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Energy Levels in ^{156}Gd Populated by 5.4-Day ^{156}Tb

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γ-ray singles and coincidence measurements have been carried out on the decay of ^{156}Tb with Ge(Li) detectors to study levels of ^{156}Gd. A total of 102 transitions were observed, of which 52 were previously unreported. Of these 78 were placed in the decay scheme with levels at: 88.967, 2^+0; 288.16, 4^+0; 584.74, 6^+0; 1129.52, 2^+0; 1154.23, 2^+2; 1242.5, $1^-(0)$; 1248.08, 3^+2; 1258.4, 2^+0; 1276.22, $3^-(0)$; 1297.7, 4^+0; 1319.69, $2^-(1)$; 1355.52, 4^+2; 1366.6, $1^-(1)$; 1462.4, 4^+0; 1468.5, (4^-1); 1510.67, $4^+(4)$; 1539.0, (3^-1); 1622.64, $5^+(4)$; 1852.09, $3^-(2)$; 1943.41, 3^-; 2045.04, $4^-(4)$; 2103.49, 3^-; 2175.6, 2181.5, and 2232.9 keV. The spin, parity, and K assignments are given where known after each level. 12 of these levels are reported in this decay for the first time.

I. INTRODUCTION

Studies of levels in ^{152}Sm and ^{154}Gd which exhibit the rotational and vibrational properties of nuclei with permanently deformed ground states, yet are soft to nuclear deformation, have provided a great wealth of significant information for comparison with the Bohr-Mottelson model. In particular, in recent years the first evidence on β bands[1,2] in deformed rare-earth nuclei and for large $E0$ admixtures[2,3] in $\Delta I = 0$ transitions from these bands[1] came from these nuclei. The first evidence for the failure of the Bohr-Mottelson model to predict branching ratios from the β bands occurred in these nuclei.[4,5] At the same time similar evidence[6] was obtained for the 2^+ level of the β band in ^{156}Gd. These nuclei are spoken of as transitional nuclei because they are in the region where the transition from near spherical to large permanent deformation sets in. Since the ^{156}Gd nucleus is further into the region of strongly deformed nuclei, one may expect to see changes in the level structures of ^{154}Gd and ^{156}Gd.

Thus we have extended our studies of deformed nuclei by carrying out careful γ-ray singles and coincidence measurements on the decay of ^{156}Tb to ^{156}Gd. Since the ground state of ^{156}Tb is 3^-, as is that of ^{154}Eu which decays to ^{154}Gd, one could expect similar levels to be populated. Earlier ^{156}Tb studies[7-11] have reported 13 excited states in ^{156}Gd populated by ^{156}Tb. These studies included electron[7-9] and γ-ray[7,8,10] measurements and low-temperature nuclear-orientation experiments.[11] There are also several earlier studies[12] of the ^{156}Gd levels from the decay of ^{156}Eu which has a 0^+ ground state. The ^{156}Eu decay populates 0^+ and

1^+ states not seen from ^{156}Tb, whereas the ^{156}Tb decay populates higher-spin states not seen from ^{156}Eu. Inelastic deuteron scattering,[13] Coulomb excitation with ^{16}O ions,[14] and (α, xn)[15] experiments have supplied much information about the collective levels. More recently, since this work was completed, ^{155}Gd(n, γ)[16] and new studies of the ^{156}Eu decay[17,18] have provided interesting new information. In addition the authors learned of new, extensive conversion-electron work[19] on the decay of ^{156}Tb that complements our own work.[20,21] Finally Peek[22] has recently published some conversion-electron and γ-ray measurements on a limited number of transitions (intensities for 32 γ and 17 K lines) from 12 of the excited levels. Our γ-ray measurements are considerably more extensive and were carried out with detectors with considerably better resolution and efficiency. His conversion-electron work[22] parallels our own[20] except that he carried out L-subshell measurements on the transitions below 360 keV and we carried out more extensive K-electron measurements above 500 keV. Preliminary results of our work have appeared previously.[23]

The present work includes careful γ-ray spectrum measurements with a lithium-drifted germanium detector Ge(Li) and coincidence studies. A total of 102 transitions are observed of which 52 are reported for the first time. These data combined with the conversion-electron work of the previous paper[20] provide much detailed information on the levels in ^{156}Gd. These data are compared with the predictions of nuclear models.

II. EXPERIMENTAL APPARATUS AND PROCEDURES

The ^{156}Tb sources were produced by the reaction ^{156}Gd$(p, n)^{156}$Tb on isotopically enriched ^{156}Gd. The production and chemical separation procedures for this work were the same as for the electron studies.[20]

Singles spectra of the γ rays emitted by ^{156}Tb were obtained with a lithium-drifted germanium Ge(Li) detector and two 4096-channel-analyzer systems. The detector had a depleted volume of 30 cm^3 and an efficiency of 3.8% relative to a 7.5-cm by 7.5-cm NaI(Tl) detector at 1.3 MeV. A peak-to-Compton ratio of 15:1 was attained which permitted identification of many weak peaks previously obscured by the high Compton background of smaller detectors.

Pulses from the detector were amplified by a Tennelec TC-135 FET preamplifier and a Tennelec TC-200 amplifier. The preamplifier featured pole-zero cancellation of the pulses to optimize the resolution of the system. Pulses shaped and amplified by the TC-200 amplifier were fed into a Nuclear Data 3300, 4096-channel analyzer. The memory capacity of the ND 3300 of 10^6 counts per channel allowed long experiments without strong, low-energy lines overflowing the memory. Also used in these experiments was a Nuclear Data 161, 4096-channel analyzer which is identical to the ND 3300 in the singles mode except for a smaller memory (2.6×10^5 counts per channel). Both of these analyzers have ramp-type analog-to-digital converters to digitize the pulses received from the amplifier for storage in the memory. The over-all resolution of the system as determined from the full width at half maximum (FWHM) of the γ-ray peaks was 1.75 keV at the 122-keV line of ^{57}Co and 2.9 keV at the 1333-keV line of ^{60}Co.

The efficiency curve for the 30-cm^3 Ge(Li) detector was determined by using several standard sources with well-known γ-ray intensities. A combination of two methods was used to determine the efficiency curve from 60 to 3250 keV. One, as described by Kane and Mariscotti,[24] involved measurements of the relative photopeak areas of a standard source which has two or more γ rays with accurately known intensities. With sources of ^{108}Ag, ^{22}Na, ^{228}Th, ^{24}Na, ^{160}Tb, and ^{56}Co, the relative efficiency curve of the Ge(Li) detector was extended from 46 to 87 keV and from 200 to 3250 keV with that procedure. All measurements were taken at a source-to-detector distance of approximately 10 cm. The standard sources, however, have no accurately measured γ-ray intensities within the region 100 to 200 keV. This is the region of turnover in which the relative efficiency changes drastically with energy. In order to locate some data points in this region, a second method of efficiency determination was used. This was the measurement of the absolute efficiency of the detector. The Vienna International Atomic Energy Agency calibrated sources used for these measurements were placed in a reproducible geometry approximately 10 cm from the detector. Absolute efficiencies were obtained for the ^{57}Co lines at energies of 122 and 136 keV. Other absolute efficiencies were determined for the 59-keV line of ^{241}Am, the 662-keV line of ^{137}Cs, and the 511- and 1274-keV lines of ^{22}Na. The relative efficiency curve obtained previously was normalized to the absolute efficiency curve through the point at 1274 keV of ^{22}Na which was used in both measurements. A computer least-squares fit of the log ϵ versus energy to the experimental points above 100 keV gave the complete curve as shown in Fig. 1. The over-all error of this curve is estimated to be 6% in the region of turnover (40–200 keV) and 3% at higher energies.

A check of the relative efficiency curve of the 30-cm^3 detector at various source-to-detector distances revealed that, for the most part, the curve was independent of distance. For example, the relative efficiencies at distances 10, 20, and 30 cm as calculated from the 1368- and 2754-keV lines of ^{24}Na agreed within 1%. Data taken with the ^{160}Tb source at distances 1 and 10 cm showed that only for the low-energy lines of 46, 52, and 87 keV was there any deviation of the relative efficiency. Therefore, throughout the ^{156}Tb experiments the efficiency curve of Fig. 1 was used in the calculation of relative intensities for γ rays above 200 keV even though all experiments were not conducted at the same source-to-detector distances.

The ^{156}Tb γ-γ coincidence experiments were performed with a 5-cm by 5-cm NaI crystal and the 30-cm^3 trapezoidal Ge(Li) detector described above. Energy gates were selected from the NaI detector while the Ge(Li) detector was used to record the spectrum in coincidence with the gate. The gate channel consisted of the scintillation detector along with a RIDL anti-walk single-channel analyzer which employed crossover timing. Pulses from the Ge(Li) side were amplified by a Tennelec TC-135 preamplifier and a TC-200 linear amplifier. Both channels were fed into a RIDL fast-slow coincidence circuit which generated gate-pulses to a Nuclear Data 161, 4096-channel analyzer when coincidences were established. The resolving time of the coincidence circuit was $2\tau = 140$ nsec. The Ge(Li) and NaI detectors were arranged in a 90° geometry throughout the experiments. A lead collimator placed over the NaI crystal prevented low-energy Compton photons scattered in the Ge(Li) detector from directly reaching the NaI detector.

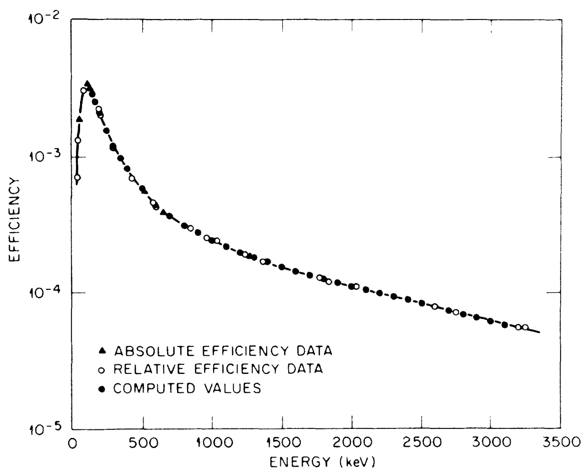

FIG. 1. Absolute efficiency of a 30-cm^3 Ge(Li) detector at a source-to-detector distance of 10 cm. The curve above 100 keV is a least-squares fit to the experimental points by computer.

III. RESULTS

γ-Ray Singles Work

The energies of the γ rays observed in the ^{156}Tb decay were measured by determining first the energies of the stronger lines. In this work well-known standards were used as calibration lines. Then the stronger lines were used as calibration lines to determine the energies of the weaker lines. Two experiments were run to measure the energies of the stronger lines. In both, the standard sources were run simultaneously with ^{156}Tb, rather than before or after the ^{156}Tb run, in order to eliminate the problems of zero level and gain shifts between runs. Totals of 11 and 15 standard lines with energies known to within 0.1 keV were used over the range of 122 to 2035 keV. The peak position of a line was taken as the peak position of a Gaussian curve which was fit to the data points corrected for background by a three-parameter least-squares-fitting procedure by computer. A minimum of six points in the photopeak was used in each fit. The linear background subtracted from the data points was calculated by computer from a fit to background points on either side of the photopeak. The accuracy of the peak location by this methods was estimated to be 0.1 channel. A calibration of energy versus peak channel number for the standard lines was obtained through a least-squares fit to an Nth degree polynomial. In these experiments a second-degree polynomial provided an accurate calibration.

Table I gives the results of the two experiments conducted to measure the energies of the strong γ rays of ^{156}Tb. Weighted averages are listed in the third column. These were the energies used to calibrate the Ge(Li) spectrometer for the energy determinations of the weaker lines. For comparison the energy measurements of these transitions by Kenealy, Funk, and Mihelich (KFM)[10] are given in the last column of Table I. Some discrepancies exist between our measurements and those of the earlier work[10] for the higher-energy γ rays. In ^{160}Tb γ-ray energy measurements[25] similar deviations were also observed between our results and the results of the Notre Dame group[26] for the higher-energy transitions. In that case, however, our results are in good agreement with the measurements of the University of Michigan.[25] One consequence of the higher ^{156}Tb γ-ray energies of this work is that the high-energy level energies of ^{156}Gd are altered slightly from those given by KFM.[10]

Peek[22] reports accurate energy measurements for only 18 transitions. His results agree with our work except for his values of 576.2 ± 0.09 and 1264.2 ± 0.18 keV compared with our results of 578.8 ± 0.2 and 1266.56 ± 0.12 keV. In the latter case, our value is consistent with both his and our level energies but his 1264.2 keV is not. KFM[10] and Fujioka[19] both report energies consistent with our 578.8 keV in the other case.

The errors quoted for the energy measurements in this work arise from two sources – statistical error of the least-squares fit, and uncertainty in the linearity of the Ge(Li) detector-multichannel-analyzer system. Errors associated with the least-squares fit were calculated by computer. This calculation takes into account the absolute energy error of the standard lines along with the estimated error in peak location of the calibration and ^{156}Tb photopeaks. Errors in the linearity of the Ge(Li) detector-multichannel-analyzer system are significant in precise γ-ray energy measurements.[27] Studies of the nonlinearity of the system used in these experiments were carried out with a precision pulser. The system was found to be linear within ±0.5 channels from channel 400 to 3700.[28] Most of the linearity error, however, is negated by using a nonlinear polynomial to calibrate the spectrometer. Therefore, a reasonable estimate of ±0.2 channels for the linearity uncertainty is included in the errors quoted for these energy measurements.

A complete list of ^{156}Tb γ rays is given in Table II. The energy values represent weighted averages of from two to four independent measurements. Errors in the least significant figures of the mean values are given in parentheses. The energy measurements of KFM[10] are listed for comparison. The peak locations of weak γ rays seen in the singles spectrum were determined by hand. In these cases the error of the energy is based on the error of the peak position.

