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THE DECAY OF ^{160}Tb TO LEVELS IN ^{160}Dy

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Abstract: The gamma radiation associated with the beta decay of ^{160}Tb to levels in ^{160}Dy has been studied with curved-crystal and Ge(Li) spectrometers. Eight previously unreported transitions were observed with energies 237.638 ± 0.086 keV, 242.5 ± 0.8 keV, 246.489 ± 0.016 keV, 349.94 ± 0.11 keV, 432.7 ± 0.6 keV, 1005 ± 1 keV, 1069.1 ± 0.4 keV and 1300.0 ± 0.8 keV. The existence of transitions at 176, 379, 486, 872 and 1286 keV has been confirmed. Gamma-gamma coincidence studies employing two Ge(Li) detectors have led to a decay scheme which is essentially that given by previous investigators with the addition of levels at 1155.8, 1288.7 and 1535.2 keV. The level at 1155.8 keV has been identified as the 4^+ member of the gamma-vibrational band. No evidence was obtained for the population of any $K^\pi = 0^+$ beta-vibrational levels from the decay of ^{160}Tb.

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RADIOACTIVITY ^{160}Tb [from ^{159}Tb(n, γ)]; measured E_γ, I_γ, $\gamma\gamma$-coin.
^{160}Dy deduced levels, log *ft*, *J*, π, cc. Natural target.

1. Introduction

The beta decay of ^{160}Tb to levels in ^{160}Dy has been repeatedly investigated [1-22]. Although the results of these studies have led to a fairly well-established decay scheme, several discrepancies still exist. A large number of unconfirmed transitions have been reported, and the placement of many of these is in doubt.

Recently there have been reported [23]) discrepancies between experiment and theory including first-order band mixing in relative E2 transition probabilities in the depopulation of the lowest $K^\pi = 0^+$ vibrational bands. Further information on the properties of these 0^+ vibrational bands as one goes into the strongly deformed region is of considerable interest, therefore careful searches for population of such states in ^{160}Dy were performed.

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In the present study, energy measurements and relative photon intensities have been obtained using curved-crystal and Ge(Li) spectrometers. Also, coincidence data have been obtained using two Ge(Li) detectors. The work described in this paper summarizes the results of our two groups [21-22]), who simultaneously and independently arrived at the conclusions discussed below.

2. Experimental arrangements

The University of Michigan curved-crystal spectrometer and the experimental techniques associated with it have been described previously [24-26]). The curved-crystal spectrometer source was a Tb_2O_3-epoxy mixture irradiated for a period of eight months in the University of Michigan Ford Nuclear Reactor (thermal neutron flux $\approx 3\times10^{13}$ neutrons/cm$^2\cdot$sec). The activity of the sample was about 0.5 Ci. The energy resolution of the spectrometer using this particular source was ΔE (FWHM) $= (1.6\times10^{-5})\ (E^2/n)$ keV, where n is the order of reflection and E the gamma-ray energy in keV. Measurements were performed in reflection orders appropriate to the intensity of the line measured. This varied from first order for the weak 238 keV line to fifth order for the intense 879 keV line. Most of the measurements were in third order. At least three measurements were averaged to obtain the energy value.

The Ge(Li) spectrometers consisted of the following components: either an Ortec planar detector with depleted volume 8 cm$^2\times$0.5 cm or an Ortec coaxial detector with depleted volume of 17 cm^3; an Ortec 118A (FET) preamplifier and TC-200 amplifier and a Victoreen (SCIPP) 1600-channel pulse-height analyser. For the study of the high-energy portion of the spectrum, a Tennelec TC-250 biased amplifier and stretcher was coupled to the TC-200. The resolution of this system was 3.3 keV at 880 keV for the 8 cm$^2\times$0.5 cm detector and 3.7 keV at 880 keV for the 17 cm^3 coaxial detector. A description of the efficiency calibration and non-linearity of this system is presented elsewhere [27]). During the latter stages of this work, a Nuclear Diode 40 cm^3 detector coupled to a Canberra 1408C preamplifier was also used. The resolution of this system was 2.7 keV at 1330 keV. The source used in the present investigation consisted of a small drop of radioactive Tb_2O_3 in HCl solution evaporated onto a lucite disc. The radioactive Tb_2O_3 was obtained by irradiating natural Tb_2O_3 in the Ford Nuclear Reactor for a period of 24 h. Analysis of the gamma-ray spectrum indicated no appreciable isotopic impurities.

The sources for studies at Vanderbilt and Oak Ridge were prepared by irradiating ^{159}Tb in a flux of 10^{15} n/cm$^2\cdot$sec for 23.6 d at Oak Ridge National Laboratory. Gamma-ray spectra were measured with 2 cm^3, 15 cm^3 and 35 cm^3 Ge(Li) detectors coupled to TC-200 amplifiers and Nuclear Data 4096-channel analysers. Work with the 35 cm^3 detector was carried out at Oak Ridge. In these studies, the resolution was 2.5 keV at 1333 keV. Other studies were also carried out at ORNL with a small volume Ge(Li) detector and anti-Compton annulas. The Vanderbilt system was calibrated for energy and intensity measurements with ^{241}Am, ^{57}Co, ^{203}Hg, ^{182}Ta, ^{192}Ir, ^{22}Na, ^{137}Cs, ^{54}Mn, ^{88}Y, ^{207}Bi and ^{60}Co and with ten intensity standards prepared by IAEA, Vienna. In some measurements, the spectrum was split into two parts, above and below 600 keV, and a TC-250 biased amplifier used. The Vanderbilt results for the strongest transitions were used to calibrate the ORNL system for energy and intensity measurements of the weaker transitions.

