η_K for each orbital which is unity near the ground state and decreases linearly with excitation energy has been found to describe the observations, but other attenuation schemes seem to be feasible. The origin of the matrix-element attenuation is at present not understood. It has been suggested[7] that it might be due to dilution of the wave functions for the high-lying states. The present analysis does not support this suggestion, since the transfer cross sections indicate spectroscopic factors near unity for the uncoupled states.[8]

We are grateful for discussions with Professor B. R. Mottelson and Dr. M. Bunker. One of the authors (R.F.C.) would like to thank the Los Alamos Scientific Laboratory, which was very generous in allowing the time for completion of this work, and another (P.J.D.) acknowledges the support of the U. S. Atomic Energy Commission.

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Quasirotational Levels in ^{152}Gd and Excited Levels of ^{152}Tb from the Decay of 4.2-min ^{152m}Tb†

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In the decay of the 4.2-min isomeric state in ^{152}Tb, 8 γ rays are found to be associated with the deexcitation of levels in ^{152}Tb and 25 γ rays with that in ^{152}Gd. Experimental studies were made chiefly with Ge(Li) γ-ray detectors in singles and coincidence modes. Conversion-electron spectra were obtained with a Si(Li) spectrometer. The isomeric state, believed to be an 8^+ state, is at 501.8 keV, and the isomeric transition is a 159.59-keV $E3$ transition to a level at 342.2 keV. Other levels in ^{152}Tb are proposed at 58.9, 65.1, and 106.7 keV. An alternative but less likely level scheme is also possible. The ground state (2^-) and levels at 58.9, 342.2, and 501.8 keV appear to be best described in terms of Nilsson states. The electron-capture decay of the 501.8-keV isomeric state is by an allowed unhindered transition ($\log ft$ 4.7) which leads almost entirely to a level at 2394.5 keV in ^{152}Gd. The deexcitation of the latter level populates 6^+ and 8^+ members of the quasiground-state and quasi-β-vibrational bands. The quasirotational character of levels in ^{152}Gd which has been proposed by Sakai and coworkers appears to be amply confirmed. A previously unreported level in ^{152}Gd at 1861.7 keV (5^+) is proposed. In contrast to previous work, no α-decay branch was observed.

I. INTRODUCTION

Isomerism in Tb nuclides is very common, especially among the odd-odd isotopes.[1] Since the neutron number of known Tb nuclides ranges from the 82-neutron region well into the region of stable deformation, a systematic study of the odd-odd Tb nuclides provides a basis for analyzing the coupling of the odd neutron and odd proton as a function of deformation. In this work we describe the results obtained from studying the decay of 4.2-min ^{152m}Tb.

Since the decay of the 18-h ground state[2,3] of ^{152}Tb populates chiefly low-spin levels in ^{152}Gd, we hoped that the isomeric state would undergo β decay to higher-spin states. The quasirotational character of ^{152}Gd levels[4] which has been observed in reaction spectroscopy, at least insofar as the high-spin levels are concerned, has not been apparent from the decay of either ^{152}Eu[5] or 18-h ^{152}Tb.[2,3]

Only one previous reference has been found to the decay scheme of 4.2-min ^{152m}Tb. Olkowsky *et al.*[6] reported in a scintillation study γ rays of 140 and 235 keV, K x rays, and an α-decay branch of 2×10^{-5}. In this work we confirm the assignment of the 4.2-min activity to mass 152. The γ-ray spectrum with Ge(Li) detectors was found to be much more complex than the previous work suggested; no α branch was observed.

Low-lying levels in ^{152}Gd have been rather well established by decay studies of ^{152}Eu and, to a lesser extent, ^{152}Tb. In the latter case only a partial level scheme for ^{152}Gd has been proposed.[2,3] Studies of ^{152}Gd levels have also been made by the ^{152}Gd(d,d') reaction,[7] the ^{153}Eu(p, $2n\gamma$)^{152}Gd reaction, and the ^{150}Sm(α,$2n\gamma$)^{152}Gd reaction, in which prompt conversion-electron spectra were obtained.[4]

II. EXPERIMENTAL METHODS AND RESULTS

A. Source Preparation

γ-ray sources for Ge(Li) singles and coincidence spectrometry were prepared by the ^{151}Eu(α, $3n$)^{152}Tb or the ^{153}Eu(α, $5n$)^{152}Tb reactions. Targets were in the form Eu$_2$O$_3$ which had been enriched to 96% or higher in the Eu isotope indicat-