The relative intensity measurements of ^{156}Tb γ rays are also presented in Table II and compared with the results of KFM.[10] Four experiments were conducted to measure these intensities. Counting times of these experiments ranged from 24 to 44 h. Typical γ-ray spectra are shown in Figs. 2–4. Each γ ray listed in Table II was seen in at least two of these experiments. One γ ray of 995 keV previously reported by KFM[10] was not observed in the present work. The ^{156}Tb γ-ray intensities are normalized to a value of 100 for the strong 1222.4-keV γ ray. The error limit corresponding to the standard deviation of the mean is again given in parentheses following the measured value.

The relative intensities were obtained from the areas of the photopeaks corrected for the efficiency of the Ge(Li) detector. For a strong peak on a well-defined background, the accuracy of this method was estimated to be approximately 2–3%. Error limits placed on other less well-defined line areas include contributions from statistical error as well as errors in background determination. The photopeak-area error limits together with the uncertainty of the efficiency correction were the basis for the quoted errors of the intensities in Table II.

The ^{156}Tb γ-ray spectrum includes several doublets and triplets which are only partially resolved even by the high resolution obtained with the Ge(Li) detector. Among these are the strong 1038-1041-, 1065-1067-, and 1154-1159-keV doublets which represent, in most cases, transitions from the β

TABLE I. Energy measurements of strong lines of ^{156}Tb.

Experiment 1	Experiment 2	Average	KFM (Ref. 10)
155.14 ± 0.13	155.13 ± 0.12	155.14 ± 0.09	...
199.29 ± 0.13	199.17 ± 0.12	199.23 ± 0.09	...
262.69 ± 0.13	262.55 ± 0.12	262.62 ± 0.09	...
296.67 ± 0.13	296.49 ± 0.12	296.58 ± 0.09	...
422.47 ± 0.13	422.39 ± 0.12	422.43 ± 0.09	...
534.36 ± 0.13	534.32 ± 0.12	534.34 ± 0.09	534.1 ± 0.3
780.16 ± 0.13	780.22 ± 0.13	780.19 ± 0.09	780.4 ± 1
925.98 ± 0.13	925.95 ± 0.13	925.97 ± 0.09	926.4 ± 0.4
949.27 ± 0.16	949.31 ± 0.17	949.29 ± 0.12	949.5 ± 1
959.82 ± 0.16	959.96 ± 0.17	959.89 ± 0.12	960.2 ± 0.3
1222.41 ± 0.13	1222.47 ± 0.12	1222.44 ± 0.09	1222.1 ± 0.5
1421.72 ± 0.13	1421.62 ± 0.12	1421.67 ± 0.09	1420.0 ± 0.5
1646.27 ± 0.13	1646.19 ± 0.16	1646.24 ± 0.10	1644.5 ± 0.5
1845.50 ± 0.14	1845.38 ± 0.16	1845.45 ± 0.10	1844.0 ± 0.5
2014.50 ± 0.19	2014.34 ± 0.30	2014.45 ± 0.16	2012.3 ± 0.5

TABLE II. ^{156}Tb γ-ray energies and intensities observed in the decay of ^{156}Tb. Errors in the last digit are given in parentheses.

E_γ (keV) Present work		KFM[a]		I_γ Present work		KFM[a]	
89.2	(3)	89		57	(6)	63	(15)
112.0	(2)	112		4.8	(5)	4.7	
115.8	(2)			0.17	(4)		
155.14	(9)	155		5.1	(4)	5.7	
199.23	(9)	199.2		132	(7)	131	
213.0	(4)			0.13	(3)		
249.2[b]	(4)			0.07	(2)		
262.62	(9)	262.5		18.6	(9)	19.2	
267.4	(2)			0.22	(9)		
296.58	(9)	296.3		13.6	(5)	14	
356.47	(9)	356.3		42.0	(17)	41.5	
374.2	(4)			0.11	(2)		
381.1	(2)	381.4		1.96	(13)	2.1	
407.1[b]	(3)			0.18	(4)		
422.43	(9)	422.4		24.4	(10)	26.1	
445.7[b]	(3)			0.12	(4)		
496.8	(3)			0.19	(5)		
534.34	(9)	534.1	(3)	209	(7)	215	
567.8	(6)			0.09	(2)		
578.8	(2)	579.3	(3)	1.41	(9)	1.8	(4)
593.0	(4)			0.06	(2)		
596.8[b]	(4)			0.14	(3)		
603.7	(3)			0.29	(4)		
609.6	(3)			0.06	(2)		
614.58	(15)	614	(1)	0.56	(5)	...	
626.3[b]	(2)			0.97	(12)		
634[c]				0.05	(2)		
641.1	(3)			0.20	(4)		
651.0[b]	(5)			0.04	(2)		
658.2	(3)	659	(1)	0.63	(9)	...	
668.6[b]	(4)			0.18	(4)		
673.8[b]	(4)			0.15	(4)		
676.2	(4)			0.31	(4)		
686.3	(2)	686	(1)	1.46	(16)	1.3	(5)
689.5	(5)			0.52	(11)		
691.7	(4)	690	(1)	0.73	(10)	0.8	(3)
697.6	(3)			0.40	(6)		
704.3[b]	(3)	705	(1)	0.46	(6)	...	
713				<0.10			
717.4	(4)	717	(1)	0.33	(6)	...	
748.0	(2)	747	(1)	0.85	(10)	0.6	(3)
771				<0.11			
780.19	(9)	780.4	(10)	7.73	(31)	7.6	
796.9	(4)			0.12	(4)		
804.9	(2)	805	(1)	0.78	(7)	0.9	(4)
816.3[b]	(4)			0.08	(3)		
827.7	(4)			0.12	(6)		
841.2	(2)	841	(1)	0.75	(8)	1.0	(4)
845.6	(5)			0.15	(3)		
855.3	(2)	855	(1)	0.99	(12)	1.1	(5)
860.9	(3)			0.44	(8)		

TABLE II *(Continued)*

E_γ (keV) Present work		KFM[a]		I_γ Present work		KFM[a]	
866.0	(2)	866	(1)	1.04	(11)	<1.2[d]	
877.0[e]	(5)			0.15	(5)		
898.9	(5)			0.08	(2)		
921.9[b]	(5)			0.23	(11)		
925.97	(9)	926.4	(5)	12.4	(4)	13.5	(15)
949.29	(12)	949.5	(10)	4.72	(20)	5.0	(10)
959.89	(12)	960.2	(3)	5.94	(22)	5.5	(8)
969.9	(4)			0.24	(6)		
974.1	(3)			0.31	(7)		
984.8	(4)			0.34	(8)		
988.1	(2)			0.93	(13)		
		995	(1)[f]			...	
1009.6	(4)			0.20	(5)		
1037.93	(14)	1039.5	(10)	3.31	(22)	5.4	(10)
1040.57	(14)	1039.5	(10)	2.06	(13)	5.4	(10)
1065.26	(14)	1065.0	(10)	34.6	(13)	45.0 (15)	35.0 (50)[g]
1067.34	(14)	1067.0	(10)	9.0	(6)	45.0 (15)	9.0 (15)
1129.6	(2)	1129	(1)	0.52	(6)	0.6	(2)
1153.5							
1154.24	(13)	1154.0	(5)	34.0	(13)	35.0	(40)
1159.14	(13)	1159.4	(5)	23.2	(9)	25.0	(30)
1169.5	(3)			0.19	(4)		
1174.2	(3)			0.36	(5)		
1180.3	(3)			0.16	(4)		
1187.2	(2)	1188	(1)	1.82	(11)	1.5	(5)
1208.7	(4)			0.10	(3)		
1222.44	(9)	1222.1	(5)	≡100		≡100	
1230.71	(13)	1228	(2)	2.60	(17)	2.6	(6)
1242.5	(2)	1240	(1)	0.62	(7)	0.8	(2)
1250.7	(5)			0.09	(3)		
1258.4	(5)			0.07	(2)		
1266.56	(12)	1265	(1)	3.21	(17)	3.9	(5)
1277.5	(5)			0.08	(3)		
1334.46	(10)	1333	(1)	8.21	(35)	7.7	(11)
1366.8	(6)			0.04	(1)		
1374.0	(7)			0.08	(2)		
1421.67	(9)	1420.0	(5)	39.1	(15)	39.0	
1450.2	(4)			0.11	(4)		
1564.0	(4)			0.14	(4)		
1646.24	(10)	1644.5	(5)	11.7	(4)	12.0	(15)
1739.1[b]	(6)			0.07	(2)		
1763.1	(6)			0.27	(10)		
1815.32	(14)	1814	(1)	1.27	(7)	1.6	(4)
1845.45	(10)	1844.0	(5)	13.0	(5)	13.4	(16)
1887.4	(3)	1885	(1)	0.22	(2)	0.4	(2)
1893.4	(3)	1889	(1)	0.13	(2)	0.2	(1)
1944.8	(4)	1942	(2)	0.07	(2)	0.10	(5)
1987.4[b]	(4)			0.04	(1)		
2014.45	(16)	2012.3	(5)	3.63	(14)	3.4	(4)
2051.2[b]	(4)	2047	(3)	0.05	(1)	0.05	(3)

TABLE II (*Continued*)

E_γ (keV) Present work		KFM[a]		I_γ Present work		KFM[a]	
2092.4	(3)	2089	(1)	0.13	(2)	0.22	(5)
2103.5	(5)			0.020	(6)		
2138.4[b]	(5)	2138	(3)	0.032	(6)	...	

[a] Energies and intensities as given in Ref. 10. The energies ≤422.4 keV have been taken from the adopted values of the Nuclear Data group. Intensity errors are ±10% unless otherwise noted.
[b] Not placed in decay scheme.
[c] Probable doublet; not placed in decay scheme.
[d] Indicated in Ref. 10 to be composite with the double-escape peak of the 1893-keV transition.
[e] Possible doublet since this energy fits more than one place in the decay scheme.
[f] The 995-keV transition was not observed in the present work.
[g] Intensity of the composite peak at 1065 keV has been listed along with the intensities of the 1065- and 1067-keV transitions as determined from coincidence measurements. (See Ref. 10.)

or γ-vibrational band to the ground-state band. In order to measure accurately the line areas of these transitions, the composite lines were stripped by computer. The computer routine fits a reference line shape derived from a strong line in the spectrum to the two lines of the doublet by a least-squares-fitting procedure. The program required the FWHM of the reference line shape to vary as the square root of the γ-ray energy, a relationship which is typical of Ge(Li) detectors for photons of these energies.[29] A reference line shape for all three doublets was taken from the

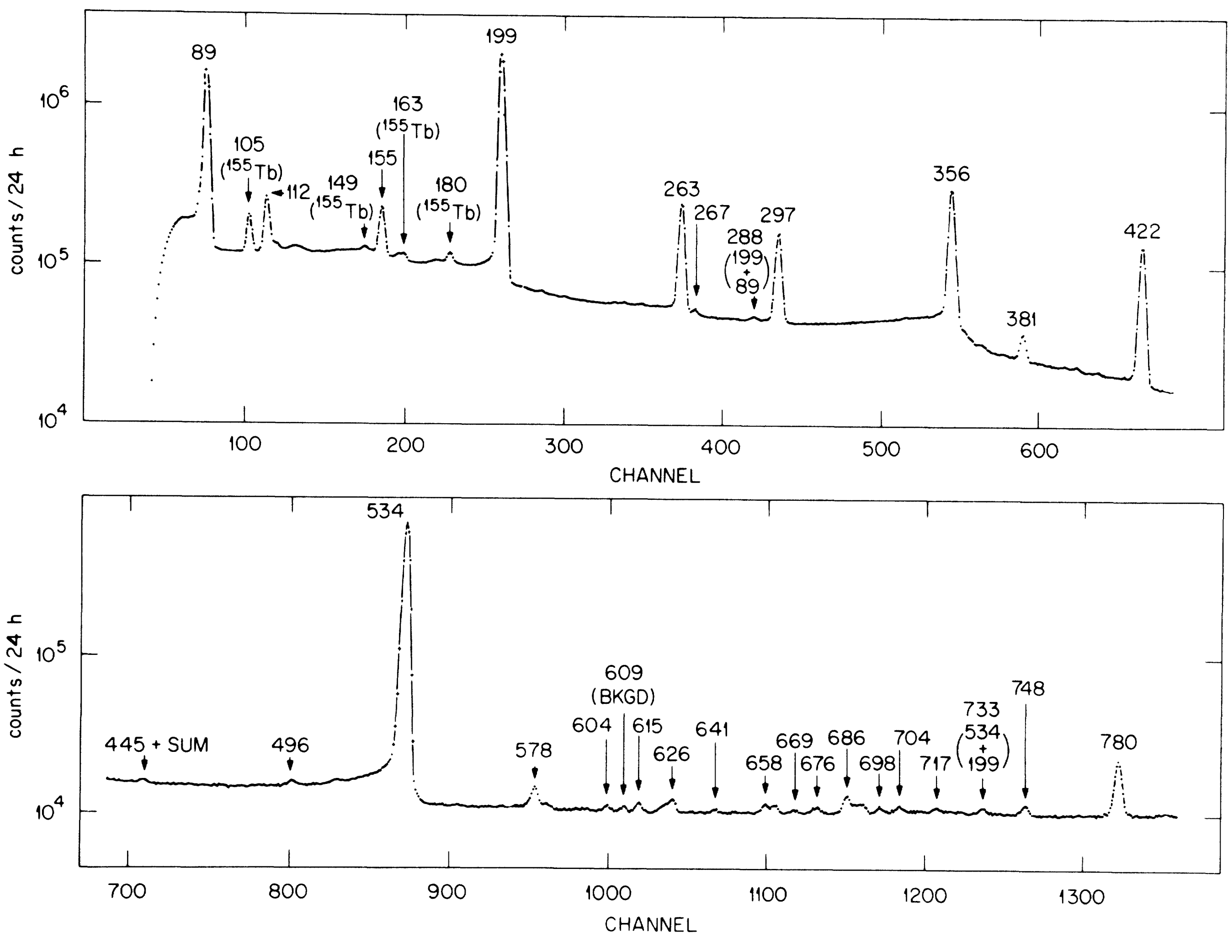

FIG. 2. The 80- to 800-keV region of the ^{156}Tb γ-ray spectrum obtained with a 30-cm^3 Ge(Li) detector.

strong 1222.4-keV transition. Figure 5 shows the computer fit to the data points of the 1038-1041- and 1065-1067-keV doublets in one of the γ-ray experiments. The smooth curve through the data points is the composite line determined by the least-squares fit. The stripped peaks are shown plotted on the baseline while the linear background as fixed by computer is shown by a dashed line. Also plotted for each data point is the residual, which is defined by the error of the fit divided by the statistical error at that point. The quantity χ^2 given for each doublet is a measure of the goodness of fit to the experimental points. A fit with the experimental points on the average of one standard deviation from the curve has an χ^2 value, $\chi^2 = 1$.

