$(t,p)^{46}$Ca reaction, the ^{18}O first excited state at 1.980 MeV. The ground-state Q values assumed were figured from the 1964 mass tables of Mattauch *et al.*,[26] and are as follows: ^{12}C(t,p), 4.641 MeV; ^{16}O(t,p), 3.707 MeV; ^{40}Ca(t,p), 11.353 MeV; and ^{44}Ca(t,p), 9.339 MeV.

The calibration points were used to establish a linear relationship between pulse height and proton energy. The use of a quadratic correction term to the calibration curve was investigated, but it did not appear to offer any advantages over the assumption of strict linearity.

The energy of the reference groups in question was calculated assuming the excitation energies and ground-state Q values given above. The linear calibration function was essentially determined by the calcium reference groups in the low-excitation region and by the light-element groups in the high-excitation region. Since the light-element Q values have listed uncertainties of less than 1 keV, and the ^{40}Ca and ^{44}Ca Q values have listed uncertainties of 5 keV and 10 keV, respectively, the Q values for the highly excited states of ^{42}Ca and ^{46}Ca (whose proton groups lie near those of the light elements) are more accurately known than the excitation energies, whereas for the lower excited states the reverse is true.

The 7.5-MeV tritons lose energy in traversing matter at a greater rate than do the reaction protons. Hence, the energy of the protons arising in a (t,p) transition depends upon the amount of the target the incident triton traverses before the reaction takes place. The targets were thin enough so that the energy resolution was not significantly affected. However, the calcium is deposited on one side of the carbon backing and the position of the oxygen is uncertain; hence, protons arising in the calcium interactions may not undergo exactly the same energy loss as those from the carbon and oxygen transitions used as energy standards. To obtain an estimate of this effect, the targets were rotated 180° and the measurements repeated; this comparison was done for two different values of the detector angle. The corrections required for target thickness were less than 10 keV.

The energies of most of the proton groups assigned to levels of ^{42}Ca and ^{46}Ca in this work were determined at five or more angles and the excitation energy figured. The mean of these values was taken to be the excitation energy and the standard deviation was taken to be the precision of the determination. Some measurements were rejected when they were found to deviate excessively from the results of several other measurements

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TABLE I. Summary of the ^{40}Ca$(t,p)^{42}$Ca measurements. σ_I is the differential cross section integrated over the forward hemisphere. θ_m is the center-of-mass angle at which the differential cross section is a maximum and $d\sigma_m/d\Omega$ is the center-of-mass differential cross section at that angle. The next column gives the value of (J,π) deduced from our angular distributions, with the less certain values appearing in parentheses. The last two columns give the results of previous work.

Level No.	Energy (keV)	σ_I (mb)	θ_m (deg)	$d\sigma_m/d\Omega$ (mb/sr)	J,π	Other work Energy (keV)	Other work J,π
0	G.S.	1.24	10.3[a]	1.45[a]	0+	0	0+
1	(1523)[b]	1.22	28	0.426	2+	1523±4[c]	2+[c]
2	(1836)[b]	0.161	10.3[a]	0.135[a]	0+	1836±4[c]	0+[c]
3	2423[b,d]	0.534	28	0.159	2+	2423±4[c]	2+[c,e]
4	2751±4	0.747	48	0.201	4+	2751±4[c]	4+[e,f]
5	3186±6	0.366	72	0.082	6+	3191±8[c]	6+[f]
6	3253±5	∼0.16				3252±5[c]	
7	3437±9	0.184	∼40	0.056	(3−)	3442±6[c]	3−[g]
8	3651±6	0.268	28	0.118	2+	3651±6[c]	2+[h]
9	4090±8	∼0.1		∼0.02		4100±30[g]	5−[g]
10	4448±11	0.936	29	0.305	2+	4450±30[h]	4+[h]
11	4757±9	1.254	27	0.498	2+		
12	4869±7	0.754	27	0.345	2+		
13	5011±7	0.535	48	0.133	4+		
14	5201±5	∼0.25	∼35	∼0.055			
15	5366±9	∼0.17					
16	5471±9	0.561	48	0.133	4+		
17	5779±11	∼0.37		∼0.08			
18	5863±10	1.45	10.3[a]	1.85[a]	0+	5850[i]	0+[i]
19	6015±9	0.421	10.3[a]	0.573[a]	0+	6010[i]	0+[i]
20	6106±7	0.226	∼46	0.056	(4+)		
21	6273±7	∼0.4					
22	6518±8	∼0.5	15.5[a]	∼0.30[a]	(0+)	6510[i]	0+[i]
23	6723±8	∼0.4					
24	6920±4	∼1.11	∼30	0.437	2+	(6700)[i]	(0+[i])
25	7134±8	∼0.7					
26	7259±7	∼0.3		∼0.08			
27	7385±5	1.77	28	0.637	2+		

[a] Values at smallest angle measured; peak appears to be at 0°.
[b] Taken from Ref. 27.
[c] Reference 27
[d] Adopted as energy standard for upper end of proton spectrum.
[e] Reference 2.
[f] Reference 31.
[g] Reference 28.
[h] Reference 29. The 4.45-MeV 4+ state may not be the same as our 4.448-MeV state.
[i] Reference 30.

that agreed well with each other. In many such cases, it was found that the rejected measurement was derived from a peak whose exact position was difficult to determine because it exhibited a nonstandard shape. The usual causes of this effect were poor counting statistics, instrumental or detector effects, or the presence of two or more unresolved levels making comparable contributions at the particular angle in question.

If impurity groups were present, the apparent excitation energy would shift systematically with angle because of the different kinematic effects unless the impurity mass number were very close to that of the intended target. Differences in mass number of five units would have been obvious; differences of two units would probably have been detected. No proton groups corresponding to possible impurities in this mass region were detected. Aside from the carbon backings and the ubiquitous oxygen contamination, the only impurity groups definitely found were a few very weak groups apparently arising in a small silicon impurity.

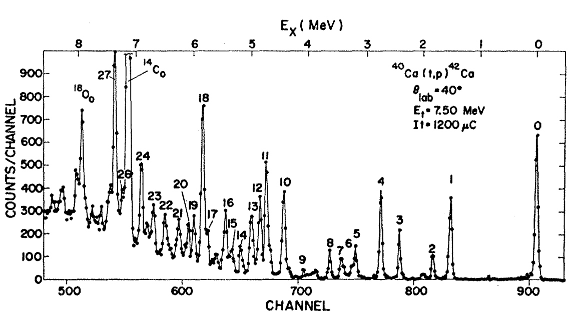

FIG. 1. Proton spectrum observed at 40° in the ^{40}Ca$(t,p)^{42}$Ca reaction. Levels are numbered as in Table I.

The calibration of the angular scale used in setting the detector angles was made by optical sighting with a transit and is believed to be accurate to 0.2°. This measurement was repeated at later times and no detectable changes were found. Error in this measurement would result in error in the excitation energies, especially for the highly excited states, since the energy standards employed included proton groups arising in carbon and oxygen, and the latter show much larger kinematic shifts than do the calcium proton groups. However, any such errors would be several times greater for detector angles over 40° than for angles in the 10°–20° range, and there was no systematic shift of apparent excitation with angle to within the precision of our measurements.

Hence, the accuracy of our measurement should not be significantly impaired by errors from this source.

IV. RESULTS AND DISCUSSION

A. ^{40}Ca$(t,p)^{42}$Ca

Figure 1 shows a proton spectrum taken at a beam angle of 40°. In the forward hemisphere, statistical uncertainties in the areas of the stronger peaks were generally under 10%, except for deep minima in the angular distributions. Statistical uncertainties were sometimes greater for the weaker transitions, but even for these, statistics were the limiting factor on the accuracy only for a few well-resolved groups at excitation energies below 4 MeV.

Table I summarizes the results of our measurements. The second column gives the excitation energy and the precision obtained as described in the preceding section. The absolute cross section integrated over the forward hemisphere is given in the third column. Since no data were obtained for angles less than 10°, the differential cross sections had to be extrapolated to 0°. The amount of solid angle involved is quite small and no significant error is introduced except for those transitions showing a forward peak in their angular distributions.

The fourth and fifth columns of Table I give, respectively, the approximate center-of-mass angle at which the peak differential cross section occurs and the value of the cross section at that angle. The sixth column gives the spins and parities that we have deduced from the angular distributions, as will be described later. The 0+ states show angular distributions that peak at 0°, and for these the indicated peak differential cross sections and corresponding angles are those observed at the smallest angle at which measurements could be made, usually 10.3° c.m.