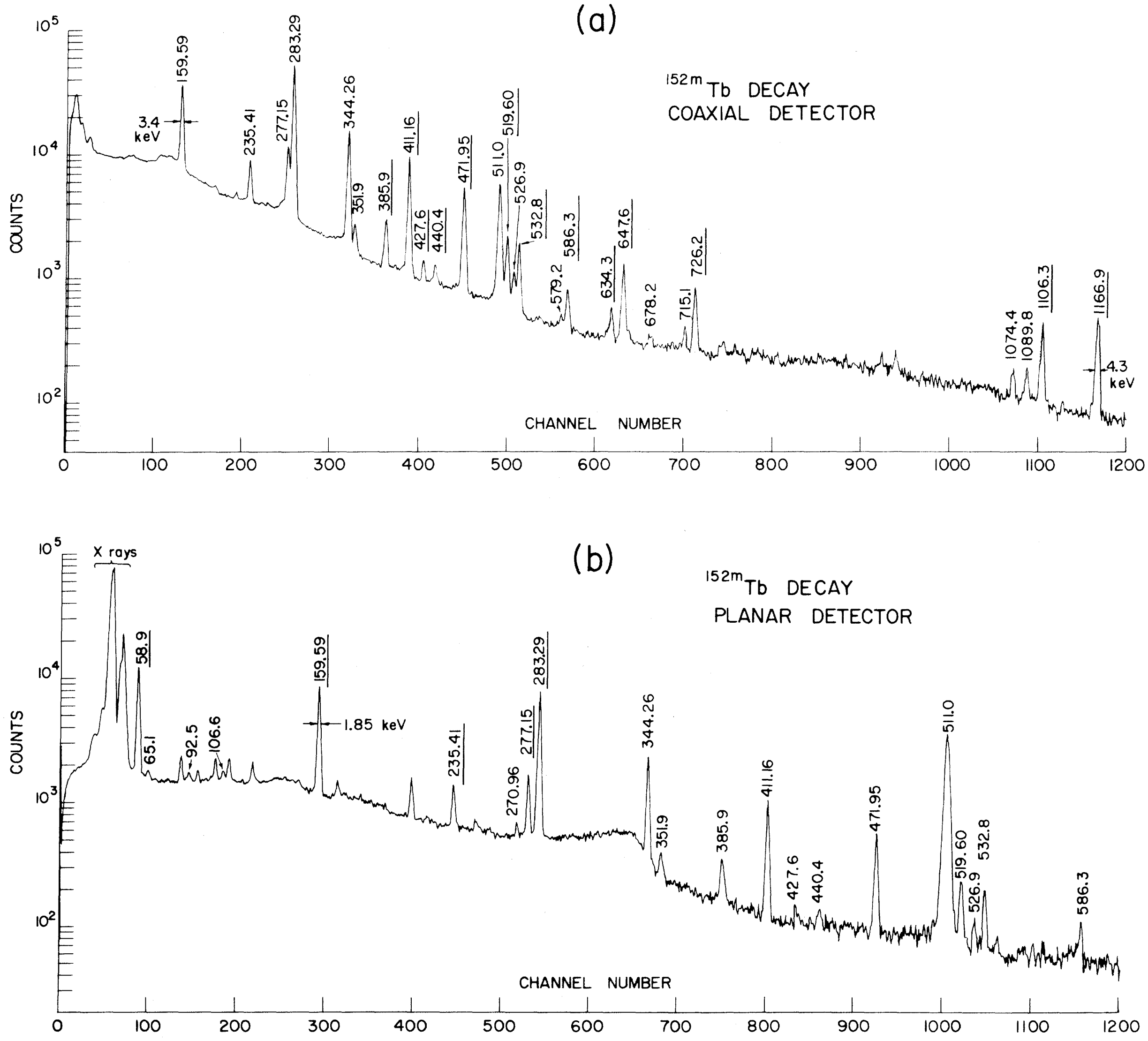

FIG. 1. Typical singles spectra of γ rays emitted in the decay of 4.2-min ^{152m}Tb as observed on (a) a 20-cm^3 coaxial Ge(Li) detector and (b) a 6-cm^3 planar Ge(Li) detector. In each case the collection time was 4 min (live) and the total counting rate at the beginning of the count was $\approx 3\times10^4$/sec. This coaxial detector was used as the gating detector in coincidence experiments for the γ rays whose energy values are underlined in (a). Similarly this planar detector was the gating detector in coincidence experiments involving the γ rays whose energy values are underlined in (b).

ed. Typical target thicknesses were 3–5 mg/cm^2. Irradiations were performed on the variable energy cyclotron at Texas A & M University with 34-MeV α particles for the (α, 3n) reaction and with 60-MeV α particles for the (α, 5n) case.

No chemical separations were made. For a short irradiation time (usually 2 min at 5 μA) the only interfering γ rays of any consequence were the radiations of 2.3-min ^{28}Al (1780 keV) and 6.6-min ^{29}Al (1274 keV) which were easily distinguished from those of ^{152m}Tb. The aluminum activities were produced from the aluminum envelope in which Eu$_2$O$_3$ targets were contained.

A source suitable for conversion-electron spectrometry was prepared by catching recoil atoms from a thin target of Eu$_2$O$_3$ ($\approx$0.3 mg/cm^2), which had been molecular plated on 1-mg/cm^2 aluminum foil. The catcher was 150-μg/cm^2 aluminum foil. In this experiment a beam of 40-MeV α particles, collimated to 3-mm diam, was used.

B. Mass Assignment of the 4.2-min Activity

Since many Tb nuclides appear to have isomeric states, we considered it appropriate to confirm the assignment of the 4.2-min species to mass 152. Irradiations of ^{151}Eu were carried out at α-particle bombarding energies of 24, 27, 31, 35, and 38 MeV. No 4.2-min activity was observed at either 24 or 27 MeV. At 31 MeV, the spectrum of 4.2-min γ rays was the same as that at 35 or 38 MeV.

The Q values for the ^{151}Eu(α, 3n)^{152}Tb and ^{151}Eu-

TABLE I. γ rays observed in the decay of 4.2-min ^{152m}Tb.

E_γ (keV)	I_γ[a]	I_t[b,c]	Transition[d] Tb	Transition[d] Gd	Remarks
≈48		(7)	106.7→ 58.9		Coincidence spectra only
58.9 ± 0.2	10.8 ± 0.9	(118 ± 10)	58.9→ 0		($M1$)
65.1 ± 0.3	0.11 ± 0.03		65.1→ 0		
92.5 ± 0.2	0.45 ± 0.05			2394.5→ 2301.9	
106.6 ± 0.3	0.57 ± 0.10		106.7→ 0		
159.59 ± 0.10	26.0 ± 0.5	127 ± 3	501.8→ 342.2		$E3$
235.41 ± 0.10	6.9 ± 0.3		342.2→ 106.7		
270.96 ± 0.10	<0.3[e]			615.2→ 344.26	
277.15 ± 0.10	15.5 ± 1.0		342.2→ 65.1		
283.29 ± 0.05	≡100	107 ± 5	342.2→ 58.9		$E2$
315.2 ± 0.5	<0.2[e]			930.6→ 615.2	
344.26 ± 0.07	33.7 ± 2.0	35.0 ± 2.1		344.26→ 0	$E2$
351.9 ± 0.2	2.3 ± 0.3			1282.4→ 930.6	
385.9 ± 0.2	5.2 ± 0.6			1668.3→ 1282.4	
411.16 ± 0.07	32.1 ± 1.2			755.4→ 344.26	
427.6 ± 0.2	1.8 ± 0.3			1861.7→ 1433.9	
440.4 ± 0.3	1.4 ± 0.3			f	Doublet
471.95 ± 0.10	21.1 ± 1.1			1227.4→ 755.4	
519.60 ± 0.10	8.9 ± 1.0			1747.0→ 1227.4	
526.9 ± 0.2	2.9 ± 0.6			1282.4→ 755.4	
532.8 ± 0.2	7.1 ± 0.8			2394.5→ 1861.7	
579.2 ± 0.5	0.4 ± 0.2			1861.7→ 1282.4	
586.3 ± 0.2	2.8 ± 0.2			930.6→ 344.26	
634.3 ± 0.2	1.7 ± 0.2			1861.7→ 1227.4	
647.6 ± 0.2	7.1 ± 0.5			2394.5→ 1747.0	
678.2 ± 0.3	0.6 ± 0.2			1433.9→ 755.4	
715.1 ± 0.2	1.1 ± 0.2			1470.5→ 755.4	
726.2 ± 0.2	4.7 ± 0.6			2394.5→ 1668.3	
930.5 ± 0.4	0.6 ± 0.2			930.6→ 0	
1074.4 ± 0.3	1.2 ± 0.2			2301.9→ 1227.4	
1089.8 ± 0.4	1.2 ± 0.3			1433.9→ 344.26	
1106.3 ± 0.2	5.3 ± 0.6			1861.7→ 755.4	
1166.9 ± 0.2	6.1 ± 0.5			2394.5→ 1227.4	

[a] γ-ray intensity normalized to 100 for the 283.29-keV transition.

[b] Transition intensities are listed only when multipolarity assignments are known or can be inferred.

[c] Quantities in parentheses are inferred from indirect evidence and are to be regarded with caution.

[d] As placed in level schemes; see Figs. 5, 6, and 7(a).

[e] Dominated by long-lived component.

[f] See text for a discussion of the doublet.

TABLE II. Weak transitions possibly attributable to the decay of 4.2-min ^{152m}Tb.

E_γ (keV)	I_γ
703.7 ± 0.4	0.2 ± 0.1
755.9 ± 0.4	0.7 ± 0.3
816.3 ± 0.3	0.4 ± 0.2
946.0 ± 0.4	1.0 ± 0.4
1041.4 ± 0.3	0.5 ± 0.3
1290.6 ± 0.7	0.5 ± 0.3
1316.7 ± 0.4	0.3 ± 0.2
1341.9 ± 0.7	0.3 ± 0.2

$(\alpha, 4n)^{151}$Tb reactions are −27.2 and −36.4 MeV, respectively.[8] From these data we conclude that the 4.2-min Tb activity is not the product of the (α, n) or $(\alpha, 2n)$ reactions since it is not observed at 24 or 27 MeV and cannot be an $(\alpha, 4n)$ product because it is seen well below the threshold for the $(\alpha, 4n)$ reaction. The only remaining choice is an $(\alpha, 3n)$ product and hence ^{152}Tb. The excitation function for producing the 4.2-min ^{152m}Tb is roughly parallel to that for producing the well-known 18-h ^{152}Tb.

