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Levels of ^{44}Ti from the ^{40}Ca(α,γ)^{44}Ti reaction

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Evidence on the lifetimes and spins of the bound levels of ^{44}Ti as obtained from the ^{40}Ca(α,γ)^{44}Ti reaction is presented. Lifetimes were obtained by the Doppler shift attenuation method, and spins from angular distribution and transition strength arguments. Weak γ-ray branches have been established in γ-γ coincidences between Ge(Li) and NaI(Tl) detectors. Present information supports the interpretation of most of the bound levels of ^{44}Ti in terms of rotational-like bands.

[NUCLEAR STRUCTURE ^{44}Ti; measured levels, $T_{1/2}$, $\gamma(\theta)$, $\gamma\gamma$ branching; deduced J, π, transition strengths. Enriched targets, Ge(Li) and NaI(Tl) detectors.]

I. INTRODUCTION

Energy levels of ^{44}Ti have now been established from studies of the ^{40}Ca(α,γ)^{44}Ti reaction,[1-7] the ^{46}Ti(p,t)^{44}Ti reaction,[8-10] the ^{40}Ca(^{6}Li$,d$)^{44}Ti reaction,[11] the ^{40}Ca(^{7}Li$,t$)^{44}Ti reaction,[12,13] the ^{40}Ca(^{16}O$,^{12}$C)^{44}Ti reaction,[14,15] the ^{32}S(^{14}N$,pn\gamma$)^{44}Ti reaction,[16-20] and the ^{28}Si(^{19}F$,p2n\gamma$)^{44}Ti reaction.[17] In this paper we give a summary of the known energy levels (Table I) and summarize the evidence from (α,γ) studies which has led to many of the lifetime and spin assignments. Important evidence on the γ-ray branching of the bound levels has been obtained from γ-γ coincidence measurements in the (α,γ) experiments and is also presented.

The yrast levels up to 12^+ are very well described by an $(fp)^4$ shell-model calculation.[2,16] However, there are many more levels at low excitation energy than can be accounted for by the $(fp)^4$ model. These levels, which can be grouped into rotational-like bands,[18] undoubtedly arise from deformed many-particle–many-hole configurations which are not amenable to easy calculation. However, we have shown[19] that the low-lying positive-parity levels can be described by the soft asymmetric rotor model, although this model would not appear to be satisfactory for the 10^+ and 12^+ yrast levels.

Most technical details of the (α,γ) experiments will be found in previous publications[3,5] and only essential or novel details will be presented here.

II. EXCITATION FUNCTIONS

Excitation functions for the ^{40}Ca(α,γ)^{44}Ti reaction for the energy range $4.5 < E_\alpha < 6$ MeV are shown in Figs. 1 and 2. Two γ-ray windows on the NaI(Tl) detector have been chosen. The window $7.5 < E_\gamma < 11.0$ MeV includes the transitions ($R\to$ g.s.) and ($R\to 1083$), while resonances which appear only in the $4.5 < E_\gamma < 7.5$ MeV window feed the higher bound states. Excitation functions below $E_\alpha = 4.5$ MeV can be found in earlier papers by Vernotte *et al.*[1] and by Simpson, Dixon, and Storey.[3]

The excitation functions in Figs. 1 and 2 were taken with an automatic scanning device which proved adequate for survey purposes but was not used for the detailed study of individual resonances. The National Research Council 4-MV Van de Graaff accelerator was used to supply singly and doubly charged α beams up to 6 MeV.

Resonances in the ^{40}Ca(α,γ)^{44}Ti reaction are listed in Table II. In many cases there are unresolved resonances or other experimental difficulties which have made the γ-ray decay schemes ambiguous. Since our main concern has been to obtain information on the bound levels of ^{44}Ti, we have not attempted to make a complete investigation of all of these resonances, but have rather selected a few for more detailed study. The branching ratios for these resonances are given in Table III. It should be noted that there are many incorrect branchings given in similar, but apparently preliminary reports of Chilosi, Rossi-Alvarez, and Vingiani[6] and of Britz *et al.*[7]

Some resonance strengths have also been measured by comparing the intensity of resonant γ rays with a calibrated ^{60}Co source located at the same position as the target. A brief description of the method is given in Ref. 3. These strengths are listed in Table II.

TABLE I. Levels of ^{44}Ti from various reactions. See text for references.

Best values E (keV)	Best values J^π	^{40}Ca(α,γ)^{44}Ti	J^π	^{32}S(^{14}N,$pn\gamma$)^{44}Ti	^{28}Si(^{19}F,$p2n\gamma$)^{44}Ti	J^π	(p,t) (±5 keV)	J^π	(^{6}Li,d) (±20 keV)	J^π	(^{16}O,^{12}C) (±30 keV)
0	0^+	0	0^+	0	0	0^+	0	0^+	0	0^+	0
1083.05 ±0.07	2^+	1082.9 ±0.1	2^+	1082.9 ±0.1	1083.2 ±0.1		1082 ±2	2^+	1080	2^+	1070
1904.3 ±0.3	0^+	1904.3 ±0.3	(0^+)				1903 ±7	0^+	1900	0^+	
2454.3 ±0.2	4^+	2454.1 ±0.3	4^+	2454.3 ±0.5	2454.4 ±0.2	(4^+)	2450	(4^+)	2440	4^+	2450
2530.6 ±0.2	2^+	2530.6 ±0.2	2^+				2535	(2^+)	2520	2^+	2540
2886.6 ±0.4	2^+	2886.6 ±0.4	2^+				2885	2^+			
3175.8 ±0.3	(3^-)	3175.7 ±0.4	(3^-, 2^+)	3175.8 ±0.8	3176.4 ±0.8	(3^-)	3175	(2^+)			
3364 ±1	4^+	3364 ±1					3365	4^+	3350	4^+	3370
3415.3 ±0.3	3^+	3415.3 ±0.3	(3^+, 2^+)								
3645.8 ±0.3	(4^-)	3645.8 ±0.4	(4^-, 3^+)	3645.4 ±0.8	3646.3 ±0.8	(4^-)					
3755.9 ±0.4	(2^+)	3755.9 ±0.4	(1, 2^+)				3760 ±30	(2^+, 3^-)	(3740)		3780
3942.7 ±0.3	(3^-)	3942.7 ±0.3					3942	(3^-, 2^+)	3920		
3980 ±1	4^+	3980 ±1					3980	4^+			
4015.3 ±0.2	6^+	4015.2 ±0.4	6^+	4015.0 ±0.6	4015.3 ±0.2	(6^+)	4015	(5^-, 6^+)	4000	>4	3990
4061.2 ±0.3	(5^-, 3^-)	4060.5 ±0.4	(5^-, 3^-, 4^+)	4060.9 ±0.5	4062.1 ±0.4	(5^-)	4060	4^+			
4116.5 ±1.0	2^+	4116.5 ±1.0	2^+						4100	2^+	4120
4227 ±1		4227 ±1									
							4605	0^+			
4792.2 ±0.5		4792.2 ±0.5					4792	(2^+, 4^+)			
									4840	(0^+)	4870
							5055	(4^+)	5080		
									5230		5250
5305 ±2		5305 ±2					5315 ±10		5330	(4^+))	5380
		5423 ±5					5415 ±10	(2^+)			
							6030 ±10	(4^+)	6030		6050
									6220		6270
									6470		
6508.6 ±0.3	(8^+)			6507.7 ±1.4	6508.6 ±0.3	(8^+)					
							6535 ±10				6540
							6600 ±10	2^+, $T=1$			
							6965 ±10	(4^+, $T=1$)			6960
											7140
7216 ±2	1^+, $T=1$	7216 ±2	1^+, $T=1$								
											7360
									7560		
7671.1 ±0.4	(10^+)			7670.5 ±1.5	7671.1 ±0.4	(10^+)	7670 ±10		7670		7658
											7690
											7780
8039.9 ±0.4	(12^+)			8039.5 ±1.5	8039.9 ±0.4	(12^+)			8040	>6	8050
									8380		8390
									8540	(0^+)	8570
9338 ±2	0^+, $T=2$	9338 ±2 [a]	0^+, $T=2$				9330 ±10				9310

[a] See Table II for 42 levels in the region 8565–10 520 keV.