The last two columns of Table I give the excitation energies[27–30] and $J(\pi)$ values [2,27–31] that have been reported previously. Our excitation energies are seen to lie within the quoted experimental errors of the previous values in all cases.

It was evident from the spectra that there were many other levels above 3 MeV in addition to those listed in Table I. Above 4 MeV, the level spacing is probably less than the experimental resolution. We have not reported these poorly resolved levels. Some of the proton groups corresponding to levels reported in Table I appeared to be complex at a few angles, but at most angles each of these proton groups appeared to be dominated by the same single transition, and the good reproducibility of the excitation energies from angle to angle supports this conclusion. We would be unable to distinguish doublets from single levels if the spacing were of the order of 10 to 20 keV, even if the two components were of comparable intensity.

In general, then, there are undoubtedly other weakly excited levels lying very close to some of those listed in Table I, but each of the excitation energies listed is believed to correspond to a single level that is considerably more strongly excited than any other level that may be present. This is almost certainly true for the relatively strong transitions.

We believe that the integrated absolute cross sections and peak differential cross sections given in Table I are accurate to 20% for excitation energies below 3 MeV and that the relative intensity of excitation of these levels is accurate to about 10%. The uncertainty for the 3.186-MeV level may be slightly greater, as it was incompletely resolved from other, less strongly excited levels lying just above it. For similar reasons, the uncertainties are somewhat greater for the levels at higher excitation energies, especially for the less strongly excited levels. Those marked with the approximation symbol (∼) are the most uncertain; they may be in error by factors of 1.5 to 2.

Reaction Mechanism: Fluctuation Analysis

Direct-interaction reaction amplitudes vary only slowly as a function of bombarding energy, while compound-nucleus reaction amplitudes are expected to undergo relatively rapid, random fluctuations as the bombarding energy is varied. Though the compound-nucleus amplitude may correspond to a very small average contribution to the cross section, interference with the direct-interaction amplitude can result in a sizeable effect on the differential cross section at any one specific energy if the energy spread of the beam traversing the target is less than the compound-nucleus coherence width, as it is here. Even when the effect is sizeable, the angular distribution may still show what appears to be a stripping pattern,[32] and analysis under the assumption of pure direct interaction would produce misleading results.

Compound-nucleus effects reveal themselves as fluctuations in the cross section as the beam energy is varied in small steps. The analysis of these fluctuations has been discussed in detail elsewhere[33–38]; we reproduce here only some of the basic results of the theory, since

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TABLE II. Results of the fluctuation analysis of several $^{40}Ca(t,p)^{42}Ca$ transitions for $E_t=7.00$–8.00 MeV and at an angle of 50° to the beam. N_{eff} is an estimate of the effective number of magnetic substates. The values of R and N_{eff} were used to calculate the values of $\sigma_{cn}/\langle\sigma\rangle$ in column 6. $\langle\sigma\rangle$ is the average differential cross section at 7.5 MeV.

Excitation	J_π	N_{eff}	$1/\langle N_i\rangle$	R	$\sigma_{cn}/\langle\sigma\rangle$	$\langle\sigma\rangle$ (mb/sr)	$d\log\langle\sigma\rangle/dE$ (MeV^{-1})
Ground state	0+	2	0.00154	0.00242	0.0024	0.270	−0.15
1.523	2+	5.6	0.00487	0.00363	0.0103	0.086	−0.41
1.836	0+	2	0.00835	0.00208	0.0021	0.050	0.11
2.423	2+	5.6	0.00695	0.00455	0.0128	0.060	−0.30
2.751	4+	8	0.00205	0.00220	0.0088	0.204	−0.06
3.186	6+	9	0.00618	0.00377	0.017	0.067	0.07
3.651	2+	5.6	0.0194	0.0347	0.097	0.021	−0.30
4.448	2+	5.6	0.00307	0.0119	0.033	0.136	−0.27
4.757	2+	5.6	0.00579	0.00743	0.021	0.072	−0.40
4.869	2+	5.6	0.00753	0.00733	0.021	0.055	−0.37
5.863	0+	2	0.00152	0.00113	0.0011	0.276	−0.51

our purpose is only to show that direct interaction dominates the reaction.

The magnitude of the fluctuations may be expressed in terms of the quantity R, defined as

$$R=(\langle\sigma_i^2\rangle-\langle\sigma_i\rangle^2)/\langle\sigma_i\rangle^2-1/\langle N_i\rangle, \quad (4.1)$$

where $\langle\ \rangle$ denotes an average taken over the range of energy studied, σ_i is the differential cross section for the population of the ith level of the product, and $\langle N_i\rangle$ is the average number of counts observed for the transition to this level. The quantity $1/\langle N_i\rangle$ is subtracted from R in order to remove the contribution to R that results from the "ordinary" statistical counting errors. According to fluctuation theory, the value of R to be expected is

$$R=(1-y^2)/N_{eff}, \quad (4.2)$$

where y is the fraction of the cross section that proceeds by direct interaction and N_{eff} is the effective number of magnetic substates participating in the reaction. N_{eff} is a function of the entrance and exit channel energies and of the angle at which σ is determined; in general, rather involved calculations are needed to determine it. We have not attempted to calculate N_{eff}, though we have made estimates of it by extrapolation from some of the calculations of Gibbs.[36,37]

Use of Eqs. (4.1) and (4.2) is valid only for an infinite sample size.[34,35] In the present case, compound-nucleus systematics indicates that the coherence width Γ should be of the order of 20 to 25 keV.[38] Since we have taken 21 measurements at 50-keV intervals, the effect of finite sample size will be small enough for our purposes.

In studies of this type, it is desired to determine the fluctuations about the average value of the cross section at the energy in question. However, this average value can itself be a slowly varying function of the bombarding energy. Since the fluctuations can be measured only by studying the excitation function over an appreciable energy range, the value of R from Eq. (4.1) will be too large unless the effect of this "moving average" is allowed for. There are a number of ways of doing this, but the simplest is to assume that the average cross section $\langle\sigma\rangle$ varies linearly with bombarding energy over the range of interest, determine the relationship by a least-squares fit to the data, and measure the fluctuations relative to the value of $\langle\sigma\rangle$ given by the regression line at each energy. This assumption of a linear relationship between $\langle\sigma\rangle$ and E_t should be quite adequate for an energy interval of 1 MeV, and it has been employed here.

Table II gives the results of our analysis for several selected transitions. The first column gives the excitation energy. The second gives the probable spin and parity, and the third gives our estimate of N_{eff}. The fourth column gives $1/\langle N_i\rangle$, the fifth gives the value of R, and the sixth gives the ratio of the compound-nucleus (CN) cross section to the total cross section, obtained from Eq. (4.2) using the estimated value of N_{eff}. The next column gives $\langle\sigma\rangle$ at 7.5 MeV, as determined from the least squares line, and the following column gives the logarithmic derivative of $\langle\sigma\rangle$ with respect to the bombarding energy.

The value of $\sigma_{cn}/\langle\sigma\rangle$ is small in all cases, even for those levels where $\langle\sigma\rangle$ itself is small. Furthermore, R is seen to be of the same order of magnitude as $1/\langle N_i\rangle$. This means that the compound-nucleus effects contributed no more to the observed variation in the numbers of counts for each transition than did the random counting errors. Since the counting statistics in these measurements were comparable to the counting statistics of the angular-distribution data, we may expect that the effect of compound-nucleus processes on the latter is at most comparable to our experimental errors.

It should be noted that any experimental errors in the fluctuation study in addition to statistical counting errors can only increase the apparent value of R, and thus the values of $\sigma_{cn}/\langle\sigma\rangle$ listed in Table II should be regarded as upper limits.

We have made no fluctuation measurements for any other (t,p) reaction. However, the cross section for transitions to any one level in the residual nucleus by compound-nucleus mechanisms should decrease as the total number of open channels for compound-nucleus decay increases. This number may vary considerably from one nucleus to another, but the main trends are a rather rapid increase with increasing mass number and increasing excitation energy available to the various residual nuclei, especially the residual nucleus formed by neutron emission. Hence, it is very probable that the effects of compound-nucleus processes are small or negligible for all (t,p) reaction transitions for which $E_t \geq 7$ MeV and $A \geq 40$. The only probable exception would be the case of transitions for which the differential cross section is smaller than any of those listed in Table II.