C. Singles γ-Ray Spectra

The singles γ-ray spectra were investigated with two Ge(Li) detectors. One of them was a 20-cm^3 five-sided coaxially drifted detector and the other a planar detector, 6 cm^2 × (10 mm drifted depth), with a preamplifier utilizing a cooled field-effect transistor (FET). Typical energy resolution of the system at low counting rates was 3 keV at 1332 keV for the coaxial detector and 1.2 keV at 122 keV for the planar detector. γ rays of energy less than 40 keV were not readily detected with these systems. Conventional shaping amplifiers, base-line restorers, and multichannel analyzers were used.

The system was calibrated for intensity with a standard set of absolutely calibrated γ-ray sources from the International Atomic Energy Agency (IAEA). The energy calibration was made with the IAEA sources which were run simultaneously with ^{152m}Tb sources to eliminate gain shifts between measurement and calibration. The energies of the γ rays were obtained by interpolation with a least-squares four-parameter fit to a cubic function.

To obtain good counting statistics with reasonable energy resolution for a short-lived activity, one can either sum the spectra from many sources, each spectrum taken at relatively low count rates, or attempt to use electronic methods to maintain comparable resolution at high counting rates and obtain data from a single intense source. We adopted the latter practice in order to determine the half-lives of weak lines. In Figs. 1(a) and 1(b) are shown typical spectra obtained with (a) the coaxial detector and (b) the planar detector in 4 live minutes of counting. The initial total counting rate was about 30 000/sec in each case. Coincidence gates have been set on those γ rays whose energy value is underlined.

The γ-ray spectra were analyzed for energy and intensity by the computer code RAGS.[9] In Table I are listed the γ rays which we assign to 4.2-min ^{152m}Tb. Intensities listed in column 2 are the averages from many spectra obtained with the two detectors. The "440.4"-keV line is a doublet which is not resolved by any of our detectors.

The half-lives of the strong γ rays of energy 159.59, 235.41, and 283.29 keV were found by analysis of decay curves to be 4.2 ± 0.1 min. Except for those lines which had an 18-h or other long-lived component (270.96, 315.2, 344.26, 411.16, 526.9, 586.3, 678.2, 930.5, and 1089.8 keV) the intensity of each γ ray listed in Table I relative to that of the 283.29-keV γ ray was independent of time over many half-lives.

Eight other γ rays, all of low intensity, were observed to have half-lives of about 4 min; these are listed in Table II. No attempt has been made to fit these γ rays into the level scheme.

D. Conversion-Electron Spectra

A Si(Li) detector with a cooled-FET input stage

TABLE III. Conversion-electron intensities in the decay of 4.2-min ^{152m}Tb.

159.59-keV transition							
	I_e[b]			$K/L/M$			
I_γ[a]	K	L	M	Exp	Theory[c]	Multipolarity	Assignment
					4.5 /1.00/0.22	$M2$	
26.0 ± 0.5	30.2 ± 1.8	60.4 ± 3.0	16.3 ± 1.2	0.50/1.00/0.27	0.53/1.00/0.25	$E3$	$E3$
					2.2 /1.00/0.23	$M3$	

[a] Intensity scale of Table I.

[b] Intensity scale of conversion electrons normalized such that α_K of the 159.59-keV transition is 1.16, the theoretical value for an $E3$ transition.

[c] See Ref. 10.

was used to study the conversion-electron spectrum. The energy resolution for 100-keV electrons was 1.5 keV full width at half maximum. Tables III and IV summarize the results. The ratio of intensities $K:L:M$ of the 159.59-keV transition is $(0.50 \pm 0.05):1.00:(0.27 \pm 0.02)$. This clearly establishes the transition as $E3$; the calculated $K:L:M$ ratio is 0.53 : 1.00 : 0.25.[10] The intensity scale used in Tables III and IV is based on a relative 159.59K intensity of 30.2 which, when divided by the γ-ray intensity 26.0, yields $\alpha_K = 1.16$, the calculated value of α_K for a 159.59-keV $E3$ transition.[10] The well-known 344.26-keV transition from the first excited 2^+ state in ^{152}Gd is confirmed to be $E2$, and the 283.29-keV transition is also found to be $E2$. Internal-conversion coefficients could not be reliably determined for other transitions.

The total internal-conversion coefficient for a 159.59-keV $E3$ transition is 3.90 [10]; hence the transition intensity is 127 ± 3 units on the I_γ scale of Table I. If this transition depopulated a level in ^{152}Gd, that level must lie below the 344.26-keV level since the intensity of the 344.26-keV transition is 35.0 ± 2.1 units. No even-even nucleus we know of has a 3^- first excited state; we conclude that the 159.59-keV transition is between ^{152}Tb levels and in fact must be the isomeric transition. One would expect also that a low-lying 3^- state in ^{152}Gd would be populated in the β decay of 12-yr ^{152}Eu, a 3^- nuclide. No such level has been reported.[5] Similarly on intensity grounds the 283.29-keV transition also must be a transition in ^{152}Tb.

E. Ge(Li)-Ge(Li) Coincidence Spectra

Two-parameter coincidence spectra were obtained with combinations among the two Ge(Li) detectors listed above and two other Ge(Li) detectors, one of them a coaxially drifted detector essentially similar to that used in singles experiments but of somewhat poorer resolution (≃4 keV at 1332 keV) and a second planar detector larger [10 cm^2 × (1.4 cm depletion depth)] than that used in singles experiments. The choice of detector was based on the usual criteria of time and energy resolution and efficiency as a function of γ-ray energy. The electronics were arranged in the slow-fast coincidence configuration which has been described elsewhere.[11] Typically the fast resolving time was 100 nsec. In early experiments a coincidence analyzer was used. In the later experiments a 100-nsec window was set on the output of a time-to-amplitude converter to obtain the time region of interest.

Conversion gain for the gating detector was 1024 channels while that for the spectrum-recording detector was either 512 or 1024 channels. Our multichannel analyzer system allows us to collect simultaneously four 1024-channel or eight 512-channel spectra in which the four or eight windows on the spectrum of the gating detector are set digitally.

The detectors were placed face to face with the source between them. Backscattering was not a problem. Typical singles counting rates in each detector were as high as 50 000/sec. The source was replaced approximately every 15 min. As many as 20 sources were required to obtain reasonable statistics in some cases. For each γ ray whose coincidence relationship was investigated, an off-peak gate (of the same width) was set to determine the effect of Compton background underlying a peak. The ratio of true events to accidental coincidences for a particular gate was always greater than 10 to 1.

In Fig. 2 are shown the spectra in coincidence with the 1106.3- and 1166.9-keV γ rays. The gate width was 7.4 keV (five channels), approximately centered about each peak. The spectrum labeled "BKGD" is that in coincidence with a 7.4-keV gate

TABLE IV. Conversion-electron intensities in the decay of 4.2-min ^{152m}Tb.

Transition energy (keV)	I_γ [a]	I_e [b] K	K/L	Exp α_K [d]	Multipolarity	Theory [c] α_K	K/L	Assignment
283.29	100	5.4 ± 0.4	4.0 ± 0.5	54 ± 4 −3	$E1$	17 −3	7.2	$E2$
					$E2$	56 −3	3.7	
					$M1$	106 −3	6.8	
344.24	33.7 ± 2.0	1.23 ± 0.24	5 ± 3	36 ± 7 −3	$E1$	10 −3	7.0	$E2$
					$E2$	31 −3	4.5	
					$M1$	57 −3	7.1	

[a] Intensity scale of Table I.