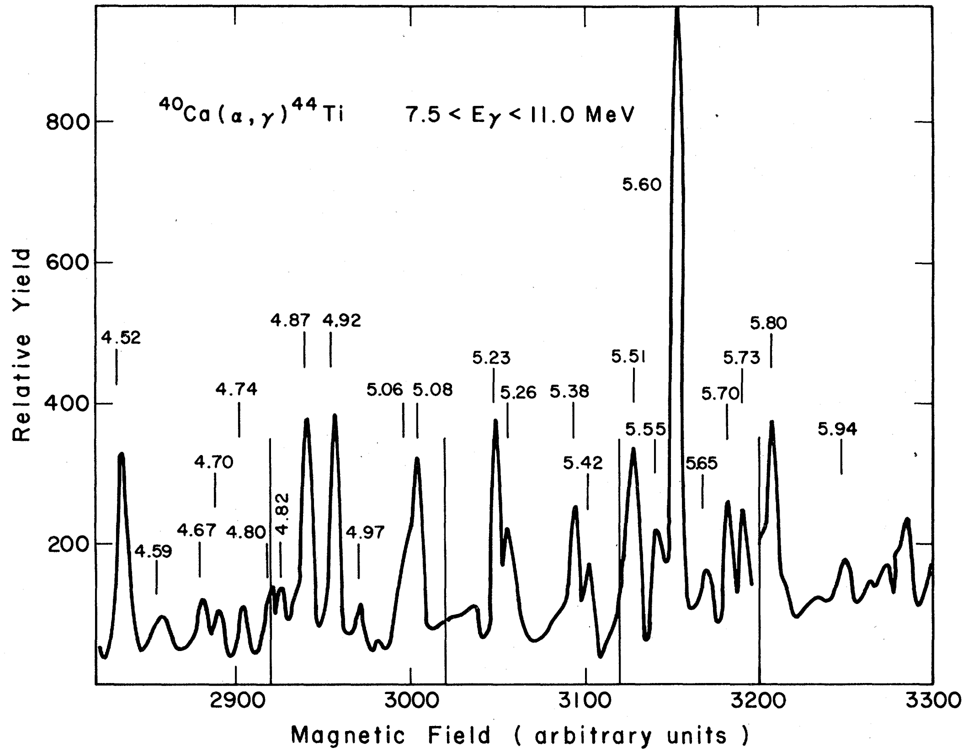

FIG. 1. γ-ray excitation curve for ^{40}Ca(α, γ)^{44}Ti taken with an NaI(Tl) detector. The γ-ray window includes the ($R \rightarrow 0$) and ($R \rightarrow 1083$) transitions. The peaks are labeled with the resonance energies in MeV. The light vertical lines indicate the limits of individual scans; scans are not exactly normalized to one another.

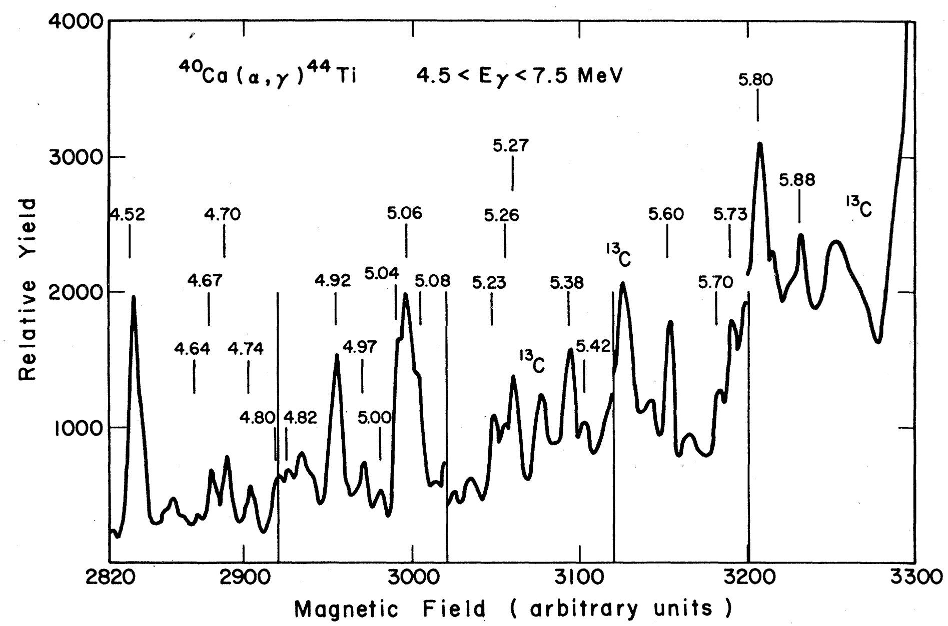

FIG. 2. γ-ray excitation curve for ^{40}Ca(α, γ)^{44}Ti taken with a γ-ray window 4.5–7.5 MeV. See caption for Fig. 1.

TABLE II. Resonances in the ^{40}Ca(α,γ)^{44}Ti reaction.

E_α (MeV)	E_x (keV)	J^π	$\omega\gamma$ (eV)
3.79	8565 ± 5	(0^+)	
3.86	8629 ± 10	2^+	
4.00	8754 ± 3	$1^-, 2^+$	
4.21	8946 ± 3		0.11 ± 0.02
4.22	8954 ± 3	1^-	0.6 ± 0.1
4.22	8955 ± 3		
4.257	8987 ± 2	2^+	0.3 ± 0.06
4.263	8992 ± 2	4^+	0.6 ± 0.1
4.35	9073 ± 5		
4.38	9100 ± 5		
4.40	9120 ± 5		
4.42	9140 ± 5		
4.47	9180 ± 5		
4.52	9227 ± 2	2^+	6 ± 1
4.59	9290 ± 5		
4.64	9338 ± 2	$0^+, T=2$	0.24 ± 0.05
4.67	9361 ± 3	($2^+, 3^-$)	1.2 ± 0.3
4.70	9388 ± 5		
4.74	9427 ± 5	(4^+)	0.9 ± 0.3
4.80	9478 ± 5		
4.82	9500 ± 10		
4.87	9542 ± 5		
4.92	9589 ± 5		
4.97	9632 ± 10		
5.00	9668 ± 10		
5.04	9698 ± 5	2^+	
5.06	9713 ± 3	(4^+)	2.5 ± 0.5
5.08	9737 ± 5		
5.23	9873 ± 10		
5.26	9895 ± 5		
5.27	9908 ± 3	{$2^+, 3^-$ / $4^+, 5^-$}	1.9 ± 0.4
5.38	10 014 ± 10		
5.42	10 046 ± 10		
5.51	10 129 ± 5	(1, 2)	
5.55	10 166 ± 10		
5.60	10 209 ± 5	≤2	
5.65	10 258 ± 10		
5.70	10 303 ± 5		
5.73	10 327 ± 5		
5.80	10 386 ± 6	($2^+, 3^-$)	5 ± 1
5.88	10 461 ± 10		
5.94	10 520 ± 10		

III. DOPPLER SHIFT ATTENUATION (DSA) LIFETIME MEASUREMENTS

All of our Doppler shift lifetime measurements for levels in ^{44}Ti, including many new results, are summarized in Table IV. The method used has been described in an earlier publication.[5] We merely mention here two essential features: (1) the use of thick Ca targets to serve both as target and as the slowing-down medium for the recoiling ^{44}Ti ions; (2) the use of both zero-point and gain stabilization with radioactive sources to permit an accurate measurement of the Doppler shift.

As an example of the method, the measurement of the lifetime of the 6^+ state at 4015 keV is shown in Fig. 3. At the $E_\alpha = 4.74$ MeV resonance, the (4015 → 2454), $6^+ \to 4^+$ transition is observed to have a 0°–90° shift of 3.3 ± 0.3 keV, and the kinematic shift is calculated to be 6.95 keV (attenuated by a factor of 0.97), so that $F(\tau) = 0.47 \pm 0.04$. The corresponding value of the mean lifetime is $\tau = 0.56 \pm 0.08$ ps.

Also included in Table IV are a few values of τ that have been estimated from line shapes at 0°. Most of these line shapes have been obtained in the γ-γ coincidence runs; some examples are shown in Fig. 4. For the case shown in Fig. 4 the target was not thick enough to stop completely the recoiling ^{44}Ti ions, and since the slowing-down time in the Au backing is much shorter than in Ca, the unshifted peak is relatively stronger than in the thick target case. Figure 4 shows how the lifetime of the 3980-keV, 4^+ level can be estimated from the (3980 → 1083) line shape, although it overlaps the shifted part of the (2886 → g.s.) line shape, by using the shape of the (2886 → 1083) transition for the latter.

Measurement of the lifetimes of the 4792- and 5305-keV levels has presented some difficulty because these levels seem to be excited at the same resonances and have overlapping escape peaks. The lifetime of the 5305-keV level was estimated from the 0° line shape of the (5305 → 1083) transition at the $E_\alpha = 4.70$ MeV resonance. The lifetime of the 4792-keV level was estimated from the 0° line shape obtained in a γ-γ coincidence run in which the primary ($R \to 5305$) γ ray was excluded in the NaI(Tl) window. (See Sec. IV.) The centroid shifts of the (4792 → 1083) double-escape peak at 2687 keV were found to be uncertain because of the single-escape peak of a contaminant γ ray of about 3200 keV.