Angular Distributions

Absolute differential cross sections are portrayed in Fig. 2 for those transitions for which adequate data could be obtained. They are grouped according to the known or deduced spins of the states of the residual nuclei. The dashed curves in Fig. 2 were drawn as smoothed out approximations to the experimental data. Statistical errors are not indicated because they were rarely the limiting factor on accuracy. The relative errors are best estimated by the scatter of the points about the dashed curves. For angles $\geq 30°$, statistical errors may be estimated from the fact that the bombardment conditions in the ^{40}Ca(t,p) studies were such that a cross section of 1 mb/sr would yield about 2500–4000 counts; thus, the uncertainty in σ from counting statistics for $\theta \geq 30°$ is roughly $0.018\sigma^{1/2}$.

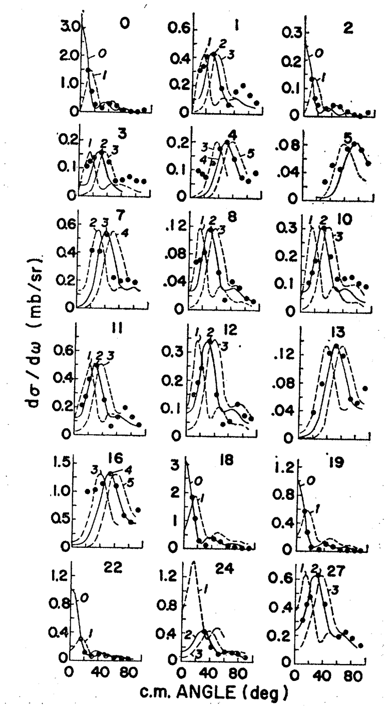

FIG. 3. DWBA fits to the ^{40}Ca$(t,p)^{42}$Ca angular distributions. Levels are numbered as in Table I. The theoretical angular distributions for the L values giving the best fit to the principal stripping peak are portrayed by solid curves. Dashed curves indicate the theoretical distributions for L values giving the next best fit. The theoretical curves are normalized to the experimental data at the peaks in the angular distributions.

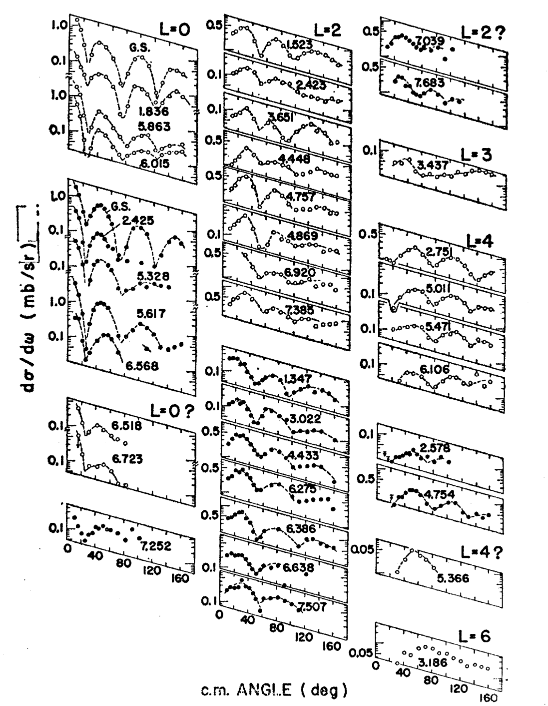

FIG. 2. Absolute differential cross sections for the observed ^{40,44}Ca(t,p) transitions. Open and solid symbols designate levels of ^{42}Ca and ^{46}Ca, respectively. Numbers associated with each curve give the excitation energy in MeV. The curves through the points have no theoretical significance.

In order to determine the spins of the various states, we have compared the experimental angular distributions with the predictions of the DWBA double-stripping code developed by Henley and Yu.[10] This program employs entrance- and exit-channel wave functions generated by a modified version of the SCAT-4 optical-model code. For the stripped nucleons, wave functions of an infinite harmonic oscillator are used.

The oscillator strength $\hbar\omega$ appears in this theory as an adjustable parameter. If it is set at the value giving the best fit to shell-model level spacings, the wave functions at the nuclear surface, where the (t,p) reaction is expected to occur, will fall off much more rapidly than do the more realistic Woods-Saxon wave functions. A better procedure would be to adjust $\hbar\omega$ so that the asymptotic behavior gives the best obtainable fit to the asymptotic behavior of the Woods-Saxon wave functions, as Henley and Yu suggest. However, in the present case, there are several levels whose spins are well established, and we adjusted $\hbar\omega$ to give the best fit to the principal stripping peak for these levels. The levels used were the ground state (0+), the 2+ state at 1.523 MeV, and the 4+ state at 2.751 MeV. The optimum value of $\hbar\omega$ was found to be 3.5 MeV, which is close to the value

TABLE III. Summary of the $^{44}Ca(t,p)^{46}Ca$ measurements. See caption to Table I.

Level No.	Energy (keV)	σ_I (mb)	θ_m (deg)	$d\sigma_m/d\Omega$ (mb/sr)	J, π	Other work Energies (keV) Ref. 43	Ref. 44	J, π
0	G.S.	1.79	10.3^{a}	1.90^{a}	0+			
1	1347^{b}	0.508	~20	0.22	2+	1347±3^{c,d}	1347±1	2+
2	2425±8	0.323	10.3^{a}	0.388^{a}	0+	2423±5^{c}		
3	2578±8	0.142	~47	0.032	4+	2575±5^{c}		
4	3022±6	0.444	~23	0.158	2+	3023±5^{c,d}	3015±5	2+
5,6	Unresolved	0.337	~15	0.120		{3614±5^{c,d}	3621±3	3−
						{3645±6^{c}		
...	Not observed					3780±10^{c}		
7	3858±7	0.149		0.035				
8	4433±7	1.20	~25	0.427	2+	4434±8^{d}	4454±6^{e}	3−
9	4754±7	0.957	48	0.258	4+			
10	5011±7	~0.4					(5047±5	2−, 3−)^{e}
11	5328±4	0.56	10.3^{a}	0.50^{a}	0+			
12	5544±15	~0.4						
13	5617±6	3.13	10.3^{a}	3.38^{a}	0+			
14	6275±5	1.25	27	0.428	2+			
15	6386±5	1.68	28	0.657	2+			
16	6568±8	0.484	10.3^{a}	0.347^{a}	(0+)			
17	6638±9	0.79	~25	0.23	2+			
18	7039±8	~1.31	~28	~0.35	(2+)			
19	7252±8	~0.54	10.3^{a}	~0.21^{a}	(0+)			
20	7507±8	~1.09	~30	~0.25	(2+)			
21	7683±5	~0.72	~28	~0.26	(2+)			
22	7759±8	~0.57						
23	7929±8	~1.5						
24	8397±5	~1.4	~25	~0.33				

[a] Values at smallest angle measured; peak appears to be at 0°.
[b] Adopted as energy standard for upper end of proton spectrum.
[c] Observed in the (p,p') reaction.
[d] Observed in the (d,d') reaction.
[e] May not be the same as the level observed in the reaction studies.

of 3 MeV used by Henley and Yu. All other theoretical angular distributions were then calculated without altering any of the parameters.

Triton optical-model parameters were taken from the work of Glover and Jones,[39] while the proton parameters were those given by Bjorklund *et al.*[40] Some calculations were repeated using other parameters; the main features of interest were not sensitive to the choice of parameters.

All new spin assignments in Table I and Fig. 2 were obtained by comparing these theoretical angular distributions with the experimental results. The main emphasis was on the fit to the first maximum in the angular distribution and the only purpose was to determine the L values of the transitions. We have not attempted to give any quantitative interpretation of the absolute magnitudes of the measured cross sections.

Comparisons of the theoretical and experimental angular distributions are given in Fig. 3. The theoretical curves are normalized to the experimental results at the first maximum in the angular distributions. In each case, the solid curve is the theoretical curve for the value of L giving the best fit, while the dashed curves give the theoretical predictions for the values of L giving the next best fit. In most cases, the results speak for themselves. The $L=4$ transitions at 5.011 and 5.471 MeV are examples of the worst cases for which L values were assigned to levels of previously unknown spin. Even for these, the choice seems clear.

Our spins and parities (column 6, Table I) agree with all earlier assignments (column 8, Table I) with the possible exception of the state at 4.448 MeV. However, the 4.45-MeV 4+ state reported in Ref. 29 may not be the same as our 4.448-MeV state, and thus the "disagreement" may be spurious.