With the above analysis procedure, very consistent results were obtained for the photon intensities of the strong ^{156}Tb doublets in three independent intensity experiments. In all cases the total area of the two stripped lines agreed with that of the composite line as determined by hand (within the limits of experimental error). Furthermore, the energy differences, as determined by the separation of the peak positions of the stripped lines, were consistent to within 0.1 keV in the three experiments. The intensities of the 1065- and 1067-keV transitions are in very good agreement with the results of other investigators,[10] where these intensities were measured through coincidence experiments.

Other doublets and triplets observed in the ^{156}Tb γ-ray spectrum were stripped by hand, since poor statistics or uncertainties in the background limited the usefulness of the computer analysis. These included the 686-689-692- and 985-988-992-keV triplets and the 86-89-, 624-626-, 658-662-, 970-974-, and 1887-1893-keV doublets. (The 86-keV peak is identified as a ^{155}Tb transition, the 624- and 992-keV peaks as double-escape peaks, and the 661-keV peak as a background peak and therefore are not listed in Table II.) In each of these cases a strong line of nearly the same energy was used as a reference line shape in the stripping analysis.

Care was taken in these experiments to properly identify weak peaks which appeared in the ^{156}Tb singles spectrum. Contributions from summing background, and single- and double-escape radiation have been eliminated from the list of ^{156}Tb

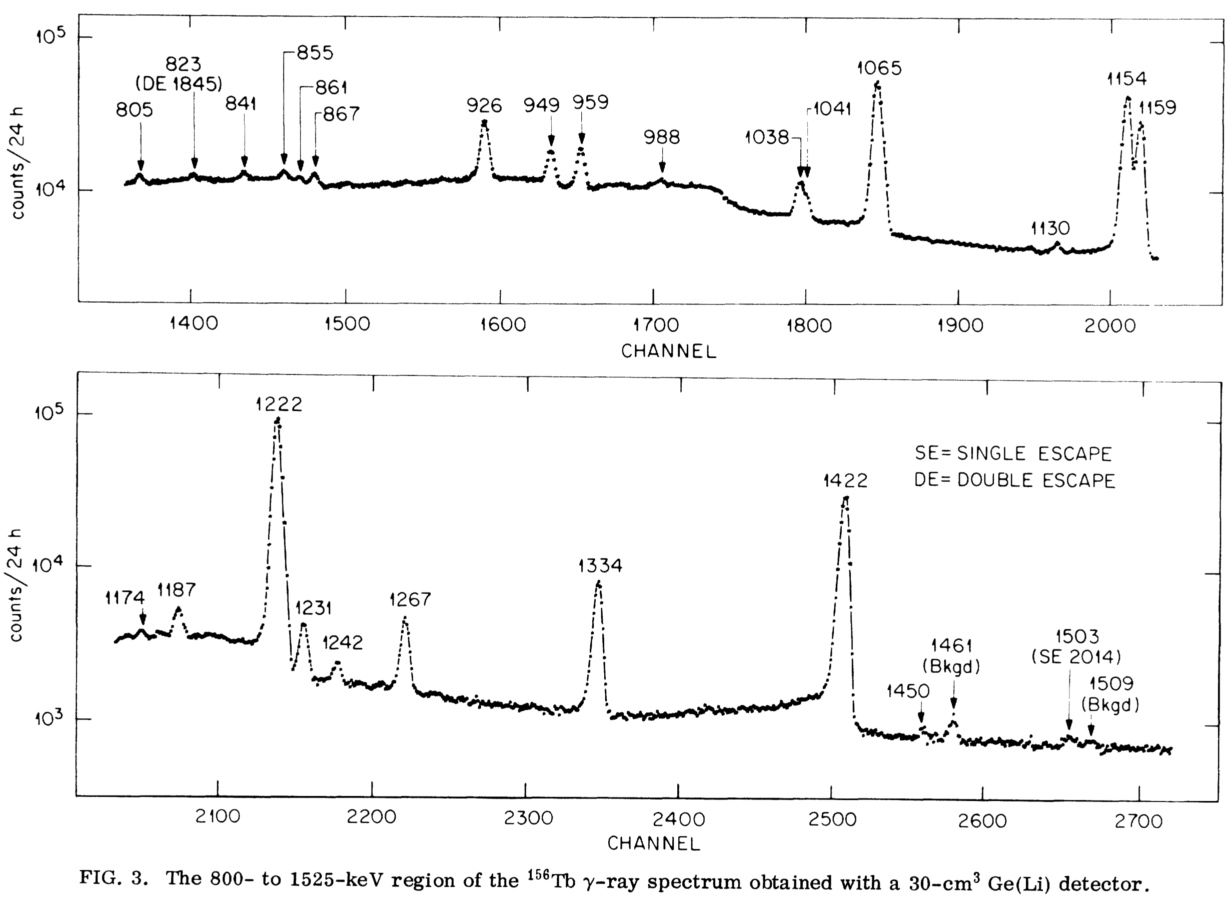

FIG. 3. The 800- to 1525-keV region of the ^{156}Tb γ-ray spectrum obtained with a 30-cm^3 Ge(Li) detector.

γ rays in Table II. Four γ rays listed in Table II have the same energy as sum peaks of strong ^{156}Tb transitions. These are 445.7-, 496.8-, 796.9-, and 2103.5-keV transitions. Each of these lines was identified by comparing its intensity with the intensity of a known sum peak of nearly the same energy. The intensities given for these γ rays have been corrected for the summing contributions. A background spectrum revealed a number of background peaks, most of them transitions from the naturally occurring thorium (^{232}Th) uranium (^{238}U) radioactive chains. Three of these, the 609.3-keV transition of ^{214}Bi, the 969-keV transition of ^{228}Ac, and the 1764-keV transition of ^{214}Bi, fall at energies comparable to weak ^{156}Tb lines. The ^{156}Tb 610-, 970-, and 1763-keV γ-ray intensities, therefore, have been corrected for the background enhancement.

γ-γ Coincidence Results

Two ^{156}Tb γ-γ coincidence experiments were conducted – one gating on the 89-keV $2^+ \to 0^+$ γ ray, and the other gating on the 199-keV $4^+ \to 2^+$ γ ray. A coincidence background experiment was also run with the NaI gate set in the region between the 89- and 199-keV γ rays. Figure 6 shows a NaI spectrum of the low-energy ^{156}Tb lines. Indicated in the figure are the approximate gate settings for the two coincidence experiments and the coincidence background experiment. The gate widths of the 199-keV experiment and the coincidence background experiment were nearly equal while the width of the 89-keV experiment was approximately half as great. The coincidence spectra which were recorded by a 30-cm^3 Ge(Li) detector covered an energy range of 280 to 2200 keV. The counting times for the three experiments ranged from 81 to 93 h.

Coincidence intensities measured in the 89- and 199-keV gated experiments are presented in Table III. The intensities are normalized to the intensity of the 1222-keV γ ray which is in coincidence with both gate transitions. For reference, the γ-ray intensities as measured in the singles spectrum are listed in column 2. Transitions which are not expected to be completely coincident with the gate transition from their placement in the decay scheme are indicated with a letter b in columns 3 and 4. The coincidence intensities given in Table

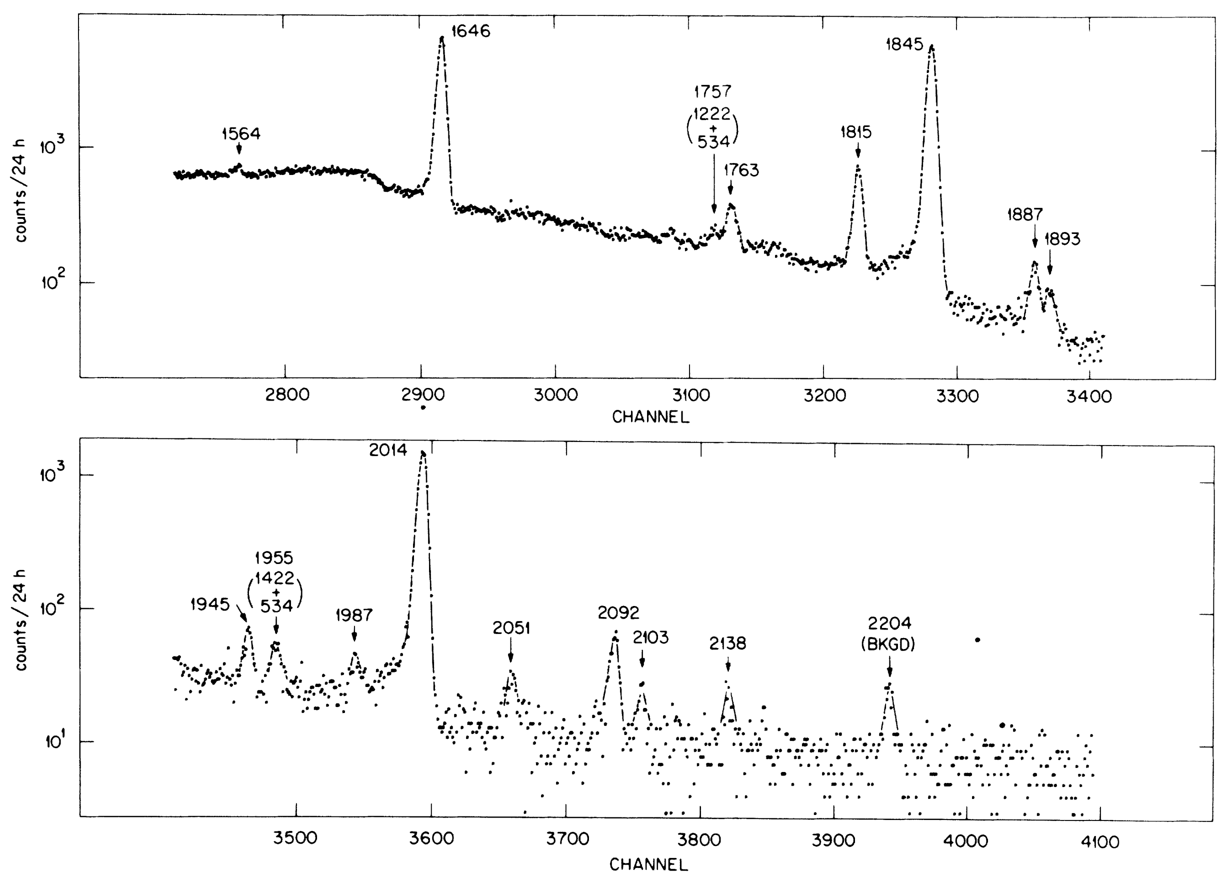

FIG. 4. The 1525- to 2300-keV region of the ^{156}Tb γ-ray spectrum obtained with a 30-cm^3 Ge(Li) detector.

III have been corrected for the coincidence background as determined from the coincidence background experiment. In making these corrections, allowances were made for the radioactive decay of the source and for the relative gate widths of the coincidence experiments with the background-gated experiment. Additional corrections were applied to the coincidence intensities of the 1067- and 1267-keV transitions because of the presence of the 155-keV transition in the coincidence background experiment. The 1067- and 1267-keV γ rays are known to be in coincidence with the 155-keV transition from previous coincidence studies of the ^{156}Tb decay.[10] The 155-1267-keV coincidence counting rate was determined by comparing the 1267-keV intensity in the background gate with its intensity in the 199-keV experiment. The 1267-keV transition was assumed not to be in coincidence with the 199-keV γ ray in agreement with the observed 155-1267-keV coincidence and the established placement of the 155-keV transition in the decay scheme from the earlier coincidence studies.[10] From the 155-1267-keV counting rate the 155-1067-keV counting rate was determined and was then used to correct the 1067-keV coincidence intensities.

In these studies chance contributions to the coincidence intensities were estimated to be less than 1% and therefore have been neglected. Angular-correlation effects which could cause intensity variations of several percent have also been neglected. Errors associated with the coincidence intensities of Table III are estimated to be ±10% in the most favorable cases.