Table IV also contains three measurements of lifetimes using the recoil-distance method,[20] or pulsed-beam electronic timing.[21] The recoil-distance measurements are in agreement with the DSA measurements within the quoted errors.

IV. BRANCHING RATIOS

Table V summarizes branching ratios for the bound levels of ^{44}Ti. In many cases the weaker branches have been obtained from γ-γ coincidence measurements taken with an annular NaI(Tl) detector surrounding the target and a Ge(Li) detector placed at 0° to the beam. A broad window was set on the NaI side to detect primary γ rays and the coincidence spectrum in the Ge(Li) detector was recorded. The observed relative intensities of

TABLE III. γ-ray branching ratios for some resonances in $^{40}Ca(\alpha,\gamma)^{44}Ti$.

Resonance E_α (MeV)	E_x (keV)	Decay in percentages to (E_x, J^π) 0 0^+	1083 2^+	2454 4^+	2531 2^+	2886 2^+	3176 (3^-)	3415 3^+	3646 (4^-)	3756 ($1,2^+$)	Other
4.52	9227 ± 2	1.3 ± 0.5	24 ± 1		45 ± 2	8 ± 2		22 ± 2			
4.64	9338 ± 2										7216(100)
4.67	9361 ± 3	6 ± 2	18 ± 2	3 ± 1	4 ± 1	4 ± 1	19 ± 2	2 ± 1	4 ± 1		3943(5 ± 1), 3980(6 ± 1), 4116(4 ± 1), 4227(4 ± 1), 4792(12 ± 2), 5305(6 ± 2) 5423(3 ± 1)
5.04	9698 ± 5	1.3 ± 0.3	1.3 ± 0.3	3 ± 1	6 ± 2	28 ± 2	3 ± 1	49 ± 2			4116(9 ± 2)
5.06	9713 ± 3		8 ± 2			12 ± 3		19 ± 3		46 ± 3	4227(3 ± 1), 4792(12 ± 3)
5.27	9908 ± 3		3.0 ± 1.5				8 ± 3		31 ± 3	11 ± 3	4061(47 ± 4)
5.80	10 386 ± 6	2 ± 1	21 ± 2			16 ± 2	23 ± 3		13 ± 2		3943(20 ± 3), 4227(4 ± 2)

course pertain to 0° and have been corrected by angular distribution factors, if known, to give the true branching ratios, or if not known, the error on the branching ratio has been made large enough to include this uncertainty. The observed intensities of crossover transitions must be corrected for cascade summing in the Ge(Li) detector; estimates of the expected summing intensities were made using radioactive sources of known strengths in the same geometry. Although the γ-γ coincidence method reduces the general background, and eliminates many contaminant γ rays which obscure the weaker γ rays in singles spectra, there are still some contaminant γ rays in the coincidence spectra, for example from $(\alpha, n\gamma)$ reactions for which the neutron may be recorded in the NaI(Tl) detector and the γ ray in the Ge(Li). Specific contaminant problems are mentioned in the summary of levels in Sec. VI.

The importance of the coincidence method lies in establishing weak transitions. Consider for example the (3176 → g.s.) transition shown in Fig. 5(c). The observed peak intensity is well in excess of that expected from γ-γ summing in the Ge(Li)

TABLE IV. Mean lifetimes of ^{44}Ti levels.

Level (keV)	Transition energy (keV)	(α,γ) Resonance energy (MeV)	Centroid shift in thick target $F(\tau)$	τ (ps)	τ (ps) Estimated from 0° line shape	τ (ps) Other methods
1083	1083	4.00	0.068 ± 0.012	4.5 ± 1.1 [a]		5.0 ± 2.0 [a,b]
1904	821	4.22	< 0.4	> 0.7		
2454	1371	4.26	0.43 ± 0.04	0.6 ± 0.1		$1.0^{+1.0}_{-0.5}$ [b]
2531	1448	4.52	0.23 ± 0.02	1.4 ± 0.2		
2886	2886	4.52, 5.80	0.51 ± 0.04	0.5 ± 0.1		
	1803	4.70			0.5 ± 0.1	
3176	2093	4.22	< 0.12	> 3.0		
3364	2281	4.70	0.46 ± 0.09	0.6 ± 0.2	0.5 ± 0.1	
3415	2332	4.52, 4.70	0.41 ± 0.03	0.7 ± 0.1		
3756	3756	5.06	0.72 ± 0.05	0.24 ± 0.05		
	2673					
3943	2860	4.70, 5.80	0.29 ± 0.04	1.2 ± 0.3		
3980	2897	4.70, 4.74			0.5 ± 0.2	
4015	1561	4.74	0.47 ± 0.04	0.56 ± 0.08		
4061	1607	5.27	0.18 ± 0.08	$2.1^{+1.9}_{-0.7}$		
4116	4116	4.70	0.80 ± 0.08	0.16 ± 0.07		
	3033					
4792	3709	4.70			0.5 ± 0.2	
5305	4222	4.70			0.5 ± 0.2	
7671	1163					2.7 ± 0.5 [a,c]
8040	369					3.0 ± 0.6 ns [d]

[a] Corrected for precursors.
[b] Recoil-distance method, $^{32}S(^{14}N, pn\gamma)^{44}Ti$ (Ref. 20).
[c] DSAM, $^{32}S(^{14}N, pn\gamma)^{44}Ti$ (Ref. 16).
[d] Reference 21.

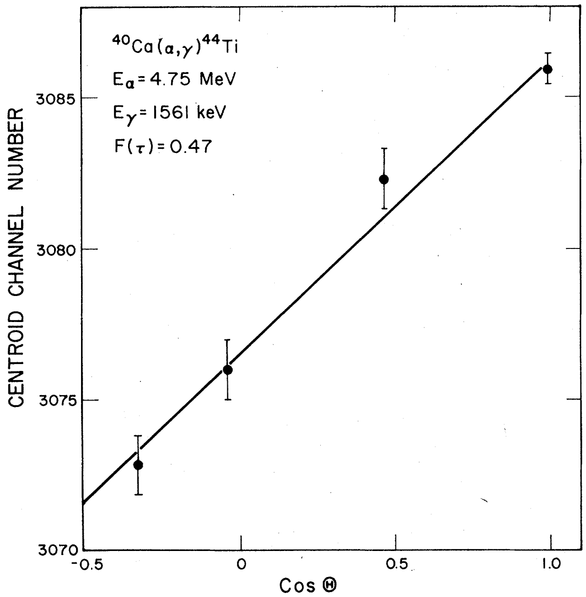

FIG. 3. Centroid shifts for the 4015→2454 transition observed with a thick ^{40}Ca target at $E_\alpha = 4.75$ MeV.

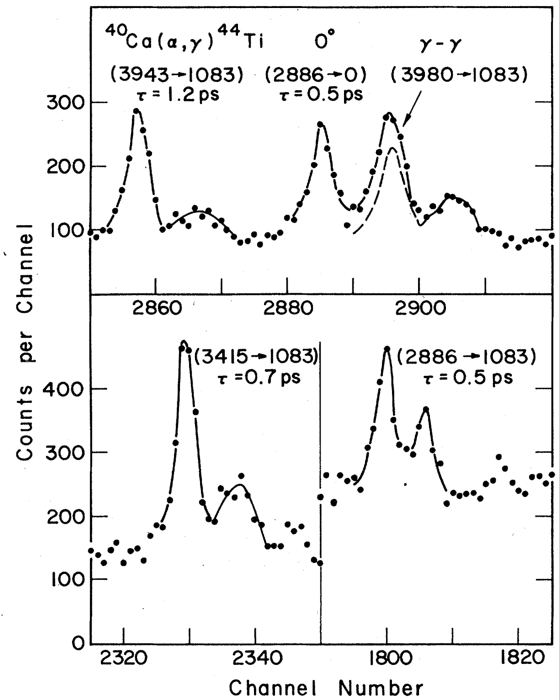

FIG. 4. Line shapes at 0° observed with γ-γ coincidences at $E_\alpha = 4.70$ MeV. The target thickness was about 50 keV. The line shape of the (2886→0) γ ray can be obtained from the shape of the (2886→1083) γ ray, and then subtracted from the observed shape to obtain the approximate shape of the (3980→1083) stopped peak (dashed line). The (3415→1083) and (3943→1083) line shapes are included for purposes of comparison.

detector, the net amount being about 2% of the main (3176→1083) branch. A correction must be made for the γ-ray angular distributions, and can be easily estimated since the NaI(Tl) detector essentially integrates over 2π. The result is a branch to the ground state of (1 ± 0.5)%. The fact that the decay of the 3176-keV level can be seen in these mea-

TABLE V. γ-ray branching ratios (%) for ^{44}Ti levels.

