Isospin forbidden γ-decay of the the lowest $T = 2$ state in ^{44}Ti

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A reported splitting of the lowest $T = 2$ strength in ^{44}Ti has been confirmed by examining resonances in the ^{40}Ca(α, γ) ^{44}Ti reaction at excitation energies in the region of 9.28–9.36 MeV. A level at 9298 ± 2 keV in ^{44}Ti is found to have γ-decays to the 1^+, $T = 1$ level at 7216 keV and to a $T = 0$ level at 3756 keV. The former transition is attributed to a $T = 2$ component in the 9298 keV level, with, however, the main $T = 2$ strength remaining in the level at 9338 ± 2 keV, as reported previously. Evidence is presented for a weak (9338→3756), $\Delta T = 2$ transition in addition to the dominant (9338→7216), $\Delta T = 1$ γ-decay branch. The two levels at 9298 and 9338 keV are interpreted as an isospin-mixed doublet. The perturbing matrix element is estimated to be 16 ± 3 keV, and the unperturbed $T = 2$ state to lie at 9330 ± 4 keV.

[NUCLEAR STRUCTURE Splitting of lowest $T=2$ level ^{44}Ti; measured γ decays, $\omega\gamma$ from ^{40}Ca(α, γ); deduced transition strengths, isospin mixing.]

I. INTRODUCTION

The study of the γ decay of $T=2$ states in $N=Z$ nuclei affords an opportunity to look for isospin-forbidden $\Delta T=2$ transitions. Such transitions can arise from isospin mixing or from a possible isotensor component in the electromagnetic interaction. In ^{44}Ti the first $T=2$ state (which is the double analog of the ground state of ^{44}Ca) was located by Simpson *et al.*[1] at 9338 ± 2 keV, with the main decay branch being a γ transition to a $1^+, T=1$ state at 7216 keV, which in turn decays primarily to the ground state. (See Fig. 1.) Later a more careful search[2] for a possible $\Delta T=2$, $E2$ transition to the first 2^+ state of ^{44}Ti at 1083 keV failed to reveal its presence, with an upper limit [one standard deviation (s.d.)] of 0.16% for the branching ratio. This result at first suggested a rather high degree of isospin purity in the $T=2$ state. On the other hand two ^{46}Ti(p,t) experiments have suggested a significant splitting of the $T=2$ strength. Moalem *et al.*[3] found a subsidiary triton peak above the $T=2$ triton peak, with an intensity of about $\frac{1}{4}$ and apparently the same angular distribution as the $T=2$ peak. Freedman *et al.*[4] measured t-α coincidences and concluded that $\Gamma_{\alpha 0}/\Gamma < 8\%$ (90% confidence limit) for the $T=2$ level, and $\Gamma_{\alpha 0}/\Gamma < 22\%$ for the subsidiary peak. These numbers have now been revised to $\Gamma_{\alpha 0}/\Gamma = 32 \pm 5\%$ and $87 \pm 20\%$, respectively.[5] If one assumes that the triton peaks in question are due mainly to a $T=2$ configuration, then the (p,t) experiments suggest that there is an isospin doublet (of separation 40 $\pm$ 2 keV) which originates in the mixing of two 0^+ levels with isospins $T=2$ and $T=T_<$. In order to clarify this situation we have studied the γ-decay of resonances in the ^{40}Ca $(\alpha,\gamma)^{44}$Ti reaction at excitation energies near 9298 keV, and reexamined

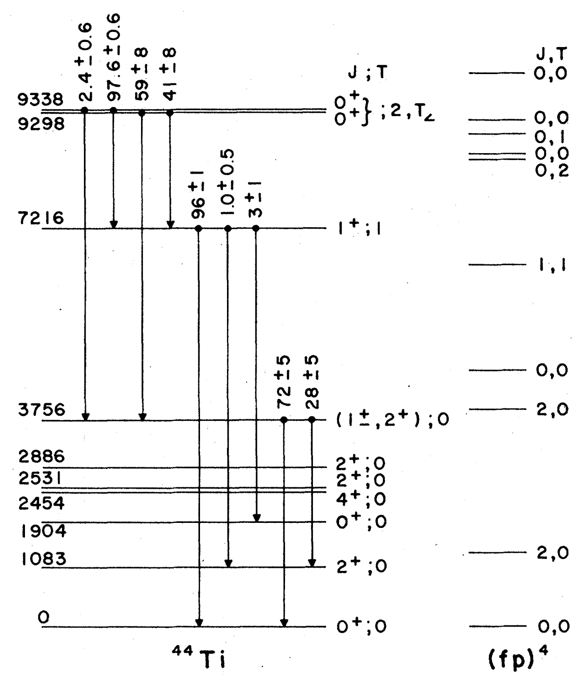

FIG. 1. γ-decay branches and energy levels of ^{44}Ti involved in the γ-decay of the $T=2$ doublet are shown at the left (Ref. 6). At the right are shown relevant shell-model states calculated in the full f-p shell, including the first five 0^+, $T=0$ states, the lowest 0^+, $T=2$ state, and the lowest 0^+, and 1^+, $T=1$ states.