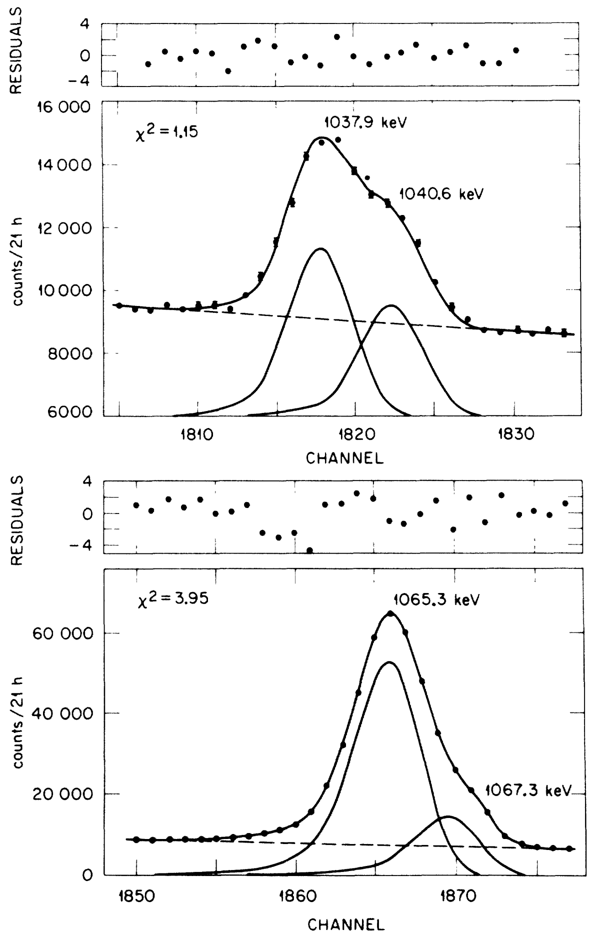

FIG. 5. Stripping analysis of the ^{156}Tb 1038-1041- and 1065-1067-keV γ-ray doublets. The residuals represent the error of the least-squares fit divided by statistical error. The error bars for the 1065-1067-keV lines are smaller than the plotted points.

Levels in ^{156}Gd Populated by ^{156}Tb

Levels in ^{156}Gd populated by the ^{156}Tb decay as determined in our work are shown in the decay scheme given in Fig. 7. The ^{156}Tb decay is entirely by electron capture. A limit of the β^+ to K-capture ratio has been established at less than 5×10^{-4} by Ofer.[7] The 25 excited levels of Fig. 7 (which include 12 new excited levels) account for 78 of the 102 observed transitions of ^{156}Tb. The level energies of the first two excited states of ^{156}Gd are those derived from an average of accurate electron energy measurements of the ^{156}Eu decay.[30,31] All other level energies indicated in Fig. 7 and presented in this section have been determined from the γ-ray energy measurements of this work. γ-ray intensities are given in parentheses. Those γ rays whose placement in the decay scheme is supported by the 89- and 199-keV coincidence experiments of this work and by coincidence experiments of other work[10] are designated in Fig. 7 by a filled circle. Otherwise the transitions are placed entirely on the basis of energy

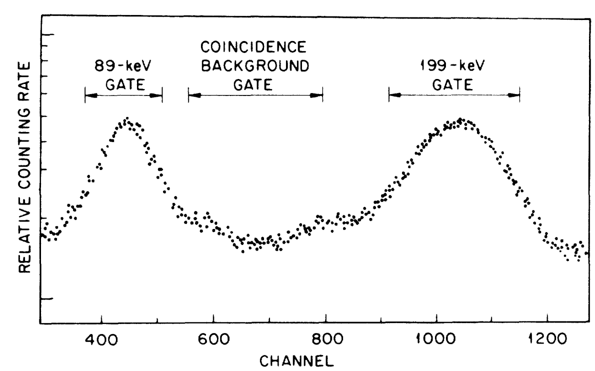

FIG. 6. A NaI spectrum of the ^{156}Tb 89- and 199-keV γ rays. (Only every third channel is plotted.) The approximate gate settings for the 89- and 199-keV coincidence experiments and the coincidence background experiment are indicated.

TABLE III. ^{156}Tb coincidence intensities obtained with a NaI- 30-cm^3 Ge(Li) detector system.

Energy (keV)	Singles intensity	89-keV gate [a]	199-keV gate [a]
297	13.6 ±0.5	12	10
356	42.0 ±1.7	24 [b]	0.8
381	1.96±0.13	1.5	0.3 [b]
422	24.4 ±1.0	27	16 [b]
534	209 ±7	193 [b]	113 [b]
748	0.85±0.10	~0.9	0.8 [b]
780	7.7 ±0.3	4.5 [b]	<0.3
841	0.75±0.08	~0.5	0.7
866	1.04±0.11	~0.7	1.3
878 [c]	0.37±0.06 [c]		~0.45 [c]
926	12.4 ±0.4	11	10
949	4.72±0.20	2.3*	<0.4
960	5.94±0.22	6.6	5.6
988	0.93±0.13	1.0	1.4
1038	3.31±0.22	6.4	2.9
1041	2.06±0.13	6.4	
1065	34.6 ±1.3	44 [d]	
1067	9.0 ±0.6	44 [d]	8.3 [d]
1154	34.0 ±1.3	4.9	0.2
1159	23.2 ±0.9	24	0.1
1174	0.36±0.05		~0.50
1180	0.16±0.04		~0.2
1187	1.82±0.11	2.5	0.1
1222	≡100	≡100	≡100
1231	2.60±0.17	3.0	<0.20
1242	0.62±0.07	<0.4	<0.25
1267	3.21±0.17	2.5 [d]	...
1334	8.21±0.35	10	9.3
1422	39.1 ±1.5	45	0.7
1646	11.7 ±0.4	12	13
1763	0.27±0.10	~0.2	<0.1
1815	1.27±0.07	1.3	1.2
1845	13.0 ±0.5	14	<0.1
1887	0.22±0.04	0.3	0.3
1893	0.13±0.03	0.3	0.1
1945	0.07±0.02	~0.2	0.1
2014	3.63±0.14	3.5	
2092	0.13±0.02	0.2	

[a] Transitions indicated with ~ sign may have errors as large as ±50%.

[b] Partial coincidence consistent with decay scheme placement.

[c] Sum of 877- and 879-keV transitions in ^{156}Tb and ^{160}Tb, respectivley (the ^{160}Tb appears as a slight impurity in the source).

[d] Coincidence intensity corrected for the 155-keV γ ray in the coincidence background gate (see discussion in text).

differences between the levels. The indicated multipolarity assignments for the transitions are based on the K conversion coefficients as reported elsewhere.[20] Electron-capture branching percentages to the levels in ^{156}Gd, calculated from the total transition intensity balances of the individual levels, are shown in the decay scheme along with the corresponding $\log ft$ values. The $\log ft$ values were determined from nomograms as given by Lederer, Hollander, and Perlman.[12] In making the $\log ft$ determinations, a Q value for the decay was taken to be 2.4 MeV.[12]

IV. LEVEL PROPERTIES

Ground-State Rotational Band

The 2^+, 4^+, and 6^+ members of the ^{156}Gd ground-state rotational band lie at 88.967±0.010 (Refs. 30 and 31), 288.16±0.02 (Refs. 30 and 31), and 584.74±0.09 keV, respectively. The rotational-band structure of the ^{156}Gd nucleus is shown in Fig. 8. The levels of the ground-state rotational band have been well established by previous investigators of the ^{156}Tb and ^{156}Eu decays as well as through Coulomb-excitation[14] and nuclear reaction studies.[15] An 8^+ member of this band was placed at 966 keV by Morinaga[15] from the evidence of a 382-keV γ ray following an (α, xn) reaction. Coincidence studies of this work, however, indicate that the 381.1-keV γ ray observed in the ^{156}Tb decay is coincident with the 89-keV ($2^+ \rightarrow 0^+$) γ ray but not entirely in coincidence with the 199-keV ($4^+ \rightarrow 2^+$) γ ray. These results are consistent with the results of KFM[10] who place the 381.1-keV γ ray between the 1510.7- and 1129.5-keV levels.

β-Vibrational Band

Two members of the $K^\pi = 0^+$, β-vibrational band are observed in the ^{156}Tb decay. One of these, the 2^+_β level at 1129.52±0.10 keV, is populated in the ^{156}Eu decay and has been established as a member of the $K=0$ band by Ewan and Bower.[32] Transitions of 1129.6, 1040.6, and 841.2 keV depopulate this level to the 0^+, 2^+, and 4^+ members, respectively, of the ground-state band. A high K conversion coefficient for the 1040.6-keV ($2^+_\beta \rightarrow 2^+$) transition indicates that it has an appreciable $E0$ component, a characteristic for $\Delta I = 0$ transitions from the β band to the ground-state band[2,3] in this mass region. The placement of this level at 1129.5 keV in the ^{156}Tb decay is confirmed by the observed coincidence of the 534- and 381-keV γ rays by KFM,[10] and by the 1040.6-89-keV coincidence and the unobserved 1040.6-199-keV coincidence results of this work.

A previously unobserved 4^+ member of the $K=0$

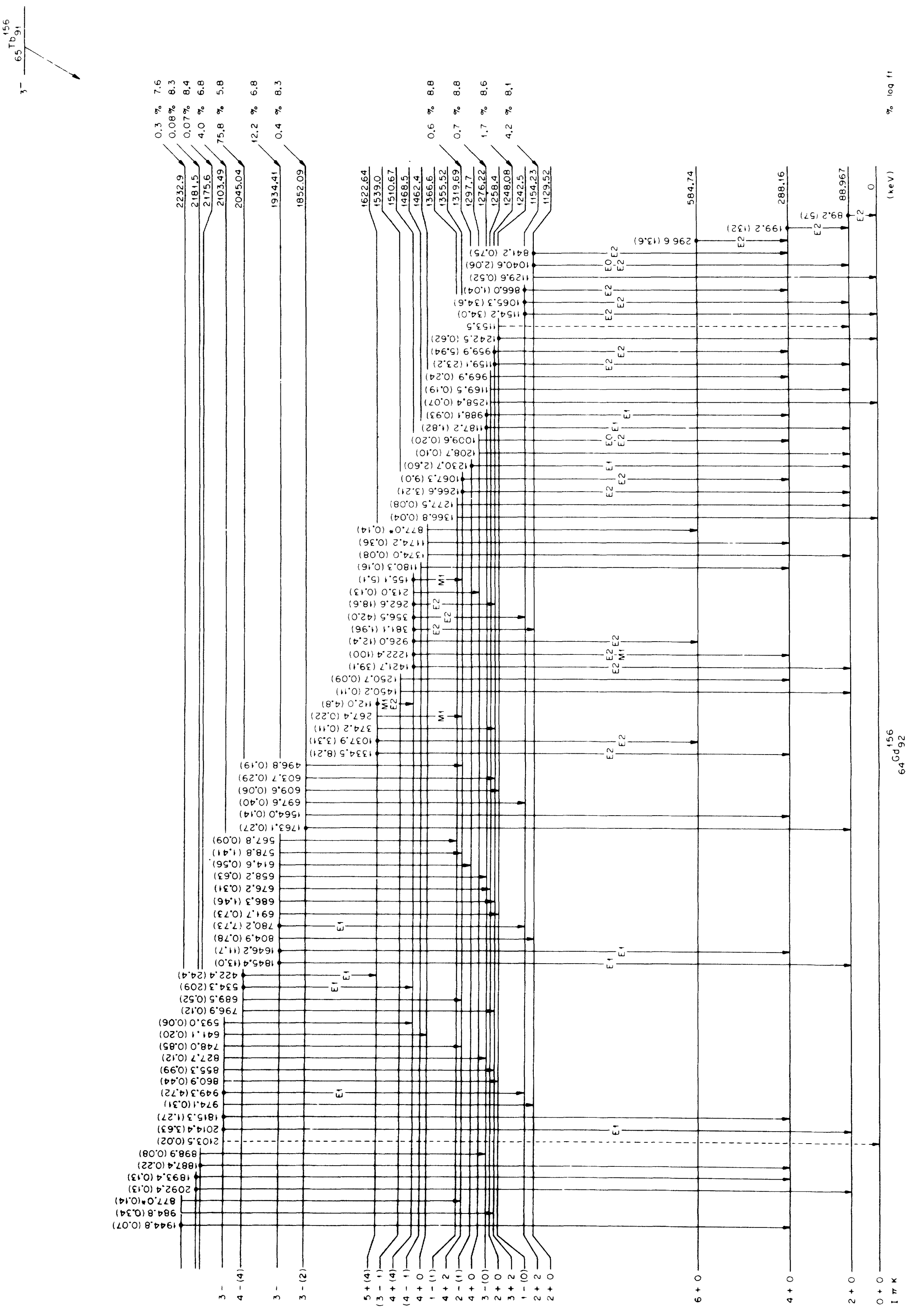

FIG. 7. Levels of ^{156}Gd populated by the ^{156}Tb decay. The energies of the first two excited states are taken from accurate electron energy measurements of the ^{156}Eu decay. (See Refs. 30, 31.) Relative γ-ray intensities are given in parentheses. The * indicates possible dual placement.

band is established at 1297.7 ± 0.3 keV. Two weak transitions of 1009.6 and 1208.7 keV are placed from this level to the 4^+ and 2^+ levels of the ground-state band. Figure 9 shows the 1009.6- and 1208.7-keV γ rays as seen in an expanded plot of the singles spectrum. Stronger evidence for the 1009.6-keV transition is found in the electron work.[20] The K line of a 1009.6-keV transition was observed to have the same relative intensity to the L line of the 959.9-keV transition over a period of three half-lives of ^{156}Tb.[20] These data eliminate the possibility that it is a contaminant in the source. The high K conversion coefficient of the 1009.6-keV transition is interpreted as resulting from a mixed $E0+E2$ transition. The $E0$ component provides the primary basis for the $4^+_\beta - 4^+$ assignment. Population of the 4^+_β level may be partially accounted for by the placement of a weak 213.0-keV γ ray from the level at 1510.7 keV and by electron capture. No evidence is found in the singles spectrum for a γ ray equivalent to the transition to the 6^+ member of the ground-state band. An upper limit for this transition (713 keV) is given in Table II.