[b] Intensity scale of conversion electrons normalized such that α_K of the 159.59-keV transition is 1.16, the theoretical value for an $E3$ transition.

[c] See Ref. 10.

[d] Notation such as 54 ± 4 −3 is to be read $(54 \pm 4) \times 10^{-3}$.

centered at 1139 keV. Channels containing no useful information have not been plotted. These data show clearly that the 1106.3-keV γ ray is in coincidence with γ rays of 344.26, 411.16, 440.4, and 532.8 keV, while the 1166.9-keV γ ray is in coincidence with γ rays of 344.26, 411.16, and 471.95 keV. These three spectra were taken simultaneously for the same counting time. Two coaxial detectors were used.

In Fig. 3 spectra in coincidence with the 58.9-, 235.41-, and 283.29-keV γ rays are shown. Here the gates were 2.8-keV wide for the 58.9-keV γ ray and 3.2 keV for the latter two γ rays. Background gates were set at 70 and 265 keV. The smaller planar detector was used as the gating detector and the larger planar detector recorded the spectra. As in Fig. 2, featureless regions of spectra or peaks not associated with 4.2-min ^{152m}Tb have not been graphed.

The 58.9-, 235.41-, and 283.29-keV γ rays are in coincidence with the 159.59-keV transition which has been shown to be the isomeric transition in ^{152m}Tb. The K-conversion coefficient for the 159.59-keV transition is 1.16; thus one would expect to observe K x rays of Tb in coincidence with the three γ rays above. The energies of the x rays found correspond to those of the $K\alpha$ and $K\beta$ lines of Tb; the contribution of Gd x rays (1.5-keV lower in energy) was evidently small.

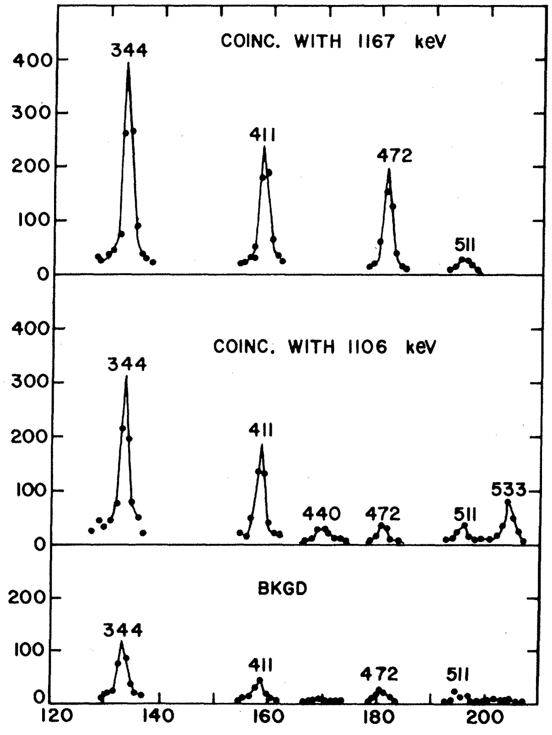

FIG. 2. Ge(Li)-Ge(Li) coincidence spectra. The gates were 7.4-keV wide and approximately centered on the 1106.3- and 1166.9-keV γ rays. The background gate was at 1139 keV. The three spectra were collected simultaneously and for the same period of time. Two coaxial detectors were used.

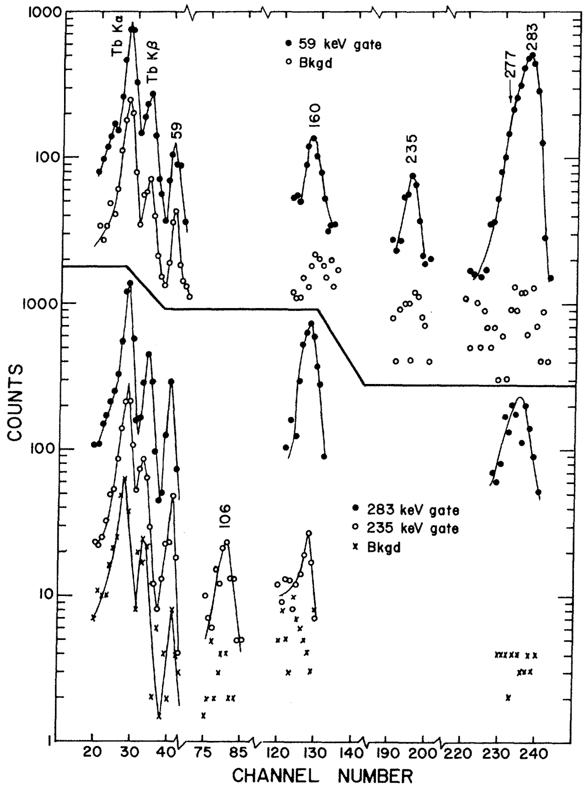

FIG. 3. Ge(Li)-Ge(Li) coincidence spectra. Gating transitions were the 58.9-, 235.41-, and 283.29-keV γ rays with background gates at 70 and 265 keV. All five spectra were obtained in a single experiment. Two planar detectors were used.

The K x-ray region in the 235-keV gate appeared to be qualitatively different from that in other spectra. This is shown on an expanded scale in Fig. 4. The spectra in coincidence with the 235.41- and 277.15-keV γ rays are shown as open circles and filled circles, respectively. These spectra have not been normalized in any way; it is fortuitous that the number of events in the two gates was essentially the same.

Figure 4 indicates that in coincidence with the 235.41-keV transition is a γ ray which is not evident in the other spectra of Figs. 3 and 4. The "peak" at 49.0 keV appears to be a doublet consisting of the Tb $K\beta$ line and a lower-energy γ ray whose energy is not well established but is approximately 48 keV. Such a γ ray would not be detectable in singles spectra of ^{152m}Tb because of the high intensity of Gd K x rays. The spectrum shape of the 277-keV gate in the K x-ray region is indistinguishable from that of the 283-keV gate.

Table V summarizes all of the coincidence relationships which were established by these determinations. An additional gate set on the 440.4-keV doublet produced no useful information.

F. Search for α Decay

Since the earlier work[6] had reported an α-decay branch of 2×10^{-5}, an attempt was made to study α spectra. Using a Si-Au surface-barrier detector with an efficiency of the order of 25% for detecting α particles with energy below 10 MeV and above the positron continuum, we could detect no α events in a thin source (prepared by recoil as in the conversion-electron case) which underwent about 6×10^{8} disintegrations during the time of observation. The α-decay branch is thus less than 10^{-8}.

III. PROPOSED DECAY SCHEMES

A. Levels in ^{152}Gd

Analysis of the experimental data led to the level scheme for ^{152}Gd as shown in Figs. 5 and 6. In Fig. 5 levels are drawn in a way to suggest the existence of a quasiground-state band and a quasi-β-vibrational band. All of these levels and transitions between them have been identified previously in the prompt conversion-electron spectra of the ^{150}Sm(α, $2n$)^{152}Gd and ^{153}Eu(p, $2n$)^{152}Gd reactions by Sakai and coworkers.[4] The present work has led to more precise energies and intensities than were previously available. A circle at the head of an arrow indicates that coincidence data support the placement of a particular transition. Spin and parity assignments are those of Gono, Ishihara, and Sakai.[4]

In Fig. 6 are shown the remaining levels in ^{152}Gd which are deduced from the experimental data. Transitions occurring between the levels shown in Fig. 5 have been omitted in Fig. 6.