The coincidence system at the University of Michigan was a fast-slow type. The total spectrum channel consisted of an Ortec 17 cm^3 coaxial Ge(Li) detector coupled to an Ortec 118A preamplifier and TC-200 amplifier. Optimum resolution was obtained using double differentiated pulses at the high count rates involved. The gate channel consisted of an Ortec 8 cm^2 × 0.5 cm planar Ge(Li) detector coupled to an Ortec 118A preamplifier, TC-200 amplifier and TC-250 biased amplifier and stretcher. The biased amplifier was used to broaden the gamma-ray peak to make it suitable for use with the single-channel analysers. The remainder of the fast coincidence system consisted of a Sturrup 1410 linear amplifier used to obtain timing pulses on the gate side, Sturrup 1435 timing single-channel analysers and Sturrup 1441 fast coincidence unit. Optimum time resolution was obtained using cross-over timing on the display side and leading edge timing on the gate side.

Later. coincidence spectra were also taken with the 40 cm^3 detector in the display channel and the 17 cm^3 detector in the gate channel. For these studies, leading edge timing was employed.

The usual procedure was to set the gate for the fast system to include both the photopeak being gated and a portion of the Compton distribution above it. Individual gates from the output of the biased amplifier were selected with timing single-channel analysers (one for the photopeak of interest and one of equal width for the Compton distribution). A fast-slow was established with a Sturrup 1445 coincidence unit. The output from the slow unit was used to trigger a Sturrup 1450 linear gate whose input was the display spectrum. The coincidence spectra were recorded on a SCIPP 1600-channel analyser. Routing pulses from the slow-gate timing single-channel analysers were used to determine which half of the analyser memory to use for storage. Ortec 427 delay amplifiers were used to delay the output of the fast coincidence unit and the display spectrum into the linear gate in order to offset the inherent delay of the biased amplifier. The efficiency of the coincidence system was determined to be greater than 92 % over an energy range of 20 : 1 at a resolving time of 48 nsec. Similar results were obtained with the 17 cm^3-40 cm^3 arrangement with a resolving time of 105 nsec. The net coincidence spectrum was obtained by subtracting the contribution of the Compton distribution under the photopeak and the chance coincidences determined by the counting rates of the two channels.

Coincidence measurements were carried out at Vanderbilt with an RIDL fast-slow coincidence system described elsewhere[30]) but now coupled to a 4096-channel analyser.

The gamma-ray spectra were analysed by hand and by a computer program [28]) with consistent results.