A 4^+_β level at 1297.7 keV gives a level spacing for the β-vibrational band which is very similar to the spacing of the ground-state band. The slight compression of the β band indicates an increase in the moment of inertia for the band of approximately 10% over that of the ground-state band. This 4^+ level is now confirmed in recent work.[16,19] From (d, d') experiments, Bloch, Elbek, and Tjøm[13] tentatively assigned 4^+_β to a level at 1324 keV. Their spin-parity assignments were based on intensity and systematics only. No evidence for this level was found in these experiments.

In the ^{156}Eu decay, evidence is found for the 0^+ level of the β-vibrational band at 1049.6 keV.[32] A search of the ^{156}Tb electron spectrum at this energy gave no indication of the pure $E0$ $0^+_\beta - 0^+$ transition. An upper limit for the intensity of the 1049.6-keV K line was placed at 0.5 relative to 100 for the K line of the 1222.4-keV transition.[20] The close proximity of the β and γ band may suggest that these levels could be easily mixed and that a perturbational treatment[33] that includes mixing of these levels must be applied.

γ-Vibrational Band

The $K^\pi = 2^+$ γ-vibrational band has established members at 1154.23 ± 0.09 (2^+_γ), 1248.08 ± 0.10 (3^+_γ),

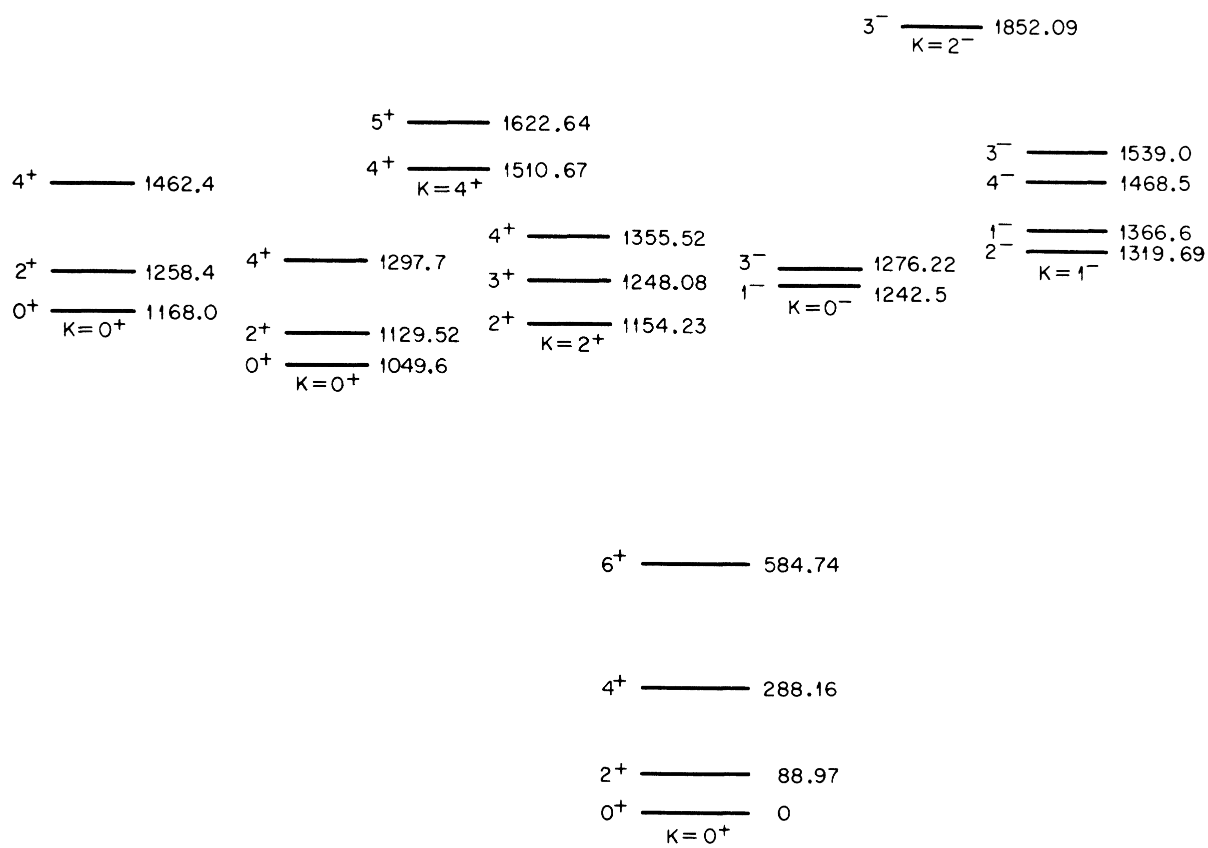

FIG. 8. Rotational-band structure of the ^{156}Gd nucleus. The $K=0^-$, 1^-, and 2^- assignments are not definitive. The 0^+ states are from ^{156}Eu work. (See Refs. 17, 32.)

and 1355.52 ± 0.09 (4_γ^+) keV. Relatively strong feeding of these levels from higher excited states in the ^{156}Tb decay allows the identification of all but one of the expected transitions to the ground-state band. The exception is the $4_\gamma^+ \to 6^+$, 771-keV transition. An upper limit for the intensity of this γ ray is indicated in Table II.

Some disagreement has occurred concerning the feeding of the 1154.2-keV 2_γ^+ level in the ^{156}Tb decay. Hansen, Nielsen, and Sheline[8] postulated electron-capture feeding to this level on the basis of the intensity ratio of the 356- and 89-keV γ rays when gating on the 1065-keV γ ray. But KFM[10] suggest that this measurement could be explained by the presence of the 1067-keV γ ray unknown in the earlier work, and therefore electron capture would not be required. From the photon intensities of this work, however, an electron-capture feeding of (4.2 ± 1.0)% is required for the intensity balance of the 2_γ^+ level. The resulting $\log ft$ value, 8.1, for decay to the 2_γ^+ level is similar to the $\log ft$ value of 8.6 derived for the 3_γ^+ level. However, little if any electron-capture feeding to the 4_γ^+ level is indicated from our intensity measurements. From our results a lower limit for the $\log ft$ value for the 4_γ^+ level is set at 8.9.

Second $K^\pi = 0^+$ Band

From (n, γ) work,[16] 0^+ band was assigned at 1168.2 keV with associated 2^+ and 4^+ levels at 1258.0 and 1462.3 keV. A 0^+ state is now well established[17] at 1168 keV in the decay of ^{156}Eu and is assigned as the band head. Our coincidence data confirm the level at 1462.4 keV. There is good energy agreement for our observed transitions from levels at 1258.4 ± 0.2 and 1462.4 ± 0.3 keV. No evidence is seen for the population of the 0^+ level from ^{156}Tb.

These states appear to be fed by electron capture. However, unplaced transitions between these states and new levels above could account for the balance of the γ-ray intensity out of these states. The 877-keV transition out of the 1258.4-keV state has three placements in the decay scheme on the basis of energy fits.

$K^\pi = 0^-$ Octupole Band

In a strongly deformed even-even nucleus one expects a series of negative-parity levels which arise from collective octupole oscillations of the nuclear surface about the equilibrium shape. The octupole vibrational motion coupled to the rotational motion of the deformed nucleus results in rotational bands with $K = 0$, 1, 2, and 3. The symmetry requirements for $K = 0$ permit only odd-spin states for a $K^\pi = 0^-$ rotational band. Other octupole components, however, are expected to have a monotonically increasing sequence of spin states.

The $K^\pi = 0^-$ band head in ^{156}Gd is tentatively proposed to be at 1242.5 ± 0.2 keV with the second member of the band located at 1276.22 ± 0.14 keV. The 1242.5-keV level is well established as a 1^- state from studies of the ^{156}Eu decay.[30,31,34] Evidence for the population of this level in the ^{156}Tb decay is found in our coincidence studies where the 1242.5-keV γ ray is not observed to be in direct coincidence with either the 89- or 199-keV transitions. Limits placed on the intensities of the 1242.5-keV transition in these experiments (Table III) indicate that it is either a transition to the 0^+ ground state or to a level above the 584.7-keV, 6^+ level with branching to the ground state. The latter case is unlikely since a new level would be required with very nearly the same energy as the total energy available for decay, 2.4 MeV.[12] A transition of 1153 keV was observed to depopulate the 1242.5-keV level to the 2^+ level of the ground-state band in the ^{156}Eu studies.[30,31,34] Unfortunately, a transition of 1153 keV is obscured by the intense 1154.2-keV $2^+ \to 0^+$ transition in the singles spectrum of the ^{156}Tb decay. Some evidence is found for a transition at 1154 keV in the 89-keV gated coincidence experiment (Table III).

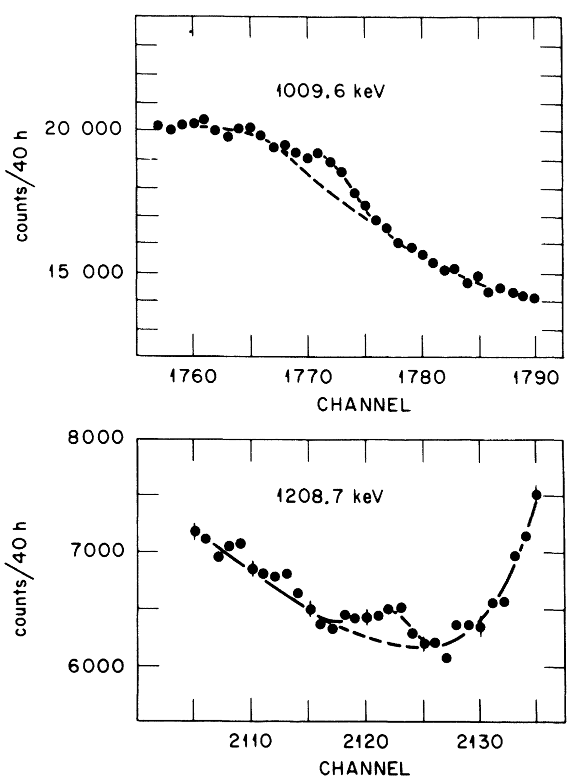

FIG. 9. The ^{156}Tb 1009.6- and 1208.7-keV γ rays observed in a 30-cm^3 Ge(Li) singles spectrum.

The coincidence intensity observed for the transition, however, is much more than one would expect for the transition from the 1242.5-keV level if the photon intensities of the 1242- and 1153-keV transitions as measured in the ^{156}Eu decay[31] are correct. On the basis of energy fits, the 609.6-, 691.7-, and 860.9-keV transitions can be placed between three high-energy 3^- levels and the 1242.5-keV level. It should be pointed out, however, that an alternate placement for the 691.7-keV transitions is between the 1276.2- and 584.7-keV levels, but such a $3^- \rightarrow 6^+$ transition should not be observed.

The level at 1276.2 keV is established in the ^{156}Tb decay scheme principally from coincidence relationships of the 1187.2-keV γ ray. An 1187-89-keV coincidence is observed, but the 1187-keV γ ray is not present in the 199-keV coincidence spectrum. The 988.1-keV transition is placed from the 1276.2-keV level to the 4^+ level of the ground-state band on the basis of coincidences seen in the 89- and 199-keV gated spectra. In (d, d') scattering experiments[13] the spin-parity assignment for the 1276-keV level is 3^-. Only this assignment is consistent with the $E1$ multipolarities found for the 1187.2- and 988.1-keV transitions.[20]

The ratios of the reduced $E1$ transition probabilities, $B(E1)$, from the 1242.5- and 1276.2-keV states to members of the ground-state rotational band are given in Table IV. For reference theoretical $B(E1)$ ratios as predicted by the adiabatic symmetric rotor model are listed for the K allowed, $\Delta K \leq \Delta I$ transitions. All transitions are assumed to be pure $E1$ in character. The ratio for the 1242.5-keV level is taken from the ^{156}Eu studies of Kluk, Johnson, and Hamilton.[18] The $B(E1)$ ratios from these levels are not in exact agreement with theoretical $K=0$ values. Deviations from theory, however, could be explained by a strong coupling of the $K^\pi = 0^-$ band into other bands as was suggested in ^{154}Gd.[35] The work of Bloch, Elbek, and Tjøm[13] is consistent with a $K^\pi = 0^-$ assignment for the 1242.5- and 1276.2-keV levels. In that work[13] evidence was also found for a level at 1411 keV which they suggested might be the 5^- member of the $K^\pi = 0^-$ band. A 5^- level is reported at 1407.6 keV from the (n, γ) work.[16] No evidence was found in these studies for population of the 1411-keV level in the ^{156}Tb decay.

$K^\pi = 1^-$ Octupole Band

Levels at 1319.69 ± 0.13, 1366.6 ± 0.4, 1468.5 ± 0.3, and 1539.0 ± 0.3 keV are postulated to be members of a $K^\pi = 1^-$ octupole band. None of these levels have been previously placed in the ^{156}Tb decay scheme, even in most recently published work.[10] The first two are strongly populated in the ^{156}Eu decay.[30,31,34] The 1319.7-keV level has been assigned a 2^- spin-parity from the ^{156}Eu studies.[30,31,34] In these studies a transition of 1231 keV from the 1319.7-keV level was found to feed the 2^+ level of the ground-state band. Our coincidence results confirm the 1231-89-keV coincidence while no evidence is found for the 1231-keV γ ray in the 199-keV gate. The conversion

TABLE IV. Reduced $B(E1)$ transition probability ratios from levels at 1242.5 (1^-), 1276.2 (3^-), 1366.6 (1^-), and 1852.1 (3^-) keV. Errors in the last figures of the experimental ratios are given in parentheses.

