Angular correlation and decay mode measurements in ^{41}Ca using the ^{42}Ca(^{3}He, $\alpha\gamma$)^{41}Ca reaction*

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γ-ray angular correlations have been measured for the 2.010, 2.960, 3.200, 3.526, 3.740, and 4.090 MeV states in ^{41}Ca using the ^{42}Ca(^{3}He, $\alpha\gamma$)^{41}Ca reaction. An $E3$ strength of $(1.5^{+0.9}_{-0.7})$ Weisskopf units has been determined for the 2.010 → 0 MeV transition from the measured mixing ratio, $\delta = -0.095 \pm 0.022$, and a previous lifetime measurement. The decay scheme and angular correlations imply a spin assignment of $J^{\pi} = \frac{3}{2}^{+}$ for the 3.526 MeV state and strongly suggest that $J^{\pi} = \frac{3}{2}^{+}$ for the 3.740 MeV state and $J^{\pi} = \frac{5}{2}^{+}$ for the 4.090 MeV state. Decay schemes have been measured for four $T = \frac{3}{2}$ states in ^{41}Ca at 5.814, 6.820, 7.146, and 8.54 MeV. Analog to antianalog state transitions have been observed from the 5.814, 6.820, and 7.146 MeV levels. Such a transition was not reported in a previous study of the decay of the 5.814 MeV state. The 8.54 MeV state decays primarily by neutron emission but has a 1 to 3% γ-decay branch. In addition, the ^{41}K(^{3}He, t)^{41}Ca reaction was used to verify the $T = \frac{3}{2}$ assignment for the 5.814 MeV state and the ^{40}Ca($d, p\gamma$)^{41}Ca reaction was used in the study of the 3.731-3.740 MeV doublet.

[NUCLEAR REACTIONS ^{42}Ca(^{3}He, α), $E = 18$ MeV; ^{41}K(^{3}He, t), $E = 18$ MeV; ^{40}Ca(d, p), $E = 11$ MeV; measured coinc. γ spectrum, $I_{\gamma}(\theta\gamma)$. ^{41}Ca deduced δ, $B(\Lambda)$, J, branching ratios.]

I. INTRODUCTION

The shell closure at $Z = N = 20$ has been the subject of considerable experimental and theoretical work in recent years. In particular, the possible presence[1] of low-lying deformed states of a many-particle many-hole nature has led to intensive study of nuclei in this region. The nucleus ^{41}Ca is of interest in this connection for a number of reasons. Because of its accessibility to both single-nucleon pickup[2-4] and stripping[5-8] reactions, much is known about the overlap of states in ^{41}Ca with those in both ^{40}Ca and ^{42}Ca. This information is clearly useful in investigating single-particle degrees of freedom. In addition, the study of electromagnetic transitions in ^{41}Ca[9-18] has enabled additional information to be accumulated concerning possible collective components of the wave functions. The recent availability of a ^{41}Ca target has led to the location of much of the collective strength in this nucleus using α-particle inelastic scattering.[19]

The present work was undertaken with a view towards extending our knowledge of the electromagnetic properties of levels in ^{41}Ca. In particular, the determination of the ($E3/M2$) mixing ratio for the transition from the lowest $\frac{3}{2}^{+}$ state to the ground state gives some indication of the collective strength present in the $\frac{3}{2}^{+}$ level. [The strength is too small to be observed in the (α, α') experiments referred to above.] In addition, information has been obtained which restricts spin-parity hypotheses for several other levels up to 4.727 MeV. Finally, the electromagnetic decays of four $T = \frac{3}{2}$ levels have been studied. These states, which lie at excitation energies between 5.814 and 8.54 MeV, are the isobaric analogs of low-lying states in ^{41}K. Consequently, they have relatively simple configurations and it is possible to make some progress towards an understanding of their decays from a theoretical point of view. In particular, these states can decay by $\Delta T = 1$, $M1$ transitions which have been calculated theoretically by Maripuu[20] and others within the framework of the shell model. Measurement of the branching ratios of these states thus gives information both about the analog states and the low-lying $T = \frac{1}{2}$ states to which they decay.

In the present work the electromagnetic decays of levels in ^{41}Ca were studied by measuring the angular correlations of γ rays in coincidence with α particles populating states in ^{41}Ca via the ^{42}Ca(^{3}He, α)^{41}Ca reaction. In one case the ^{40}Ca($d, p\gamma$)^{41}Ca reaction was used. A singles measurement of the ^{41}K(^{3}He, t)^{41}Ca reaction was also performed for excitation energies near 6 MeV. The experimental arrangement and the main considerations leading to the choices of reaction,

TABLE I. Results of angular correlation measurements and the mixing ratios determined from them.

E_I	E_F	J_I	J_F	A_2	A_4	δ [a]
2.010	0	$\frac{3}{2}$	$\frac{7}{2}$	0.050 ± 0.017	-0.019 ± 0.025	-0.095 ± 0.022
2.960	0	$\frac{7}{2}$	$\frac{7}{2}$	0.173 ± 0.030	-0.003 ± 0.044	0.307 ± 0.033
3.200	0	$\frac{5}{2}$	$\frac{7}{2}$	-0.153 ± 0.139	0.136 ± 0.209	0.001 ± 0.090
						$7.64^{+20.58}_{-3.27}$
		$\frac{7}{2}$	$\frac{7}{2}$			$0.597^{+0.194}_{-0.166}$
						$-3.99^{+1.60}_{-6.45}$
		$\frac{9}{2}$	$\frac{7}{2}$			-0.094 ± 0.067
						$9.10^{+18.73}_{-3.70}$
3.526	2.670	$\frac{3}{2}$	$\frac{1}{2}$	-0.100 ± 0.135	0.168 ± 0.200	-0.216 ± 0.072
						$3.11^{+0.90}_{-0.59}$
3.740	2.010	$\frac{3}{2}$	$\frac{3}{2}$	0.164 ± 0.048	-0.002 ± 0.071	0.148 ± 0.032
						$-9.38^{+2.20}_{-4.11}$
3.740	2.605	$\frac{3}{2}$	$\frac{5}{2}$	-0.130 ± 0.056	-0.028 ± 0.084	-0.030 ± 0.047
						$5.38^{+2.06}_{-1.18}$
4.090	2.010	$\frac{3}{2}$	$\frac{3}{2}$	-0.126 ± 0.047 [b]	0.016 ± 0.071 [b]	0.458 ± 0.100
						$6.07^{+3.89}_{-1.73}$
		$\frac{5}{2}$	$\frac{3}{2}$			-0.060 ± 0.046
4.090	0	$\frac{3}{2}$	$\frac{7}{2}$	-0.143 ± 0.055	-0.150 ± 0.084	-0.298 ± 0.054
						$3.04^{+0.60}_{-0.44}$
		$\frac{5}{2}$	$\frac{7}{2}$			-0.013 ± 0.039
						$8.50^{+4.08}_{-2.10}$

[a] When two values of δ are consistent with the correlation and spin hypothesis, they are listed on successive lines.