Though the angular distributions for a given L value show many similarities, they do differ from one another in some respects. In particular, the $L=2$ transitions can be divided into two families, one with a deep minimum near 50° and the other having a shallow minimum at this angle. This difference does not appear to be correlated with either the strength of the transition or the excitation energy, as the moderately weak transition at 2.423 MeV and the strong one at 4.448 MeV[41] show shallow minima while the weak transition at 3.651 MeV and the strong ones at 1.523, 4.757, and 4.869 MeV all show the relatively deep minima. Presumably the effect is not related to any compound-nucleus process since the fluctuation study carried out at this angle failed to indicate the presence of a significant compound-nucleus contribution. It would be very interesting if this

[39] R. N. Glover and A. D. W. Jones, Nucl. Phys. **81**, 268 (1966).
[40] F. Bjorklund, G. Campbell, and S. Fernbach, Helv. Phys. Acta, Suppl. **6**, 432 (1961).

[41] It should be noted that Bernstein *et al.* (Ref. 29) report observing a 4+ state at 4.45 MeV in their $^{42}Ca(\alpha,\alpha')$ studies. We could not, of course, resolve this level from our 4.448-MeV state. If the 4+ level is excited here, the first maximum in its angular distribution would lie near 50° and would, therefore, give a spurious filling in of the minimum in the $L=2$ angular distribution.

difference could be correlated with some feature of the structure of the final nuclear states. For single-nucleon transfer reactions, the presence or absence of deep minima in the backward hemisphere can sometimes be helpful in distinguishing $j=l-\frac{1}{2}$ states from $j=l+\frac{1}{2}$ states.[42]

Middleton and Pullen[2] studied the ^{40}Ca(t,p) reaction at an incident energy of 7.2 MeV. They reported absolute differential cross sections for the levels of ^{42}Ca up to 2.75 MeV and obtained L values by comparison with plane-wave Born-approximation (PWBA) theory. Their angular distributions, L values, and relative transition intensities are all in good agreement with ours. Their absolute cross sections are from 20% to over 50% larger than ours. The slight difference in bombarding energies is unlikely to be the source of most of this discrepancy (see the last column of Table II).

B. ^{44}Ca$(t,p)^{46}$Ca

A proton spectrum taken at 40° to the beam is shown in Fig. 4. The statistics are somewhat poorer than for the ^{40}Ca(t,p) reaction, because of the thinness of the ^{44}Ca targets available. In addition, the low-lying excited states of ^{46}Ca are populated with appreciably lower cross sections than was the case for the levels of ^{42}Ca.

Table III summarizes the results of our measurements on this reaction. The first six columns give the same information as do the corresponding columns of Table I. As in the case of the ^{40}Ca(t,p) reaction, there were many other weakly excited and poorly resolved groups that we have not reported. The fact that somewhat fewer levels are reported for ^{46}Ca than for ^{42}Ca probably reflects only the greater experimental difficulties, not any lack of levels.

Belote *et al.*[43] observed levels of ^{46}Ca at excitations of up to 4.4 MeV by means of inelastic deuteron and proton scattering, and Parsa and Gordon[44] observed several levels of ^{46}Ca in their studies of the ^{46}K decay scheme. Their results are given in the last three columns of Table III. The energy uncertainties quoted for Ref. 44 were deduced from the uncertainties in the γ-ray energies quoted by the authors. As can be seen, our energies agree unnecessarily well with the results reported by Belote *et al.* Agreement is poorer for the two levels above 4 MeV reported in the decay scheme work. It is possible that they are not the same levels that we observe; in particular, the energy difference between the 5.047-MeV level (decay scheme) and the 5.011-MeV level (t,p) appears to be outside the errors of the two measurements. Our spin assignments agree with those of Refs. 43 and 44, except for the 4.433 MeV level.

The angular distributions are shown in Fig. 2 for those

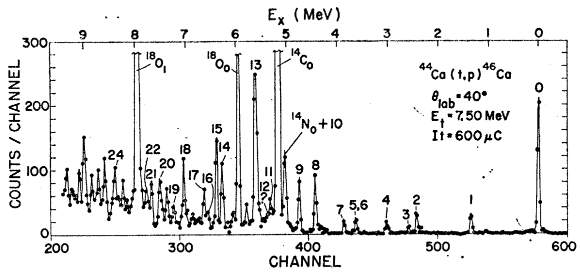

FIG. 4. Proton spectrum observed at 40° in the ^{44}Ca$(t,p)^{46}$Ca reaction. Levels are numbered as in Table III.

transitions for which fairly complete data were obtained. For the more highly excited levels, data are missing at some angles due to obscuration by proton groups arising in carbon and oxygen (t,p) transitions. For angles greater than 20°, the bombardment conditions were such that a cross section of 1 mb/sr would yield about 700 to 1500 counts; hence, the error in σ due to counting statistics is about $0.03\sigma^{1/2}$. Other cross-section uncertainties are about the same as they were for the ^{40}Ca(t,p) measurements.

The first excited state of ^{46}Ca at 1.347 MeV is expected to be 2+, and the measurements reported in Refs. 43 and 44 confirm this expectation. These experiments also lead to a 2+ assignment for the 3.022-MeV level. As would be expected, our angular distributions for these two states are quite similar to those found for $L=2$ transitions in the reaction ^{40}Ca$(t,p)^{42}$Ca. However, it does appear that these angular distributions peak at a slightly lower angle than was observed for the ^{40}Ca(t,p) reaction. The experimental errors are large enough so that it is difficult to be certain of this point.

We have made L assignments for a number of ^{44}Ca(t,p) transitions by comparison with the angular distributions found for the ^{40}Ca(t,p) transitions to levels of known spin and parity. This procedure was adopted in preference to comparison with theoretical angular distributions, partly because no triton parameters were available for ^{44}Ca and it would not have been possible to do better than to use the ^{40}Ca triton parameters. Under these conditions, theoretical calculations for the ^{44}Ca(t,p) reaction would have amounted to little more than a rerun of the ^{40}Ca(t,p) calculations, which, in turn, amounts to the assumption that the angular distributions will be similar for the two reactions when the L values are the same.

The level at 2.578 MeV is excited only very weakly. The statistics are consequently poor, but there does appear to be a maximum in the angular distribution at about 45°; repeating the measurements at every 10° gave the same result. This maximum is near the positions of the $L=4$ maxima for the ^{40}Ca(t,p) reaction, which were located between 45° and 50°. Belote *et al.* do not observe this or any other 4+ state in their (d,d') experiments, and they indicate that this result is consistent with the low theoretical cross sections pre-

[42] L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. Letters **12**, 108 (1964); Phys. Rev. **136**, B405 (1964).
[43] T. A. Belote, J. H. Bjerregaard, O. Hansen, and G. R. Satchler, Phys. Rev. **138**, B1067 (1965).
[44] B. Parsa and G. E. Gordon, Phys. Letters **23**, 269 (1966).

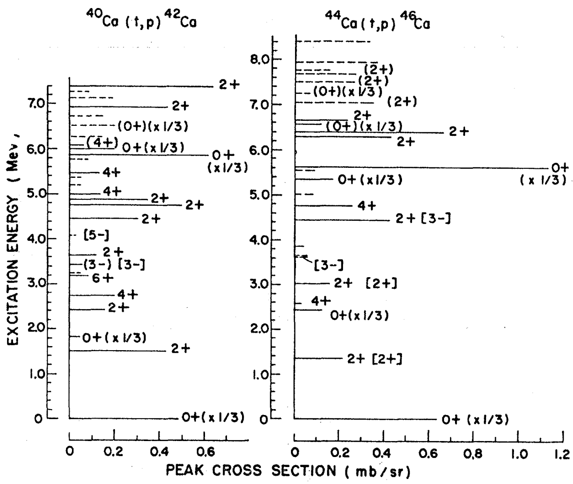

FIG. 5. Summary of ^{40,44}Ca(t,p) measurements. The length of each line indicates the maximum value of $d\sigma/d\Omega$ for the excitation of the corresponding level, except for the 0+ states; for these, the 10.3° c.m. cross section, arbitrarily multiplied by $\frac{1}{3}$, is indicated. Dashed lines are used when the peak cross section is uncertain by a factor of 1.5 or more. The levels are labeled with the J, π values we have deduced from the angular distributions in each case for which we have made assignments. Our less certain assignments appear in parentheses. Assignments from other work are in brackets.

dicted for the excitation of a 4+ state in their experiments. They did find that this state was excited in the (p,p') reaction, but no information was reported as to its spin. The level was not observed in the ^{46}K decay studies, a result consistent with a 4+ assignment. A 4+ state is expected in this region of the ^{46}Ca spectrum, and all other known states up to 3.6 MeV have been given other assignments which appear to be quite certain. Taken together, all available evidence indicates that the 4+ assignment for the 2.578-MeV level is very probably correct.