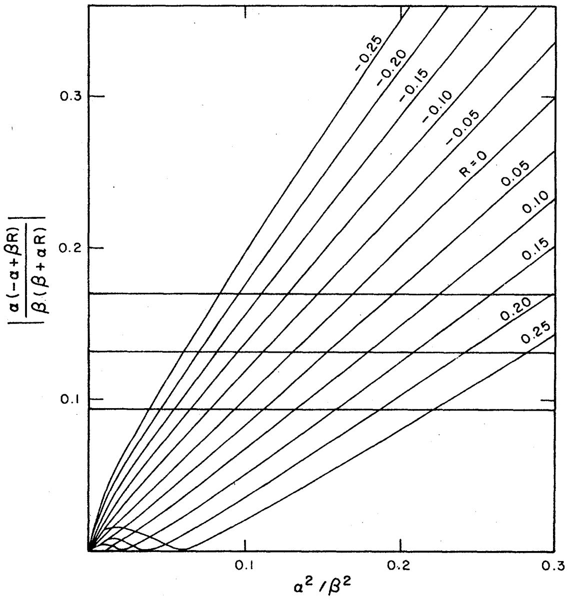

FIG. 8. Graphical solution for the mixing parameter α^2/β^2 in a two-level mixing model, for various values of the $M1$ amplitude ratio R for transitions to the 7216 keV level. The horizontal lines show limits of one standard deviation as determined from the experimental strengths of the γ-ray decays to the 7216 and 3756 keV levels.

ues for the 9338 keV level, and using a ratio of penetrabilities of 0.85, Eq. (4) imposes the constraint that

$$\frac{\Gamma_\gamma(9298 \rightarrow 3756)}{\Gamma_{\alpha 0}(9298)} = 0.062 \pm 0.027 .$$

This leads to

$$(\Gamma_{\alpha 0}/\Gamma)_{9298} = 0.905 \pm 0.045 ,$$

where we have used the measured γ-ray branching ratios of $(59 \pm 8)\%$ to the 3756 keV level and $(41 \pm 8)\%$ to the 7216 keV level. This result for $\Gamma_{\alpha 0}/\Gamma$ may now be combined with the measured $\omega\gamma$ for the 9298 keV level to yield the following widths:

$$\Gamma_{\alpha 0}(9298) = 1.2 \pm 0.6 \text{ eV} ,$$

$$\Gamma_\gamma(9298 \rightarrow 3756) = 0.073 \pm 0.025 \text{ eV} ,$$

$$\Gamma_\gamma(9298 \rightarrow 7216) = 0.051 \pm 0.012 \text{ eV} .$$

Returning to Eq. (4), we find

$$\alpha^2/\beta^2 = 0.26 \pm 0.13 .$$

This result is consistent with the analysis based entirely on the $\omega\gamma$ values only if $R \gtrsim 0.1$, i.e., the $(T_< \rightarrow 7216)$ $M1$ strength may be a few percent of the $(T=2) \rightarrow 7216$ strength.

In the two-level mixing model, the difference in the total energies of the unmixed states is given by $(\beta^2 - \alpha^2)\Delta E$, where ΔE is the separation after mixing, i.e., 40 ± 2 keV. Using $\alpha^2/\beta^2 = 0.26 \pm 0.13$, the difference before mixing then is 24 ± 7 keV. The Coulomb mixing matrix element is just $\alpha\beta\Delta E = 16 \pm 3$ keV, and the unperturbed $T=2$ state is at 9330 ± 4 keV.

Although all of the experimental data seems to be consistent with two-level mixing, it is not yet possible to say if $T_< = 0$ or 1. At first sight the small α widths for both the 9338 and 9298 keV levels seem to suggest $T_< = 1$, in which case the α width for the pure $T_<$ state could be thought of as arising from a $T=1$ admixture in the ground state of ^{40}Ca. Estimates of this admixture range from about 0.2% in intensity by Bohr and Mottelson[7] to 1.8% by Soper,[8] leading to "$\Delta T = 1$" α-width upper limits in the range of 10–90 eV, for a Wigner limit of about 5 keV. While $T_< = 1$ is therefore a possible choice, $T_< = 0$ of course is not precluded by the α widths.

An analysis of the electromagnetic transition strengths is also inconclusive. We note first that if the $T_< \rightarrow 7216$ $M1$ transition can be regarded as established at about 1% of the $(T=2) \rightarrow 7216$ transition, i.e., at about 0.04 W.u., then according to the limits of Endt and van der Leun[9] it must be a $\Delta T = 1$ transition, and therefore $T_< = 0$. Similar considerations for the $T_< \rightarrow 3756$ transition are summarized in Table III for the three possible spin choices for the 3756 keV level; the transition strength is not large enough to exclude for certain the isospin-retarded cases.

Finally with regard to the determination of $T_<$, we note that in ^{44}Sc there does not appear to be an analog of the 9298 keV level in ^{44}Ti, implying that $T_< = 0$ rather than 1. There is, however, still a question as to whether the levels in ^{44}Sc have been studied in sufficient detail to make a firm conclu-

TABLE III. Intrinsic transition strength for $T_< \rightarrow 3756$, assuming the spin of the 3756 keV level to be 1^+, 1^-, or 2^+. The value of $T_<$ is not determined.