[b] Correlation for the unresolved sum of the 4.09 → 2.01 MeV and 2.01 → 0 MeV transitions.

geometry, etc., are discussed in Sec. II. The data reduction and analysis procedure are also described in Sec. II, and the results and conclusions are presented in Sec. III.

II. EXPERIMENTAL METHOD AND DATA ANALYSIS

A considerable amount of experimental information already exists concerning the radiative decays of levels in ^{41}Ca. McIntyre[13] has performed an extensive study of the ^{40}Ca$(d,p\gamma)^{41}$Ca reaction for levels below $E_x = 4.5$ MeV. Additional work using the ^{39}K$(^3$He$,p\gamma)^{41}$Ca [14] and other reactions[9-11,15-18] has also been reported. Since two of the principal motivations of the present work were to assign spins in a model-independent way and to measure electromagnetic multipole mixing ratios, it was desirable to prepare the initial state in such a way that its alignment was known *a priori*. The ^{42}Ca$(^3$He$,\alpha)^{41}$Ca reaction was chosen for this reason. If the α particles in this reaction are detected along the beam direction, then in the residual nucleus ^{41}Ca only the $|M| = \frac{1}{2}$ magnetic substates can be populated. For comparison, if the ^{40}Ca$(d,p)^{41}$Ca reaction is used, both the $|M| = \frac{1}{2}$ and $|M| = \frac{3}{2}$ magnetic substates can be populated and an additional free parameter enters into the analysis of the measured angular correlations. Another advantage of the $(^3$He$,\alpha)$ reaction in the present experiment results from our interest in the $T = \frac{3}{2}$ states in ^{41}Ca. These states can be reached by direct single-neutron pickup from the $T = 1$ target ^{42}Ca, but are isospin-forbidden in first order in the (d,p) reaction since the ^{40}Ca$+d$ system has isospin $T = 0$.

The experiments reported here were all performed using the University of Pennsylvania zero degree spectrometer and associated angular correlation apparatus. The equipment has been described in the literature,[21] so only a brief outline will be presented here. Outgoing particles from a nuclear reaction were detected at 0° with respect to the beam by a solid-state position-sensitive detector located at the focus of a magnetic spectrometer. This arrangement combines good energy resolution with the large count rates obtained at forward angles from direct single-nucleon pickup. As a result of the small acceptance half angles of the spectrometer (1.75° and 3.5° in the vertical and horizontal planes, respectively) corrections to the alignment resulting from the finite size of the particle detector were judged to be negligible.

For the ^{42}Ca(^{3}He, α)^{41}Ca experiments, an 18 MeV ^{3}He^{++} beam from the University of Pennsylvania tandem accelerator was incident on a 100 μg/cm^2 target of Ca metal enriched to 94% in ^{42}Ca on a 50 μg/cm^2 carbon backing. The target was never exposed to the atmosphere. The same beam was utilized for the ^{41}K(^{3}He, t)^{41}Ca singles measurement; in that case the target consisted of ^{41}KCl of areal density 200 μg/cm^2 evaporated on a gold backing. The ^{40}Ca($d, p\gamma$)^{41}Ca measurements were performed with a 7 MeV deuteron beam and a natural calcium target of areal density 400 μg/cm^2 evaporated on a carbon backing. Protons from the ($d, p\gamma$) reaction were detected at 23° rather than 0° relative to the beam. γ rays were detected in time coincidence with particles using an array of four 7.6 $\times$10.2 cm NaI(Tl) crystals placed at angles of 90, 113, 136, and 159° with respect to the incident beam. γ rays were also detected in coincidence with particles from the 6.820 and 7.146 MeV states using a 65 cm^3 Ge(Li) detector placed at 90°. For each coincidence event the particle energy and position, γ-ray energy, time difference, and routing information were written onto magnetic tape for subsequent off-line analysis. In addition, various live displays were generated to monitor the progress of the experiment. Finally, the particle and γ singles spectra were sampled and stored using the same electronic circuitry as for the coincidence events. These spectra were useful for estimating the fractional radiative decay width in the case of unbound states as well as serving to monitor the stability of the over-all system.

Afterwards, the γ-ray coincidence spectra were accumulated by placing digital windows on the particle energy and momentum corresponding to a particular state in ^{41}Ca and on the time-difference spectrum. The same particle windows and a displaced equal-width time window were used to approximately subtract random coincidences from the γ spectra. The yield of a given γ ray at a given angle was usually obtained by summing all counts in the full-energy peak; in some cases the single- and double-escape peaks were included in the sum.

The experimental angular correlations were fitted to a series of even-order Legendre polynomials; the resulting normalized coefficients are listed in Table I as a summary of the experimental data. The coefficients presented have been corrected for the finite size of the γ detectors.