Level energy (keV)	$\frac{B(E1; I_iK_i \rightarrow I_f'K_f)}{B(E1; I_iK_i \rightarrow I_fK_f)}$	$\frac{E_f' - E_i}{E_f - E_i}$	Experimental ratios [a]	Theoretical ratios [b] $K=0$	$K=1$	$K=2$	$K=3$
1242.5	$\frac{B(E1;\ 1K \rightarrow 00)}{B(E1;\ 1K \rightarrow 20)}$	$\frac{1242.5}{1153.3}$	0.86 (8) [c]	0.50	2.0		
1276.2	$\frac{B(E1;\ 3K \rightarrow 20)}{B(E1;\ 3K \rightarrow 40)}$	$\frac{1187.2}{988.1}$	1.13 (17)	0.75	1.33		
1366.6	$\frac{B(E1;\ 1K \rightarrow 00)}{B(E1;\ 1K \rightarrow 20)}$	$\frac{1366.6}{1277.5}$	0.45 (3) [c]	0.50	2.0		
1852.1	$\frac{B(E1;\ 3K \rightarrow 20)}{B(E1;\ 3K \rightarrow 40)}$	$\frac{1763.1}{1564.0}$	1.35 (51)	0.75	1.33	1.33 [d]	
1852.1	$\frac{B(E1;\ 3K \rightarrow 32)}{B(E1;\ 3K \rightarrow 22)}$	$\frac{603.7}{697.7}$	1.1 (2)		8.78	1.4	0.35
1852.1	$\frac{B(E1;\ 3K \rightarrow 42)}{B(E1;\ 3K \rightarrow 22)}$	$\frac{496.8}{697.6}$	1.3 (4)		11.25	1.8	0.05

[a] Transitions assumed to be pure $E1$ in character.
[b] Predictions of the adiabatic symmetric rotational model. (See Ref. 42.)
[c] These ratios were taken from the ^{156}Eu studies of Kluk, Johnson, and Hamilton. (See Ref. 18.)
[d] Calculated from the reduced transition probability for a K-forbidden $E1$ transition as given in Ref. 39.

coefficient of the 1230.7-keV[20] transition indicates an $E1$ multipolarity assignment which is in agreement with the 2^- assignment for the 1319.7-keV level. Absence of transitions to the 0^+ and 4^+ members of the ground-state band in comparison with the decays of the lower energy 1^- and 3^- states, respectively, supports the 2^- assignment. A single transition of 614.6 keV can be placed feeding the 1319.7-keV level from established levels. The intensity of the transition does not account for the observed intensity of the 1230.7-keV γ ray. Therefore, electron-capture feeding to this level is postulated although the unplaced γ rays in the ^{156}Tb decay could explain the observed intensity imbalance.

Evidence is found in the ^{156}Tb singles spectrum for weak γ rays of 1277.5 and 1366.8 keV. On the basis of corresponding γ rays of 1277.4 and 1366.4 keV (energy measurements of Ewan, Graham, and Geiger[30]) depopulating a 1^- level at 1366.4 keV in the ^{156}Eu decay,[30,31,34] the 1366.6-keV level is placed in the ^{156}Tb decay scheme. The intensity ratio of the 1277.5- and 1366.8-keV γ rays is roughly the same in our ^{156}Tb measurements as is found in the ^{156}Eu decay. Population of the 1366.6-keV level may take place through the 567.8-keV transition from the 1934.4-keV, 3^- level.

A tentative placement was made for a 4^- level at 1468.7 keV in (n, γ) work.[16] In our work a 1180.3-keV transition was seen in the 199-keV gate. This coincidence supports but does not confirm a level at 1468.5 keV as the 1180.3-keV γ ray could feed the 6^+ 584.74-keV level. There are no transitions observed that fit to other energy gaps whether the 1180.3 feeds the 288.16-keV 4^+ or 584.74-keV 6^+ state. Since ^{156}Tb has a 3^- ground state only, 4^+ or 5^+ states are candidates for β population and subsequent decay to the 6^+ level. Each of these choices, however, would also populate the 4^+ state and such is not observed. Thus the most consistent assignment is 4^- for the level at 1468.5 keV.

A 3^- level depopulated by 1250.8- and 1449.7-keV transitions was placed at 1538.8 keV in the (n, γ) work.[16] Previously unreported transitions of 1250.7 ± 0.5 and 1450.2 ± 0.4 keV are observed in the present ^{156}Tb work. On the basis of the good energy agreement, a level at 1539.0 ± 0.3 keV is placed in the present decay scheme. The errors in the transition intensities from this level are too large to obtain information from a comparison of experimental and theoretical branching ratios. Although both states can be populated by allowed electron capture, the transitions out of these levels are weak enough to be accounted for by unplaced transition from new states above them. If there is no γ population, the $\log ft$ values are 9.8 and 9.6 for the 1468.5- and 1539.0-keV levels, respectively. These large $\log ft$ values support the $K=1$ assignment since then the decays are K forbidden, $\Delta K = 2$.

The $K^\pi = 1^-$ assignment for the 1319.7-keV, 2^- level has been previously proposed by Cline and Heath[34] and is supported by Donner and Greiner.[36] The latter authors have performed calculations to predict the relative spacings of the octupole bands of the ^{156}Gd nucleus.

The $B(E1)$ ratio from the 1366.6-keV, 1^- level to the ground-state band is given in Table IV. The ratio has been calculated from accurately determined ^{156}Eu intensities[18] rather than from our ^{156}Tb measurements. Although the $B(E1)$ ratio

TABLE V. Reduced $E2$ transition probabilities from levels at 1510.7 (4+) and 1622.6 (5+) keV. The errors in the last figures of the experimental ratios are given in parentheses.

Level energy (keV)	$\frac{B(E2;\, I_iK_i \to I_f'K_f)}{B(E2;\, I_iK_i \to I_fK_f)}$	$\frac{E_f' - E_i}{E_f - E_i}$	Experimental ratios	Theoretical ratios [a] $K=0$	$K=1$	$K=2$	$K=3$	$K=4$
1510.7	$\frac{B(E2;\, 4K \to 20)}{B(E2;\, 4K \to 40)}$	$\frac{1421.7}{1222.4}$	0.23 (1) [b]	1.10	12.5	0.34	0.34	0.34
1510.7	$\frac{B(E2;\, 4K \to 60)}{B(E2;\, 4K \to 20)}$	$\frac{926.0}{1421.7}$	2.72 (14)	1.59	1.02	0.25	0.25	0.25
1510.7	$\frac{B(E2;\, 4K \to 60)}{B(E2;\, 4K \to 40)}$	$\frac{926.0}{1222.4}$	0.62 (2) [b]	1.75	12.4	0.09	0.09	0.09
1510.7	$\frac{B(E2;\, 4K \to 32)}{B(E2;\, 4K \to 22)}$	$\frac{262.6}{356.5}$	2.03 (13)	14	6.86	2.24	0.14	0.56
1622.6	$\frac{B(E2;\, 5K \to 60)}{B(E2;\, 5K \to 40)}$	$\frac{1037.9}{1334.5}$	1.42 (11)		1.75	0.57	0.57	0.57

[a] Predictions of the adiabatic symmetric rotational model. (See Ref. 42.) K-forbidden ratios as given in Ref. 39.
[b] Calculated assuming the 1222.4-keV transition is 81% $E2$ as deduced from ICC measurements.

does not favor a $K=1$ assignment, the relative transition probabilities could be considerably altered by coupling of the $K^\pi=1^-$ band with other bands. If the tentative $K^\pi=1^-$ assignment for the 1366.6-keV level is correct, there is an inversion of the $K^\pi=1^-$ band from the predicted $I=1, 2, 3, 4$, etc. sequence of Donner and Greiner.[36] A similar inversion is found in neighboring ^{154}Gd with a $K^\pi=1^-$ assignment to levels in a sequence $I=2, 1, 4, 3$. Meyer[35] postulates that the energy sequence of the band is altered because of a rotation-vibration-type Coriolis coupling of the $K^\pi=0^-$ and $K^\pi=1^-$ bands.

$K^\pi=4^+$ Rotational Band

The 4^+ and 5^+ levels at 1510.67 ± 0.06 and 1622.64 ± 0.09 keV, previously well established,[7-11] are thought to be members of a $K^\pi=4^+$ rotational band.[8,10] Reduced $B(E2)$ ratios from these levels are given in Table V. In these calculations the 1222.4-keV transition is taken to be 81% $E2$ as determined from our internal-conversion-coefficient (ICC) measurements.[20] The poor agreement with the theoretical $K=4$ ratio is not unexpected. As pointed out by KFM[10] the K selection rule will be violated if the wave function of the state in question contains admixtures of states with differing K quantum numbers, and in general, the character of the admixture is unknown for states with $K\leq3$. The $K=4$ assignment for the 1510.7-keV level, proposed by Hansen, Nielson, and Sheline[8] is based on the observed lifetime of the level. A rotational state with a lifetime of 1.88×10^{-10} sec, as is found for the 1510.7-keV level,[37] would be expected to strongly excite lower members of the rotational band unless the level is the lowest member of the band. Since lower members are unobserved, the probable K assignment is $K=4$. Gallagher and Soloviev[38] have identified the 1510.7-keV level as a proton two-quasiparticle state with a $[413]\downarrow[411]\uparrow$, $\Sigma=0$ assignment. Their predicted $\log ft$ value for the level, 8.5, is within the error limits of the intensity balance measured in this work. The probable $K=4$ assignment[10] for the 5^+, 1622.6-keV level results from the good agreement with theory of the $B(E1)$ ratio from the 2045.0-keV level when $K=4$ is assumed for both the 2045.0- and 1510.7-keV levels (see Table VI).

Level at 1852.1 keV

A level at 1852.09 ± 0.18 keV, first observed in the ^{156}Tb decay in our preliminary experiments,[23] is supported by the placement of five transitions into the ^{156}Tb decay scheme from the level spacings. Transitions of 1763.1 and 1564.0 keV depopulate the level to the first and second excited states, respectively, while transitions of 697.6, 603.7, and 496.8 keV can be placed between the

TABLE VI. Reduced $B(E1)$ transition probability ratios from levels at 1934.4 (3^-), 2045.0 (4^-), and 2103.5 (3^-) keV. Errors in the last figures of the experimental ratios are given in parentheses.

Level energy (keV)	$\frac{B(E1;\ I_iK_i\to I_f'K_f)}{B(E1;\ I_iK_i\to I_fK_f)}$	$\frac{E_f'-E_i}{E_f-E_i}$	Experimental ratios [a]	Theoretical ratios [b] $K=0$	$K=1$	$K=2$	$K=3$	$K=4$
1934.4	$\frac{B(E1;\ 3K\to42)}{B(E1;\ 3K\to22)}$	$\frac{578.8}{780.2}$	0.45 (3)	11.25	11.25	1.8	0.05	
1934.4	$\frac{B(E1;\ 3K\to32)}{B(E1;\ 3K\to22)}$	$\frac{686.3}{780.2}$	0.28 (3)	8.78	8.78	1.4	0.35	
1934.4	$\frac{B(E1;\ 3K\to20)}{B(E1;\ 3K\to40)}$	$\frac{1845.4}{1646.2}$	0.79 (4)	0.75	1.33	1.33	1.33	
2045.0	$\frac{B(E1;\ 4K\to54)}{B(E1;\ 4K\to44)}$	$\frac{422.4}{534.3}$	0.24 (1)			4.28	2.0	0.25
2045.0	$\frac{B(E1;\ 4K\to32)}{B(E1;\ 4K\to42)}$	$\frac{796.9}{689.5}$	0.15 (5)		0.18	1.7	1.7	0.18
2103.5	$\frac{B(E1;\ 3K\to42)}{B(E1;\ 3K\to22)}$	$\frac{748.0}{949.3}$	0.37 (5)		11.25	1.8	0.05	
2103.5	$\frac{B(E1;\ 3K\to32)}{B(E1;\ 3K\to22)}$	$\frac{855.3}{949.3}$	0.29 (4)	8.78	8.78	1.4	0.35	
2103.5	$\frac{B(E1;\ 3K\to20)}{B(E1;\ 3K\to40)}$	$\frac{2104.4}{1815.3}$	2.09 (14)	0.75	1.33	1.33	1.33	

[a] Transitions assumed to be pure $E1$ in character.
[b] Predictions of the adiabatic symmetric rotational model. (See Ref. 42.) K-forbidden ratios as given in Ref. 39.

level and the three observed members of the γ-vibrational band. Evidence was found in the 89-keV coincidence experiment for the 1763.1-keV transition, but its intensity had an error of 50% so that a definite 89-1763-keV coincidence relationship could not be established. No coincidences were observed, however, for the 1763.1-keV γ ray in the 199-keV gated experiment. The 1852.1-keV level is assumed to be the same as the 3^- level observed at 1852 keV in inelastic deuteron scattering experiments.[13]

It should be pointed out that the intensities for two transitions depopulating the 1852.1-keV level have been corrected for contributions from extraneous sources. The 1763.1-keV transition is unresolved from a prominent background peak (the 1764.45-keV line of ^{214}Bi) in the singles spectrum, while the 496.8-keV transition corresponds to a sum peak of two strong, low-energy γ rays. The 496.8-keV peak was determined to be a real γ ray from intensity comparisons with a known sum peak (288 keV) for source-to-detector distances ranging from 1 to 50 cm.

Reduced $E1$ transition probability ratios for transitions from the 1852.1-keV level (assumed to be a 3^- state) to levels of the ground-state band and γ-vibrational band are presented in Table IV. The two ratios obtained from transitions to the γ band are in good agreement with a $K=2$ assignment. The transition rates to the ground-state band also agree with a $K=2$ assignment since the K-forbidden ratio is expected be to 1.33.[39] Hindrance factors for transitions from the 1852.1-keV level to levels of the $K^\pi=0^+$ ground-state band relative to transitions to the $K^\pi=2^+$ γ-vibrational band with the same spin are listed in Table VII. The high retardation of the transitions to the ground-state band relative to the $K^\pi=2^+$ band favor a $K=2$ assignment rather than $K=0$ or 1 for the 1852.1-keV level.