$J^\pi(3756)$	Multipolarity	$\lvert M\rvert^2$ (W.u.)	Isospin-retarded upper limit[a]	Favored $T_<$
1^+	$M1$	0.026 ± 0.008	0.03	1
1^-	$E1$	$(6.4 \pm 2.0) \times 10^{-4}$	0.003	1
2^+	$E2$	2.4 ± 0.8	10	0

[a] Reference 9.

pure isospin $T=2$ and $T=T_<$, where $T_<$ is either 0 or 1. The transitions to the $T=0$ level at 3756 keV are considered to arise solely from the $T_<$ component in both the 9338 and 9298 keV levels. On the other hand it is not obvious that the 9298 $\rightarrow$ 7216 transition is purely $(T=2)\rightarrow(T=1)$, although the 9338 $\rightarrow$ 7216 transition must be nearly so if the mixing is small.

In a two-level mixing model the wave functions may be written as

$$\begin{aligned}\psi(9338)&=\alpha\phi(T_<)+\beta\phi(2)\,,\\ \psi(9298)&=\beta\phi(T_<)-\alpha\phi(2)\,,\end{aligned}\tag{1}$$

in an obvious notation, where $\alpha^2+\beta^2=1$. (α and β are taken to be real.) If we assume initially that the $(R\rightarrow 7216)$ transitions arise solely from the $T=2$ component, and the $(R\rightarrow 3756)$ transitions solely from the $T_<$ component, then it is easily shown that

$$\begin{aligned}\frac{\alpha^2}{\beta^2}&=\left[\frac{\Gamma_\gamma(9338\rightarrow 3756)\Gamma_\gamma(9298\rightarrow 7216)}{\Gamma_\gamma(9338\rightarrow 7216)\Gamma_\gamma(9298\rightarrow 3756)}\right]^{1/2}\\ &=\left[\frac{\omega\gamma(9338\rightarrow 3756)\omega\gamma(9298\rightarrow 7216)}{\omega\gamma(9338\rightarrow 7216)\omega\gamma(9298\rightarrow 3756)}\right]^{1/2},\end{aligned}\tag{2}$$

where we have neglected energy-dependent factors which nearly cancel in the ratios. It should be emphasized that the determination of α^2/β^2 from Eq. (2) requires only the experimentally measured values of $\omega\gamma=\Gamma_\gamma\Gamma_{\alpha 0}/\Gamma$, but not the individual values of Γ_γ (for which a knowledge of $\Gamma_{\alpha 0}/\Gamma$ is also required). Inserting the measured $\omega\gamma$ values from Table II, we obtain $\alpha^2/\beta^2=0.13\pm0.04$.

If we now admit some intrinsic width for the $T_<$ $\rightarrow$ 7216 transition, then in Eq. (2), α^2/β^2 is replaced by

$$\left|\frac{\alpha(-\alpha+\beta R)}{\beta(\beta+\alpha R)}\right|,\tag{3}$$

where R is the ratio of the $M1$ amplitude for $T_<$ $\rightarrow(T=1)$ to $(T=2)\rightarrow(T=1)$. The quantity (3) is plotted in Fig. 8 for various values of R. Again using the values of $\omega\gamma$ from Table II to evaluate the right-hand side of Eq. (2), we see for example that even for R^2 small, e.g., $-0.10<R<0.10$, a considerably extended range of mixing is allowed, in this case $0.066<\alpha^2/\beta^2<0.226$.

Thus the γ-ray yields can be understood in terms of a two-level mixing model in which, for example, there is a $(12\pm3)\%$ component by intensity of lower isospin impurity in the 9338 keV level, for $R=0$. However, the amount of isospin mixing deduced from the γ-ray yields is sensitive to the assumed value of the ratio R.

An alternative method of analysis makes use of the available information on the α widths. Freedman *et al.*[5] have measured $\Gamma_{\alpha 0}/\Gamma=0.32\pm0.05$ for the 9338 keV level, and $\Gamma_{\alpha 0}/\Gamma=0.87\pm0.20$ for the 9298 keV level. For the 9338 keV level this number is combined with our $\omega\gamma$ value to give $\Gamma_{\alpha 0}=0.36$ ±0.08 eV, $\Gamma_\gamma(9338\rightarrow 7216)=0.75\pm0.20$ eV (a value in excellent agreement with the shell-model calculation[1]), and $\Gamma_\gamma(9338\rightarrow 3756)=0.019\pm0.007$ eV (see Table II). The α width is about 8×10^{-5} of the Wigner limit and is consistent with $T=2$ α widths in other $N=Z$ nuclei. Unfortunately the $\Gamma_{\alpha 0}$ of the 9298 keV level is not determined from the measurement of $\Gamma_{\alpha 0}/\Gamma$, which gives only a lower limit: $\Gamma_{\alpha 0}(9298)\gtrsim 0.34$ eV. However, a better determination can be made if one introduces the constraints of the two-level mixing model, using as the basic equations

$$\begin{aligned}\frac{\alpha^2}{\beta^2}&=\frac{\Gamma_\gamma(9338\rightarrow 3756)}{\Gamma_\gamma(9298\rightarrow 3756)}\\ &=\frac{\Gamma_{\alpha 0}(9338)P(9298)}{\Gamma_{\alpha 0}(9298)P(9338)}\,,\end{aligned}\tag{4}$$

where P is a penetrability factor. Here we attribute to the $T_<$ components in the wave functions all of the γ-ray strength to the 3756 keV ($T=0$) level, as well as the α widths. Inserting the known val-

TABLE II. γ-ray yields, γ widths, and transition strengths for the decay of the 9338 and 9298 keV levels. For the 9338 keV level a value of $\Gamma_{\alpha 0}/\Gamma=0.32\pm0.05$ from Freedman *et al.* (Ref. 5) is used to calculate Γ_γ. For the 9298 keV level the assumption of an isospin mixed doublet leads to $\Gamma_{\alpha 0}/\Gamma=0.91\pm0.05$ (see text).