For purposes of obtaining spin assignments and multipole mixing ratios, the experimental angular correlations were directly compared with theoretical predictions generated by the computer program $M2$. The analysis procedure is described in more detail in a previous report[22] on angular correlation measurements on ^{39}Ca. The agreement between the predicted and measured correlations was quantified by calculating the normalized χ^2. For a given spin hypothesis, the full range of values of the γ-ray multipole mixing ratio δ was first scanned in discrete intervals. An iterative procedure was then used to determine the value of δ for which χ^2 achieves a local minimum and to

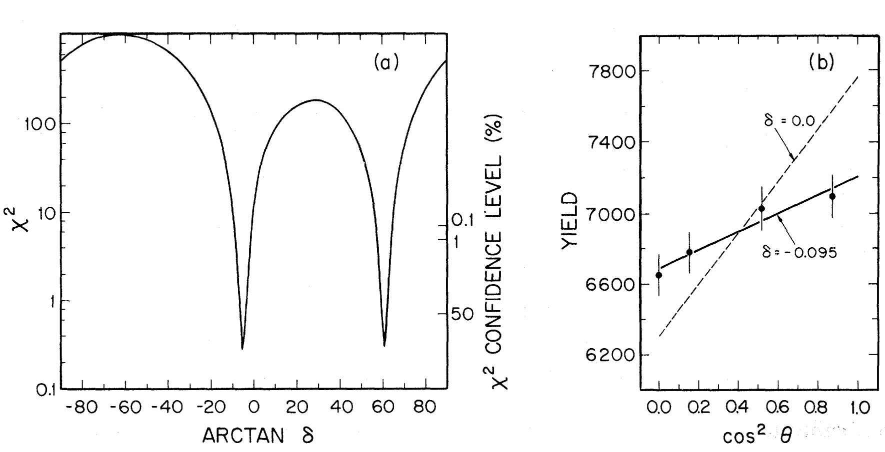

FIG. 1. The 2.010 → 0 MeV γ-ray angular correlation and the χ^2 fit to the data. Predicted angular correlations for the best-fit value of δ, and for $\delta = 0$, are shown for comparison.

estimate the uncertainty in δ.[23] The values of δ which are consistent with the experimental angular correlations and previously known spin restrictions are also presented in Table I. The phase convention defined by Rose and Brink[24] is used for δ.

III. RESULTS AND DISCUSSION

A. $T=\frac{1}{2}$ states

2.010 MeV level. The angular correlation of the 2.010 MeV γ ray from this state was measured simultaneously with that of the 1.943 and 2.010 MeV γ rays from the 2.670 MeV $\frac{1}{2}^+$ state. The isotropic angular correlation of the 2.670 MeV level was used to verify the isotropy of the system. Two independent measurements were made of the 2.010 MeV angular correlation. The correlation resulting from the combined statistics of the two measurements is shown in Fig. 1 along with the χ^2 fits. The best fit value of the mixing ratio is $\delta(E3/M2) = -0.095 \pm 0.022$. The values of δ obtained from the separate measurements agree well within this uncertainty. The predicted angular correlation for the best fit value of δ is shown as a solid line in Fig. 1(b) for comparison with the data. Although it is rejected at the 0.1% confidence level, the predicted angular correlation for a pure $M2$ decay is shown as a dashed line in the same figure just to indicate the nature of its deviation from the data.

The $E3$ strength of the $\frac{3}{2}^+ \rightarrow \frac{7}{2}^-$ transition is determined by this mixing ratio and the lifetime measurement of Holland and Lynch,[25] $\tau = 0.8 \pm 0.2$ nsec. These measurements yield a strength of $B(E3) = 150^{+90}_{-70}\ e^2\,\mathrm{fm}^6$ or $1.5^{+0.9}_{-0.7}$ Weisskopf units (W.u.). The effects of uncertainties in the lifetime and mixing ratio determinations were added in quadrature to estimate the uncertainty in the value of the transition strength. The small value of the mixing ratio does not significantly affect the $M2$ strength reported by Holland and Lynch.[25] The other possible value of mixing ratio which fits the measured correlation, $\delta = 1.78$, is unlikely because of the unreasonably large $E3$ strength of 125 W. u. that it would imply.

Kurath and Lawson[26] have treated the 2.010 MeV state as a $d_{3/2}$ hole coupled exclusively to the $J=0$, $T=1$ state of the core. They were able to explain most of the retardation of the $M2$ ground state transition strength of this level as an isospin cancellation effect without requiring significant admixtures of core-excited states. The $E3$ strength for the single particle transition

$$|f^2_{7/2}(J=0,\ T=1)d_{3/2}{}^{-1}\rangle_{J^\pi=3/2^+} \rightarrow |f_{7/2}{}^1\rangle_{J^\pi=7/2^-},$$

assuming bare nucleon charges, is about $\frac{1}{10}$ the experimental value.[27] However, the measured $E3$ strength is consistent with the 2p-1h picture because an assumption of reasonable octupole effective charges would raise the calculated strength to the experimental value.

If the lowest $\frac{3}{2}^+$ state were exclusively an $f_{7/2}$ particle weakly coupled to the 3^- state of the ^{40}Ca core, the ground state $E3$ transition strength of the $\frac{3}{2}^+$ state in ^{41}Ca could be equal[27] to that of the 3^- state in ^{40}Ca, which is 31 ± 3 W.u.[28]. The small effect on the 3^- state from Pauli principle blocking of some degrees of freedom by the extra nucleon was ignored in making this comparison. Hence, the measured $E3$ strength indicates a rather small, if any, admixture of this core-excited configuration.

A somewhat larger admixture of the core-excited configuration appears to be present in the 3.370 MeV $\frac{11}{2}^+$ state. This is suggested by the value of 4.5 ± 2.0 W.u. measured by Lieb *et al.*[18] for the ground state transition strength of this state.

2.960 MeV level. Seth *et al.*[29] have assigned $J^\pi = \frac{7}{2}^-$ to this state based on an $l=0$ angular distribution in the ^{43}Ca$(p,t)^{41}$Ca reaction. The experimental angular correlation implies an $(E2/M1)$ mixing ratio of $\delta = 0.307 \pm 0.033$ for the $2.960 \rightarrow 0$ MeV transition. The observation of a decay branch to this state from the 7.146 MeV $T=\frac{3}{2}$ state will be discussed with the latter state.

3.200 MeV level. Lynen *et al.*[4] have assigned $l=3$ to this state in the ^{42}Ca$(^3$He$,\alpha)^{41}$Ca reaction. However, Johnson *et al.*[10] have suggested that $J^\pi = \frac{9}{2}^+$ for this state by comparison with a possible analog level in ^{41}Sc.