While a coincidence gate set on the 440.4-keV doublet produced no useful information, a γ ray of 440 keV was seen in other gates (427.6, 471.95, 726.2, and 1106.3 keV). This information together with levels determined by other data suggests that the doublet consists of a transition between the 6_β^+ and 6_g^+ levels[12] (440.9 ± 0.5 keV) and between the 2301.9- and 1861.7-keV levels (440.2 ± 0.5 keV). Sakai and coworkers assign a 441-keV transition as the $6_\beta^+ \rightarrow 6_g^+$ transition.[4]

A brief discussion follows of the levels in Fig. 6 which are not members of quasirotational bands. The 1433.9-keV level is seen also[5] in the decay of

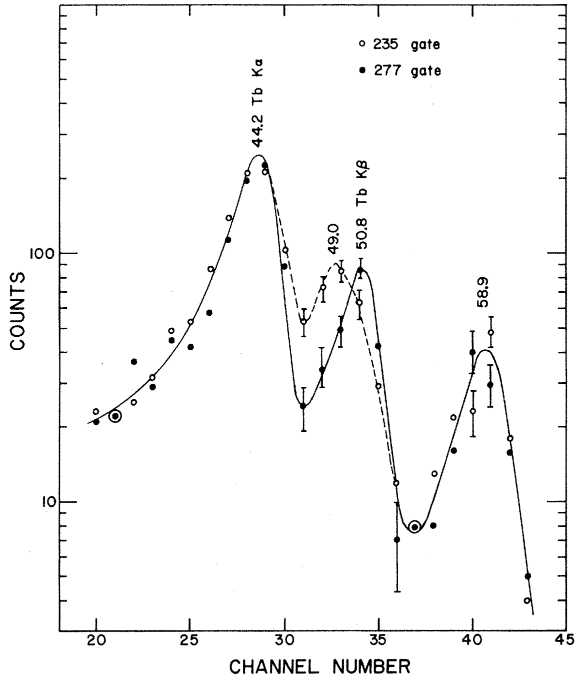

FIG. 4. Ge(Li)-Ge(Li) coincidence spectra in the x-ray region. Gating transitions were the 235.41- and 277.15-keV γ rays. The former spectrum is the same as that in Fig. 3; and the latter spectrum was collected at the same time. No background correction (see Fig. 3) has been made. Errors from counting statistics are shown for some points. The peak near channel 33 in the 235.41-keV gate appears to include the Tb $K\beta$ x ray and a γ ray of slightly lower energy.

TABLE V. γ-γ coincidence relationships observed in the decay of 4.2-min ^{152m}Tb.

Principal transition in gate (keV)	Coincident γ rays (keV) Definite	Probable
58.9	160, 235, 277, 283	48
159.59	59, 283	48, 277
235.41	59, 106, 160	48
277.15	59, 160	
283.29	59, 160	
385.9	344, 411, 527, 586, 726	352, 930
411.16	344, 386, 472, 520, 533, 634, 648, 726, 1106, 1167	715
427.6	344, 411, 533, 678	440
471.95	344, 411, 520, 648, 1167	440, 634
519.60	344, 411, 472, 648	
532.8	344, 411, 428, 472, 634, 678, 1089, 1106	
586.3	344, 352, 386, 726	
634.3	344, 411	472, 533
647.6	344, 411, 472, 520	
726.2	344, 352, 386, 527, 586	440
1106.3	344, 411, 440, 533	
1166.9	344, 411, 472	

^{152}Eu. Angular-correlation studies[13] of the 1089.8-344.26 cascade in ^{152}Eu decay suggest the spin to be 3. The internal-conversion coefficient for the 678.2-keV transition establishes the parity of the 1433.9-keV level as positive.[5]

The existence of the 1470.5-keV level is here based entirely on the weak 715.1-keV γ ray seen in the 411-keV gate. This level is probably the same as that seen in ^{152}Eu decay (5^- level at 1468.7 keV)[5] and in ^{152}Gd(d,d') (5^- level at 1467 keV).[7] No γ-ray transitions appear to feed this level.

The 1861.7-keV level, which has not been reported previously, appears to be well established by the many coincidence relationships among transitions in and out of the level. The γ-ray intensities in and out nearly balance, indicating that this level is not fed appreciably by β decay. The transitions out are to the 4_g^+, 4_β^+, and 6_g^+ levels and the 3^+ level at 1433.9 keV. The dominant transition into the 1861.7-keV level is from the 2394.5-keV level which we believe (see below) to be 7^+. For reasonable assignments of multipolarities to the transitions involved, the 1861.7-keV level is probably 5^+.

The level at 2301.9 keV is only weakly established by the present data. No coincidence information has been obtained. The 440.4-keV γ ray is part of a doublet. A level at 2300 keV was seen in the ^{152}Gd(d,d') spectra.[7] The decay pattern in and out suggests that the 2301.9-keV level is 5^+, $6^\pm$, or 7^+.

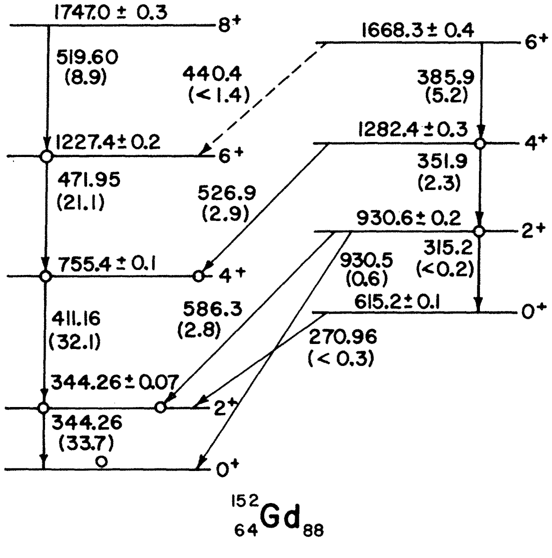

FIG. 5. Levels in ^{152}Gd from ^{152m}Tb decay which constitute the quasiground-state and quasi-β-vibrational bands. Energies are in keV. Relative γ-ray intensities are given in parentheses. Transitions whose placement has been confirmed by coincidence experiments are identified by a circle at the head of the transition arrow. Spin and parity assignments are from Ref. 4. The 440.4-keV transition is part of a doublet (see text).

β decay of the 4.2-min ^{152m}Tb occurs predominantly to the 2394.5-keV level. High-intensity γ rays deexcite this level to the 6_g^+, 6_β^+, and 8_g^+ levels of the quasiground and quasi-β bands as well as to the 1861.7-keV level. The placement of these transitions has been confirmed by coincidence data. No transitions were observed to any 4^+ levels. If Q_β of ^{152m}Tb is taken to be 4320 keV,[14] logft for decay to the 2394.5-keV level is 4.7 ± 0.1. Little β decay to other levels in ^{152}Gd occurs (log$ft \geq 6.2$). We conclude from these data that the spin of the 2394.5-keV level is probably 7. A level at 2395 keV was observed in the ^{152}Gd(d,d') reaction,[7] but no I^π assignments were made.

B. Levels in ^{152}Tb

The coincidence data establish that the 159.59-, 283.29-, and 58.9-keV γ rays are in cascade. No crossover transitions were observed for this sequence. There was no evidence, for example, of a 4.2-min 342.2-keV transition which would result in a change in the line shape of the 344.26-keV transition with time (the latter has both a 4.2-min and 18-h component). In order for intensities to balance it is necessary to assume that the 58.9-keV transition is $M1$ ($\alpha_T = 9.9$). Experimental internal-conversion coefficients indicate that the 159.59- and 283.29-keV transitions are $E3$ and $E2$, respectively.