Transition	Final J^π	$\omega_\gamma=\frac{\Gamma_{\alpha 0}\Gamma_\gamma}{\Gamma}$ (eV)	Γ_γ (eV)	$\|M\|^2(M1)$ (W.u.)	$\|M\|^2(E2)$ (W.u.)
9338 → 7216	1^+	0.24 ± 0.05	0.75 ± 0.20	3.8 ± 1.0	···
9338 → 3756	$(1^\pm,2^+)$	0.006 ± 0.002	0.019 ± 0.007	(0.005 ± 0.002)	(0.5 ± 0.2)
9338 → 2886	2^+	$<1.2\times10^{-3}$	$<3.8\times10^{-3}$	···	<0.046
9338 → 2531	2^+	$<1.2\times10^{-3}$	$<3.8\times10^{-3}$	···	<0.035
9338 → 1083	2^+	$<3.9\times10^{-4}$	$<1.2\times10^{-3}$	···	<0.0042
9298 → 7216	1^+	0.046 ± 0.011	0.051 ± 0.012	0.27 ± 0.07	···
9298 → 3756	$(1^\pm,2^+)$	0.066 ± 0.022	0.073 ± 0.025	(0.021 ± 0.007)	(1.9 ± 0.7)

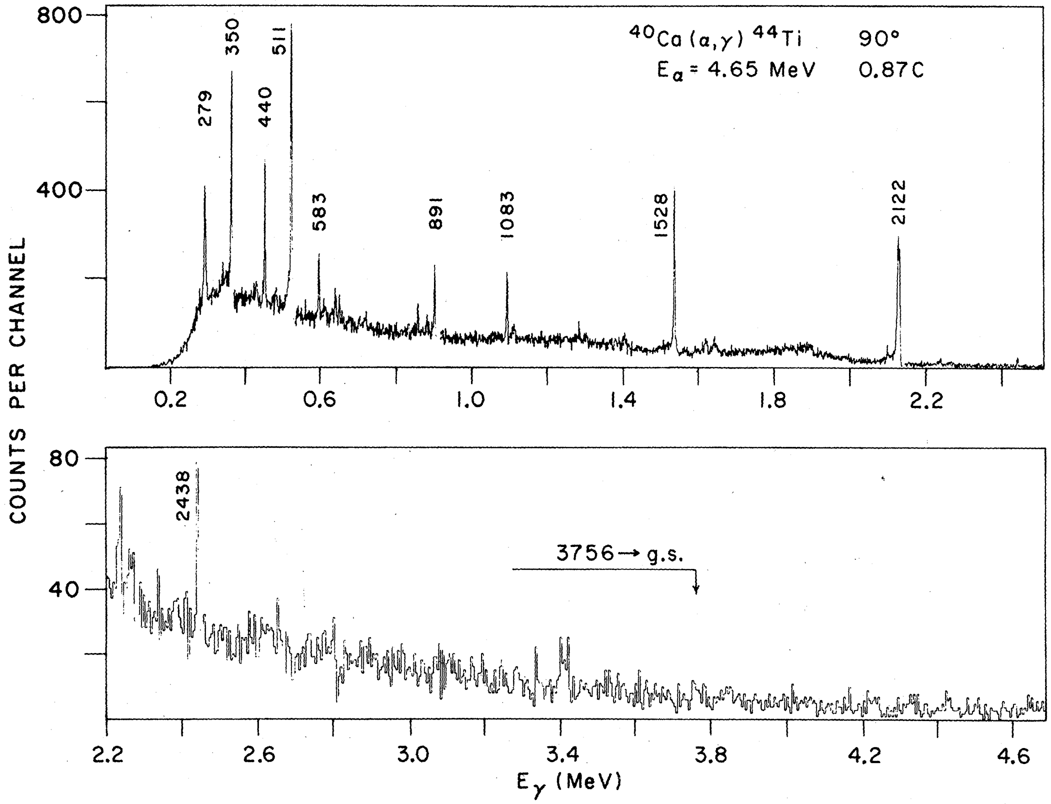

FIG. 6. Spectrum at 90° for coincidences between a Ge(Li) and a NaI(Tl) detector when more than 4.2 MeV is given up in the NaI(Tl) detector. The 2122 keV peak is the main decay transition of the $T=2$ level in ^{44}Ti, viz. 9338→7216, and has an area of 1950 ±51 counts, with no significant random contribution. The full-energy peak for the (3756→g.s.) transition has an area of 21±8 counts; the efficiency for the escape peaks is less than one half of that of the full-energy peak. The channel width for the lower half of the figure is four times that for the upper half.