The observed angular correlation of the ground state decay γ ray of the 3.20 MeV level is consistent with spin hypotheses of $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$. The possible mixing ratios are listed in Table I. Spin and parity $J^\pi = \frac{7}{2}^+$ are unlikely for this state because the mixing ratio and lifetime[11] would imply an $M2$ strength of greater than 35 W. u. Similarly, the assumption of positive parity for this state would imply even greater $M2$ strengths for all three spin hypotheses for the mixing ratio solutions with $\delta > 1$.

The value of mixing ratio implied by the γ-ray angular correlation and the spin hypothesis of $J=\frac{9}{2}$ agrees well with the value $|\delta| \leq 0.10$ measured by Lieb *et al.*[17]

3.526 MeV level. Two ^{42}Ca$(p,d)^{41}$Ca reaction studies[2,3] have assigned $l=2$ for the transferred neutron to this state. An older ^{42}Ca$(^3$He$,\alpha)^{41}$Ca study[4] assigned $l=3$ for this state, but the $(^3$He$,\alpha)$ reaction appears[2] less able to distinguish between $l=2$ and $l=3$. The question of l value is further complicated by the neighboring 3.495 MeV level which was not resolved from the 3.526 MeV state

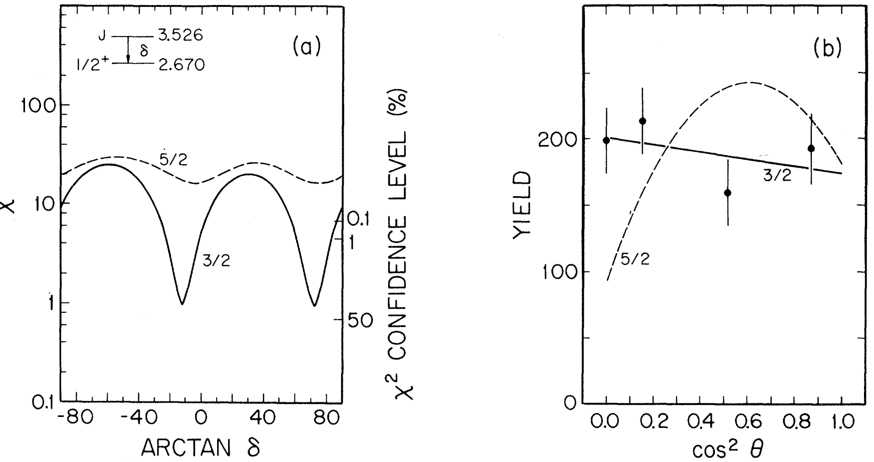

FIG. 2. The 3.526→2.670 MeV γ-ray angular correlation and the χ^2 fit to the data. The best-fit angular correlations for the two spin hypotheses are also shown.

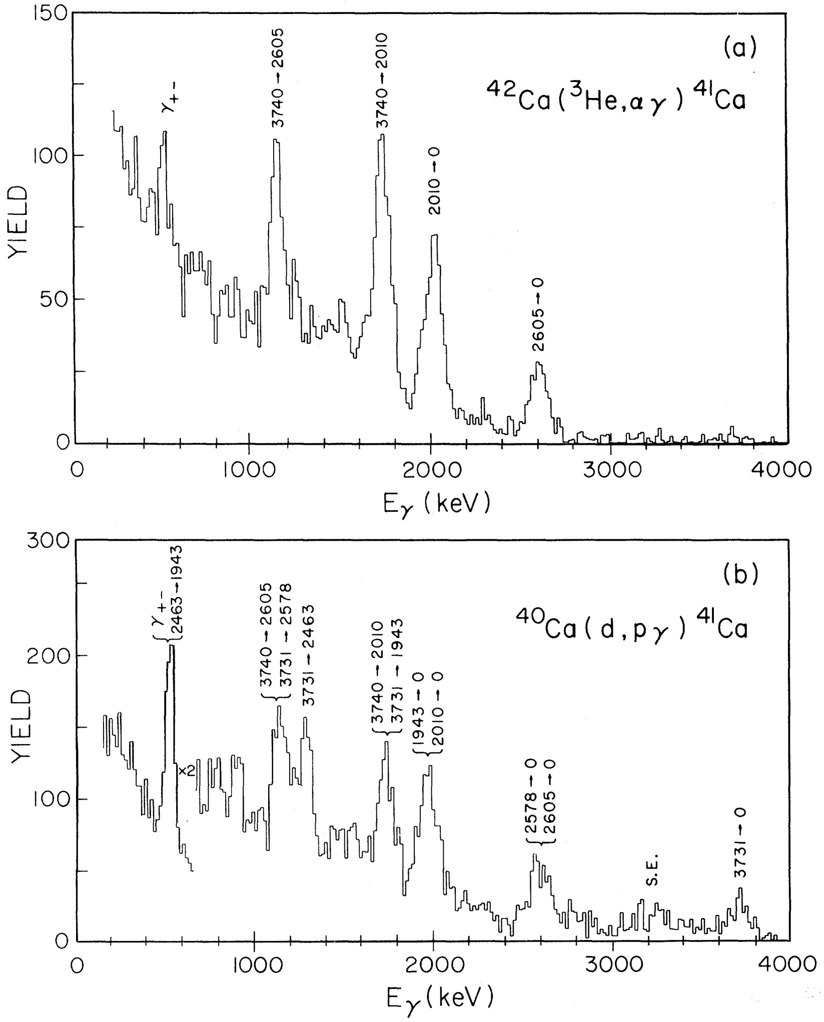

FIG. 3. γ-ray spectra measured in coincidence with particles from the (^{3}He, α) and (d, p) reactions at an excitation energy of about 3.73 MeV. The single lepton escape peak of the 3731 keV γ ray is labeled "SE."

in any of these pickup reactions.