A doublet at 3.614 and 3.645 MeV was observed in the (p,p') studies of Belote *et al.* They also observed the 3.614-MeV level in their (d,d') experiments and reported that the level was a 3− state; this level was also observed in the decay-scheme studies of Parsa and Gordon. We cannot, of course, resolve this doublet, but from the appearance of the peak and its apparent shift in energy with angle, it appears that both levels are excited. The cross sections reported in Table III are for the sum of the two. Neither level is excited strongly.

Belote *et al.* observed a level at 3.780 MeV in their (p,p') experiments. We do not observe this level. There is a previously unreported state at 3.858 MeV which is weakly excited. The angular distribution is rather formless and we can draw no conclusions as to the nature of this state.

The first excited state of ^{46}Ca that is strongly populated is the level at 4.433 MeV. The angular distribution is very similar to what we have observed for $L=2$ transitions for both the ^{40}Ca(t,p) and ^{44}Ca(t,p) reactions. Belote *et al.* observed this level in their (d,d') experiments, but they found the angular distribution to be consistent with a 3− assignment. However, their published angular distributions show considerable statistical scatter and data were missing at many angles, and it is not clear whether their results are inconsistent with a 2+ assignment. The level is also populated in ^{46}K decay, with the scheme being about equally consistent with either a 2+ or a 3− assignment. Although the spin of this level may be open to some question, we consider the 2+ assignment to be the more probable.

It may be seen from Tables I and III that we have made more assignments for $L=2$ transitions than for any other L value in both the ^{40}Ca(t,p) and the ^{44}Ca(t,p) reaction studies. In part, this may reflect the ease of identifying $L=2$ transitions, since they have large cross sections, distinctive angular distributions, and peak at angles reasonably accessible to measurement. The $L=0$ transitions are most distinctive at angles of less than 20°, where measurements are difficult, and the $L\geq 4$ transitions show lower cross sections and a less pronounced diffraction pattern. On the other hand, part of this preponderance of $L=2$ transitions is probably real. More of the available two-neutron shell-model configurations can be recoupled to form 2+ states than is possible for other spins and parities.

C. Transition Intensities and Interpretation

The general pattern of the levels of ^{42}Ca and ^{46}Ca excited here is displayed in Fig. 5. The excitation energy of each level is given by its position against the vertical scale to the left. The length of each line gives the peak differential cross section in mb/sr. The peak cross sections were read from a smoothed curve drawn through the data when the latter showed considerable scatter. We have, in general, taken the peak cross sections, rather than the integrated cross sections, as representative of the transition intensities, as the former are expected to be less sensitive to contributions from nonstripping-reaction mechanisms and to experimental effects such as incorrect allowance for background and the presence of unresolved levels. For the 0+ states, the indicated quantity is the differential cross section at 10.3° c.m. arbitrarily divided by a factor of 3 for convenience in plotting. Dashed lines are used when the peak cross sections are uncertain by a factor of 1.5 or more, but the existence of the levels themselves is not considered uncertain. The two unresolved levels at 3.614 and 3.645 MeV in ^{46}Ca are plotted as if both contributed equally to the observed proton group. Where possible, each level is labeled with the spin and parity, as deduced from our angular-distribution data. The less certain values appear in parentheses. Values in square brackets are from other work (Refs. 2, 27–31 for ^{42}Ca, Refs. 43 and 44 for ^{46}Ca).

Seniority Coupling Scheme

We have made no attempt to determine absolute spectroscopic factors. However, the Q values for the

^{40}Ca(t,p) and ^{44}Ca(t,p) reactions are not too different, and the cross sections for transitions to corresponding states of ^{42}Ca and ^{46}Ca should be in approximately the same ratio as their spectroscopic factors. In the neutron seniority coupling scheme, we neglect the protons completely and assume that the ground states have a pure $(f_{7/2}{}^n)$ configuration with neutron seniority $v=0$, while the first 2+, 4+, and 6+ states are $(f_{7/2}{}^n)J$ with $v=2$. Using these assumptions, Bassani *et al.*[45] have given the spectroscopic factors expected for the (p,t) reaction, which is the inverse of the (t,p) reaction. For the ground-state transition in even-even isotopes, the spectroscopic factor is

$$S_0=n(2j+3-n)/2(2j+1). \quad (4.3)$$

For the $L=J\neq0$ transitions to the excited states with $v=2$, it is

$$S_L=n(n-2)(2L+1)/(2j-1)(2j+1). \quad (4.4)$$

Here, n is the number of neutrons in the subshell j in the target. If the (t,p) reaction can be viewed as the pickup of a pair of neutron holes, the same spectroscopic factors should apply, provided n is taken to be the number of *vacancies* in the j subshell of the target. Hence $n=8$ for ^{40}Ca and $n=4$ for ^{44}Ca.

Using Eq. (4.3), we find that the cross-section ratio $\sigma(^{46}\mathrm{Ca})/\sigma(^{42}\mathrm{Ca})$ should be $\frac{3}{2}$ for the ground-state transitions. The observed ratio, 1.45 ± 0.15, agrees within experimental error. This ratio was determined from the integrated cross sections, rather than from the 10.3° differential cross sections, as the ratio of the latter is sensitive to the slight differences in shape between the two angular distributions.

For the $L\neq0$ transitions, Eq. (4.4) predicts the cross-section ratio to be $\frac{1}{6}$. This is within experimental error of the measured ratio, 0.159 ± 0.025, for the transitions to the first 4+ states of ^{46}Ca and ^{42}Ca, assuming that the 4+ assignment is correct for the 2.578-MeV state in ^{46}Ca. If, as predicted, the 6+ state of ^{46}Ca is populated only one-sixth as strongly as is the 3.186-MeV 6+ state of ^{42}Ca, we would be unable to identify the former, which is consistent with the fact that we failed to do so. However, the cross-section ratio for the first 2+ states is 0.51 ± 0.10, about three times the value predicted by Eq. (4.4).

It is possible that some or all of the levels involved show some collective-vibrational character, which could account for the enhanced $L=2$ strength observed for the ^{44}Ca(t,p) reaction, since the matrix element for a (t,p) transition to a phonon state is expected to be a maximum in the middle of a shell.[1,3] In the vibrational model, the first excited state is interpreted as a one-phonon state and the 0+, 4+, and second 2+ states are interpreted as a two-phonon triplet. The "center of gravity" of the triplet should be at twice the excitation energy of the one-phonon state. In ^{42}Ca, the triplet is at 2.52 MeV, in disagreement with the predicted energy of 3.05 MeV. In ^{46}Ca, on the other hand, the triplet is at 2.78 MeV, in surprisingly good agreement with the predicted value of 2.69 MeV. This agreement may be partly fortuitous, as the states of interest exhibit evidence of nonvibrational character. For example, from the ^{46}K decay studies, the crossover/cascade ratio for the deexcitation of the 3.022-MeV 2+ state was found to be about 2. For true vibrational states, the crossover transition would be a two-phonon transition and, hence, highly hindered.

Two-Neutron Configuration Energies

Qualitatively, the stronger transitions observed in the ^{40}Ca(t,p) reaction appear to fall in a pattern roughly consistent with the simple "single-pair" interpretation of the (t,p) reaction that was discussed in the introduction. We assume that the wave functions of the strongly excited states have large components corresponding to two-neutron configurations outside an undisturbed ^{40}Ca core. Such configurations may mix with other types of excitation, with the result that the (t,p) strength is spread over several states, but we neglect mixing of the two-neutron configurations with one another.

According to this interpretation, the ground state and low-lying, strongly populated excited states are assigned to the $(f_{7/2}{}^2)$ configuration. The 2.751-MeV (4+) and 3.186-MeV (6+) states are interpreted as containing most of the $(f_{7/2}{}^2)$ $L=4$ and $L=6$ strengths, respectively, while the $(f_{7/2}{}^2)$ $L=2$ strength is shared between the 2+ states at 1.523 and 2.423 MeV. This allocation exhausts the possibilities of the $(f_{7/2}{}^2)$ configuration; hence, we find no strongly excited levels in the region immediately above the 3.186-MeV level.