Initial level		Decay in percentages to (E_x, J^π)							Other levels
		0	1083	1904	2454	2531	2886	3176	
E_x	J^π	0^+	2^+	0^+	4^+	2^+	2^+	(3^-)	E_x (%)
1083	2^+	100							
1904	0^+		100						
2454	4^+		100						
2531	2^+	25 ± 5	71 ± 5	3.7 ± 0.5					
2886	2^+	59 ± 10	38 ± 10	3 ± 2					
3176	(3^-)	1 ± 0.5	97 ± 2		2 ± 1	<1			
3364	4^+		95 ± 2			5 ± 2			
3415	3^+		98 ± 1			<1.5	2.2 ± 0.5		
3646	(4^-)		<1		4 ± 2			96 ± 2	
3756	(2^+)	72 ± 5	28 ± 5	<4					
3943	3^-		94 ± 3		5 ± 2	<2		1 ± 1	
3980	4^+		52 ± 8		15 ± 5		25 ± 5	4 ± 3	3415(4 ± 2)
4015	6^+				100				
4061	(5^-)		<2		50 ± 5			50 ± 5	
4116	2^+	29 ± 5	45 ± 7	<5		21 ± 5	5 ± 5		
4227			6 ± 3			17 ± 4	29 ± 4	34 ± 4	3415(5 ± 3), 3646(9 ± 4)
4792			88 ± 3				3 ± 2	5 ± 2	3756(4 ± 2)
5305			× [a]						
5423			× [a]						

[a]Only transition observed.

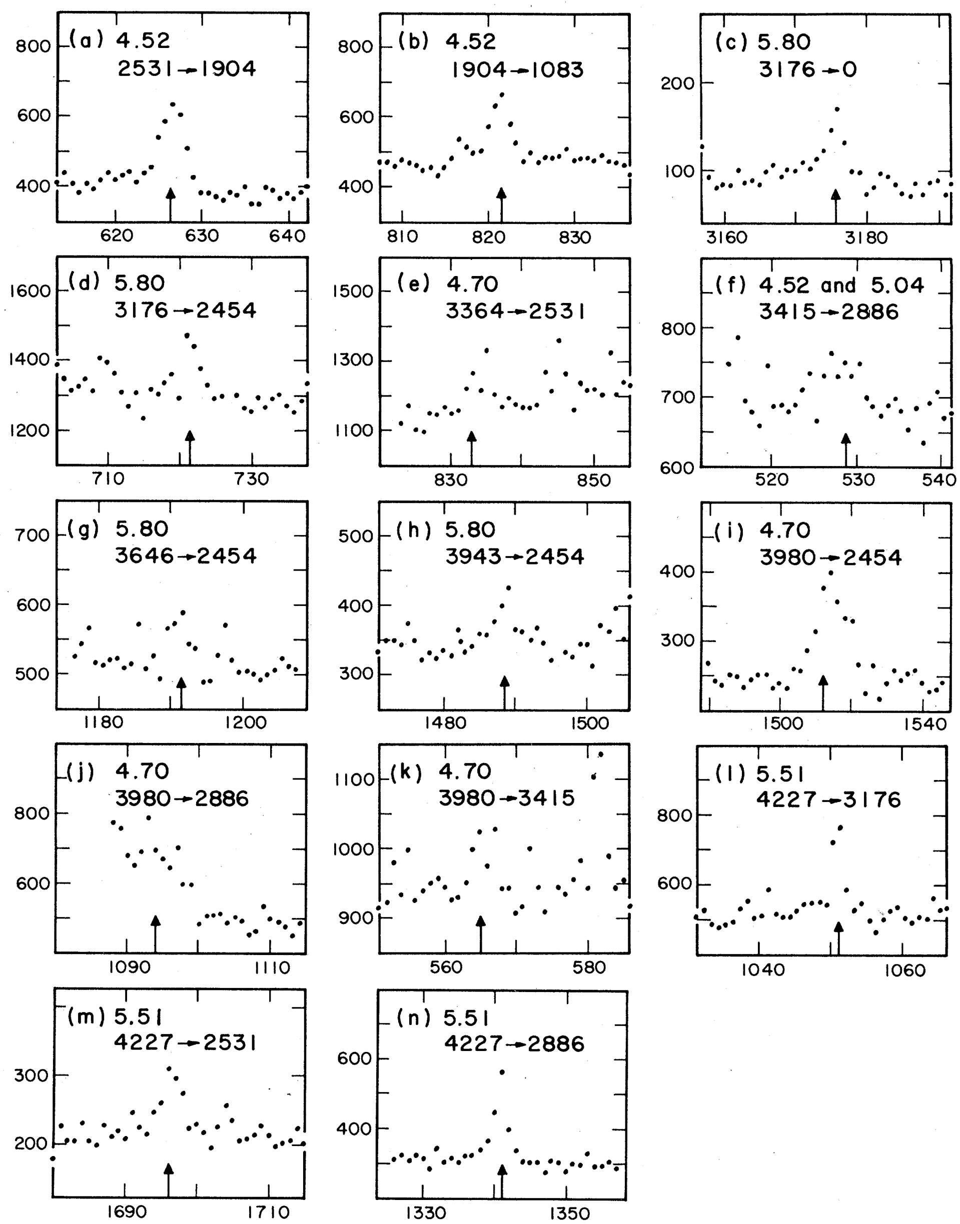

FIG. 5. A number of transitions in ^{44}Ti seen in γ-γ coincidences between an annular NaI(Tl) detector and a large Ge(Li) detector at 0°. In each figure the α-particle resonance energy is given in MeV, and below, the level energies in keV. The ordinates are counts per channel and the abscissas are keV. A number of contaminant γ rays arise from neutron interactions, e.g., 583, 891, and 1528 keV from ^{19}F$(\alpha,n)^{22}$Na, and 563, 596, 693, 834, 868, and 1039 keV from Ge isotopes. Observation of the ^{44}Ti γ rays at several resonances is therefore generally useful to check the intensities of the weak branches.

surements means that its lifetime is less than the coincidence resolving time (about 10 ns); spin 4 can now be ruled out for the 3176-keV level because the corresponding $E4$ transition strength would be at least 120 W.u.[22,23] Similarly the observation of the 3176 → 2454 (4$^+$) transition [Fig. 5(d)] rules out spin 1 for the 3176-keV level.

V. ANGULAR DISTRIBUTIONS

Angular distribution studies for the 2454-, the 2531-, and the 3415-keV levels have been presented in some detail in an earlier paper.[3] Some further clarifications on the 2454- and 3415-keV levels are given below, followed by new results on the

3756-, 4015-, and 4116-keV levels. Finally the assignment of negative parity to the levels at 3176, 3646, and 4061 keV will be discussed. In the following discussion the multipole mixing ratios δ are defined by the phase convention of Rose and Brink.[24]

A. (2454 → 1083) transition

Our earlier analysis[3] of the (2454 → 1083) transition showed that the spin of the 2454-keV level could be 4 [with $\delta = -(0.07^{+0.20}_{-0.12})$] or 3 [with $\delta = -(0.42^{+0.12}_{-0.09})$]. A spin of 3^- can be ruled out because of the $M2$ strength which would be implied for the 2454 → 1083 transition. We now argue that a spin of 3^+ is also highly unlikely on the basis of the distribution of strengths of T-inhibited $M1$ transitions as shown by Endt and van der Leun.[23] For $\delta = -0.42$, the $M1$ strength is 0.017 Weisskopf units (W.u.), which although not precluded has a low probability since it is well on the high side of the distribution of isoscalar $M1$ strengths; however, the probability of a much larger mixing ratio, which would reduce the $M1$ strength significantly, can be seen from our analysis to be small. The (α,γ) results therefore favor strongly the assignment of 4^+, in agreement with the results from other reactions.