McIntyre[13] has shown that the 3.526 MeV level decays to the 1.943 MeV $\frac{3}{2}^-$, 2.010 MeV $\frac{3}{2}^+$ and 2.670 MeV $\frac{1}{2}^+$ states. The angular correlation of the 3.526 → 2.670 MeV transition is shown in Fig. 2. The observed correlation has been fitted for spin hypotheses of $\frac{3}{2}$ and $\frac{5}{2}$, which are consistent with $l=2$. Even if $l=3$ for this level, $J=\frac{7}{2}$ is unlikely because of the decay branch to the $\frac{1}{2}^+$ state. The χ^2 fits for spins $\frac{3}{2}$ and $\frac{5}{2}$ are also shown in Fig. 2. $J=\frac{5}{2}$ does not fit the measured correlation at the 0.1% confidence level. Therefore the spin is $\frac{3}{2}$. This confirms the $l=2$ assignments and also the positive parity of the state.

3.731 and 3.740 MeV levels. States at approximately this excitation energy have been seen with an $l=2$ angular distribution in both pickup[2-4] and stripping[5] reactions. McIntyre and Donahue[12] have shown that two states exist near this excitation energy. The 3.731 MeV state decays to the 0, 1.943, 2.463, and 2.578 MeV levels, while the 3.740 MeV state decays to the 2.010 and 2.605 MeV levels.

The different decay modes of these two states provide a means of identifying which one is populated in a given reaction. We have measured γ spectra from this region of excitation in ^{41}Ca in coincidence both with α particles detected at 0° relative to the beam from the ^{42}Ca(^{3}He, $\alpha\gamma$)^{41}Ca reaction and with protons detected at 23° (near the stripping peak) from the ^{40}Ca($d, p\gamma$)^{41}Ca reaction. These spectra are shown in Fig. 3.

The spectra in Fig. 3 indicate that the (^{3}He, α) reaction populates predominately the 3.740 MeV level and that the (d,p) reaction populates both levels with comparable strength. The spectrum in Fig. 3(a) shows the two decay branches to the 3.740 MeV level. The 3.731 and 1.268 MeV γ rays are very weak, indicating that the 3.731 MeV level is at most weakly populated. On the other hand, the presence of the 3.731 and 1.268 MeV γ rays in Fig. 3(b) proves that the (d,p) reaction populates the 3.731 MeV level. The unresolved 1.730–1.788 MeV peak in Fig. 3(b) is too strong to be produced solely by the 3.731 → 1.943 MeV transition. It indicates that the 3.740 MeV level is also populated in the (d,p) reaction.

Thus, it is the 3.740 MeV state which is populated by $l=2$ neutron transfer in the (^{3}He, α) reaction. The observation that both states are populated in the (d,p) reaction is consistent with the assignment of $l=2$ to the 3.740 MeV level and $l=1$ to the 3.731 MeV level made by Seth and Iverson[30] from a high resolution (d,p) study. The fact that both states are populated in the (d,p) reaction invalidates the $J=\frac{5}{2}$ assignment made from a (d,p) vector analyzing power measurement.[6]

The observation of a decay branch from the 6.820 MeV $\frac{1}{2}^+$, $T=\frac{3}{2}$ state to the 3.740 MeV state and the $l=2$ assignment to the latter state strongly suggest that $J^\pi=\frac{3}{2}^+$ for the 3.740 MeV state. We will return to this point in the discussion of the 6.820 MeV state. Seth, Saha, and Greenwood[8] have assigned $J^\pi=\frac{5}{2}^+$ to the 2.605 MeV level. The mixing ratios implied by the measured angular correlations and these spin assignments are given in Table I.

4.090 MeV level. The angular distribution to this state has been assigned $l=2$ in the ^{42}Ca(p, d)-^{41}Ca reaction[2,3] and $l=0$ dominates in the ^{39}K(^{3}He,p)^{41}Ca reaction.[31] An assignment of $l=3$ was made to this state from the ^{42}Ca(^{3}He, α)^{41}Ca reaction.[4] This discrepancy is probably due to the difficulty of distinguishing between $l=2$ and $l=3$ in the (^{3}He, α) reaction.

Since the two γ rays in the 4.090 → 2.010 → 0 MeV cascade are not resolved in the NaI(Tl) spectra, the correlation of the sum of these γ rays was compared with the calculated correlation for the possible spins of $\frac{3}{2}$ and $\frac{5}{2}$. The previously measured mixing ratio was used for the 2.010 MeV transition. Both spin hypotheses are consistent with the unresolved correlation. The measured correlation of the 4.090 → 0 MeV transition is also consistent with both spin hypotheses. The resulting mixing ratios are listed in Table I.

The possibility that $J^\pi=\frac{3}{2}^+$ for the 4.090 MeV level is highly unlikely in view of its ground state decay branch. If the $M1$ transition strength of the 4.090 → 2.010 MeV branch is only 0.01 W.u., the mixing ratio for the ground state branch implies an $M2$ transition strength of 4 W.u. and an $E3$ strength of 100 W.u. These enhancements are unreasonably large and strongly suggest that $J^\pi=\frac{5}{2}^+$ for the 4.090 MeV level. The angular correlation is consistent with $\delta(M2/E1)=0$ for the ground state transition if $J=\frac{5}{2}$.

B. $T=\frac{3}{2}$ states

5.814 MeV level. This level has been identified[4] as the isobaric analog state (IAS) of the $\frac{3}{2}^+$ ground state of ^{41}K. In a previous study[14] of its decay scheme using the ^{39}K(^{3}He,$p\gamma$)^{41}Ca reaction, decay branches to the 3.400, 3.740, and 4.090 MeV levels were observed. No decays were seen to the corresponding antianalog or $T_<$ (AIAS) state at 2.010 MeV.