We now attempt to estimate the location of the strongly populated levels corresponding to excited two-neutron configurations by considering their separation energies. The two-neutron separation energies for even-even nuclei in their ground state, $S_{2n}{}^0$, are larger than twice the one-neutron separation energies of adjacent odd-A nuclei, because the two neutrons removed are coupled to zero spin, which provides them with an "extra" stability, the pairing energy. This energy is responsible for the familiar odd-even mass difference. However, the pairing stability is lost if the two neutrons are coupled to $J\neq0$. We will therefore assume that, in an even-even nucleus of mass number $A+2$, two neutrons in the configuration $(j_1,j_2)J\neq0$ will each be bound about as tightly as is a single neutron of the nucleus $A+1$ when in the same orbital j_1 or j_2. We therefore write

$$S_{2n,A+2}(j_1j_2,J\neq0)\approx S_{n,A+1}(j_1)+S_{n,A+1}(j_2), \quad (4.5)$$

whether j_1 is or is not equal to j_2. The expected excitation energy is then given by

$$E(j_1j_2,J\neq0)=S_{2n}{}^0-S_{2n}(j_1j_2,J\neq0)$$
$$\approx S_{2n}{}^0-S_n(j_1)-S_n(j_2), \quad (4.6)$$

[45] G. Bassani, N. M. Hintz, and C. D. Kavaloski, Phys. Rev. **136**, B1006 (1964).

where the subscripts $A+1$ and $A+2$ have been dropped. If $j_1=j_2=j$ and $J=0$, the appropriate pairing energy $P(j^2,0+)$ must be added to the excited configuration two-neutron separation energies:

$$E(j^2,0+)\approx S_{2n}{}^0-2S_n(j)-P(j^2,0+). \qquad (4.7)$$

We will estimate $P(j^2,0+)$ from the odd-even mass difference of isotopes in the mass region A', where the j subshell is being filled; thus,

$$P(j^2,0+)\approx S_{2n,A'+2}{}^0(j^2)-2S_{n,A'+1}{}^0(j). \qquad (4.8)$$

The model described above ignores residual interactions other than pairing. Predictions based upon the model are expected to be in error by at least a few hundred keV for this reason alone. Any failure of our earlier assumption that the "active" two-neutron configurations do not mix with one another will perturb the energies still further. In particular, strongly collective states will be found at much lower energies than are predicted by Eq. (4.6) for any of their component configurations.

In ^{42}Ca, $S_{2n}{}^0=19.83$ MeV, while $S_n{}^0=S_n(f_{7/2})$ in ^{41}Ca is 8.36 MeV.[26] The ^{40}Ca$(d,p)^{41}$Ca reaction measurements indicate that the unperturbed $2p_{3/2}$ and $2p_{1/2}$ single-particle orbitals lie, respectively, about 2.1 [46,47] and 4.1 MeV[46] above the $f_{7/2}$ orbital, giving $S_n(p_{3/2})\approx 6.26$ MeV and $S_n(p_{1/2})\approx 4.26$ MeV. We estimate the pairing energy $P(p_{3/2}{}^2,0+)$ from the one-neutron and two-neutron separation energies of ^{49}Ca and ^{50}Ca, respectively, which are 5.15 [48] and 11.50 MeV,[30,49] giving $P(p_{3/2}{}^2,0+)\approx 11.50-10.30=1.20$ MeV.

The $(f_{7/2}p_{3/2})$ configuration may be coupled to construct states having spins of 2+, 3+, 4+, and 5+; only the natural parity states 2+ and 4+ are expected to be identifiable in the (t,p) reaction. Equation (4.6) gives $E(f_{7/2}p_{3/2},J)\approx 19.83-8.36-6.26=5.21$ MeV, which is as close as expected to the observed strongly excited 2+ states at 4.448, 4.757, and 4.869 MeV (centroid = 4.71 MeV) and the 4+ states as 5.011 and 5.471 MeV (centroid = 5.24 MeV).

For the $(p_{3/2}{}^2)$ 0+ state, Eq. (4.7) yields $E(p_{3/2}{}^2,0+)\approx 19.83-12.52-1.20=6.11$ MeV, which is gratifyingly close to the strongly excited 5.863-MeV 0+ state and its weaker companion at 6.015 MeV (centroid = 5.90 MeV). Likewise, Eq. (4.6) yields $E(p_{3/2}{}^2,2+)\approx 7.31$ MeV, to be compared with the strongly excited 2+ states observed at 6.920 and 7.385 MeV (centroid = 7.18 MeV).

It is to be noted that the agreement between the estimated configuration energies and the observed states was not obtained by selecting some transitions of the appropriate L value and omitting others. For each L value, the states included contained the great majority of the observed total strength, with no strong transitions omitted. Likewise, all two-neutron configurations expected below 8 MeV have been accounted for, with the single exception of the $(f_{7/2}p_{1/2})$ 4+ configuration, predicted to lie at about 7.21 MeV. This exception is scarcely disturbing. Comparison with the 5.011- and 5.471-MeV states suggests that the cross section would not be very large, especially if the strength is fragmented, while the high density of levels, intense interference from the ^{12}C$(t,p)^{14}$C$_0$ transition, and our limited resolution have permitted us to identify only the most conspicuous transitions at this excitation energy.

In general, agreement is remarkably good, in view of the extreme simplicity of the model and its total lack of adjustable parameters.

To some extent, the pattern of the more strongly excited levels of ^{46}Ca can be accounted for in the same manner. In ^{46}Ca and ^{45}Ca, respectively, S_{2n} and $S_n(f_{7/2})$ are 17.82 and 7.42 MeV.[26] The $p_{3/2}$ orbital in ^{45}Ca has not been located; we assume it to be 2.1 MeV above the ground state, giving $S_n(p_{3/2})=5.32$ MeV. Using these data, Eq. (4.6) gives $E(f_{7/2}p_{3/2},J)=5.08$ MeV, somewhat higher than the observed strongly excited 2+ and 4+ states at 4.433 and 4.754 MeV, respectively. Equation (4.7) predicts $E(p_{3/2}{}^2,0+)$ to be 5.98 MeV, which is reasonably close to the observed strong 0+ state at 5.617 MeV (if the 5.328-MeV state is included, the centroid is 5.58 MeV). Finally, Eq. (4.6) predicts $E(p_{3/2}{}^2,2+)$ to be 7.18 MeV, which is considerably higher than the observed strong 2+ states at 6.275 and 6.386 MeV (centroid = 6.34 MeV). There is, however, considerable $L=2$ strength at higher excitation energies, some of which may represent fragments of the $(p_{3/2}{}^2)$ 2+ strength. It is equally possible that mixing with configurations such as $(p_{3/2}p_{1/2})$ 2+ has resulted in sizeable perturbations.

Qualitatively, then, our model gives a good description of the pattern of the strong transitions in the ^{44}Ca(t,p) reaction. The quantitative fit to the energies is somewhat poorer than it was for the ^{40}Ca(t,p) reaction. In particular, the actual levels are shifted to somewhat lower energies than are predicted.

The ^{43}Ca$(d,p)^{44}$Ca measurements (using $E_d=8.532$ MeV) recently reported by Bjerregaard and Hansen[50] support our conclusions as to the location of the $(f_{7/2}{}^{n-1}p_{3/2})$ states of the even-A calcium isotopes of mass number $40+n$. They expressed their results in terms of the spectroscopic strength

$$S'=[(2J_f+1)/(2J_i+1)]S(J_i+j\rightarrow J_f).$$

For (d,p) transitions of a given l and j, S' is expected to sum to the number of (l,j) neutron holes in the target.[51] They found relatively little $l_n=1$ strength at low excita-

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tion energies (total strength ~0.07 below 3.9 MeV, $\lesssim$0.1 between 3.9 and 4.6 MeV), while a total $l_n=1$ spectroscopic strength ~4.2 was found for the region between 4.6 and 6.2 MeV.

If, as is likely, the ^{43}Ca ground-state wave function is predominantly $(f_{7/2}{}^3)$, the ^{43}Ca(d,p) reaction is actually a much better tool for testing our method of locating the unperturbed $(f_{7/2}p_{3/2})$ configuration energy than is the (t,p) reaction. The (d,p) reaction can reach all components, not just those with natural parity, and configuration mixing will not alter the $l_n=1$ centroid. The measurements reported in Ref. 50 did not extend above 6.2 MeV and some $p_{3/2}$ strength may have been missed, while some $p_{1/2}$ strength may have been included. However, the total $l_n=1$ strength observed was 4.3, in good agreement with the value to be expected for four $2p_{3/2}$ neutron holes, and none of the observed $l_n=1$ transitions showed the deep dip in the backward hemisphere that has been found to be characteristic of $2p_{1/2}$ transitions on even targets.[42] It is therefore probable that the measurements reported in Ref. 50 do give a good representation of the $2p_{3/2}$ strength function. In ^{44}Ca, $S_{2n}{}^0=19.06$ MeV while in ^{43}Ca, $S_n(f_{7/2})=7.93$ MeV[26] and $S_n(p_{3/2})=5.74\pm.09$ MeV[52]; Eq. (4.6) yields $E(f_{7/2}p_{3/2})=5.39$ MeV. The observed $l_n=1$ centroid is 5.40 MeV.