B. (3415 → 1083) transition

The (3415 → 1083) transition was studied at the $E_\alpha = 5.04$ MeV resonance which provides strong feeds to the 2886- and 3415-keV levels. (There are two other resonances nearby, at 5.06 and 5.08 MeV, which also feed these levels, and it was necessary to keep the beam energy below them.) The spin of the $E_\alpha = 5.04$ MeV resonance was established as 2^+ from the (R → 2886) and (2886 → g.s.) transitions, given that the spin of the 2886-keV level is 2^+. Analysis of the (3415 → 1083) transition then showed that only spins 2 and 3 are acceptable for the 3415-keV level (see Fig. 6). For the choice of 2 for the spin of the 3415-keV level, the χ^2 for the (3415 → 1083) transition has a minimum in the (δ_1, δ_2) plane for large negative δ_2, and δ_1 not far from zero; we find $\delta_2 = -2.3^{+1.2}_{-4.0}$. For the choice of 3 for the spin of the 3415-keV level, we find that the only possibility is $|\delta_2| > 11$; a second value for δ_2 which was given previously[3] is now ruled out. The 3415-keV level cannot have negative parity because the $M2$ strengths would then be too large. Since the

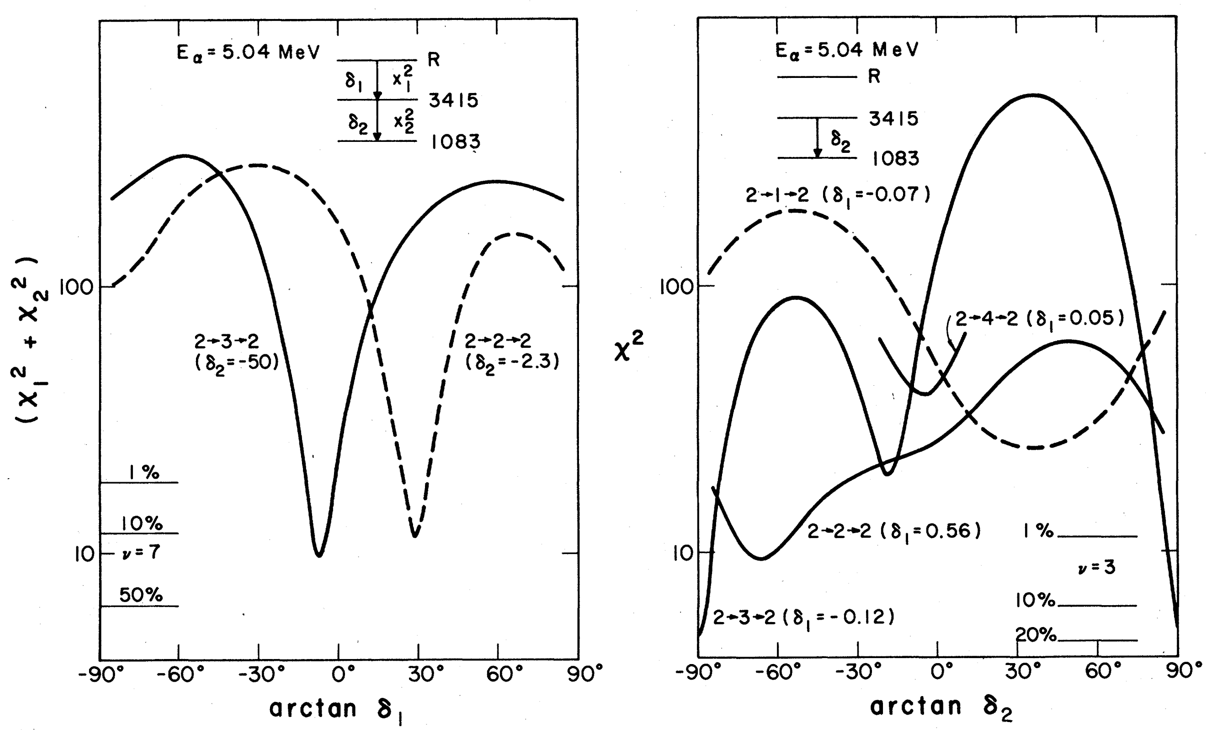

FIG. 6. Analysis of the (3415 → 1083) and (R → 3415) angular distributions at the $E_\alpha = 5.04$ MeV resonance. On the right χ^2 for the (3415 → 1083) angular distribution is plotted against δ_2 for choices of δ_1 determined either by minima in the (δ_1, δ_2) plane or by minima in the primary χ^2. (For 2 → 4 → 2, δ_1 is chosen close to zero to keep the octupole strength small.) On the left the χ^2 vs δ_1 plots for the primary have been improved by adding the χ^2 vs δ_1 of the secondary for selected δ_2's.

3415-keV level is not seen in the particle transfer reactions, it likely has unnatural parity and hence $J^\pi = 3^+$.

C. Spin of the 3756-keV level

The lifetime of the 3756-keV level and the presence of a 72% branch to the ground state limit its spin to $1^\pm$ or 2^+. An analysis of the angular distributions of the ($R \to 3756$) and the ($3756 \to$ g.s.) transitions at the $E_\alpha = 5.06$ MeV resonance has been carried out, with the result that the combinations $1\to1$, $1\to2$, $3\to2$, and $4\to2$ are all acceptable at the 1% confidence limit for the ($R \to 3756$) transition when the χ^2 for the primary and the secondary are combined (see Fig. 7). The $1^- \to 2^+$ and $3^- \to 2^+$ possibilities, however, both have large mixing ratios for the primary, which taken in conjunction with the measured $\omega\gamma$ (2.5 ± 0.5 eV) imply $M2$ strengths greater than 10 W.u. and can therefore be ruled out. A spin of 1^- for the resonance can also be ruled out on the ground that the $R \to 3415$ (3^+) transition is too strong, unless one supposes there to be an additional resonance within 1 or 2 keV. The remaining choice $4^+ \to 2^+$ is consistent with all available information on the resonance and provides a ready explanation for the observed fact the primary and secondary transitions have very similar distributions (stretched $E2$), although the fit is not particularly good. Additional evidence for the 2^+ assignment comes from the (p, t) results of Baer *et al.*,[10] who allowed spins of 2 and 3, but not 1.

D. 4015 → 2454 transition

Rapaport *et al.*[8] reported that the spin of the 4015-keV level was either 5^- or 6^+. Figure 8 shows how the ratio of 0° to 90° yields suffices to distinguish between these two possibilities and to establish the spin as 6.

E. Spin of the 4116-keV level

The 4116-keV level is seen at the $E_\alpha = 5.04$ MeV resonance (but not the 5.06 or 5.08 MeV resonances). Since it has a short lifetime and has a 29% branch to the ground state, its spin is restricted to 1 or 2. The analysis shown in Fig. 9 suggests that the spin is 2. If so, the parity must be positive since the $M2$ strength for an isoscalar ($2^- \to 0^+$) transition would be about 6 W.u., well above the limit of 0.1 W.u. recommended by Endt and van der Leun.[23]

F. "Negative-parity band"

The levels at 3176, 3646, and 4061 keV have interconnecting γ rays and relatively long lifetimes,

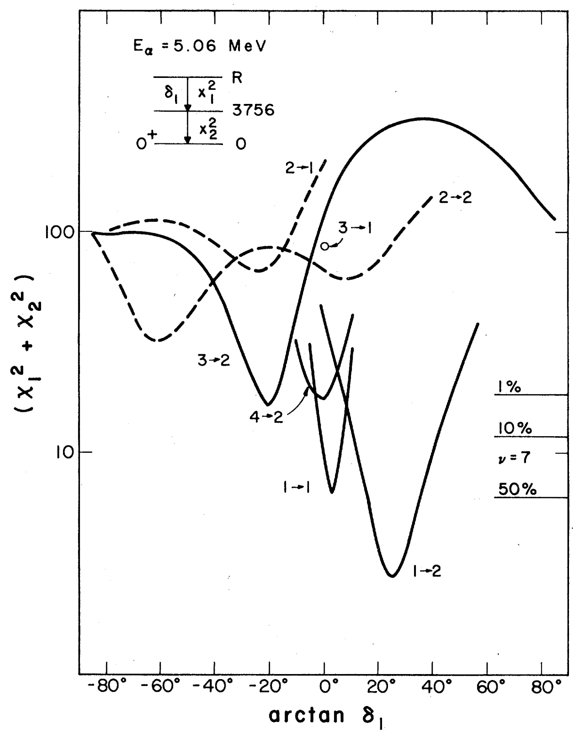

FIG. 7. Simultaneous fits to the $R \to 3756$ and $3756 \to 0$ angular distributions at the $E_\alpha = 5.06$ MeV resonance. The χ^2's for the two distributions are added and plotted against δ_1.

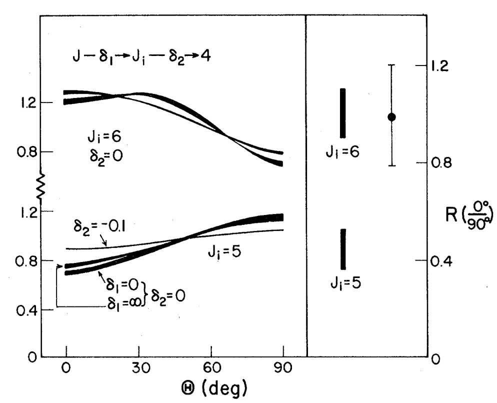

FIG. 8. Theoretical angular distributions are shown for the 4015 → 2454, $J_i \to 4^+$ transition for $J_i = 5^-$ and 6^+. Resonance spins of J_i, $J_i \pm 1$, and $J_i - 2$, and primary quadrupole-dipole mixing ratios of 0 and ∞ are included. The lifetime measurement restricts the secondary mixing ratio to values near zero. The ratio of intensities at 0° to 90° relative to the same ratio for the following $4^+ \to 2^+$ transition is shown at the right. The experimental ratio suffices to fix the spin as 6^+. A 60° to 90° ratio not shown also confirms spin 6^+.

suggesting a negative-parity band. A detailed study of the γ-ray angular distributions at the $E_\alpha = 4.22$ and 5.27 MeV resonances has been made to delimit possible spin combinations.