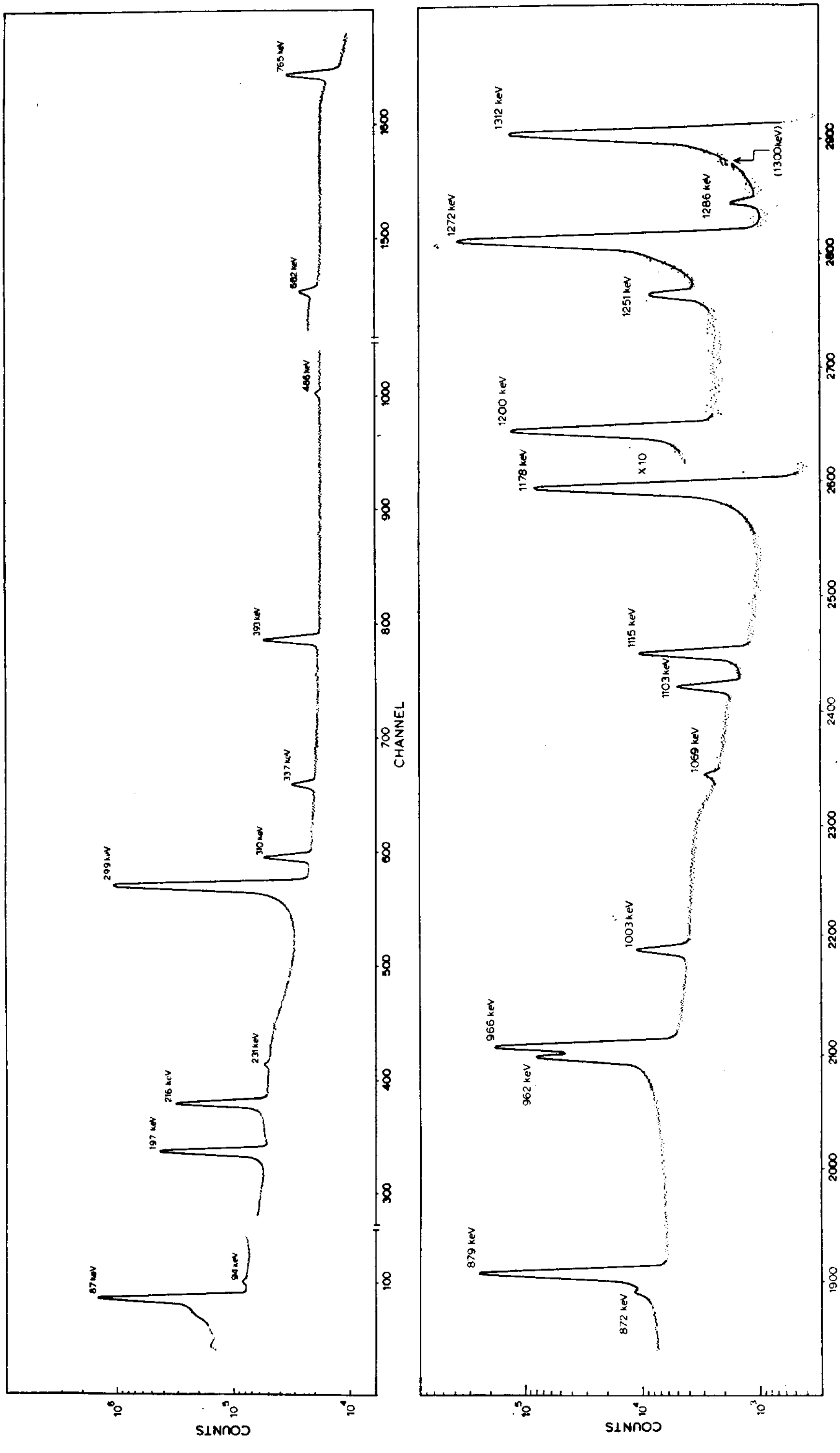

Fig. 1. Gamma-ray spectrum of ^{160}Dy obtained with the 35 cm^3 detector.

TABLE 1

Gamma-ray energies and intensities in the decay of ^{160}Tb

Gamma-ray energy			Gamma-ray intensity c)			
Michigan	Vanderbilt a)	Vanderbilt b)	Michigan	Vanderbilt a)	Vanderbilt b)	Weighted average
86.788(0.002)	86.82 (0.2)		13.7 (2.0)		13.7 (2.0) d)	13.7 (2.0)
93.919(0.006)		93.72(0.20)	0.083 (0.020)		0.061 (0.012) d)	0.067 (0.010)
176.490(0.030)		177.34(0.6)	0.0048(0.0010)		0.0045(0.0010)	0.0047(0.0007)
197.035(0.008)	196.98 (0.08)		5.54 (0.85)	5.18 (0.31)		5.22 (0.29)
215.646(0.008)	215.62 (0.08)		4.13 (0.64)	3.90 (0.23)		3.93 (0.22)
230.628(0.013)	230.78 (0.4)	230.65(0.20)	0.066 (0.018)	0.071(0.009)	0.074 (0.011)	0.071 (0.007)
237.638(0.086)		237.3 (0.5)	0.0039(0.0014)		0.009 (0.003)	0.007 (0.003)
		242.5 (0.8)			0.004 (0.003)	0.004 (0.003)
246.489(0.016)		246.41(0.5)	0.027 (0.009)		0.016 (0.004)	0.018 (0.004)
298.582(0.010)	298.58 (0.08)		27.6 (4.3)	27.0 (1.7)		27.1 (1.6)
309.557(0.018)	309.62 (0.2)	309.60(0.20)	0.82 (0.12)	0.93 (0.06)	0.90 (0.07)	0.90 (0.04)
337.324(0.030)	337.19 (0.2)		0.34 (0.06)	0.33 (0.03)		0.33 (0.03)
349.935(0.110)		350.17(0.8)	0.015 (0.007)		0.014 (0.004)	0.014 (0.003)
379.449(0.090)		379.38(0.7)	0.021 (0.007)		0.011 (0.005)	0.014 (0.004)
392.514(0.026)	392.53 (0.2)		1.41 (0.25)	1.34 (0.06)		1.36 (0.05)
		432.72(0.6)			0.013 (0.004)	0.013 (0.004)

a) Weighted average of two runs with 2 cm^3 and 3 runs with 15 cm^3 Ge(Li) detectors. Some lines were too weak for accurate measurements with these detectors and are left blank.

b) One run with a 35 cm^3 Ge(Li) detector at Oak Ridge National Laboratory. Where there are no data given, the transition was used as a standard to calibrate the ORNL system (see discussion in text).

c) The intensities are given in percent per disintegration where the 879.3 keV transition intensity of 30.0 is used as a normalizing standard as discussed in the text.

d) A value of 13.7 was assumed for the 86.8 keV transition and the 93.7 keV transition intensity is measured relative to that of the 86.8 keV value.

TABLE 1 (continued)