The γ rays of 235.41 and 48 keV are in coincidence and parallel the 283.29-keV transition. The 106.6-keV transition is considered to be the crossover transition for the 48–58.9-keV cascade. The 277.15-keV transition is believed to be in coincidence with the 65.1-keV γ ray (too weak to be seen in the 277-keV gate).

These observations are combined into two alternative level schemes for ^{152}Tb as shown in Fig. 7. The present data cannot distinguish between them. In order to achieve intensity balance we must postulate an unobserved 6-keV transition feeding the 58.9-keV (a) or the 277.2-keV level (b).

One might expect the odd-odd nucleus ^{152}Tb to have a number of levels below about 100 keV as in the case of the isobaric odd-odd nucleus ^{152}Eu.[15] Hence, we favor scheme (a) and the discussion which follows is in that context.

The logft value of 4.7 for β decay of ^{152m}Tb to the 2394.5-keV level in ^{152}Gd suggests that the transition is allowed unhindered. As we show in Sec. IV, states in ^{152}Tb are well described by Nilsson orbitals. In the region of $Z = 65$ and $N = 88$, reasonable choices of proton and neutron orbitals for an allowed unhindered transition are $\pi\frac{5}{2}^-[532]$ to $\nu\frac{3}{2}^-[532]$.[16] Since the spin of the 2394.5-keV level is probably 7, this two-neutron state probably has the configuration $\frac{3}{2}^-[532]+\frac{11}{2}^-[505]$. The isomeric state in ^{152}Tb is then $\pi\frac{5}{2}^-[532]+\nu\frac{11}{2}^-[505]$, an $I^\pi=8^+$ state.

From multipolarities of the transitions in the high-intensity cascade, we judge that the 342.2- and 58.9-keV levels are 5^- and 3^-, respectively. The ground state is then probably 2^-. A recent atomic-beam measurement indicates that the ground-state spin is 2.[17]

Gromov *et al.*,[3] who studied the β^+ spectra and γ-ray spectra from the decay of 18-h ^{152}Tb, conclude that the ground state is 1^-. They find β^+ branches to the 0_g^+, 0_β^+, 2_g^+, and 2_β^+ levels with log*ft* values 8.2 ± 0.3, 8.2 ± 0.2, 7.7 ± 0.2, and 7.6 ± 0.2, respectively, which are calculated from the intensity balance in the decay scheme they propose. They show also a log*ft* value of 8.0 ± 0.2 for populating the 4_g^+ level though no β^+ branch is reported. These log*ft* values appear to be consistent with a hindered first-forbidden transition.[18] The ground state of ^{152}Tb may well then be 2^-.

IV. DISCUSSION

A. Levels in ^{152}Gd

The quasirotational pattern of levels has now been observed in many even-even nuclei.[19] Usually such patterns have been studied by $(\alpha, xn\gamma)$ or $(p, xn\gamma)$ reaction spectroscopy. Before the present study only in the case of ^{154}Ho decay to levels in ^{154}Dy have quasiground and quasi-β bands been clearly seen in β decay.[20] The pattern of levels in ^{154}Dy, as shown in Fig. 8, is strikingly similar to that in ^{152}Gd; even the energies are nearly the same.

This study presents confirmation of the quasirotational pattern of levels in ^{152}Gd which were reported by Sakai and coworkers.[4] Gono[21] has analyzed in some detail the properties of these levels, their energy-level spacings, and the relative $B(E2)$ values for the deexcitation of members of the quasi-β band. He concluded that neither the phonon approach, the vibrating rotor, nor the asymmetric rotor can account for level-energy systematics or transition probabilities; a quasirotational description, however, appeared to be a reasonable possibility.

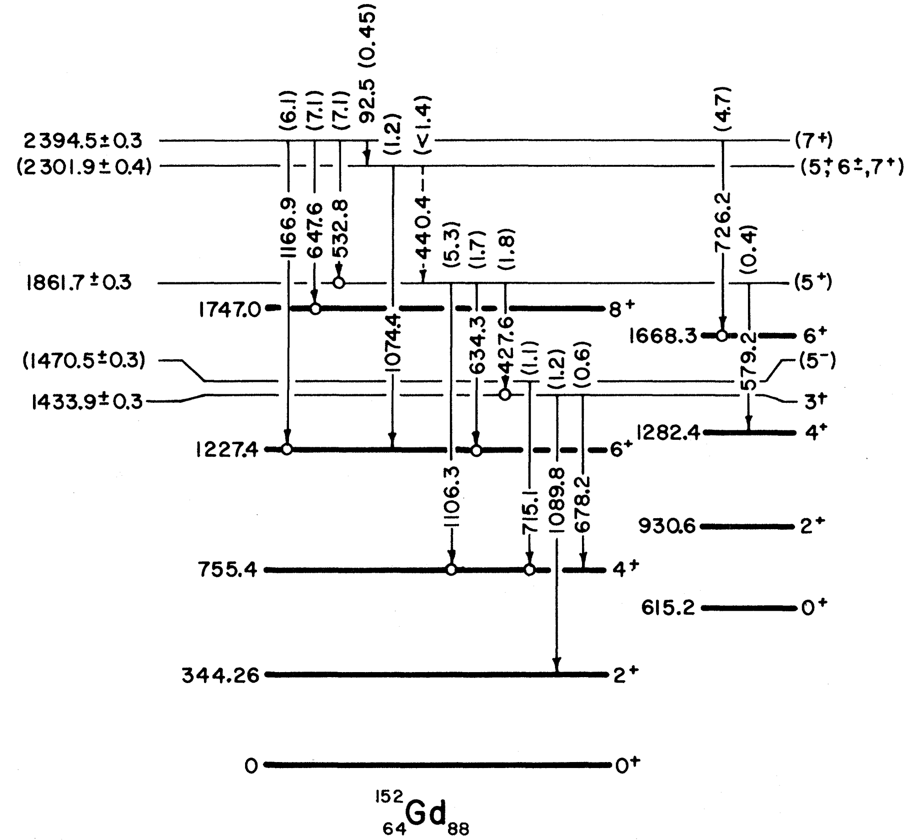

FIG. 6. Other levels in ^{152}Gd populated by ^{152m}Tb decay. Levels drawn as heavy lines are those in Fig. 5; transitions between these levels have been omitted. The notation is the same as that in Fig. 5.