The 3176-keV level has spin 2^+ or 3^-. The evidence for this is summarized in Sec. VI below. The 3646-keV level is not seen in any of the particle transfer reactions, and hence is assumed to have unnatural parity. The angular distribution of the (3646 → 3176) transition at the $E_\alpha = 5.27$ MeV resonance requires a P_4 term, ruling out 0 and 1 for the spin of the 3646-keV level. Since this transition is seen in γ-γ coincidences, the lifetime of the 3646-keV level is less than about 10 ns. Further evidence on the 3646- and 3176-keV levels was obtained from a detailed study of angular distributions, which we now outline. The angular distribution of the (R → 3646) primary transition at the $E_\alpha = 5.27$ MeV resonance permits only spin combinations $J \to J \pm 1$ but not $J \to J$ or $J \to J \pm 2$. The angular distribution of the secondary (3646 → 3176) transition rules out spin sequences for which the spins of the 3646- and 3176-keV levels differ by two units. Sequences for which the spins of these two levels are the same are ruled out from the large mixing ratio δ_2 required for the 3646 → 3176 transition, and the argument that the 3646-keV level has unnatural parity in contrast to the 3176-keV level, resulting in too large an $M2$ strength. Good fits are obtained for four possible spin-parity sequences for $R \to 3646 \to 3176$: $2^+ \to 3^+ \to 2^+$, $3^- \to 4^- \to 3^-$, $4^+ \to 3^+ \to 2^+$, and $5^- \to 4^- \to 3^-$, and a rather poorer fit for $3^- \to 2^- \to 3^-$. For these sequences χ^2 has a sharp valley in the (δ_1, δ_2) plane for large values of δ_2, but the location of the valley is not sensitive to the value of δ_1. Figure 10 illustrates the dependence on δ_2, while Fig. 11 shows the sum of χ^2 for the primary and secondary plotted against δ_1 for the minimum in δ_2. The possibility that the 3646-keV level has spin 2 while the 3176-keV level has spin 3 can be firmly ruled out from a similar analysis of the $E_\alpha = 4.22$ MeV resonance leaving only the combinations 3^+ and 2^+, or 4^- and 3^- for these two levels.

The $E_\alpha = 5.27$ MeV resonance also feeds the 4061-keV level strongly, which in turn decays to the 2454-keV (4^+) and 3176-keV levels. The angular distribution of the 4061 → 2454 transition precludes spins 2 and 6 for the 4061-keV level, and the further detailed analysis of both secondary transitions leads to the possible spin combina-

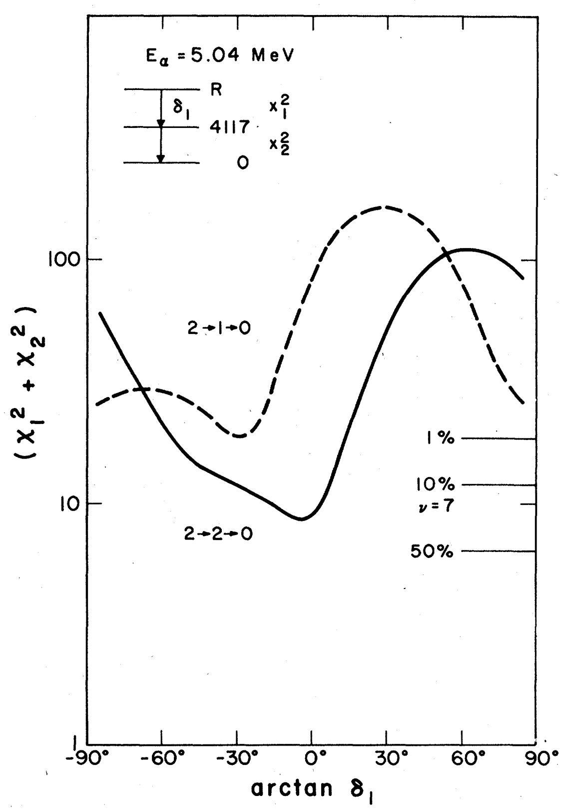

FIG. 9. Simultaneous fits to the (R → 4117) and (4117 → 0) angular distributions at the $E_\alpha = 5.04$ MeV, resonance. The χ^2's for the two distributions are added and plotted against δ_1.

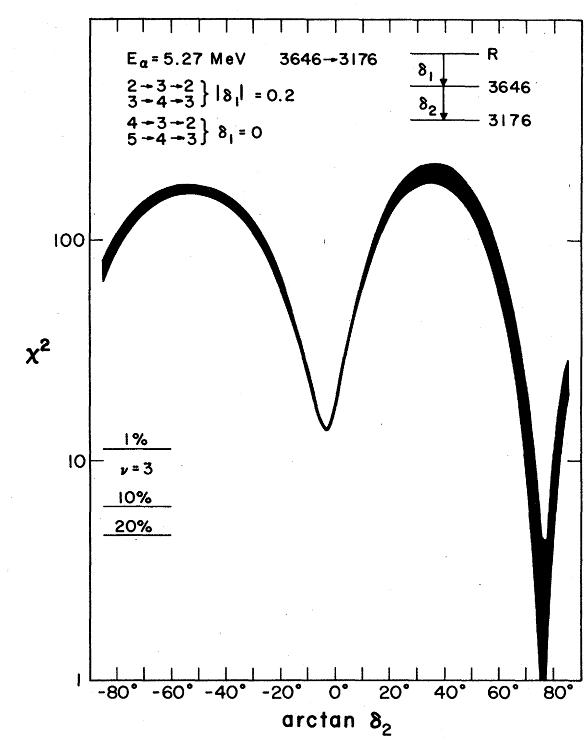

FIG. 10. Analysis of the (3646 → 3176) angular distribution at the $E_\alpha = 5.27$ MeV resonance. The four spin sequences shown (with δ_1's chosen from the analyses of the primaries) all favor large, positive values of δ_2.

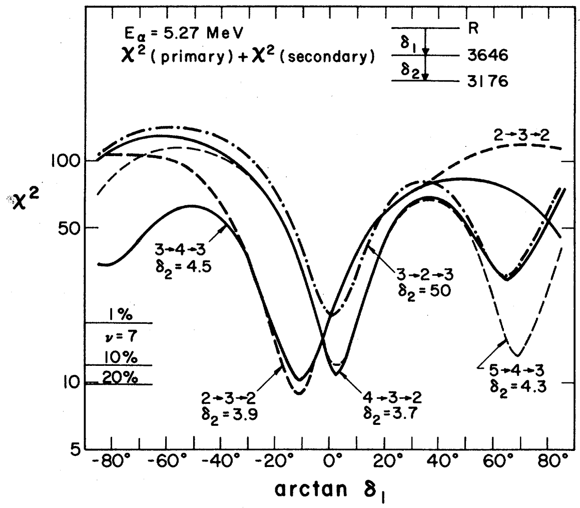

FIG. 11. Simultaneous fits to the ($R \rightarrow 3646$) and ($3646 \rightarrow 3176$) angular distributions for the four spin sequences shown in Fig. 10. The additional sequence $3 \rightarrow 2 \rightarrow 3$ can be ruled out.

tions summarized in Table VI.

A definitive choice between the positive- and negative-parity sequences for the 4061-, 3646-, and 3176-keV levels cannot be made on the basis of the present analysis. However, the negative-parity sequence provides a natural explanation for the long lifetimes of these levels and for the absence of cross transitions. In particular the absence of alternative decays of the 3646-keV level can be readily understood if the spin is 4^-, but not if it is 3^+. Transition strengths for both parity sequences are shown in Table VII. The lifetime of the 3176-keV level is greater than 3 ps, and if the spin is 3^-, this is consistent with an isospin

TABLE VI. Acceptable spin combinations for levels seen at the $E_\alpha = 5.27$ MeV resonance.

Resonance	$2^+, 4^+$	$3^-, 5^-$
4061	4^+	$3^-, 5^-$
3646	3^+	4^-
3176	2^+	3^-

forbidden $E1$ transition to the 1083-keV level, but if the spin is 2^+, the $E2$ transition to the ground state is very weak. Table VII also points up the strength of the ($4061 \rightarrow 3176$) transition: for the $5^- \rightarrow 3^-$ and $4^+ \rightarrow 2^+$ possibilities this is 40 W.u.