Gamma-ray energy			Gamma-ray intensity [c])			
Michigan	Vanderbilt [a])	Vanderbilt [b])	Michigan	Vanderbilt [a])	Vanderbilt [b])	Weighted average
486.075(0.080)	486.05 (0.4)	486.31(0.20)	0.072 (0.018)	0.079(0.009)	0.086 (0.013)	0.080 (0.007)
682.349(0.110)	682.22 (0.3)	682.36(0.25)	0.66 (0.18)	0.44 (0.10)	0.57 (0.06)	0.545 (0.050)
765.194(0.110)	765.04 (0.3)	765.21(0.20)	1.74 (0.46)	1.73 (0.39)	2.19 (0.22)	2.03 (0.18)
871.9 (1.5)		871.95(0.50)	0.157 (0.045)		0.19 (0.05)	0.174 (0.035)
879.333(0.070)	879.32 (0.08)		≡30.0	≡30.0	≡30.0	≡30.0
962.085(0.220)	961.76 (0.4)	962.38(0.25)	9.92 (1.00)	10.0 (1.8)	10.6 (1.1)	10.2 (0.7)
966.099(0.120)	965.85 (0.2)	966.15(0.20)	24.4 (2.5)	25.0 (3.5)	25.0 (2.0)	24.7 (1.5)
1003.26(0.30)	1002.90 (0.2)		1.10 (0.13)	0.96 (0.06)		0.98 (0.05)
1005.0 (1.0)			<0.1			
1068.9 (1.5)	1068.9 (0.5)	1069.4 (0.5)	0.08 (0.02)	0.080(0.012)	0.070 (0.014)	0.076 (0.008)
1103.22 (0.25)	1102.60 (0.3)	1102.66(0.3)	0.41 (0.07)	0.48 (0.05)	0.56 (0.04)	0.50 (0.03)
1115.29 (0.19)	1115.12 (0.2)	1115.12(0.20)	1.56 (0.24)	1.41 (0.15)	1.55 (0.12)	1.50 (0.09)
1178.12 (0.19)	1178.00 (0.08)		15.2 (2.4)	14.8 (0.5)		14.8 (0.5)
1200.21 (0.37)	1199.82 (0.2)	1200.00(0.2)	2.36 (0.37)	2.23 (0.09)		2.24 (0.09)
1251.3 (0.5)	1251.46 (0.3)	1251.38(0.25)	0.10 (0.02)	0.079(0.011)	0.108 (0.011)	0.094 (0.008)
1271.87 (0.24)	1271.98 (0.08)		7.63 (1.2)	7.42 (0.22)		7.4 (0.2)
1286.1 (2.0)		1285.8 (0.5)	0.0092(0.003)		0.013 (0.004)	0.0110(0.0030)
		1300.0 (0.8)			0.005 (0.003)	0.005 (0.003)
1311.90 (0.30)	1312.04 (0.2)		2.85 (0.42)	2.78 (0.18)		2.79 (0.17)

3. Results

The singles spectrum taken at ORNL with the 35 cm^3 detector is shown in fig. 1. Spectra taken at Michigan with the 40 cm^3 detector were similar to this.

The results of the energy and gamma-ray intensity measurements are given in table 1. The energy values and their uncertainties for gamma rays below 1 MeV given in column 1 for the Michigan data were obtained with the curved-crystal spectrometer except for the 872 keV transition. The energy and relative intensity values for the 872 keV transition were obtained from the spectrum coincident with the 197 keV gamma ray. The energy of the 1005 keV transition was obtained from the spectrum coincident with the 246 keV gamma ray. The energy values for the 1069, 1251 and 1286 keV transitions were determined with the Ge(Li) spectrometer. The energies of the remaining gamma rays above 1 MeV were measured with the Ge(Li) spectrometers and the curved-crystal spectrometer and weighted averages of these measurements are presented in column 1.

In columns 2 and 3 of table 1 are given the energy measurements obtained at Vanderbilt and Oak Ridge. The absence of a transition in the Vanderbilt work indicates it was too weak to obtain good results, and an absence in column 3 indicates the transition was used as a calibration standard in those data. Such is also the case for the intensities in columns 5 and 6. The Oak Ridge results are from the 35 cm^3 detector only, as the Compton suppressed data yielded no new information.

The gamma-ray intensities given in column 4 were deduced from data obtained with the curved-crystal spectrometer and the Ge(Li) spectrometers at Michigan. The results from the curved-crystal spectrometer were analysed in the manner described by Reidy and Wiedenbeck [26]). Whenever possible, measurements were performed with both the curved-crystal and the Ge(Li) spectrometers. Reasonable consistency was found between the results of the two methods. The gamma-ray intensity values are normalized to the electron intensities of Ewan *et al.* [13]) and represent number of events per 100 decays. Ewan *et al.* measured the electron intensities relative to the total beta intensity and thus obtained the electron intensities in percent per disintegration. There remains the problem of how to normalize the relative gamma-ray intensities to the electron intensities to obtain total transition intensities and conversion coefficients. The direct conversion coefficient measurements of Jansen, Hamilton and Zganjar [19]) provide the best normalization procedure. The K-conversion coefficients of the 87, 197, 299 and 879 keV transitions were measured by the internal-external conversion method. Table 2 presents the α_K results [19, 29]) and the theoretical conversion coefficients of Sliv and Band [36]) and Hager and Setzer [31]). The experimental α_K results have been slightly altered [29]) ($\lesssim$ 1 %) from the previous report [19]) as a result of small refinements. Averages of the experimental and theoretical α_K values were used along with the electron results of Ewan *et al.* to obtain the gamma-ray intensities of the 197, 299 and 879 keV transitions in percentage per disintegration. The 87 keV transition was not included in this analysis because of the larger error associated with this electron

TABLE 2

K conversion coefficients of the 197, 299 and 879 keV transitions in ^{160}Dy and their gamma-ray intensities in percent per disintegration calculated from the average α_K and e_K values

Energy	α_K exp [a]	α_K theory [b]	α_K theory [c]	Average	e_K [d]	I_γ
197	0.154 ±0.009	0.165 (E2)	0.167 (E2)	0.160	0.88 ±0.04	5.5±0.50
299	0.0143 ±0.0010	0.0148 (E1)	0.0147 (E1)	0.0146	0.39 ±0.02	26.7±1.9
879	0.00344±0.000335	0.00335(E2)	0.00339(E2)	0.00340	0.103±0.005	30.3±2.4

a) Refs. 19,29). b) Ref. 36). c) Ref. 31). d) Ref. 13) in percent per disintegration.