Because of the apparent absence of the IAS → AIAS transition, the population of a nearby state (5.98 MeV) with comparable strength in the (^{3}He, α) reaction, and the recent reassignment[32] of the analog of the ^{41}K ground state in ^{41}Sc, we decided to seek other evidence for the analog state assign-

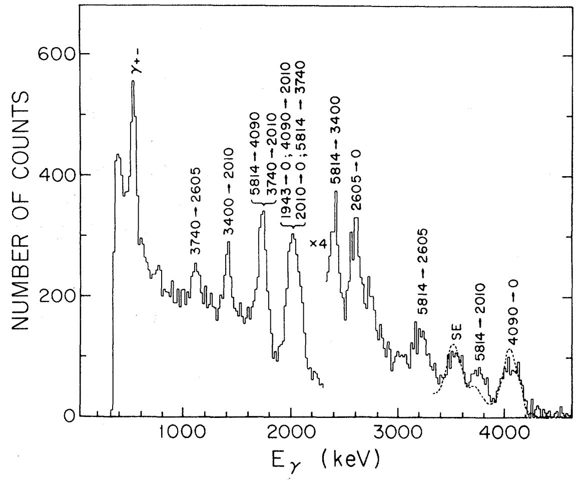

FIG. 4. γ-ray decay spectrum from the 5.814 MeV state measured with the (^{3}He, $\alpha\gamma$) reaction. The shape curve for a 4.43 MeV γ ray shifted to 4.090 MeV is shown as a dashed line. The single lepton escape peak of the 4090 keV γ ray is labeled "SE."

ment with the (^{3}He, t) charge-exchange reaction. The triton spectrum from the ^{41}K(^{3}He, t)^{41}Ca reaction was measured in the magnetic spectrometer at 0° relative to the beam. Only the 5.814 MeV state was strongly populated in this region of excitation energy. The nearby ground-state peak from the ^{35}Cl(^{3}He, t)^{35}Ar reaction was used to verify the spectrometer calibration. We conclude that the 5.814 MeV state is the analog of the ^{41}K ground state as previously reported.

Subsequently, we measured the γ spectrum from the 5.814 MeV state populated in the (^{3}He, α) reaction. This is displayed in Fig. 4. In contrast to the (^{3}He, $p\gamma$) work, a $(4 \pm 2)\%$ 5.814 → 2.010 MeV decay branch was observed. This weak 3.804 MeV γ ray can be seen between the full-energy and single-escape peaks of the 4.090 MeV γ ray. A γ-ray line shape obtained from 4.43 MeV γ rays is drawn as a dashed line in the figure for comparison. The line shape has been shifted to correspond to 4.090 MeV without changing the energy dispersion and has been normalized to equalize

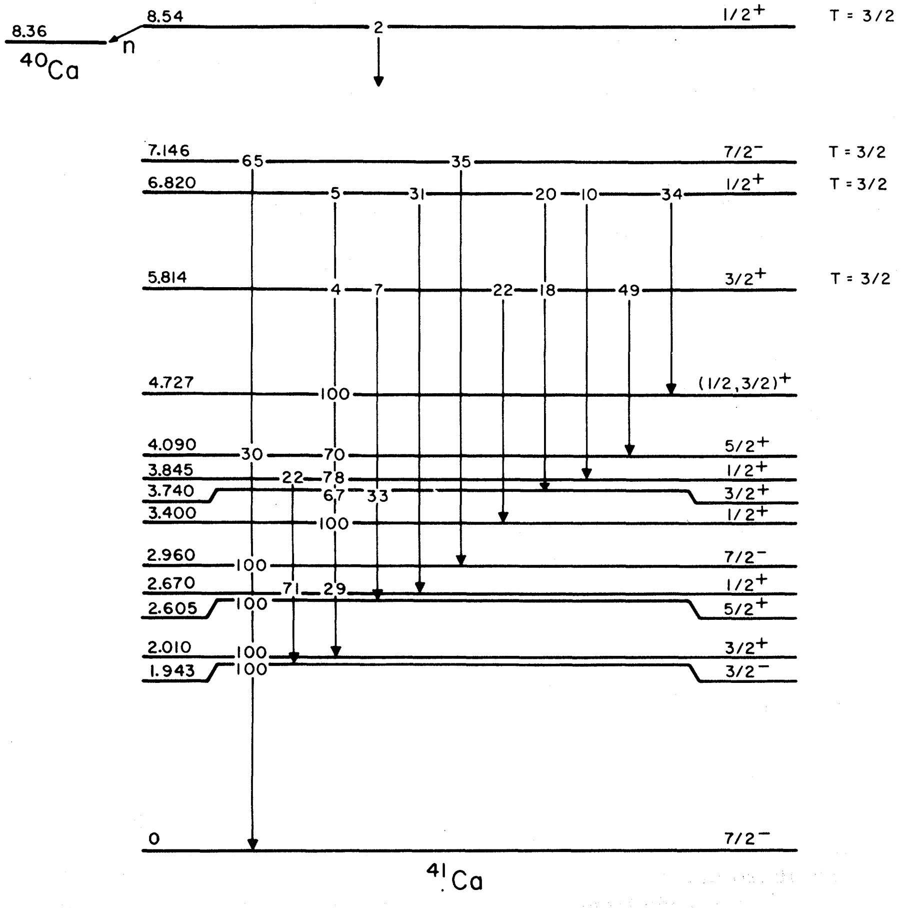

FIG. 5. Decay scheme of some $T = \frac{3}{2}$ states in ^{41}Ca. Only the $T = \frac{1}{2}$ states fed by the $T = \frac{3}{2}$ states are shown. Branching ratios for the $T = \frac{1}{2}$ states are taken from Ref. 13 except for the 4.727 MeV level.

the areas of the full energy peaks. The 3.209 MeV γ ray indicates a previously unreported (7 ± 3)% decay branch to the 2.605 MeV level.

The decay scheme of the 5.814 MeV level is shown in Fig. 5. The relative branching ratios of the other decay branches have been taken from Ref. 14. The branching ratio of 4% to the 2.010 MeV level is below the upper limit quoted by Knöpfle *et al.*[14]

Maripuu[20] has calculated the strengths of $\Delta T = 1, M1$ transitions between analog and antianalog states in a shell model framework. The transition strength between states with $J = l + \frac{1}{2}$ is predicted to be 20 to 200 times greater than between states with $J = l - \frac{1}{2}$. Hence the 5.814 → 2.010 MeV transition is expected to be weak.

Without a knowledge of the lifetime of the 5.814 MeV state, the strength of the 5.814 → 2.010 MeV transition cannot be compared with the calculation. There is at least qualitative agreement with the calculation of Maripuu since the IAS → AIAS transition is not the predominant decay mode.