For the sake of completeness, we consider also the published data on the ^{46}Ca(t,p) and ^{48}Ca(t,p) reactions.[30,49] For the latter, the first and second excited states were found to be at 1.025 and 2.999 MeV, respectively, and both were populated by strong $L=2$ transitions.[49] From the ^{48}Ca$(d,p)^{49}$Ca data,[48] $S_n(p_{3/2})=5.15$ MeV and $S_n(p_{1/2})=3.12$ MeV. The ^{48}Ca$(t,p)^{50}$Ca data gave $S_{2n}{}^0=11.50$ MeV.[30,49] Equation (4.6) then gives $E(p_{3/2}{}^2, 2+)=1.20$ MeV and $E(p_{3/2}p_{1/2}, 2+)=3.23$ MeV, in reasonable agreement with the observed energies.

Hinds *et al.*[30] have quoted results for the $L=0$ transitions observed in the ^{46}Ca$(t,p)^{48}$Ca reaction. They observed strongly excited 0+ states at 4.28 and 5.46 MeV, with the upper state being excited between two and three times as strongly as the lower. If these two states represent most of the $(p_{3/2}{}^2)$ 0+ strength, the centroid is at about 5.13 MeV. From Ref. 26, $S_{2n}{}^0=17.221$ MeV and $S_n(f_{7/2})=7.281$ MeV. Bjerregaard *et al.*[53] have studied the ^{46}Ca(d,p) reaction, with $E_d=10.129$ MeV. A level at 2.013 MeV was excited with a very strong $l_n=1$ transition, identified as $p_{3/2}$ by the absence of a back-angle dip. All other $l_n=1$ transitions up to 4.4 MeV were identified as $p_{1/2}$ by the presence of back-angle dips, with the possible exception of a level at 4.012 MeV which was very weakly excited (strength $\lesssim 2\%$ that of the 2.013-MeV level, according to Figs. 2 and 4 in Ref. 53). Back-angle data were not obtained

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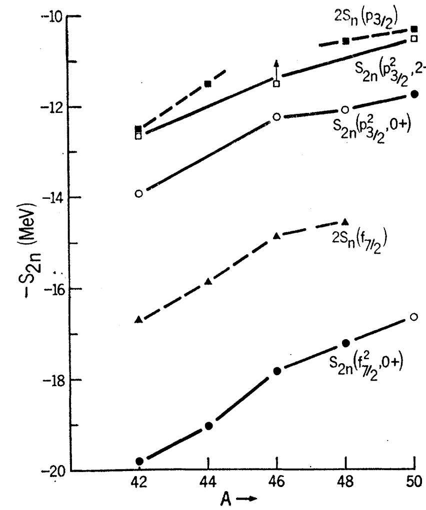

FIG. 6. Two-neutron separation energies $S_{2n}(f_{7/2}{}^2, 0+)$, $S_{2n}(p_{3/2}{}^2, 0+)$ and $S_{2n}(p_{3/2}{}^2, 2+)$ for the even-A calcium isotopes. The quantities $2S_n(f_{7/2})$ and $2S_n(p_{3/2})$ for the $A-1$ isotopes are also shown. Points are connected by straight lines as a visual aid only.

for $l_n=1$ transitions to higher excited states, but comparison with the ^{40,42}Ca(d,p) reactions[46,52] suggest that these are much more likely to be $p_{1/2}$ than $p_{3/2}$ fragments. It therefore appears that the 2.013-MeV level represents essentially all of the $p_{3/2}$ strength, giving $S_n(p_{3/2})=5.27$ MeV. Equation (4.7) then predicts $E_{2n}(p_{3/2}{}^2, 0+)=5.48$ MeV, which is not far from the observed 0+ centroid.

Two-neutron separation energies for the even-A calcium isotopes are displayed in Fig. 6 for the configurations $(f_{7/2}{}^2)$ 0+, $(p_{3/2}{}^2)$ 0+, and $(p_{3/2}{}^2)$ 2+. The points are connected by straight lines as a visual aid only. The $(f_{7/2}p_{3/2})$ configuration is omitted, due to the limited amount of data available and the fact that only the 2+ and 4+ members are observable in the (t,p) reaction. Also shown are the quantities $2S_n(f_{7/2})$ and $2S_n(p_{3/2})$ for the isotopes of mass number A-1; these data are connected by dashed lines. The indicated values of $S_n(f_{7/2})$, $S_n(p_{3/2})$, $S_{2n}(f_{7/2}{}^2, 0+)$ for $A\leq 48$, and $S_{2n}(p_{3/2}{}^2, 0+)$ for $A=50$, portrayed by solid symbols, are derived from ground-state masses and (d,p) data. The values of $S_{2n}(p_{3/2}{}^2, 2+)$, $S_{2n}(p_{3/2}{}^2, 0+)$ for $A\leq 48$, and $S_{2n}(f_{7/2}{}^2, 0+)$ for $A=50$, all portrayed by open symbols, are based upon our interpretation of the (t,p) data. The quantities derived from our interpretation of the (t,p) reaction are seen to show almost as much regularity of behavior, and to follow much the same trends, as do the other quantities, which are not subject to the ambiguities of our interpretation.

To summarize, our interpretation of the stronger (t,p) transitions is based upon two essentially independent assumptions. First, we assume that the unperturbed energy of a two-neutron configuration (with $J\neq 0$) is equal to the sum of the corresponding unperturbed single-particle energies, with the zero of energy taken to be the odd-A mass surface. Secondly, we assume that the two-neutron configurations do not mix heavily with one another, although mixing with states involving target excitation is permitted.

The second assumption can have, at most, only a limited range of validity. When the structure of the target isotope is less simple than are the calcium isotopes, or the single-particle orbitals are closer together, much more configuration mixing will occur. The expected effects include the lowering of some states below any of the predicted two-particle configuration energies, and coherence effects may enhance the intensities of the lower states at the expense of the upper. This may be happening even in the calcium region. Our model would predict a strongly excited 0+ state in ^{50}Ca corresponding to $(p_{1/2}^2)$ 0+ at 4–5 MeV, yet no such state has been found below 5.6 MeV.[30] A possible explanation is that the $(p_{3/2}^2)$ 0+ and $(p_{1/2}^2)$ 0+ states are heavily mixed and that the ground-state transition contains almost the entire (t,p) $L=0$ strength for both.[30] The regularities shown in Fig. 6 then suggest that either the same is true for the strongly excited 0+ states in the lighter isotopes, or else that the amount of mixing increases smoothly with A. In support of the latter hypothesis, we may note that the $L=0$ strengths we have assigned to the $(p_{3/2}^2)$ 0+ configurations, as estimated from the 10.3° cross sections, are approximately in the ratio of 1:1.6:2.2 in ^{42}Ca, ^{46}Ca, and ^{50}Ca, respectively. However, quantitative interpretation of this increase in intensity with increasing A must await DWBA calculations capable of reliably reproducing the Q dependence of the (t,p) cross sections.

Our method of estimating the unperturbed energies of a two-neutron configuration coupled to a given value of $J\neq 0$ in even-even nuclei can be valid only insofar as the residual interactions do not split the states of different J very widely. Although the matter is of some interest, its further evaluation is beyond the scope of the present paper.