TABLE 3

Conversion coefficients obtained from the gamma-ray intensities of table 1 and previously reported electron intensities [13, 19, 29]

Energy (keV)	Gamma-ray intensity [a]	K-conversion line intensity [b]	Total transition intensity [c]	α_K (expt)	α_K (theoretical)			Assigned multipolarity
					E1	E2	M1	
86.8	13.7 (20)	20.5 (20) [d]	78.1	1.50 (27)	3.7(−1)	1.55(0)	2.9(0)	E2
93.9	0.067(10)	0.09 (1) [e]	0.234	1.35 (27)	3.1(−1)	1.30(0)	2.4(0)	E2+(M1)
197.0	5.22 (29)	0.88 (4)	6.54	0.169 (12)	4.3(−2)	1.70(−1)	2.9(−1)	E2
215.6	3.93 (22)	0.140 (7)	4.09	0.036 (3)	3.4(−2)	1.3 (−1)	2.3(−1)	E1
230.6	0.071(7)	<0.005 [f]		<0.078 [g]	2.9(−2)	1.0 (−1)	1.9(−1)	E1
298.6	27.1 (16)	0.39 (2)	27.6	0.0144 (11)	1.5(−2)	4.9 (−2)	9.6(−2)	E1
309.6	0.90 (4)	0.0120 (15)	0.937	0.0133 (18)	1.4(−2)	4.4 (−2)	8.7(−2)	E1
337.3	0.33 (3)	<0.002 [f]		<0.0066 [g]	1.1(−2)	3.4 (−2)	7.3(−2)	E1
392.5	1.36 (6)	0.0110 (15)	1.36	0.0081 (12)	7.6(−3)	2.3 (−2)	4.7(−2)	E1
682.3	0.545(50)	0.0050 (15)	0.551	0.0092 (29)	2.2(−3)	5.9 (−3)	1.2(−2)	E2
765.2	2.03 (18)	0.0125 (10)	2.04	0.0062 (7)	1.8(−3)	4.5 (−3)	8.6(−3)	E2
879.3	30.0	0.103 (5)	30.1	0.0034 (2)	1.4(−3)	3.4 (−3)	6.1(−3)	E2
962.1	10.2 (7)	0.029 (2)	10.2	0.00284(26)	1.2(−3)	2.7 (−3)	4.8(−3)	E2
966.1	24.7 (14)	0.072 (4)	24.8	0.0029 (3)	1.2(−3)	2.7 (−3)	4.8(−3)	E2
1003.3	0.98 (5)	0.00080(15)	0.980	0.00082(16)	1.1(−3)	2.6 (−3)	4.4(−3)	E1
1103.1	0.50 (3)	<0.0002 [f]	0.504	<0.00042 [g]	9.1(−4)	2.1 (−3)	3.5(−3)	E1
1115.3	1.50 (9)	0.0016 (1)	1.50	0.00107(9)	8.7(−4)	2.0 (−3)	3.4(−3)	E1
1178.0	14.8 (5)	0.0120 (6)	14.8	0.00081(5)	8.0(−4)	1.8 (−3)	3.0(−3)	E1
1200.0	2.24 (9)	0.0018 (2)	2.24	0.00080(10)	7.8(−4)	1.7 (−3)	2.9(−3)	E1
1271.9	7.4 (2)	0.0049 (3)	7.43	0.00066(4)	7.0(−4)	1.6 (−3)	2.5(−3)	E1
1312.0	2.79 (17)	0.0019 (1)	2.79	0.00068(5)	6.6(−4)	1.5 (−3)	2.4–(3)	E1

[a] From column 7 table 1.

[b] Data of Ewan *et al.* [13]) except for two cases as noted in footnotes [d, e]).

[c] The total electron intensity contribution to the total transition intensities were obtained from the L+higher shells data of Ewan *et al.* [13]) where available or from theoretical α_L values and computing $\alpha_T = \alpha_K + 1.33\,\alpha_L$.

[d] Average of data from refs. [13, 19, 29]) (see discussion in text).

[e] Average of data from refs. [13, 15]), where $\varepsilon_k(86.8)$ is taken as 20.5.

[f] See discussion in text for method to obtain the limit.

[g] To obtain this upper limit, the gamma-ray intensity was reduced by one standard deviation.

[h] Ref. [36]).

intensity given in ref. [13]). In fact, the electron intensity of Ewan *et al.* for the 87 keV transition is about one standard deviation too large if one uses the intensities of table 2 to normalize the electron and gamma-ray spectra and then calculates the total feeding to the ground state. From the recent results of Jansen *et al.* [19, 29]) also on an iron-free double-focusing spectrometer, an independent measurement of the K-electron intensity of the 87 keV transition relative to the 197, 299 and 879 keV transitions was obtained. The relative intensities of the three higher energy transitions are in very good agreement ($\lesssim$ 5% difference in each case) with the results of Ewan *et al.*, but the K intensity of the 87 keV transition was consistently lower. An average of the two results [13, 19, 29]) gives a K-electron intensity of 20.5 for the 87 keV transition. Use of this value yields the following: an α_K in agreement with E2 theory, a α_{tot}/α_K ratio (the data of Ewan *et al.* are used for the intensities of the L+higher shells) in agreement with E2 theory (where $\alpha_T = \alpha_{K_{Th}} + 1.33\ \alpha_{L_{Th}}$) and 99.8% for the feeding to the ground state when the total electron intensity is added to the gamma-ray intensities of the 87 and 966 keV transitions. Thus, this intensity is given in table 3 which follows. In view of all these results, table 2 indicates that the best normalization procedure is to take the intensity in percent per disintegration for the 879 keV transition as 30.0, and this was done for the results presented in tables 1 and 3. The intensity measure-