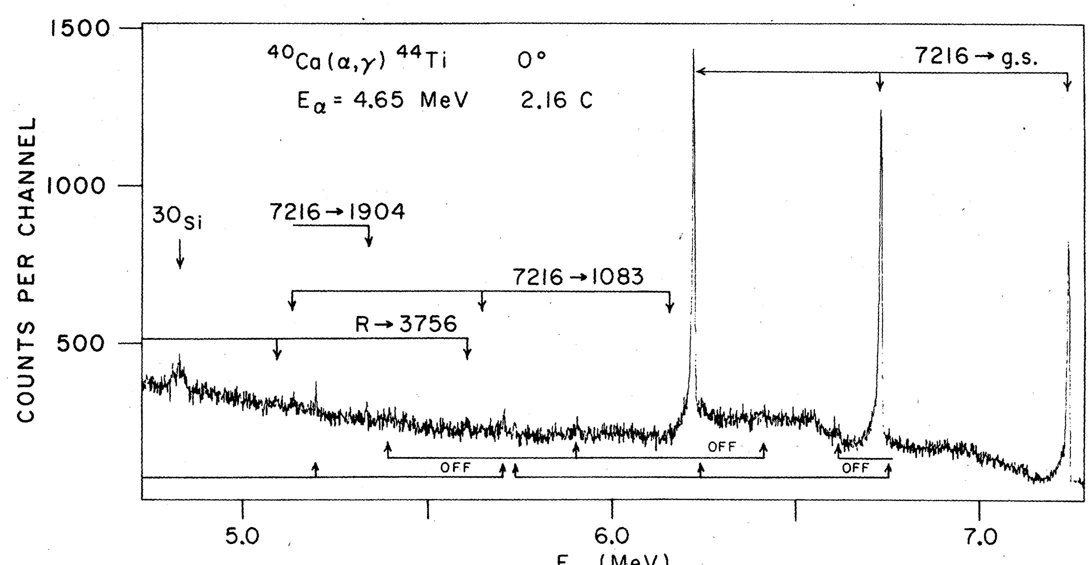

FIG. 7. Singles Ge(Li) spectrum for the $T=2$ resonance. Target thickness was about 10 keV on a W backing. The peaks marked "OFF" are not resonant at $E_α=4.65$ MeV, and in part arise from neutron capture in ^{48}Ti and ^{56}Fe in a heavy concrete shielding wall. The (R→3756) transition is present in about the same strength as the weak decay branches of the 7216 keV level.

Ta_2O_5 targets. The strength of the 2082 keV peak relative to possible contamination peaks identified from these targets shows that the 2082 keV peak cannot be attributed to either fluorine or oxygen contamination in the ^{40}Ca target, and hence must come from the $9298 \to 7216$ keV transition in ^{44}Ti.

Ge(Li) excitation curves

A partial resolution of the 9294-9298 keV doublet has been achieved by using a thin target to study excitation functions of the various transitions in the energy region of interest. These excitation functions, taken with a Ge(Li) detector, are shown in Fig. 5. The transitions ($R \to$ g.s.), ($R \to 1083$) and ($R \to 2531$) clearly peak at a lower bombarding energy than the 7216 keV γ-ray, the energy separation being about 4 keV. The former transitions are attributed to a resonance at 9294 ± 2 keV, and the 7216 keV γ-ray to a resonance at 9298 ± 2 keV. The ($R \to 3756$) transition appears to originate from both resonances. By making a least-squares fit to a sum of two components having the shapes of the excitation functions for the ($R \to$ g.s.) and ($7216 \to$ g.s.) γ-rays, respectively, we have determined the yield of ($R \to 3756$) from each resonance. The γ-branching ratios for the 9298 keV resonance are then calculated to be $(41 \pm 8)\%$ to the 7216 keV level and $(59 \pm 8)\%$ to the 3756 keV level.

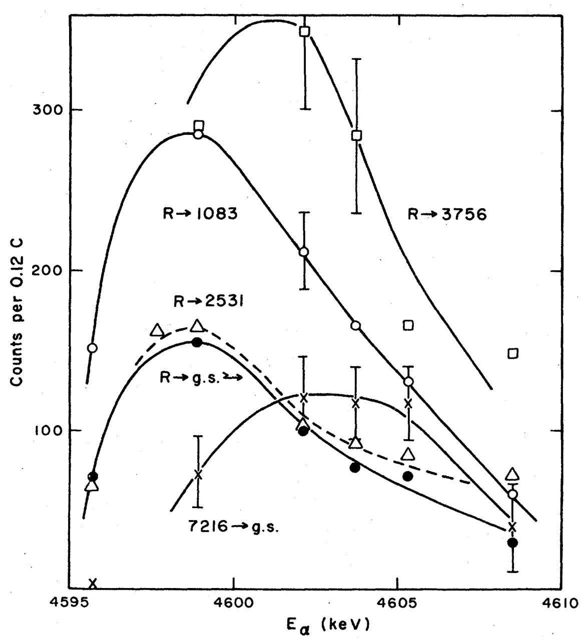

FIG. 5. Ge(Li) excitation functions at 30° for the $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction, showing that the 7216 keV γ-ray peaks at a higher energy than the other transitions. The error in the α-energy scale shown is about ± 1 keV.