Further evidence which suggests that these levels probably have negative parity is that, of the excited states outside the ground-state band, they alone are fed in the heavy-ion fusion-evaporation reactions.[16,17]

VI. SUMMARY OF LEVELS

1083 keV. The first excited state of ^{44}Ti lies at 1083.0 ± 0.1 keV and is assumed to have $J^\pi = 2^+$. The mean lifetime from the DSA method[5] is $\tau = 4.5 \pm 1.1$ ps, and from a recoil-distance measurement[20] is $\tau = 5.0 \pm 2.0$ ps.

1904 keV. The 1904-keV level is assigned 0^+ by Rapaport *et al.*[8] and Kong-A-Siou *et al.*[9] from the (p, t) reaction, by Strohbusch *et al.*[11] from the $(^6\mathrm{Li}, d)$ reaction and by Chilosi *et al.*[6] from the (α, γ) reaction. Baer *et al.*[10] prefer a spin of 2 or 3. Our angular distributions[3] imply a spin of 0 or 2. The absence of a γ-ray transition to the ground-state and the lifetime limit ($\tau > 0.7$ ps)[5] are consistent with the spin 0 assignment.

It should be noted that at high bombarding ener-

TABLE VII. γ-ray decay strengths for "negative-parity" states of ^{44}Ti.

Initial state (keV)	Spin hypothesis	Final state (keV)	Final spin	Mixing ratio δ	Transition strengths (W.u.) $E1$	$M1$	$E2$	$M2$	$E3$
3176	2^+	1083	2^+	a	···	$<1.2\times10^{-3}$	<0.8	···	···
		0	0^+	0	···	···	$<1\times10^{-3}$	···	···
	3^-	1083	2^+	-0.15 ± 0.10	$<3\times10^{-5}$	···	···	<2	···
		0	0^+	0	···	···	···	···	<15
3646	3^+	3176	2^+	3.8	···	···	×	···	···
	4^-	3176	3^-	4.4	···	···	×	···	···
3943	3^-	2454	4^+	~0	1.0×10^{-5}	···	···	···	···
		1083	2^+	~0	2.6×10^{-5}	···	···	···	···
4061	3^-	3176	3^-	$\lvert\delta\rvert<2.0$	···	<0.015	<40	···	···
		2454	4^+	-0.15 ± 0.10	5×10^{-5}	···	···	<5	···
	4^+	3176	2^+	0	···	···	40	···	···
		2454	4^+	$\lvert\delta\rvert>0.5$	···	$<1.5\times10^{-3}$	<3	···	···
	5^-	3176	3^-	0	···	···	40	···	···
		2454	4^+	$\lvert\delta\rvert<0.1$	5×10^{-5}	···	···	<1	···

[a]Mixing ratio unknown.

gies there is the possibility of a contaminant γ ray from ^{18}O of the same energy as the (1904 → 1083) transition.

The 1904-keV level is generally believed to have particle-hole configurations, e.g., 6p-2h or 8p-4h. It is seen only weakly, if at all, in the ^{40}Ca(^{16}O, ^{12}C)^{44}Ti reaction,[14,15] but it does appear in the ^{40}Ca(^{6}Li, d) and ^{40}Ca(^{7}Li, t) reactions[11,12] resulting perhaps from the 2p-2h component in the ^{40}Ca ground state or from nondirect transfer.

2454 keV. This level is assigned 4$^+$ from the (p,t) and (^{6}Li, d) reactions. The angular distribution and lifetime measurements from (α,γ) combine to indicate a spin of 4$^+$ as well. The 2454-keV level is seen strongly in the (^{6}Li, d), (^{16}O, ^{12}C), ^{32}S(^{14}N, $pn\gamma$), and ^{28}Si(^{19}F, $p2n\gamma$) reactions. It should be noted that the 1371-keV (2454 → 1083) γ ray can be frequently contaminated with the 1368-keV γ ray from ^{24}Mg. The lifetimes measured by the DSA and recoil-distance methods agree within the quoted errors.

2531 keV. The 2531-keV level is assigned 2$^+$ from the (α,γ) angular distributions[3] and confirmed by the (p,t) and (^{6}Li, d) reactions.[9,11] The main γ-decay branch is to the 1083-keV, 2$^+$ level and is nearly a pure quadrupole transition.[3] There is a weaker branch of 3.7% to the 1904-keV 0$^+$ level [see Fig. 5(a)] with an $E2$ enhancement of 24 ± 6 W.u. This transition strength is not consistent with the interpretation of the 1904- and 2531-keV states as being of two-phonon character, but rather suggests the beginning of a rotational band.

2886 keV. The 2886-keV level is the third 2$^+$ level in ^{44}Ti. Its spin is established from the (α,γ) angular distributions of the ground-state transition. (The strength of this transition definitely rules out the 3$^-$ assignment favored by Kong-A-Siou *et al.*[9]) The (2886 → 1083) γ ray is obscured in a singles spectrum by the 1809-keV γ ray from ^{23}Na($\alpha, p\gamma$)^{26}Mg, but is clearly seen in coincidence spectra at several resonances. The branching ratio for (2886 → 1083) is given as 38 ±10%, the rather large error being necessary because the angular distribution of this transition is not yet known.

3176 keV. The 3176-keV level has a spin of 2$^+$ or 3$^-$. From (p,t) studies Kong-A-Siou *et al.*[9] assigned 2$^+$ without brackets, Rapaport *et al.*[8] assigned 2$^+$ with brackets, while Baer *et al.*[10] allowed 2$^+$, 3$^-$, or 4$^+$. In Sec. IV above we have discussed how the observation of the weak branches (3176 → g.s.) and (3176 → 2454) in γ-γ coincidences precludes spin assignments of 4 and 1, respectively. Further evidence against a spin of 1 is obtained from the angular distributions of the (3176 → 1083) transitions at the $E_\alpha = 4.22$ and 5.27 MeV resonances, both of which require a P_4 term. As discussed in Sec. V F above, the 3176-, 3646-, and 4061-keV levels appear to be closely related, the long lifetimes and interconnecting γ rays favoring negative over positive parity.

It should be noted that the 3176-keV level apparently is not seen in the (^{6}Li, d) reaction, but this is perhaps because of a contaminant peak from ^{20}Ne. The 3176-keV level is also not seen by Erskine *et al.*[14] in the (^{16}O, ^{12}C) reaction.

3364 keV. The 3364-keV level has been assigned 4$^+$ from the (p,t) and (^{6}Li, d) experiments. We have measured the lifetime and established the γ decay from coincidence runs at $E_\alpha = 4.70$ MeV. The branch to the 2531-keV level [Fig. 5(e)] has an energy of 833 keV, which coincides with a line from ^{72}Ge seen via γ-neutron coincidences. The amount of this contamination was estimated from the intensity of the 596-keV γ ray from ^{74}Ge and subtracted. The net branch to the 2531-keV level is estimated to be 5 ± 2%. This corresponds to an $E2$ enhancement of about 18 W.u., suggesting a band structure for the 1904-, 2531-, and 3364-keV levels. Although the 3364-keV level may therefore be assumed to have particle-hole configurations, it is apparently strongly excited in the α-transfer experiments on ^{40}Ca targets.

3415 keV. The 3415-keV level has been seen only in (α,γ) and not in the particle transfer reactions, implying unnatural parity. The angular distribution of the (3415 → 1083) transition can be fitted with either spin 2 or 3, and both require a large mixing ratio. Negative parity is ruled out by the $M2$ strength implied for the 3415 → 1083 transition. If the 3415-keV level has unnatural parity, it must have $J^\pi = 3^+$.

A number of (α,γ) resonances strongly feed both the 3415-keV and the 2886-keV, 2$^+$ levels, suggesting a similarity in structure. A search for the (3415 → 2886) transition [see Fig. 5(f)] at the $E_\alpha = 4.52$ and 5.04 MeV resonances has shown that this transition has an intensity of 2.2 ± 0.5% relative to the (3415 → 1083) branch. However, the $E2$ enhancement is not known because the mixing ratio has not been measured. It should be noted that the (3415 → 2531) transition is not seen (<1.5%) at the $E_\alpha \doteq 4.52$ MeV resonance, although the (3415 → 2886) transition is seen there; at several higher-energy resonances an 884-keV γ ray which does appear must be attributed instead to the (4061 → 3176) transition.