TABLE 4
Gamma-ray coincidences observed in the decay of ^{160}Tb

Gate energy (keV)	Coincident gamma ray (keV)
87	197, 216, 299, 310, 337, 393, 765, 879, 962, 1003, 1115, 1178, 1200, 1251, 1272, 1312
197	87, 216, 231, 246, 299, 310, 337, 682, 765, 872, 1003, 1115, 1251
216	87, 197, 765, 962
231	87, 197, 872, 1069
246	87, 197, 1005
299	87, 197, 765, 962
310	87, 765, 962
337	87, 197, 765, 962
393	87, 197, 879, 966
872, 879	87, 299, 379, 393
962, 966	87, 216, 310, 337, 393, 486
989–1003	87, 197
1003–1007	87, 197, 246
1103, 1115	87, 197
1178	87
1200	87
1272	87
1312	87

ments in column 5 represent averages of 2 runs with a 2 cm^3 and 3 runs with a 15 cm^3 Ge(Li) detector and in column 6, 1 run with a 35 cm^3 detector and normalized as described above. Column 7 gives the average gamma-ray intensities.

Table 3 presents the conversion coefficients obtained from the gamma intensities of table 1 (column 7 of table 1 is repeated in column 2) and the electron intensities of Ewan *et al.* [13]) in column 3. Column 5 gives the K-conversion coefficients calculated from the gamma-ray intensity values from column 2 and the electron intensity values from column 3. The theoretical K-conversion coefficients were obtained from the tables of Sliv and Band [36]) for the indicated multipolarities.

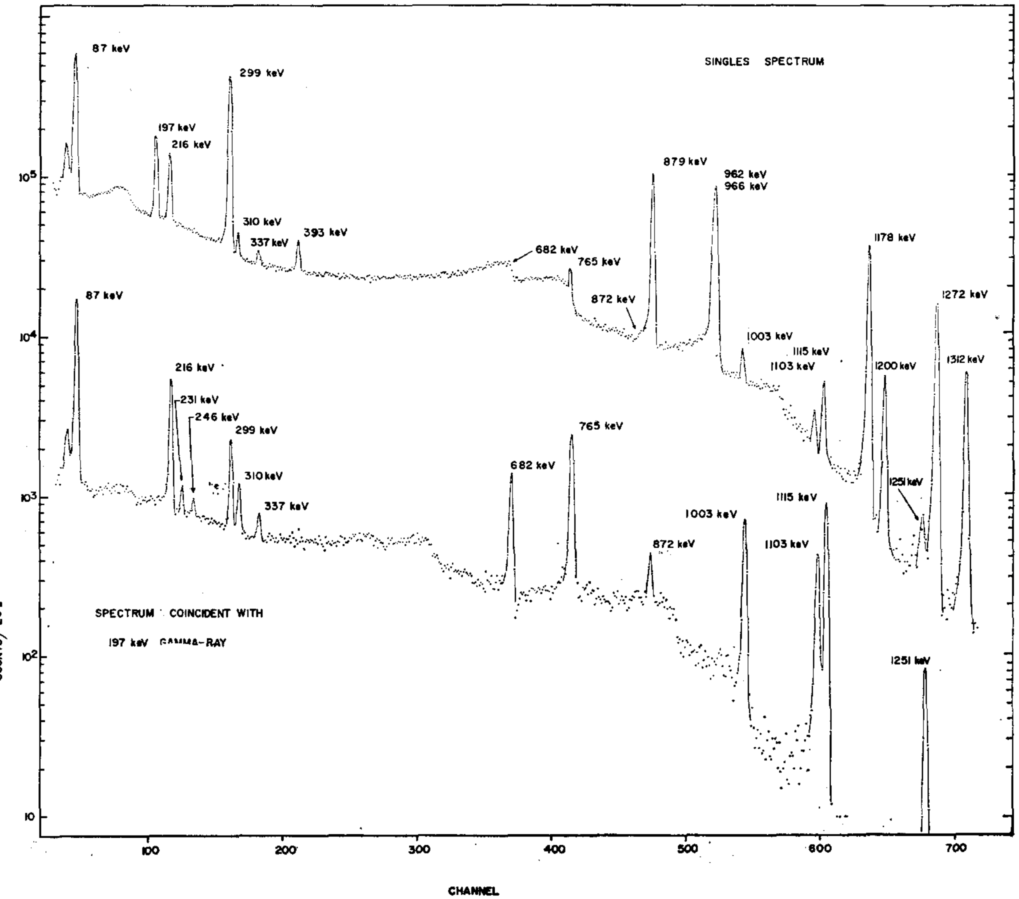

Fig. 2. The gamma-ray spectrum coincident with the 197 keV transition. A singles spectrum is shown in the upper spectrum.

Five transitions which do not appear in the work of even recent investigators were observed with energies 237.638±0.086 keV, 246.489±0.016 keV, 349.94±0.11 keV, 1005±1 keV and 1069.1±0.4 keV. Weaker evidence was obtained for new transitions of 242.5±0.8 keV, 432.7±0.6 keV and 1300.0±0.8 keV.

Five additional transitions which have been reported in only one or two works (references indicated in parentheses) but were previously unconfirmed in later works have been measured with energies 176.490±0.030 keV (1, 3), 379.449±0.090 keV (1, 3), 486.075±0.080 keV (3), 871.95±0.50 keV (10) and 1285.8±0.5 keV (3).