Resonance strength

A direct comparison has been made of the intensity of the 7216 keV γ ray at the 9298 keV resonance to the intensity at the 9338 keV resonance. The intensity ratio is $19 \pm 2\%$. The $\omega\gamma$ of the ($R \to 7216$) transition at the 9338 keV resonance has been measured previously[2] to be $\Gamma_{\alpha 0}\Gamma_\gamma/\Gamma = 0.24 \pm 0.05$ eV, and the ($9298 \to 7216$) transition therefore has $\omega\gamma = 0.046 \pm 0.011$ eV. The total $\omega\gamma$ for the 9294 and 9298 keV resonances combined is about 0.5 eV.

III. THE 9338 keV RESONANCE

The $T=2$ resonance in ^{44}Ti at 9338 keV has been studied previously.[1] The main decay branch is to the 7216 keV level, and a careful search[2] for the $\Delta T=2$, $9338 \to 1083$ $E2$ transition led to an upper limit (one s.d.) of 0.16%. The decay of the $T=2$ resonance has now been reexamined with particular interest being focused on the $9338 \to 3756$ transition (which had not been looked for previously), since observation of this transition would confirm isospin mixing in the 9338 and 9298 keV levels.

A weak 3756 keV γ ray cannot be identified in a singles Ge(Li) spectrum because of contaminant γ rays of energies 3787 keV (double escape peak of a 4809 keV γ ray) and 3770 keV, both apparently arising from the $^{27}Al(\alpha, p\gamma)^{30}Si$ reaction. A coincidence system similar to that used at the 9298 keV resonance therefore was set up, with the discrimination level in the NaI(Tl) side lowered to 4.2 MeV in order to have a reasonable efficiency for detecting the 5.58 MeV primary γ ray. Figure 6 shows the coincidence spectrum for an accumulated charge of 0.87 C on the target. A total of 1950 ± 51 counts was collected in the $9338 \to 7216$ peak, and 21 ± 8 counts in what appears to be a peak at 3756 keV. Taking into account relative efficiencies, angular correlation factors, and the branching of the 3756 keV level, the coincidence spectrum leads to an estimate of $(2.5 \pm 1.0)\%$ for the ($9338 \to 3756$) branch. A reexamination of the singles spectrum (e.g. Fig. 7 for an accumulated charge of 2.16 C) also shows small peaks which can now be interpreted as the primary ($R \to 3756$) transition. Taking all of our singles data into account as well as the coincidence spectrum, our final estimate for the ($9338 \to 3756$) branch is $(2.4 \pm 0.6)\%$.

IV. DISCUSSION

The question to which we now address ourselves is whether the 9338 and 9298 keV levels can be interpreted as an isospin-mixed doublet. In such a model we assume mixing between two 0^+ states of