6.820 MeV level. This is the analog of the 0.980 MeV $\frac{1}{2}^+$ level in ^{41}K. No γ decays were seen from this state in the (^{3}He, $p\gamma$) study[14] and it was suggested that α emission might be the principal decay mode. In the present (^{3}He, $\alpha\gamma$) experiment γ decays have been observed from the 6.820 MeV state, and the ratio of coincident γ rays to the number of α particles in the singles spectrum is consistent with a 100% γ-decay branch. Because of the observation of γ rays and the extremely low penetrability factor for 210 keV α particles, no attempt was made to search for an α-decay branch of the 6.820 MeV state.

The γ decay spectrum from this state measured with the NaI crystals was difficult to interpret because of its complexity. To better determine the decay scheme, another coincident γ spectrum was measured with a Ge(Li) detector, which was placed at 90° relative to the beam to eliminate Doppler shifts. The resulting spectrum is shown in Fig. 6. Decay branches can be seen to the following levels (branching ratios in parentheses): 2.010 MeV (5 ± 3%), 2.670 MeV (31 ± 6%), 3.740 MeV (20 ± 6%), 3.845 MeV (10 ± 5%), and 4.727 MeV (34 ± 6%).

The 660 and 727 keV γ rays prove that the 6.820 MeV state decays to the 2.670 MeV $\frac{1}{2}^+$ state. The energy of the primary γ ray for this branch, 4150 keV, provides a more accurate determination of the excitation energy of this state: 6820 ± 3 keV. The decay branch to the 2.670 MeV $\frac{1}{2}^+$ level suggests that the 2.670 MeV state is predominately the antianalog of the 0.980 MeV level in ^{41}K. The energy spacing between $T_>$ and $T_<$ states would then be reasonably similar to that for the 5.814-2.010 MeV pair. Since $J = l + \frac{1}{2}$, the $T_>$ to $T_<$ transition is predicted[20] to be strong.

A second decay branch leads to a state at 4727 ± 3 keV, which decays to the 2010 keV level. The 4727 keV state is presumably the one observed at 4724 keV by Knöpfle *et al.*[14] in the (^{3}He, $p\gamma$) reaction and at 4743 keV by Belote *et al.*[31] in the (^{3}He, p) reaction. The latter identification provides an l assignment of 90% $l = 0$ and 10% $l = 2$ and re-

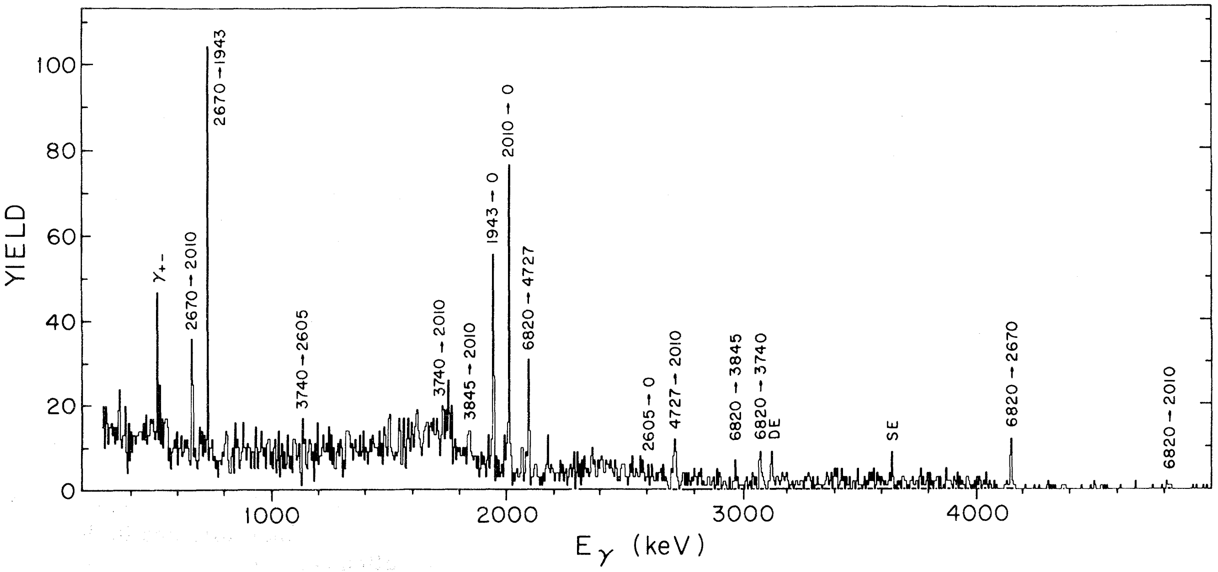

FIG. 6. γ-ray decay spectrum from the 6.820 MeV state measured with the (^{3}He, $\alpha\gamma$) reaction and a Ge(Li) detector. The single and double lepton escape peaks of the 4150 keV γ ray are labeled "SE" and "DE," respectively.

stricts J^π to $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$ for the 4727 keV state.

The possibility $J^\pi = \frac{5}{2}^+$ for the 4727 keV state is extremely unlikely because of the 6.820 → 4.727 MeV transition. Maripuu[20] has calculated an $M1$ strength of 1.95 W.u. for the 6.820 → 2.670 MeV transition. An assumption of only $\frac{1}{10}$ of this predicted strength and the observed branching ratio would imply an $E2$ strength of 1200 W.u. for the 6.820 → 4.727 MeV transition if $J^\pi = \frac{5}{2}^+$ for the latter state. Thus the spin of the 4.727 MeV state is restricted to $\frac{1}{2}^+$ or $\frac{3}{2}^+$. There is no evidence in Fig. 6 for the 10% ground state branch from the 4.727 MeV state that was reported in Ref. 14, although such a weak branch would not be inconsistent with the spectrum. A ground state branch is extremely unlikely, however, because of the restriction $J^\pi = \frac{1}{2}^+$ or $\frac{3}{2}^+$.