At the very least, we believe that our (t,p) measurements and other relevant data strongly indicate that neutron configurations of the type $[(f_{7/2}^{n-2})_{J_1=0}f_{7/2}p_{3/2}]J$ and $[(f_{7/2}^{n-2})_{J_1=0}p_{3/2}^2]J$ are not the major components of any of the states of ^{42}Ca and ^{46}Ca at excitation energies below 4.4 MeV. The ^{43}Ca(d,p) reaction studies of Ref. 50 imply that the configuration $[(f_{7/2}^2)_{J_1=0}f_{7/2}p_{3/2}]J$ is also ruled out as the major component of the states of ^{44}Ca below 4.6 MeV. Configurations of the type $[(f_{7/2}^{n-2})_{J_1\neq 0}f_{7/2}p_{3/2}]J$ and $[(f_{7/2}^{n-2})_{J_1\neq 0}p_{3/2}^2]J$ are not ruled out as the major components of low-lying states of ^{44}Ca and ^{46}Ca, since these would not be strongly excited in either the (t,p) or the (d,p) reaction. However, it is not clear why configurations of this type should lie so much lower than the $J_1=0$ configurations. In general, it seems most reasonable to explain the "extra" states of the even-mass calcium isotopes in terms of core excitations which mix in varying degrees with the $(f_{7/2}^n)J$ configurations, with $p_{3/2}$ admixtures present only as minor components of the wave functions.

Our interpretation differs somewhat from some theoretical descriptions[15,19,20] of the even-A calcium isotopes, which emphasize mixing of the various $(f_{7/2}^{n-m}p_{3/2}^m)$ configurations, with $m=0$, 1, and sometimes 2. Mixing with states of the ^{40}Ca core is considered only secondarily, if at all, especially for $A>42$. The exact results obtained depend upon how many excited configurations are included, e.g., whether $(f_{7/2}^{n-2}p_{3/2}^2)$ configurations are treated. We attempt no detailed comparison with our measurements, partly because the wave functions have not been published in most cases. However, at least some [15,19] of these treatments require inclusion of the $[(f_{7/2}^{n-2})_{J_1=0}f_{7/2}p_{3/2}]J$ or $[(f_{7/2}^{n-2})_{J_1=0}p_{3/2}^2]J$ configurations as the major components of states at energies $\lesssim 3$ MeV, which is difficult to reconcile with the results described in this paper.

Core States

In the region of the states we have ascribed to the $(f_{7/2}^2)$ configuration, there is one more 0+ state and one more 2+ state in both ^{42}Ca and ^{46}Ca than can be accounted for by the $(f_{7/2}^2)$ configuration alone. The nature of these states in ^{42}Ca has received considerable discussion. One possibility is that one or both correspond to four-particle two-hole neutron configurations such as $(d_{3/2}^{-2}f_{7/2}^4)$. If so, they should be strongly excited in the ^{44}Ca(p,t) reaction. However, the intensity pattern observed for this reaction[54] was qualitatively similar to that observed in the ^{40}Ca(t,p) reaction: The transition to ground state is at least an order of magnitude stronger than that to the 1.836-MeV 0+ state, while the intensity of the transition to the 1.523-MeV 2+ state exceeded that to the 2.423-MeV 2+ state by a lesser factor.

Bjerregaard *et al.*[55] report that these 2+ states are excited with approximately equal spectroscopic factors in the ^{43}Ca(d,t) reaction. They suggest that the ^{43}Ca ground state has a fairly pure $(f_{7/2}^3)$ configuration, while the 2+ states in ^{42}Ca are composed of roughly equal mixtures of $(f_{7/2}^2)$ and $(f_{7/2}p_{3/2})$. However, the evidence discussed in the preceding subsection indicates that there are considerable difficulties involved in any attempt to explain such low-lying states by means of the $(f_{7/2}p_{3/2})$ configuration.

In all probability, it will not be possible to explain the ^{42}Ca states at 1.836 and 2.423 MeV in terms of neutron configurations alone. Federman[18] has suggested that the lower-mass calcium isotopes should have a set of deformed states, derived by exciting two protons from the 1d-2s shell to the 1f-2p shell and recoupling to obtain an intrinsic deformation. Bertsch[21] and Gerace

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and Green[22] have proposed similar models. The 1.836- and 2.423-MeV states are then interpreted as being the 0+ and 2+ members of the rotational band built upon this deformed configuration. The theory predicts that there will be some mixing between the shell-model and the deformed states, with the mixing being large for the 2+ states and smaller for the 0+ states. Since neither the (t,p) nor the (p,t) interactions can cause proton excitation, only the shell-model components of the wave functions can contribute to either the (t,p) or the (p,t) reaction amplitudes, at least in first approximation. Consequently, we would expect the intensity patterns for these states to be much the same for the two reactions, with the difference between the intensities of the transitions to the 2+ levels being smaller than the difference between the 0+ transition intensities. Qualitatively, the experimental results are in good agreement with these expectations. On the other hand, it is less clear how to interpret the reported equality of the spectroscopic factors for the ^{43}Ca(d,t) transitions to the 2+ states, although the expected $d_{3/2}^{-2}f_{7/2}^{2}$ amplitude in the proton part of the ^{43}Ca wave function could lead to enhanced population of the second 2+ state at the expense of the first.

In ^{46}Ca, it has been suggested[19,43] that the major component of the 3.022-MeV 2+ state is the configuration $[(f_{7/2}^{4})_{J_1=0}f_{7/2}p_{3/2}]2+$. This assignment leaves unaccounted for the large $L=2$ strength observed above 4 MeV, as was true with the ^{40}Ca(t,p) reaction if the $(f_{7/2}p_{3/2})$ configuration is invoked to explain the second 2+ state of ^{42}Ca. Once again, other types of excitation are probably involved. The situation invites interpretation in terms of interacting systems of spherical and deformed states, as was suggested for ^{42}Ca. However, the "deformed" states are excited in the (t,p) reaction somewhat more strongly relative to the "spherical" states than was the case in ^{42}Ca. The excitation ratio $\sigma(0_2+)/\sigma(0_1+)$ is 0.087 ± 0.013 for ^{42}Ca and 0.20 ± 0.02 for ^{46}Ca; the ratio $\sigma(2_2+)/\sigma(2_1+)$ is 0.37 ± 0.05 for ^{42}Ca and 0.72 ± 0.1 for ^{46}Ca. If we assume that only the spherical $(f_{7/2}^{n})$ components can contribute to the (t,p) reaction amplitude, the mixing between the spherical and the deformed states must be greater in ^{46}Ca than in ^{42}Ca, which conflicts with some theoretical expectations.[20,22] Other assumptions are possible; for example, part of the (t,p) reaction amplitude of the ^{46}Ca deformed states may be due to small admixtures of spherical configurations involving $p_{3/2}$ orbitals, or the ^{44}Ca ground-state wave function may contain a larger broken-shell component than does that of ^{40}Ca.

V. SUMMARY AND CONCLUSIONS

A considerable number of ^{40}Ca$(t,p)^{42}$Ca and ^{44}Ca$(t,p)^{46}$Ca transitions have been identified. It was found that L values could be assigned to the stronger transitions by comparison of the observed angular distributions with the predictions of DWBA theory. As has been noted previously,[2] the angular distributions for a given value of L are sufficiently regular to permit assignment of L values by comparison with the angular distributions observed for (t,p) transitions to states of known spin and parity.

Qualitatively, the over-all pattern of the (t,p) transitions observed is consistent with a model emphasizing mixing of the two-neutron configurations, which contribute actively to the (t,p) reaction amplitude, with "core" states, which do not contribute strongly. Mixing of the "active" two-neutron configurations with each other is not treated as a major effect; although some such mixing must occur, it need not be invoked in order to gain qualitative understanding of much of the data. When interpreted in this fashion, our results and other relevant data indicate that states of ^{42,44,46}Ca having large components corresponding to the configurations $[(f_{7/2}^{n-2})_{J_1=0}f_{7/2}p_{3/2}]J$ and $[(f_{7/2}^{n-2})_{J_1=0}p_{3/2}^{2}]J$ lie at excitation energies above 4.4 MeV. This description is to be contrasted with a number of theoretical treatments of the calcium isotopes, which emphasize mixing of the various configurations involving $f_{7/2}$ and $p_{3/2}$ neutrons, relegate states of the ^{40}Ca core to a secondary role, and generally require assignment of $[(f_{7/2}^{n-2})_{J_1=0}f_{7/2}p_{3/2}]J$ or $[(f_{7/2}^{n-2})_{J_1=0}p_{3/2}^{2}]J$ configurations as the major component of certain states of the even-A isotopes at excitation energies $\lesssim 3$ MeV.

ACKNOWLEDGMENTS

We wish to thank Larry D. F. Allen for preparing the calcium targets, the Van de Graaff operating staff for conducting the bombardments, Dr. Edward R. Flynn for guidance with DWBA calculations, Jean Larsen for assistance with the reduction of the data, and Margaret Plageman, Barbara Ray, and Doris Jackson for typing drafts and manuscript. We express our thanks to Dr. George A. Cowan for support and encouragement during the course of this work.