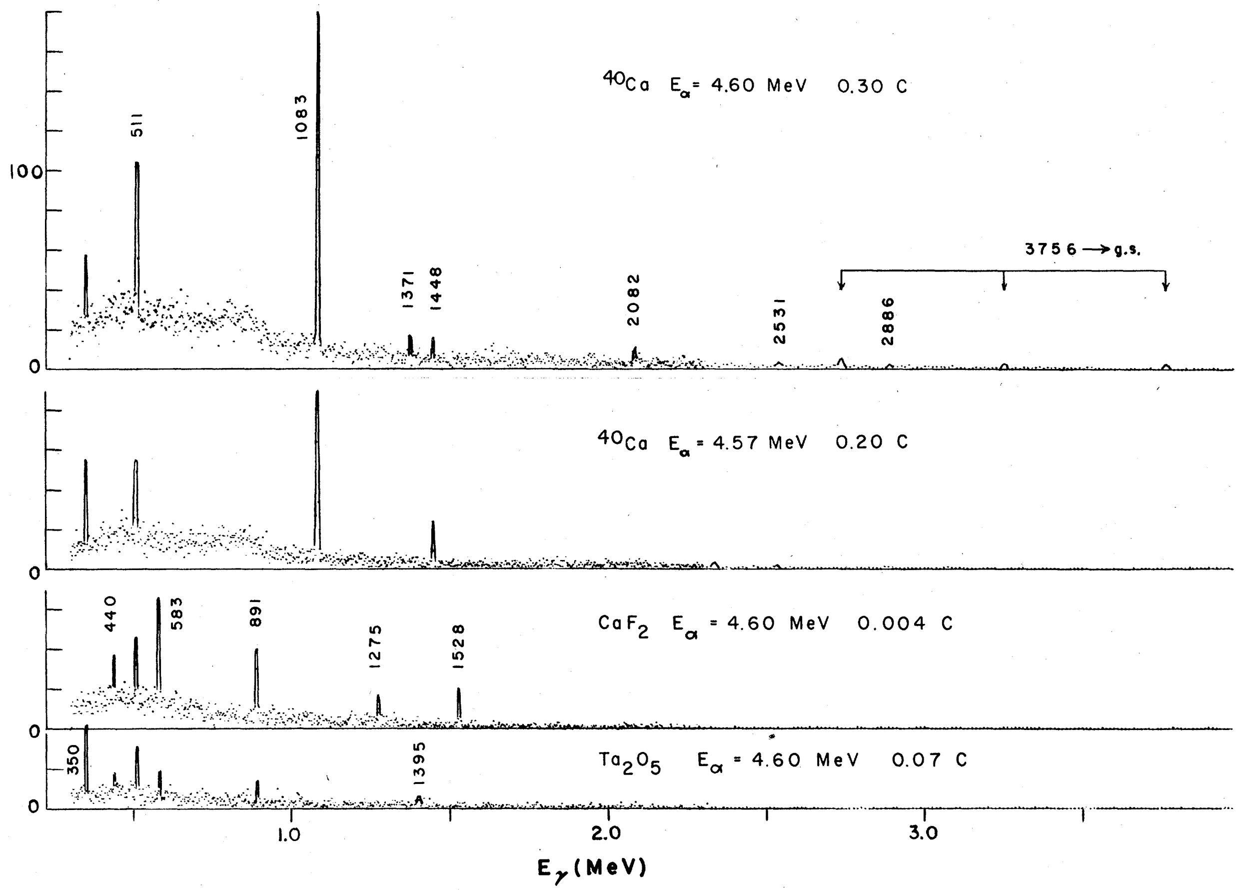

FIG. 4. Spectra at 90° for coincidences between a Ge(Li) and a NaI (Tl) detector when more than 5 MeV is given up in the NaI (Tl) detector. The "off-resonance" run at $E_\alpha = 4.57$ MeV shows evidence of the strong resonances in ^{40}Ca (α, γ) at $E_\alpha = 4.52$ MeV, the target thickness being about 30 keV. For the ^{40}Ca targets the calculated number of random coincidences is less than one for any of the labeled peaks above 1 MeV. For the CaF_2 target there is a significant random contribution for all peaks [e.g., the 1275 keV peak from the ^{19}F (α, $p\gamma$) ^{22}Ne reaction is almost entirely random, while the 1528 keV peak from ^{19}F (α, $n\gamma$) ^{22}Na is mostly real]. For the Ta_2O_5 target only the 350 keV peak contains significant random counts. These spectra show that the 2082 keV peak seen in coincidences at $E_\alpha = 4.60$ MeV with the ^{40}Ca target is not due to fluorine or oxygen contamination.

The 9298 → 7216 transition

Unfortunately the 9298 → 7216 primary γ ray is completely obscured in a singles spectrum by the 2082 keV γ ray from the ^{19}F($\alpha, p\gamma$)^{22}Ne reaction. In order to verify the decay of the 9298 keV resonance by this transition, it was necessary to set up a coincidence system which would be sensitive to a 2082–7216 cascade but not to the (α, p) reaction. Coincidences were taken between a Ge(Li) detector, and a NaI(Tl) detector for which a discriminator excluded γ rays of less than about 5 MeV. Each detector was placed at one of the 90° positions on either side of the target in the horizonal plane containing the beam in order to maximize the expected 0 → 1 → 0 angular correlation. Figure 4 shows the coincidence spectrum in the Ge(Li) detector at the $E_\alpha = 4.60$ MeV resonance. There is a peak at 2082 keV corresponding to the 9298 → 7216 transition, but there is also a significant background in this region of the spectrum. An "off-resonance" run at $E_\alpha = 4.57$ MeV shows background counts in the neighborhood of 2082 keV, as well as the 1083 and 1448 keV γ rays characteristic of ^{44}Ti. (These γ rays probably are being produced in the resonance at $E_\alpha = 4.52$ MeV). Since fluorine and oxygen are major contaminants in calcium targets, and can produce γ-n coincidences from the ^{19}F($\alpha, n\gamma$) and ^{18}O($\alpha, n\gamma$) reactions, we also show coincidence runs carried out with CaF_2 and

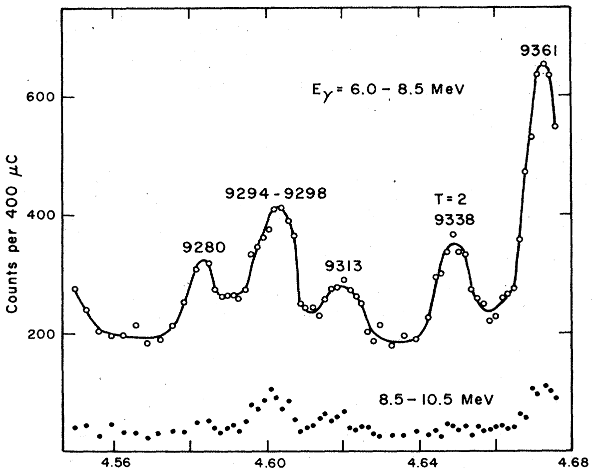

FIG. 2. Excitation function for the ^{40}Ca (α, γ) ^{44}Ti reaction taken with a NaI (Tl) detector. Target thickness was about 10 keV on a tungsten backing. Note the two γ-ray windows. Peaks are labeled with the ^{44}Ti excitation energy in keV (uncertainty ± 2 keV).

the γ decay of the $T=2$ level at 9338 keV.

Figure 1 shows some of the energy levels of ^{44}Ti which are involved both in the experimental work and in the interpretation of the results.