3646 keV. The 3646-keV level has not been seen in the particle transfer reactions, and hence is assumed to have unnatural parity. It decays mainly to the 3176-keV level with a γ ray of only 470 keV, and has the same parity as the 3176- and 4061-keV levels. The 470-keV γ ray is nearly pure quadrupole, implying a lifetime of at least

50 ps. This lifetime limit is in disagreement with a value of $\tau = 3.9 \pm 1.3$ ps measured by Kolata *et al.*,[17] but it should be noted that even if the transition were pure $M1$, $\tau = 3.9$ ps would imply a strength of 0.08 W.u., well in excess of the upper limit of 0.03 W.u. proposed by Endt and van der Leun[23] for isoscalar $M1$ transitions. The most likely spin is $J^\pi = 4^-$, but we are not able to rule out 3^+ except by plausibility arguments. A branch to the 2454-keV, 4^+ state is also seen [Fig. 5(g)].

3756 keV. The combination of the short lifetime, strong branch to the ground state, and angular distributions of the primary and secondary γ rays at the $E_\alpha = 5.06$ MeV resonance favors spin 2^+. The only other branch clearly established is (3756 → 1083), contaminants at 583 keV obscuring (3756 → 3176) even in coincidence spectra, and at 868 keV obscuring (3756 → 2886). Baer *et al.*[10] allow spins of 2 and 3 only for the 3756-keV level, supporting the 2^+ assignment.

3943 keV. Rapaport *et al.*[8] report the spin of spin of this level to be 3^-. Our measured lifetime of (1.2 ± 0.3) ps is consistent with the transitions (3943 → 1083) and (3943 → 2454) [Fig. 5(h)] being $E1$ ($\lesssim 3 \times 10^{-5}$ W.u.). However, Baer *et al.*[10] assign a definite 2^+ for the 3943-keV level, which would imply an unusually weak $E2$ transition to the ground state ($< 10^{-3}$ W.u.).

3980 keV. Rapaport *et al.*[8] assign a spin of 4^+. The branching ratios and lifetime has been obtained from coincidence spectra at 0°. Our present estimate of the lifetime is 0.5 ± 0.2 ps, considerably shorter than our previous estimate[18] of 0.9 ± 0.3 ps. The errors in the branching ratios are rather large because of the following experimental problems: the (3980 → 1083) γ ray must be disentangled from the (2886 → 0) γ ray both of which are Doppler shifted (see Fig. 4); the (3980 → 2886) γ ray [Fig. 5(j)] lies on the upper edge of the strong 1083-keV γ ray; the (3980 → 3415) γ ray [Fig. 5(k)] is possibly contaminated with the 563-keV γ ray from ^{76}Ge; a possible transition (3980 → 2531) cannot be distinguished from (2531 → 1083); the (3980 → 2454) transition [Fig. 5(i)] must be distinguished from a possible contaminant at 1528 keV from ^{19}F$(\alpha, n\gamma)^{22}$Na. We have associated the 3980-keV level with the 2886- and 3415-keV levels in a band.[18,19]

4015 keV. The 4015-keV level was assigned a spin of 5^- or 6^+ from the (p, t) work of Rapaport *et al.*[8] We have shown that the angular distribution of the (4015 → 2454) transition requires 6^+ rather than 5^-. The measured lifetime gives an $E2$ strength of 17 ± 3 W.u. for a $6^+ \to 4^+$ transition. Studies with the ^{32}S$(^{14}$N$, pn\gamma)^{44}$Ti and ^{28}Si$(^{19}$F$, p2n\gamma)^{44}$Ti reactions[16,17] have now confirmed that the 4015-keV level is the yrast 6^+ level of ^{44}Ti.

4061 keV. The 4061-keV level has already been discussed in connection with the 3176- and 3646-keV levels. We favor $J^\pi = 5^-$, but do not rule out 4^+ or 3^-. The (p, t) experiments[8] assign 4^+ for this level. The energy of this level was given previously[18] as 4059 keV.

4116 keV. The 4116-keV level is relatively short lived ($\tau = 0.16 \pm 0.07$ ps) and has a 29% branch to the ground state. Combined with this, γ-ray angular distributions at the $E_\alpha = 5.04$ MeV resonance assign spin 2^+ (Sec. V E). A state at 4100 keV in the $(^6$Li$, d)$ reaction which is probably the same state has been assigned 2^+ by Strohbusch *et al.*[11] (It should be noted that many of the α-transfer experiments do not resolve the known levels close to 4.0 MeV.)

4227 keV. There appears to be a level at 4227 keV which is fed weakly from several resonances, e.g., $E_\alpha = 4.67$, 5.06, 5.51, and 5.80 MeV. γ rays of 1051 and 1341 keV are clearly seen in γ-γ coincidence spectra [Figs. 5(l) and 5(n)], and are interpreted as decays to the 3176- and 2886-keV levels, respectively. Several other branches are also seen in the coincidence spectra and are given in Table V. The (4227 → 3646) branch is sometimes contaminated with a 583-keV γ ray from the ^{19}F$(\alpha, n)^{22}$Na reaction. A possible (4227 → 3756) transition cannot be distinguished from the (3646 → 3176) transition. A transition to the ground state is not seen, the 4222-keV γ ray seen at some resonances instead being attributed to the (5305 → 1083) transition.

The decay branches to the 3176- and 3646-keV levels suggest negative parity for the 4227-keV level, possibly $J^\pi = 2^-$ or 3^-.

4792 and 5305 keV. Primary and secondary γ rays for levels at 4792 and 5305 keV are seen at several resonances, including $E_\alpha = 4.67$ and 4.70 MeV. The overlapping escape peaks and the presence of a contaminant γ ray of about 3200 keV make quantitative analyses difficult. A γ ray of 4222 keV is interpreted as the (5305 → 1083) transition rather than a (4222 → 0) transition.[6,7] The branches (4792 → 2886), (4792 → 3176), and (4792 → 3756) listed in Table V were obtained in γ-γ coincidences at $E_\alpha = 4.70$ MeV. The latter transition is close to a contaminant γ ray of 1039 keV from ^{70}Ge.

5423 keV. A level at 5423 ± 5 keV is seen at the $E_\alpha = 4.67$ MeV resonance. The only decay branch observed is to the 1083-keV level.

Transition strengths. $E2$ transition strengths for most of the positive-parity states have been given in previous publications.[18,19] The major change in this paper is in the lifetime of the 3980-keV level, such that its decay strengths should now be increased by a factor of about 1.8. The 3364 → 2531 transition strength is now reduced from 29 ± 16 to 18 ± 9 W.u. In cases where the $E2/M1$ mixing ratio is not known, the $M1$ strengths are $\lesssim 10^{-2}$ W.u. For the negative-parity states, transition strengths are given in Table VII of this paper. $E1$ strengths are $\lesssim 10^{-4}$ W.u.

VII. THEORETICAL CALCULATIONS

To date only a few theoretical calculations have been carried out for ^{44}Ti. In the first shell-model calculations of McCullen, Bayman, and Zamick,[25] the four valence nucleons were confined to the $f_{7/2}$ shell and two-body matrix elements taken from the experimental spectrum of ^{42}Sc. Subsequently shell-model calculations of the $T=0$ levels in which the four valence nucleons were allowed the freedom of the full fp shell, were carried out. States with J up to 8 were calculated by Bhatt and McGrory,[26] and up to the maximum allowed $J=12$ by Simpson *et al.*[2,16] Although the calculated level energies do not follow a $J(J+1)$ spacing, they are in good agreement with the experimental yrast or ground-state band[16,17] and the enhanced $B(E2)$ values within the band are also well reproduced provided a sufficiently large effective charge ($0.5e$ in the full fp calculations) is added to the bare nucleon charges. Shell-model calculations of some higher isospin states and transitions from them have also been made and are not in disagreement with the experimental results.[4,27]

The main limitation of the shell-model calculations performed so far is that they do not account for most of the low-lying levels which as we have shown previously,[18] can be grouped into an additional three bands of rotational character, having relatively large intraband transitions and in general weak interband transitions. These levels almost certainly arise from predominantly many-particle–many-hole configurations and are not easily calculated in the shell model, leading one to try to take advantage of the economy of a collective model. For example, we have shown that a soft asymmetric rotor model[19] leads to reasonable qualitative agreement with both the energies and the $E2$ transition strengths for the low-lying positive-parity levels, although it would not appear to be satisfactory for the 10^+ and 12^+ yrast levels. The negative-parity band can be understood as arising from the promotion of a particle from the filled Nilsson $d_{3/2}, \Omega=\frac{3}{2}$ orbit to an unfilled Nilsson $f_{7/2}$ orbit in a deformed potential. It is interesting that a recent calculation[28] of the static potential energy surface for ^{44}Ti predicts the existence of an asymmetric minimum nearly as deep as the lowest symmetric minimum and separated from the latter by a low barrier, giving rise to a level spectrum similar to the experimental spectrum.

There have also been some Hartree-Fock[29,30] and stretch-scheme calculations[31] for ^{44}Ti which attempt to reproduce the ground-state band. To our knowledge Hartree-Fock calculations permitting an asymmetric deformation have not been carried out.

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