TABLE VII. Relative hindrance factors for $E1$ transitions to the $K^\pi=0^+$ ground-state rotational band, $K^\pi=0^+$ β-vibrational band, or $K^\pi=4^+$ band relative to the $K^\pi=2^+$ γ-vibrational band.

Level energy (keV)	J_i, J_fK_f	E_γ	Relative hindrance factor of lower transition in column 2
1852.1	3, 22	697.6	24 ± 8
	3, 20	1763.1	
	3, 42	496.8	43 ± 16
	3, 40	1564.0	
1934.4	3, 22	780.2	7.9 ± 0.4
	3, 20	1845.4	
	3, 22	780.2	11 ± 1
	3, 20 (β)	804.9	
	3, 42	578.8	2.8 ± 0.2
	3, 40	1646.2	
2045.0	4, 42	689.5	0.0011 ± 0.0002
	4, 44	534.3	
2103.5	3, 22	949.3	12.4 ± 0.7
	3, 20	2014.4	
	3, 22	949.3	16 ± 4
	3, 20 (β)	974.1	
	3, 42	748.0	9.6 ± 1.2
	3, 40	1815.3	
	3, 42	748.0	7 ± 2
	3, 44	593.0	

Levels at 1934.4 and 2045.0 keV

The strongly populated 3^- and 4^- levels at 1934.4 ± 0.1 and 2045.04 ± 0.08 keV have been well established by previous investigators[7-11] of the ^{156}Tb decay. The spin-parity assignments are based on ICC measurements,[8,20] angular-correlation experiments,[10] and nuclear-orientation studies.[11] Pyatov and Soloviev[40] have identified both of these levels as two-quasiparticle states. The 1934.4-keV level is assigned as a neutron two-quasiparticle state with a [521]↑[651]↑, $\Sigma=1$ configuration[40] and that of the 2045.0-keV level as a proton two-quasiparticle state with a [532]↑[411]↑, $\Sigma=1$ configuration.[40] Relative hindrance factors for transitions from the 1934.4-keV level to the $K^\pi=0^+$ ground-state or β-vibrational bands relative to transitions to levels of the same spin of the $K^\pi=2^+$, γ-vibrational band are given in Table VII. The magnitude of the hindrance factors indicates a K assignment of $K=1$ or 2 for the level rather than $K=3$ as expected from the two-quasiparticle identification.[40] The $B(E1)$ ratios from the 1934.4-keV level, which are presented in Table VI, are inconsistent with any K assignment up to $K=3$.

Peek[22] observed a transition of 576.2 keV and from his α_K assigned it as $M1$. To place it leaving the 1934.4-keV level as in our present work would require an $E1$ multipolarity so he left this transition unplaced. However, Fujioka[19] found α_K of a 578.9-keV transition to be consistent with an $E1$ multipolarity. The energy discrepancy in this case was discussed earlier. That discrepancy along with Peek's much larger electron intensity,[22] which led to his $M1$ assignment, suggests that he may have observed an impurity line.

KFM[10] tentatively assigned $K=4$ to the level at 2045.0 keV on the basis of the observed $B(E1)$ ratio (Table VI) of transitions to the 1510.7- and 1622.6-keV levels of the proposed $K^\pi=4^+$ rotational band. Support for this assignment is found in the strong enhancement of the 534.3-keV transition which depopulates the level to the 1510.7-keV level, with respect to the 689.5-keV transition which feeds the 4^+ level of the γ band (Table VII). Furthermore, the $B(E1)$ ratio for the transitions from the 2045.0-keV level to the 4^+ and 3^+ levels of the γ band is in good agreement with the K-forbidden, $K=4$ assignment (Table VI). A $K=4$ assignment is also consistent with the proton two-quasiparticle identification of the level.[40]

Levels at 2103.5 and 2181.5 keV

The levels at 2103.49 ± 0.09 and 2181.5 ± 0.2 keV were placed in the ^{156}Tb decay scheme in the recent work of KFM.[10] Their energies were a few keV lower than the present, more precise results. Firmly established from coincidence results, the level at 2103.5 keV is assigned a 3^- spin-parity from ICC measurements[10] and from the nuclear orientation work of Lovejoy and Shirley.[11] The latter investigators find that a level of about 2100 keV is consistent only with a 3^- assignment. A transition from this level to the 0^+ ground state is not expected since this would require that an $E3$ transition be observed in competition with several $E1$ transitions. A 2103.4 ± 0.3-keV γ ray, however, is seen in our singles spectrum which does not appear to be a sum peak (as compared with the 1422 + 534 = 1956-keV sum peak). Moreover, evidence appears in the ^{156}Tb electron spectrum[9] for a weak transition of about 2105 keV. Therefore, the 2103.4-keV transition is tentatively placed in the decay scheme only on the basis of the energy fit and is indicated in Fig. 7 by a dashed line. (Some evidence is also found in the ^{160}Tb decay for an $E3$-$E1$ competition.[25]) Relative hindrance factors for transitions to $K^\pi = 0^+$ and the $K^\pi = 4^+$ bands relative to transitions to the $K^\pi = 2^+$ band are given in Table VII for the 2103.6-keV level. $B(E1)$ ratios are listed in Table VI. No definite K assignment is indicated from the observed $E1$ transition rates or by the comparison between the experimental and theoretical $B(E1)$ ratios, although the data of Table VII would seem to favor a $K=2$ assignment. But nearly the same retardation factors are observed for the 1934.4-keV level, and it may be $K=3$ if the level's two-quasiparticle identification[40] is correct. (See discussion under 1934.4-keV level.)

The 2181.5-keV level is depopulated only by transitions to the 2^+ and 4^+ levels of the ground-state rotational band. Originally placed on the basis of energy fits and weak evidence for the 2092-89- and 1893-199-keV coincidences,[10] the level placement is definitely established in this work from the confirmation of the 2092-89- and 1893-199-keV coincidences.

Levels at 2175.6 and 2232.9 keV

Two new levels at 2175.6 ± 0.3 and 2232.9 ± 0.2 keV are proposed to be weakly populated in the ^{156}Tb decay. The two levels are established from observed coincidences of the 1887.4- and 1944.8-keV transitions, respectively, with the 199-keV $4^+ \rightarrow 2^+$ transition. The energies of these γ rays are such that the feeding of the 584-keV, 6^+ level can be ruled out if the total energy for the ^{156}Tb decay is 2.4 MeV.[12] Two additional γ rays can be placed in the ^{156}Tb decay scheme from the level spacings defined by the proposed levels. One, the 984.8-keV transition, is placed from the 2232.9-keV level to the 3^+ level of the γ band. Another, the 877.0-keV transition, can be placed from the 2232.9-keV level to the 4^+ level of the γ band. Alternate placements for the latter γ ray, however, are from the 1462.4-keV level to the 584.7-keV level or from the 2175.6-keV level to the 4^+ level of the β band.

Summary of Levels

The ^{156}Tb decay scheme as given in Fig. 7 includes 12 levels unreported in the most recent published ^{156}Tb work.[10] It is still incomplete from the standpoint that 18 of the observed γ rays in the ^{156}Tb decay remain unplaced. All of the levels below 1700 keV in Fig. 7 are seen also in the recent (n, γ) work.[16] After our work was complete, we learned of extensive conversion-electron work on the decay of ^{156}Tb by Fujioka.[19] There is very close agreement with our level structure and that of Fujioka.[19] He does not report the levels at 1366.6, 1462.4, 2181.5, and 2232.9 keV but does observe levels at 1506.79 (5^+2), 1948.87 (3^-2), and 1952.21 (4^-2) keV. In our unplaced transitions we see a 115.8- and 445.7-keV transition into and a 921.9-keV transition out of the new level at 1506.79 keV; the 704.3-, 676.2- (possible doublet), 596.8-, and 445.7-keV transitions out of the 1952.2-keV level; and the 651-keV transition out of the 1948.9-keV level. From our γ-ray intensity of the 115.8-keV transition and the electron intensity for this transition reported by Harmatz, Handley, and Mihelich[9] we calculate an α_K of 1.26 which agrees well with the theoretical α_K of 1.2 for an $M1$ transition.[41] This assignment is consistent with the 115.8-keV placement between the 1622.6-keV level and the proposed 1506.8-keV level. Three of our unplaced transitions have energies greater than 1.8 MeV so that there must be at least three levels above this energy populated in the decay. Two of these, the 2051.2- and 2138.4-keV transitions, have been seen in other ^{156}Tb work.[10] Unfortunately, these γ rays are too weak to have been seen in our coincidence experiments so that the implied levels have yet to be established.

V. BAND-MIXING PARAMETERS FOR THE β- AND γ-VIBRATIONAL BANDS

γ-Vibrational Band

Reduced transition probability ratios of $E2$ transitions from the β- and γ-vibrational bands to the ground-state band of deformed even-even nuclei have been found to deviate considerably from the values predicted from the simple rules of Alaga *et al.*[42] With the inclusion of band mixing of the β and γ bands with the ground-state band into the theory, however, the agreement with experiment is generally good for decays of γ-vibrational states particularly in strongly deformed nuclei.[43] The usual first-order procedure for comparing theory with the experimental results is to determine the value of the parameter Z_K in a one-parameter band-mixing correction factor[44] $F(Z_K, I_f, I_i)$, which is necessary to bring the theoretical $B(E2)$ ratio into agreement with the experimental ratio. In principle the value of the band-mixing parameter Z_K determined for each ratio from a given band should be the same since Z_K depends on the same matrix elements for a constant K.[44]

The $B(E2)$ ratios for transitions from the γ-vibrational band to the ground-state band of ^{156}Gd are presented in Table VIII where all γ-ray transitions are assumed to be pure $E2$ in character. The predictions of the adiabatic symmetric rotor model are given for comparison. All possible $B(E2)$ ratios have been calculated, although a given level has at most two independent ratios. In making the experimental $B(E2)$ ratio calculations, the measured intensity of the 1154.2-keV γ ray has been reduced by approximately 2% to compensate for the proposed 1153.5-keV transition. The estimate of the 1153-keV contribution was obtained from the observed 1242.5-keV γ-ray intensity and from the photon intensity ratio of the 1242- and 1153-keV transitions measured by Peek, Jungerman, and Patten[31] in ^{156}Eu studies. The limits for two of the branching ratios of the 1355.5-keV level have been determined from the upper limit established for the 771-keV, $4_\gamma \to 2$ γ-ray intensity and the intensities of the $4_\gamma \to 4$ and $4_\gamma \to 2$ transitions reduced by 1 standard deviation. The values of Z_2 required to obtain agreement between experiment and theory for various ratios are listed in column 5. The errors in Z_2 have been deduced from the experimental errors of the $B(E2)$ ratios. The poor agreement found for Z_2 from different ratios is not expected. For example, excellent agreement is found for the Z_2 parameters calculated from $B(E2)$ ratios from six levels of the γ-

TABLE VIII. Ratios of $E2$ reduced transition probabilities from the $K^\pi = 2^+$ γ-vibrational band of ^{156}Gd to the $K^\pi = 0^+$ ground-state rotational band. The errors in the last figures of the experimental ratios are given in parentheses.

Level energy (keV)	$\frac{B(E2;\ I_iK_i \to I_f'K_f)}{B(E2;\ I_iK_i \to I_fK_f)}$	Experimental ratios [a]	Pure rotation	Without β-γ mixing $10^3 Z_2$ [b]	With β-γ mixing $10^3 Z_{\beta\gamma}$ [c]
1154.2	$\frac{B(E2;\ 22 \to 00)}{B(E2;\ 22 \to 20)}$	0.65 (4)	0.70	13 ± 10	19 ± 11
1154.2	$\frac{B(E2;\ 22 \to 40)}{B(E2;\ 22 \to 20)}$	0.084 (9)	0.050	47 ± 13	3 ± 7
1154.2	$\frac{B(E2;\ 22 \to 00)}{B(E2;\ 22 \to 40)}$	7.6 (9)	14.0	34 ± 8	-5 ± 12
1248.1	$\frac{B(E2;\ 32 \to 20)}{B(E2;\ 32 \to 40)}$	1.52 (8)	2.50	39 ± 4	...
1355.5	$\frac{B(E2;\ 42 \to 20)}{B(E2;\ 42 \to 40)}$	0.152 (13)	0.34	53 ± 6	-5 ± 3
1355.5	$\frac{B(E2;\ 42 \to 60)}{B(E2;\ 42 \to 40)}$	<0.07 [d]	0.086	< -10	
1355.5	$\frac{B(E2;\ 42 \to 60)}{B(E2;\ 42 \to 20)}$	<0.43 [d]	0.254	<16	

[a] All γ-ray transitions are assumed to be of pure $E2$ multipolarity.
[b] Calculated with no β-γ band mixing.
[c] Calculated with $Z_\gamma = 0.039 \pm 0.004$.
[d] Limits based on limit of 771-keV $4_\gamma^+ \to 6^+$ transition as discussed in text.

vibrational band in the strongly deformed nucleus ^{166}Er.[43] The difficulty in ^{156}Gd cannot be entirely resolved by a relaxation of the assumption that no $M1$ mixing is present in the $\Delta I = 0$ transitions. The $2_\gamma \to 2$ transition is known[17] now to be nearly pure $E2$. The presence of an $M1$ component in the $2_\gamma \to 2$ transition, if present, would make the situation worse as it would tend to lower the already low value for Z_2 calculated from the $2_\gamma \to 1/2_\gamma \to 2$ ratio and raise the already high value for Z_2 calculated from the $2_\gamma \to 4/2_\gamma \to 2$ ratio. The $2_\gamma \to 2$ transition would have to be increased to bring the Z_2 values into agreement for the 2_γ level. A reduction in the $4_\gamma \to 4$ transition, on the other hand, would lead to more consistent Z_2 values for the 4_γ state itself and, at the same time, be more consistent with the other values of the band. An incorrect stripping of the 1065.3-1067.3-keV γ-ray doublet, such that the 1065.3-keV $2_\gamma \to 2$ intensity is 8% too low and the 1067.3-keV $4_\gamma \to 4$ intensity thus is 30% too high, could explain the Z_2 variations for the 2_γ and 4_γ levels. Our results for the 1065-1067-keV intensities are in good agreement with the 1065- and 1067-keV intensities as determined from ^{156}Tb coincidence studies.[10] (See Table II.) These intensities have been redetermined with higher resolution detectors (2.1 keV FWHM at 1065 keV). The new intensities of the 1065.3- and 1067.3-keV transitions (35.3 ± 1.5 and 9.1 ± 0.6, respectively) agree with our earlier data of Table II.