II. THE 9294-9298 keV DOUBLET

A ^{4}He$^+$ beam of 4.6 MeV was provided by the NRC Van de Graaff accelerator. Targets were made by the reduction-evaporation of ^{40}Ca onto gold or tungsten substrates, and were transferred in an inert atmosphere to the target chamber. Figure 2 shows a NaI(Tl) excitation function for α energies between 4.55 and 4.68 MeV. There are at least three resonances below the $T=2$ resonance which could be considered candidates for the lower member of an isospin-mixed doublet. When the γ-ray spectra of these resonances were examined with a large Ge(Li) detector, however, only the resonance at $E_\alpha = 4.60$ MeV showed a 7216 keV γ ray, which is a necessary (but not sufficient) condition for the presence of a $T=2$ component. At this α energy there were a number of other γ-ray transitions as well, including a transition to the ground state, so that if the 7216 keV γ ray was to be attributed to the decay of an isospin-mixed 0^+ level, then the resonance seen at $E_\alpha = 4.60$ MeV had itself to be considered a closely-spaced doublet of different spins. Measurements to be described below showed that the excitation of the stronger member of this doublet was 9294 ± 2 keV, and the resonance feeding the 7216 keV level was about 4 keV higher, i.e., at 9298 ± 2 keV.

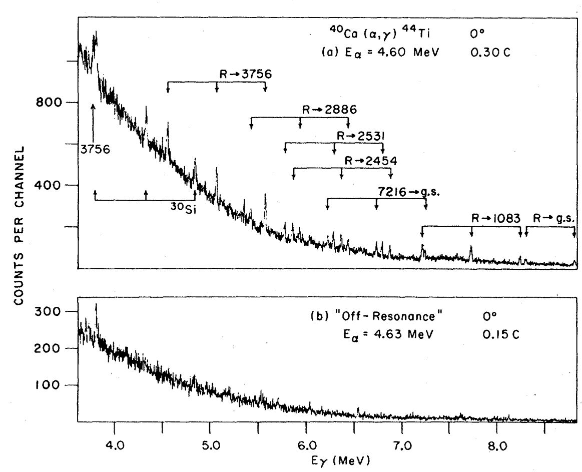

FIG. 3. Ge(Li) γ-ray spectrum for (a) the resonances at 9294–9298 keV in ^{44}Ti and (b) "off-resonance". Target thickness was about 24 keV on a tungsten backing. The 4.8 MeV γ-ray labeled "^{30}Si" originates in aluminum contamination.

TABLE I. Experimental gamma-ray branching ratios for resonances with $T=2$ component (percentages).

Final state E_x (keV)	J^π	Combined 9294–9298 keV	9338 keV
0	0^+	10 ± 2	...
1083	2^+	31 ± 3	<0.16(1 $s.d.$)
2454	4^+	8 ± 2	...
2531	2^+	7 ± 2	<0.5
2886	2^+	9 ± 2	<0.5
3756	$(1^\pm, 2^+)$	25 ± 3	2.4 ± 0.6
7216	$1^+, T=1$	10 ± 2	97.6 ± 0.6

Branching ratios and angular distributions

A γ-ray spectrum for the combined 9294–9298 keV resonances is shown in Fig. 3, and branching ratios for the primary transitions are given in Table I. The transition to the ground state is much stronger at 55° than at 0° or 90°, indicating a $2^+ \to 0^+$ transition. The angular distributions of the transitions to the 1083-, 2454-, 2531-, and 2886-keV levels are also all consistent with the spin of the resonance being 2^+. The 7216 keV γ ray is essentially isotropic, and it was assumed to arise from a 0^+ resonance at 9298 keV, although 2^+ could not be ruled out unambiguously from the angular distribution. The energy of 9298 keV is consistent with the energy of the $J=0$ state seen in the (p, t) reaction.[4]

sion.

Although the 0^+, $T=2$ state is likely to be of a simple shell-model character, there is no reason to suppose that the 0^+, $T_<$ state is exclusively of four-particle character, except that it does mix with the $T=2$ state. Nevertheless it may be of some interest to examine the shell-model 0^+ states predicted at these energies. In Fig. 1 are shown 0^+ levels predicted by $(fp)^4$ shell-model calculations within the complete f-p shell. With the single-particle energies chosen,[10] the third calculated 0^+, $T=0$ level in ^{44}Ti happens to lie very close to the calculated 0^+, $T=2$ level, and perhaps can be identified with the 0^+, $T_<$ level found experimentally. The calculated width for decay to the 1^+, $T=1$ state is $\sim 5\times 10^{-3}$ eV (using the experimental energy separation), which implies a value of $R\approx 0.08$, consistent with experiment. However, the calculated $E2$ width for decay to the first 2^+ state is $\sim 5 \times 10^{-2}$ eV (using an effective charge of $0.5e$), which is a factor of 5 to 10 higher than allowed by the upper limit[2] on the $9338 \rightarrow 1083$ transition with the assumption of mixing. This discrepancy perhaps is not serious because it is always difficult to calculate weak transitions accurately. However, we must reiterate that in contrast to the 0^+, $T=2$ state, shell-model calculations are not likely to be very helpful in accounting for the decay properties of the 0^+, $T_<$ state.

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