The 3082 keV γ ray implies a decay branch to the 3.740 MeV state. The spectrum is consistent with the existence of the secondary γ rays but they are not prominent. The existence of a decay branch to the 3.740 MeV level strongly suggests that $J^\pi = \frac{3}{2}^+$ for this level because the other possibility, $J^\pi = \frac{5}{2}^+$, would imply an unreasonably large $E2$ transition strength between the 6.820 and 3.740 MeV levels. The assumption of $\frac{1}{10}$ the predicted[20] strength for the 6.820 → 2.670 MeV transition would imply an $E2$ strength of 100 W.u. for the 6.820 → 3.740 MeV transition if $J^\pi = \frac{5}{2}^+$ for the 3.740 MeV state.

The $T_> \rightarrow T_<$ transition is predicted[20] to be strong between the $\frac{1}{2}^+$ states and it does have a larger branching ratio than the corresponding transition between the $\frac{3}{2}^+$ states. However, after dividing by $E_\gamma{}^3$, the transition strength to the 4.727 MeV level is more than 8 times stronger than that to the 2.670 MeV level.

Similarly, the 5.814 → 4.090 MeV branch has by far the strongest transition strength among the decay modes of the5.814 MeV state. This leads to an interesting similarity in the decays of the 6.820 and 5.814 MeV levels. The strongest transition from each level is to the 4.727 and 4.090 MeV levels, respectively, whose level spacing is almost identical to that of the $T_<$ states at 2.670 and 2.010 MeV.

This correspondence may be accidental. If not, one hypothesis which might account for these features is that the dominant configuration of the 4.090 and 4.727 MeV levels is

$$| d_{3/2}{}^{-1} f_{7/2}{}^2 (J = 1, T = 0) \rangle\!\rangle_{J=5/2, T=1/2}$$

and

$$| s_{1/2}{}^{-1} f_{7/2}{}^2 (J = 1, T = 0) \rangle\!\rangle_{J=3/2, T=1/2} ,$$

respectively. Strong $M1$ transitions would be expected to such states from the 5.814 and 6.820 MeV states. For example, the $M1$ strength of the transition[27]

$$| d_{3/2}{}^{-1} f_{7/2}{}^2 (J = 0, T = 1) \rangle\!\rangle_{J=3/2, T=3/2}$$
$$\rightarrow | d_{3/2}{}^{-1} f_{7/2}{}^2 (J = 1, T = 0) \rangle\!\rangle_{J=5/2, T=1/2}$$

is equal to that of the 617 → 0 keV transition in ^{42}Sc, which is 2 W.u. Some support for this hypothesis is provided by the ^{39}K(α, d)^{41}Ca reaction, which is expected to preferentially populate 2p-1h states whose two particles are coupled to $J = 1$, $T = 0$. This reaction is observed[33] to strongly populate levels at 4.10 and 4.74 MeV.

7.146 MeV level. This state is the isobaric analog of the lowest $\frac{7}{2}^-$ state in ^{41}K at 1.294 MeV. It is rather weakly populated in the (^{3}He, α) reaction at $\theta_\alpha = 0°$, but coincidence γ spectra have been measured for this state with both the NaI and Ge(Li) detectors. The 7.146 MeV state is observed to decay only to the ground state (65 ± 7%) and to the 2.96 MeV state (35 ± 7%). The 7.146 → 2.960 γ ray in the Ge(Li) spectrum implies an excitation energy of 7146 ± 4 keV.

The decay scheme of the 7.146 MeV level is of interest primarily because of the information it yields about the $T = \frac{1}{2}$ states to which it decays. It has been known for some time that it is possible to explain some of the properties of low-lying states in the calcium isotopes by mixing deformed states with those predicted by the shell model. In particular, the calculations of Gerace and Green[1] predict two low-lying $\frac{7}{2}^-$ states, the ground state and a state at 3.22 MeV. These states result mainly from mixing (1p-0h) and (3p-2h) configurations. (Particles and holes refer to the f-p and s-d shells, respectively.) In the Gerace and Green picture the wave functions of the two states are

$$| \text{g.s.} \rangle = 0.92 | \text{1p-0h} \rangle + 0.38 | \text{3p-2h} \rangle ,$$

$$| 3.22 \rangle = 0.38 | \text{1p-0h} \rangle - 0.92 | \text{3p-2h} \rangle .$$

Possible experimental counterparts for these states are suggested by the work of Seth *et al.*,[29] who studied the ^{43}Ca(p, t)^{41}Ca reaction. They observed two strong $l = 0$ transitions to the ground state and the 2.960 MeV state, the same states to which the 7.146 MeV level decays.

For the decay of the 7.146 MeV state to the lower $T = \frac{1}{2}$ states, the isovector $M1$ decay is expected to dominate over any possible isovector $E2$ component, which should not show any collective enhancement. The experimental angular correlations, although limited by poor statistics, are consistent with pure $M1$ decays. Now the $M1$ operator is a one-body operator, and in the simplest approximation can only connect the analog state to the (3p-2h) component of the $T_<$ states. Consequently, the ratio of reduced transition probabilities is

$$\frac{B(M1)(7.146 \to 2.96)}{B(M1)(7.146 \to 0)} = \left(\frac{0.92}{0.38}\right)^2 = 5.9 .$$

After removing a factor $E_\gamma{}^3$ from the branching ratios, the ratio of experimental transition strengths from the 7.146 MeV state to the 2.96 MeV state and to the ground state is 2.7 : 1, in reasonable qualitative agreement with the above prediction.

8.54 MeV level. This level is populated strongly by $l = 0$ neutron pickup[2,3]; hence $J^\pi = \frac{1}{2}^+$. Martin *et al.*[3] have identified the 8.54 MeV level as the analog of the 2.67 MeV level in ^{41}K.

The 8.54 MeV state is unbound by 180 keV to s-wave neutron decay. The α-γ time-difference spectrum in coincidence with α particles from this level shows a weak, narrow peak corresponding to γ emission and a broad peak shifted by an amount equal to the neutron flight time to the NaI crystals. The particle spectrum in coincidence with γ rays also shows a weak peak at the energy of this state after an approximate subtraction of random coincidences.

We conclude that neutron emission is the dominant decay mode but a weak γ-decay branch does exist. The value of the γ branching ratio depends on γ-ray multiplicities and detection efficiencies, but it is in the range of 1 to 3%. Not enough γ rays were observed to determine the γ decay scheme.

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