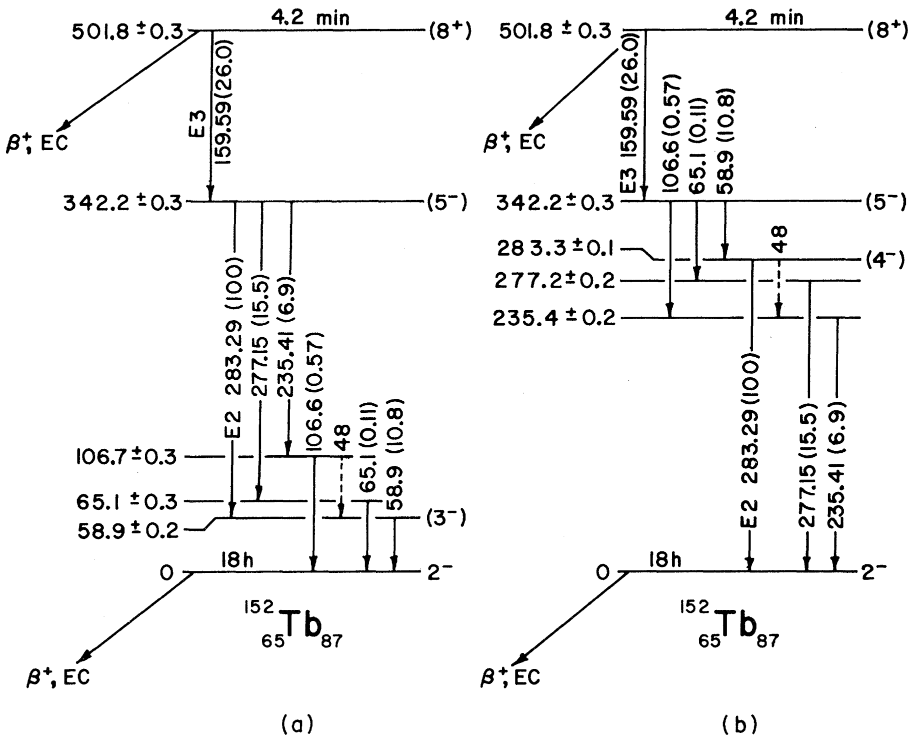

FIG. 7. Possible level schemes for ^{152}Tb levels populated by ^{152m}Tb decay. The data do not distinguish between the two choices; scheme (a) is favored on the basis of systematics. Because of the ambiguity between the two level schemes, circles which identify coincident γ rays have been omitted. See Table V for coincidence information.

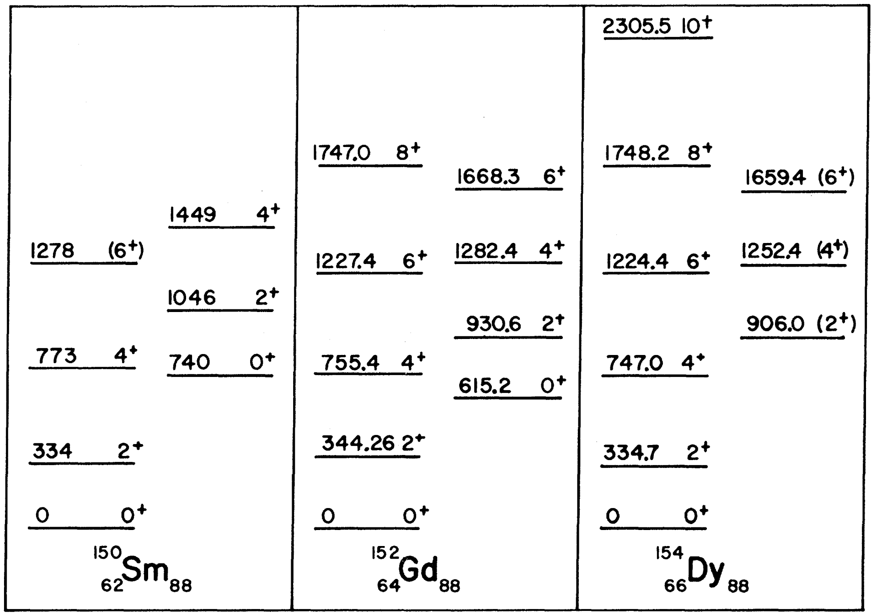

FIG. 8. Comparison of low-lying levels in the 88-neutron nuclei ^{150}Sm (Ref. 24), ^{152}Gd, and ^{154}Dy (Ref. 20).

In Table VI we summarize experimentally determined ratios R of reduced $E2$ transition probabilities for deexcitation of quasi-β-band levels in ^{152}Gd and ^{154}Dy and β-band levels in ^{154}Gd. We assume that there is no $M1$ component in the $I \to I$ transitions. The values expected for an adiabatic symmetric rotor (i.e., squares of Clebsch-Gordan coefficients) are listed in column 8. All of the recent experiments which yield R values for the 930.6- and 586.3-keV transitions in ^{152}Gd ($2_\beta^+ \to 0_g^+ / 2_\beta^+ \to 2_g^+$ which we denote hereafter as $2_\beta 0_g / 2_\beta 2_g$) are in essential agreement. The corresponding ratio in ^{154}Dy has the same value.

In the case of the R value for the 315.2- and 586.3-keV transitions ($2_\beta 0_\beta / 2_\beta 2_g$), the present results disagree with those of other workers. The discrepancy is in the intensity of the weak 315.2-keV transition; in our case experimental spectra (see Fig. 1) indicate little or no intensity attributable to the 4.2-min species. We have observed a longer-lived 315.2-keV transition; since such a transition occurs between ^{154}Gd levels,[22] the higher intensity observed by others may have resulted from ^{154}Tb or ^{154}Eu contamination of their sources. The corresponding transition in ^{154}Dy was not observed.[20]

For deexcitation of the 4^+ and 6^+ levels in the quasi-β band, the R values obtained in this work and those reported by Gono[21] are in good agreement. Since the 440-keV $6_\beta 6_g$ transition is part of an unresolved doublet, we are able to get only a lower limit. In ^{154}Dy the R value for the $6_\beta 4_\beta / 6_\beta 6_g$ transitions is 14 ± 2, much larger than that found by Gono for ^{152}Gd but possibly consistent with the present work if only about 50% of the 440-keV doublet intensity is due to the $6_\beta 6_g$ transition.

The 2^+ member of the quasi-β band deexcites to the 2^+ member of the quasiground-state band in preference to either the 0_β^+ or 0_g^+ levels. This behavior is like that of the vibrator ^{106}Pd for which the R value for the $2_2^+ \to 0_g^+ / 2_2^+ \to 2_1^+$ transitions is 0.022.[23] In the case of the 4_β^+ and 6_β^+ members, however, the largest $B(E2)$ values are for the $I_\beta \to (I-2)_\beta$ transition. Otherwise only the $I_\beta \to I_g$ transition has been observed; the $I_\beta \to (I-2)_g$ transition appears to be missing for $I = 4$ or 6.

Some of the levels in $^{150}_{62}\mathrm{Sm}_{88}$ as determined in studies of the ^{149}Sm$(n, \gamma)^{150}$Sm reaction[24] are also shown in Fig. 8. The level spacing is similar to that in ^{152}Gd and ^{154}Dy. A recent study of a 4^+ level at 1819 keV in ^{150}Sm has led Debenham and Hintz[25] to the conclusion that a 0^+ level at 1256 keV, a 2^+ level at 1417 keV and the 1819-keV level constitute a true rotational spectrum.

B. Levels in ^{152}Tb

Properties of the low-lying neutron and proton orbitals have not been very well established for odd-odd nuclei in the transition region. Takahashi, McKeown, and Scharff-Goldhaber[15] have interpreted the levels in $^{152}_{63}\mathrm{Eu}_{89}$ up to 147.8 keV in terms of Nilsson states. The deformation of ^{152}Eu implied by their choice of low-lying neutron and proton orbitals is $\delta = 0.1 - 0.2$.

The ground state of odd-A Tb nuclides in the deformed region ($A > 155$) is invariably $\frac{3}{2}^+$, presumably the $\frac{3}{2}^+[411]$ proton state.[2,17] The ground states of ^{151}Tb and ^{153}Tb have been measured[17] to be $\frac{1}{2}$ and $\frac{5}{2}$, respectively, possibly the $\frac{1}{2}^-[550]$ and $\frac{5}{2}^-[532]$ states. Other low-lying proton states are $\frac{3}{2}^-[541]$, $\frac{5}{2}^+[413]$, and $\frac{7}{2}^-[523]$. The ground states of the 87-neutron nuclides ^{149}Sm and ^{151}Gd are $\frac{7}{2}^-$; each has a low-lying $\frac{5}{2}^-$ state. If we assume ^{152}Tb to be slightly deformed (e.g., comparable to ^{152}Eu), neutron orbitals expected to be reasonably low lying are $\frac{5}{2}^-[523]$, $\frac{1}{2}^-[530]$, $\frac{3}{2}^-[532]$, $\frac{3}{2}^-[521]$, and $\frac{11}{2}^-[505]$.