The $B(E2)$ ratios in Table VIII indicate a variation in Z_2 similar to that found[45] in ^{154}Gd. In that case it was found that the experimental results for the γ band could be explained by β-γ band mixing, i.e., a small mixing of the β with the γ band as well as the mixing into the ground-state band.[45] A similar result for the γ band is now clearly found[45] in ^{152}Sm. With β-γ band mixing the unperturbed $B(E2)$ moments from the γ band are corrected by a function, $F(Z_2, Z_{\beta\gamma}, I_f, I_i)$.[33,45] In these calculations a fixed value for Z_2 allows the extraction of the second band-mixing parameter, $Z_{\beta\gamma}$, which depends upon the mixing of the β and γ bands. The value of Z_2 characteristic for the γ band is taken from the $3_\gamma \to 2/3_\gamma \to 4$ ratio since there is no mixing of the odd 3^+ level with the even β band levels and, therefore, no $Z_{\beta\gamma}$ correction to the $3_\gamma \to 2/3_\gamma \to 4$ ratio.

Values for $Z_{\beta\gamma}$ calculated from the experimental $B(E2)$ ratios are shown in Table VIII, where $Z_2 = 0.039$ was used. Because the errors are large, the $Z_{\beta\gamma}$ parameters extracted from the four ratios may be consistent with a single value. The consistency, however, in $Z_{\beta\gamma}$ is certainly not as good as in ^{152}Sm and ^{154}Gd where the same sign is found for $Z_{\beta\gamma}$ from each ratio.[45]

β-Vibrational Band

Table IX presents the ratios of reduced $E2$ transition probabilities from the β band to the ground-state band of ^{156}Gd. All γ-ray transitions are assumed to be of pure $E2$ multipolarity. Values of the band-mixing parameter Z_0 which are required to obtain agreement between experiment and the-

TABLE IX. Ratios of $E2$ reduced transition probabilities from the $K^\pi = 0^+$ β-vibrational band of ^{156}Gd to the $K^\pi = 0^+$ ground-state rotational band. The errors in the last figures of the experimental ratios are given in parentheses.

Level energy (keV)	$\frac{B(E2;\ I_iK_i \to I_f'K_f)}{B(E2;\ I_iK_i \to I_fK_f)}$	Experimental ratios [a]	Pure rotation	$10^3 Z_0$	Davydov-Chapan model [b]
1129.5	$\frac{B(E2;\ 20\to 00)}{B(E2;\ 20\to 20)}$	0.17 (2)	0.70	83 ± 6	0.6
1129.5	$\frac{B(E2;\ 20\to 40)}{B(E2;\ 20\to 20)}$	1.05 (13)	1.80	-17 ± 4	3.3
1129.5	$\frac{B(E2;\ 20\to 00)}{B(E2;\ 20\to 40)}$	0.16 (3)	0.39	24 ± 5	0.18
1297.7	$\frac{B(E2;\ 40\to 20)}{B(E2;\ 40\to 40)}$	0.21 (7)	1.10	40 ± 6	
1297.7	$\frac{B(E2;\ 40\to 60)}{B(E2;\ 40\to 40)}$	<3.4 [c]	1.75	<18	
1297.7	$\frac{B(E2;\ 40\to 60)}{B(E2;\ 40\to 20)}$	<20 [c]	1.59	<36	

[a] All γ-ray transitions are assumed to be of pure $E2$ multipolarity.
[b] Predicted by the Davydov-Chapan model with $\lambda = 10.5°$, $\mu = 0.26$. (See Refs. 48, 49.)
[c] Upper limit calculated from limit of 713-keV ($4_\beta^+ \to 6^+$) transition as discussed in text.

ory for the various ratios are given in column 5. The variation in the Z_0 parameter is much greater than that observed for the Z_2 parameter of the γ band. In particular, there is a great difference between the value of Z_0 determined from the $2_\beta\to 0/2_\beta\to 2$ ratio and the value determined from the $2_\beta\to 4/2_\beta\to 2$ ratio. This poor agreement for Z_0 can be accounted for if, as has been suggested,[6] in this nucleus an $M1$ component is present in the $2_\beta\to 2$ transition. It must be assumed in this case that approximately 65% of the transition is $M1$ to get a consistent $Z_0=0.025$ for the 1129.5-keV level.

Similar characteristics are observed for $\Delta I=0$ transitions from the β-vibrational bands in ^{152}Sm and ^{154}Gd, where $M1$ admixtures on the order of 50% in the $2_\beta\to 2$ transition are required to obtain consistent Z_0 values for the 2^+_β levels.[45] In the first theoretical formalism,[46] $M1$ admixtures were forbidden since the vibrational states were understood as quadrupole vibrations about the equilibrium deformation. Mottelson,[43] however, has pointed out that such large $M1$ admixtures in the $\Delta I=0$ transitions could be accounted for by theory. Angular-correlation experiments have been carried out on the $2_\beta\to 2$, 692.4-keV transition in ^{154}Gd to show that the $M1$ component is less than 2% in this transition.[47] This percentage is much too small to obtain a consistent band-mixing parameter for the 2_β level of that nucleus. Recent angular-correlation experiments[17] in ^{156}Gd show that the $2_\beta\to 2$ transition is nearly pure $E2$ (less than 4% $M1$) also and rule out this explanation in this case too.

Reduced $B(E2)$ ratios of transitions from the 1297.7-keV, 4_β state of ^{156}Gd also point to an inconsistent Z_0 parameter. An upper limit placed on the intensity of the unobserved $4_\beta\to 6$, 713-keV γ ray implies the upper limits of Z_0 given in Table IX. In calculating the limits of the experimental $B(E2)$ ratios, the intensities of the observed γ rays were reduced by 1 standard deviation. Again it is evident that the $4_\beta\to 4$ transition has too great an intensity to obtain a consistent Z_0. The $4_\beta\to 4$ intensity should be about 40% less to obtain consistency with the limit placed on the $4_\beta\to 6$ intensity. This same trend is seen in $4_\beta\to 4$ transitions from other even-even nuclei in this mass region.[45]

The Z_0 parameters presented in Table IX have been calculated by assuming no mixing of the β- and γ-vibrational bands. If β-γ band mixing is taken into account, the $B(E2)$ moments from the β band are corrected by a function that depends not only on Z_0 but also on a second parameter $\zeta_{\beta\gamma}$.[33,45] The parameter $\zeta_{\beta\gamma}$ is directly proportional to the previously defined $Z_{\beta\gamma}$ parameter and also depends on the unmixed reduced $E2$ transition probabilities $B_0(E2;00\to 22)$ and $B_0(E2;00\to 20)$ from the ground-state to the 2^+ levels of the β and γ bands, respectively. With the ^{156}Gd $B(E2)$ values as measured in Coulomb-excitation experiments[14] and an average $Z_{\beta\gamma}=-(0.0025\pm 0.0024)$ from the $K=2$, $B(E2)$ ratios, the value of $\zeta_{\beta\gamma}$ is so small that the various Z_0 determinations are essentially

TABLE X. Ratios of $E2$ reduced transition probabilities from the second $K^\pi=0^+$ band of ^{156}Gd with band head at 1168 keV to the $K^\pi=0^+$ ground-state rotational band. The errors in the last figures of the experimental ratios are given in parentheses.

Level energy (keV)	$\frac{B(E2;\, I_iK_i\to I_f'K_f)}{B(E2;\, I_iK_i\to I_fK_f)}$	Experimental ratios [a]	Pure rotation	$10^3 Z_0$
1258.4	$\frac{B(E2;\,20\to 00)}{B(E2;\,20\to 20)}$	0.25 (9)	0.70	68 ± 20
1258.4	$\frac{B(E2;\,20\to 40)}{B(E2;\,20\to 20)}$	3.2 (9)	1.80	24 ± 12
1258.4	$\frac{B(E2;\,20\to 00)}{B(E2;\,20\to 40)}$	0.08 (3)	0.39	44^{+10}_{-8}
1462.4	$\frac{B(E2;\,40\to 20)}{B(E2;\,40\to 40)}$	0.10 (3)	1.10	52 ± 2
1462.4	$\frac{B(E2;\,40\to 60)}{B(E2;\,40\to 40)}$	1.6 (5) [b]	1.75	3^{+7}_{-10}
1462.4	$\frac{B(E2;\,40\to 20)}{B(E2;\,40\to 60)}$	0.06 (2)	0.63	26 ± 3

[a] All γ-ray transitions are assumed to be of pure $E2$ multipolarity.
[b] The $4\to 6$, 877-keV transition can be assigned to three places in the decay scheme on the basis of energy fits. All of the intensity of this transition was assigned to this $4\to 6$ transition for the present table.

unchanged by the β-γ band mixing.

The $B(E2)$ ratios predicted by the asymmetric rotor model of Davydov and Chapan[48] given by Davidson[49] for the 2_β level are listed in the last column of Table IX, where the parameters $\gamma = 10.5°$ and $\mu = 0.26$ are defined from the energy spacings of the ground-state rotational band and γ-vibrational band. Like the Bohr-Mottelson model, the Davydov-Chapan model fails to predict the experimental $B(E2)$ ratios from the 2_β level though here too an $M1$ component in the $2_\beta \rightarrow 2$ transition would lead to agreement with theory.

Second $K^\pi = 0^+$ Band

The mixing of this new $K^\pi = 0^+$ band with band head at 1168 keV with the nearby β band with band head at 1049.6 keV could be responsible for the anomalous branching ratios from the β-vibrational band. The reduced transition probabilities were calculated for this $K^\pi = 0^+$ band and are given in Table X. Unfortunately, the 877-keV transition fits three energy gaps in the decay scheme so the ratio with this transition is uncertain. For the purposes of calculation, all of the 877-keV transition intensity was assigned to this band. With this assumption, the branching ratios are in agreement with the (n, γ) work.[16] The branching ratios are somewhat similar to those of the β band. Here too a large ($\simeq 50\%$) $M1$ admixture in the $\Delta I = 0$ transition would bring about agreement in the branching ratios for a single mixing parameter, Z_0', for mixing of this second band and the ground state. Since a large $M1$ admixture in the $2_\beta \rightarrow 2$ transition from the β band was not found,[17] one would presume that this is not the explanation here either.

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Nuclear-Orientation Study of the Decay of ^{125}Sb†

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The decay of ^{125}Sb to levels of ^{125}Te has been investigated using low-temperature nuclear orientation achieved by dilution refrigeration and adiabatic demagnetization. Angular distributions of eight γ rays were observed using Ge(Li) detectors. The values of the $E2/M1$ γ-transition multipole mixing ratios deduced were (energies in keV): $\delta(636) = +0.341^{+0.005}_{-0.006}$; $\delta(428) = -0.542 \pm 0.016$; $-1.7 \le \delta(177) \le -0.5$. In addition, mixing amplitudes of angular momentum components in the β-radiation fields were extracted.

I. INTRODUCTION

The decay of ^{125}Sb to levels of ^{125}Te has been the subject of numerous recent investigations.[1-15] The use of high resolution Ge(Li) detectors has allowed many of the previous ambiguities in the level scheme to be eliminated. However, knowledge of the multipole character of the γ rays connecting the states of ^{125}Te, and of the β radiations populating those states, is far from complete. For this reason, we have undertaken a new investigation of this isotope.

It is possible, using low-temperature techniques, to achieve a degree of nuclear orientation sufficient to observe anisotropic γ-ray angular distributions; such distributions yield information regarding the multipolarity of the radiations leading to the final nuclear state, as well as regarding the angular momenta of the sequence of levels populated by the transitions.

The present investigation has consisted of measuring the angular distribution of γ radiation emitted following the decay of oriented ^{125}Sb nuclei.

II. DECAY OF ^{125}Sb

The presently accepted decay scheme of 2.7-yr ^{125}Sb is shown in Fig. 1. The nature of the decay to the levels of ^{125}Te has been established by numerous spectroscopic investigations[1,3-5,15] of the β and γ radiations from the ^{125}Sb parent; measurements of internal-conversion coefficients[5] have yielded data regarding multipolarities of several of the γ transitions. The assignment of the spin and parity of the 443-keV level was determined from Coulomb excitation measurement.[9] Numerous perturbed angular-correlation measurements[6,7,12,16] have been performed and have yielded results for the g factors of the 321-, 443-, and 463-keV levels. Reduced transition probabilities of the ^{125}Te γ rays have been calculated from lifetimes of the ^{125}Te excited states measured by delayed-coincidence techniques.[11] Considerable information regarding the decay of ^{125}Sb has been obtained from previous nuclear-orientation measurements[2,4] and recent γ-γ angular-correlation measurements.[13,14] Results of investigations of