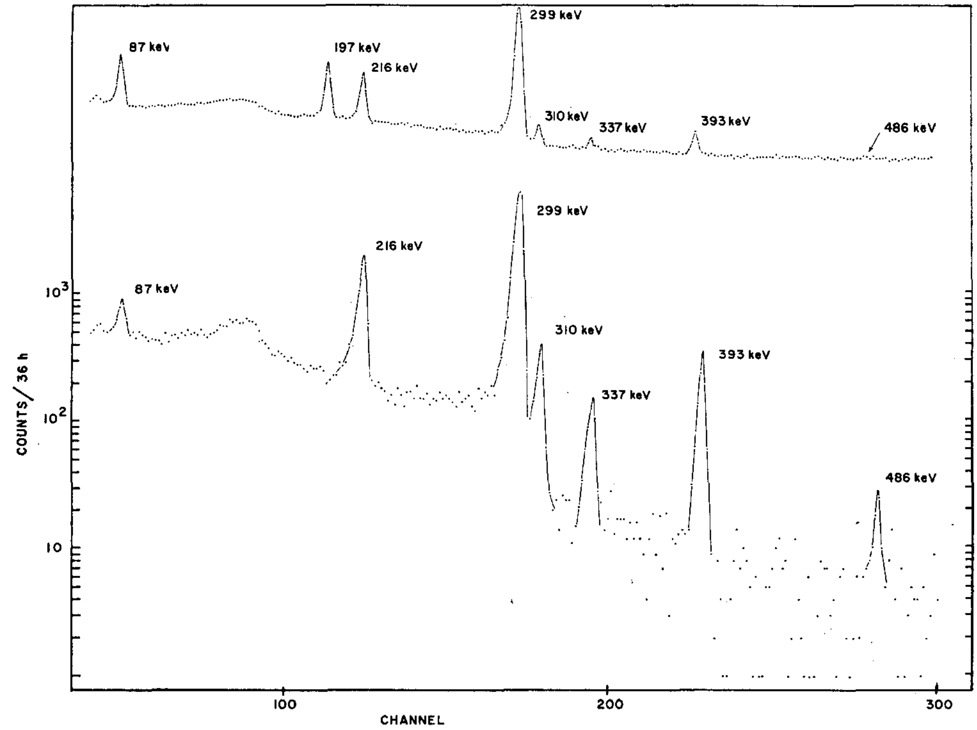

Fig. 3. The gamma-ray spectrum coincident with the 962-966 keV doublet. The upper spectrum is a singles spectrum.

A partial summary of the results of the gamma-gamma coincidence studies is presented in table 4. The relative intensity values of the coincident gamma rays are not listed, but these and similar data were used in placing transitions in the decay scheme.

The gamma-ray spectrum coincident with the 197 keV transition is shown in fig. 2. Of special interest is the presence of the 231, 246, 872 and 1251 keV gamma-ray peaks in the coincidence spectrum. Fig. 3 shows the spectrum coincident with the 962-966 keV doublet. Figs. 4(b) and (c) show the gamma-ray spectrum coincident with the regions from 1003-1008 keV and from 998-1003 keV, respectively. Fig. 4(a) is a singles spectrum. Of particular interest is the presence of the 246 keV transition in fig. 4(b). Also, the coincidence spectrum was obtained with the gate set on the 246 keV region. In addition to the 87 and 197 keV peaks, a peak lying on the high side of the 1003 keV line was observed in this coincidence spectrum.

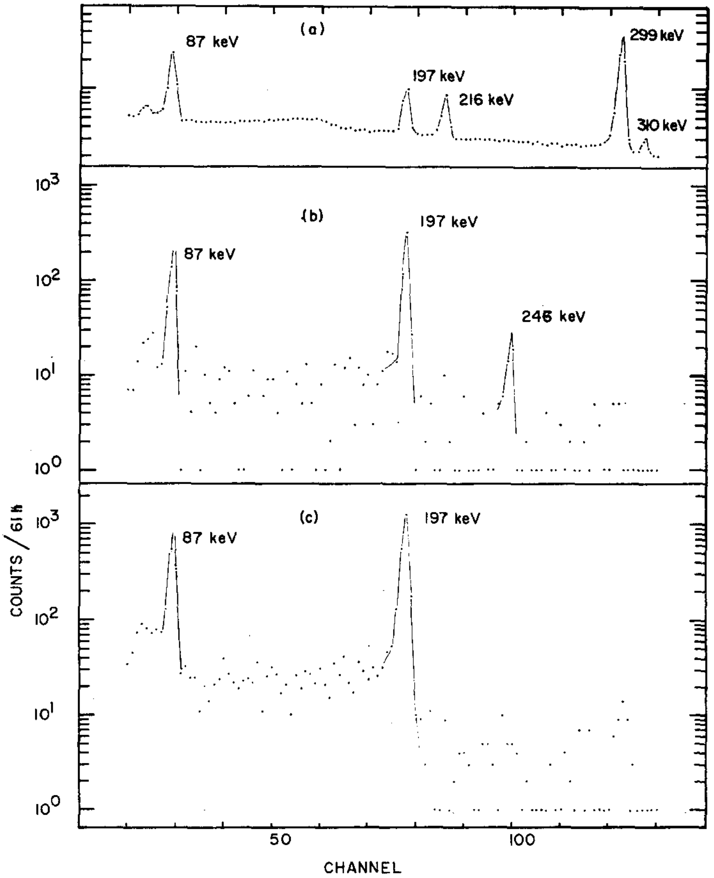

Fig. 4. (a) Singles spectrum. (b). Gamma-ray spectrum coincident with the energy region from 1003 to 1008 keV. (c). Gamma-ray spectrum coincident with the energy region from 998 to 1003 keV.