TABLE VI. Ratio of $B(E2)$ values for interband and intraband transitions in ^{152}Gd, ^{154}Dy, and ^{154}Gd.

	Experimental ratio of $B(E2)$ values						
		^{152}Gd					
Transitions	Present work	Gono (Ref. 21)	Gromov (Ref. 3)	Riedinger (Ref. 5)	^{154}Dy (Ref. a)	^{154}Gd (Ref. 5)	Adiabatic rotor
$\frac{2_\beta^+ \to 0_\beta^+}{2_\beta^+ \to 2_g^+}$	<1.6 ±0.2	5.6 ± 1.3	3.0	3.2 ± 1.0	···	···	0.7
$\frac{2_\beta^+ \to 0_g^+}{2_\beta^+ \to 2_g^+}$	0.021 ± 0.007	0.023 ± 0.006	0.017	0.011 ± 0.006	0.015 ± 0.006	0.12 ± 0.02	0.7
$\frac{4_\beta^+ \to 2_\beta^+}{4_\beta^+ \to 4_g^+}$	6.0 ±1.5	9.5 ±5.1	···	···	5.1 ± 0.5	···	1.1
$\frac{6_\beta^+ \to 4_\beta^+}{6_\beta^+ \to 6_g^+}$	>7.2 ±1.8[b]	4.4 ±4.8	···	···	14 ± 2	···	1.24

[a] Calculated from intensities given in Ref. 20.

[b] Assumes that all of the intensity of the 440-keV transition is the $6_\beta 6_g$ transition.

TABLE VII. Possible configurations of levels in ^{152}Tb.

E (keV)	I^{π}	Proton orbital		Neutron orbital
0	(2$^-$)	$\frac{3}{2}^+[411]$	+	$\frac{1}{2}^-[530]$
		$\frac{5}{2}^+[413]$	−	$\frac{1}{2}^-[530]$
58.9	(3$^-$)	$\frac{3}{2}^+[411]$	+	$\frac{3}{2}^-[521]$
		$\frac{5}{2}^+[413]$	+	$\frac{1}{2}^-[530]$
342.2	(5$^-$)	$\frac{5}{2}^+[413]$	+	$\frac{5}{2}^-[523]$
501.8	(8$^+$)	$\frac{5}{2}^-[532]$	+	$\frac{11}{2}^-[505]$

Some possible combinations of these orbitals to account for the proposed spin-parities of levels in ^{152}Tb are listed in Table VII. In each case it is assumed that the Gallagher-Moszkowski coupling rules[26] are followed. The 59-keV level may not be a two-particle state; if it is the $I=3$ member of a rotational band based on the ground state, however, the inertial constant $\hbar^2/2\mathscr{I}$ is only 10 keV.

The partial half-life of the $E3$ isomeric transition is 3.2×10^2 sec, which is 3.2×10^3 single-particle lifetime units. The hindrance is attributed to the requirement that both the neutron and proton states in the $8^+\to5^-$ transition must change.

None of the states observed to be populated by the isomeric transition in ^{152m}Tb appears to be the same as that populated in the electron-capture decay of 2.4-h ^{152}Dy in which a 257.2-keV γ ray is emitted.[2] Since the ground state of ^{152}Dy is 0^+ and Q_{ec} is small ($\simeq$0.4 MeV),[2] it is likely that ^{152}Tb has a $1^{\pm}$ level at 257.2 keV. Such a level is not likely to be populated by the decay of ^{152m}Tb.

As in the case of the 147.8-keV 8^- level in ^{152}Eu, it is difficult to account for the 8^+ level at 501.8 keV in ^{152}Tb unless the $\frac{11}{2}^-[505]$ neutron orbital is available. No reasonable combination of low-lying spherical single-particle states for an odd neutron and an odd proton in this mass region can couple to 8^+. A vibrational state of this spin at 500 keV also seems improbable. We conclude that a description of ^{152}Tb as being a deformed nucleus is not unreasonable.

V. ACKNOWLEDGMENTS

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Elastic Scattering of 1.33-MeV Photons from Lead and Uranium

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Differential cross sections for the elastic scattering of 1.33-MeV photons from lead and uranium have been measured at angles ranging from 12 to 60°, using a lithium-drifted germanium detector. Available calculations of the various elastic scattering amplitudes are briefly reviewed and an argument is presented to establish the relative phases between the two polarization components of the real scattering amplitudes. Those relative phases and the relative phases among the amplitudes of the various scattering processes permit the addition of the amplitudes to calculate theoretical cross sections. Discrepancies exist between the measured and theoretical cross sections. Suggestions by several authors for resolving these discrepancies are discussed and the need for further theoretical work is indicated.

INTRODUCTION

Continuing attempts to improve the accuracy of differential elastic scattering cross-section measurements are motivated by the desire to observe a contribution from the real part of the Delbrück scattering amplitude. In the intermediate state of the Delbrück process an electron-positron pair is created in the static Coulomb field surrounding the nucleus. Since the whole atom recoils, subsequent annihilation of this pair produces a photon of essentially the same energy as the incident photon. The contributions from real and virtual pairs are contained in the imaginary and real parts, respectively, of the scattering amplitude. Experimental verification of the importance of virtual pairs to real processes has already been established (see the review article by Kane and Basavaraju[1]). Further the detection of scattering attributable to the imaginary part of the Delbrück scattering amplitude (see Jackson and Wetzel[2] and references contained therein) provides indirect evidence for a real part because the two are connected by a dispersion relation. Nevertheless, elastic scattering measurements are still made, not only to attempt to provide very direct evidence for effects attributable to virtual pairs, but also because of increasing awareness that discrepancies exist between these measurements and theoretical calculations.

Before the Delbrück amplitudes were calculated, a discrepancy between the measurements and the coherent addition of the Rayleigh and nuclear Thomson processes could be taken as evidence for the existence of Delbrück scattering. Since Ehlotzky and Sheppey[3] performed exact numerical calculations of the Delbrück scattering amplitudes, a much more stringent comparison between theory and experiment is possible. Any significant disagreement between the measurements and a theoretical cross section which includes all the elastic scattering processes indicates a systematic error in the measurements, an incorrect theoretical calculation, or both.

As pointed out by Nath[4] and by Hardie, Merrow, and Schwandt[5] a discrepancy exists between theory and experiment for the case of 2.62-MeV photons scattered from lead. In an earlier paper (Ref. 5) results were presented for the scattering of 1.33-MeV photons from lead and uranium through large angles, and disagreements between the experimental results and theoretical calculations were discussed. The present paper reports the extension of these measurements to smaller angles and continues the discussion of discrepancies between theory and experiment. This disagreement was first considered in detail by Dixon and Storey[6] and more recently by Basavaraju and Kane.[7] These authors suggest that agreement can be secured by a suitable choice of relative phases among the various scattering amplitudes. Hence it is important to determine the theoretical restrictions which can be placed on the possible choices of relative phases. The theory section below slightly amplifies an earlier discussion[5] of this question and also summarizes the calculations of the various