4. Discussion

The decay scheme for ^{160}Tb deduced from the present work is shown in fig. 5. This scheme incorporates all the transitions which were observed in this work. It is essentially the same one proposed by previous authors with three exceptions. The population of levels at 1155.8 keV, 1288.7 keV and 1535.2 keV has been firmly established; these levels had been proposed in some previous work but never clearly established in the ^{160}Tb decay. In addition, several new transitions have been placed in the decay scheme. Transitions which are designated by a filled circle on the decay scheme are placed on the basis of energy fits, intensity values and coincidence results.

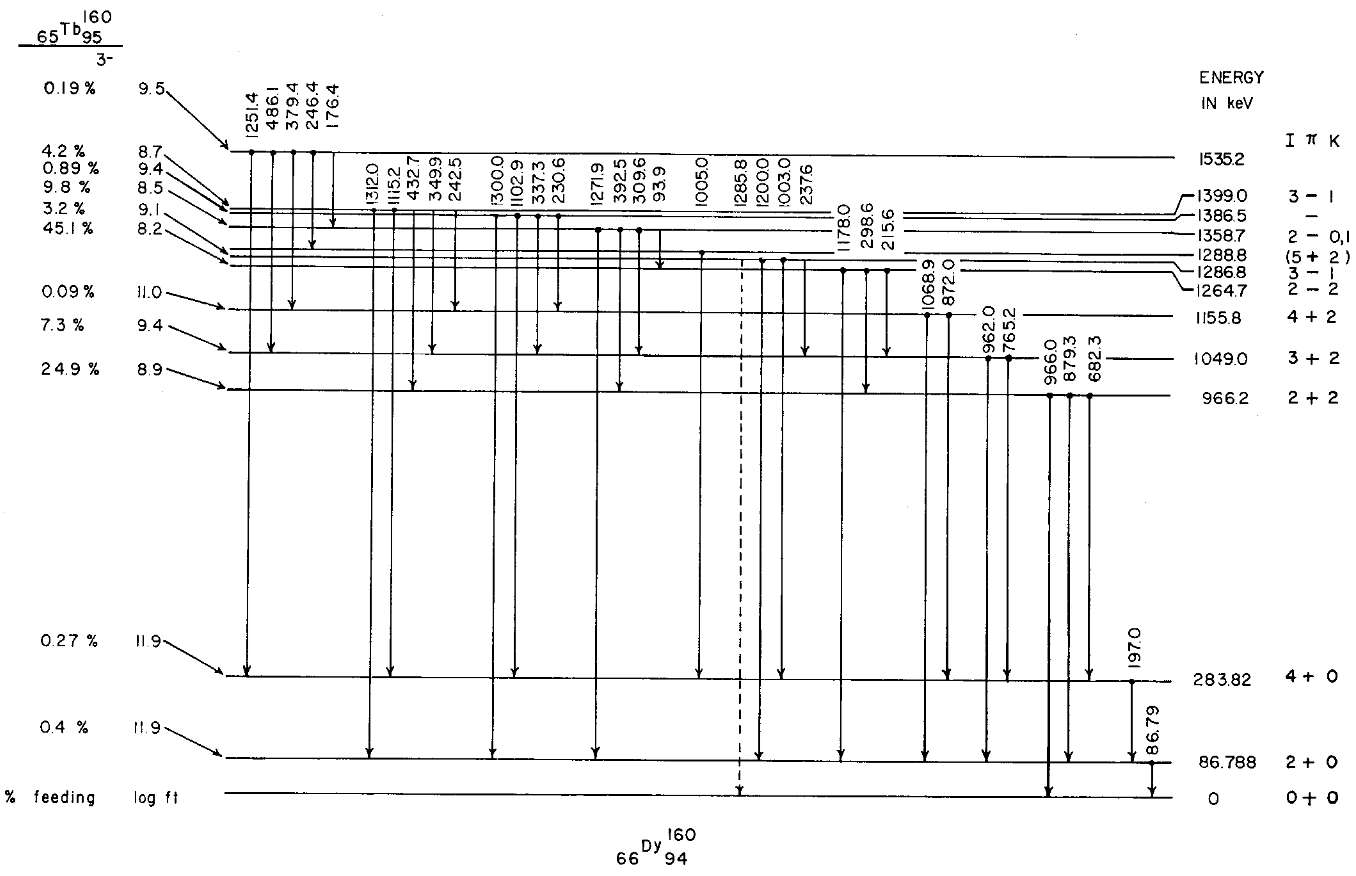

Fig. 5. The decay scheme for ^{160}Tb deduced from the present study. The beta feeding and log *ft* values for the 87 keV state are from ref. [4]). Transitions which are designated by a filled circle are placed on the basis of energy fits, intensity values and coincidence results. The remaining transitions are placed only on the basis of energy fit.

The remaining transitions are placed only on the basis of energy fit. The gamma-ray energies in the different experiments reported here agree well with each other. The somewhat less accurate energies obtained from electron spectra [13]) also agree with our results. The energies of the upper levels in our decay scheme are slightly higher than those of Jaklevic *et al.* [20]) and reflect slight discrepancies between some of the gamma-ray energy values of our work and the work reported in ref. [20]). The spins, parities and K-quantum assignments for the levels are the same as those given in the work of Jaklevic *et al.* with the exception of the levels at 1155.8, 1288.7, 1386.5 and 1535.2 keV. The $\log ft$ values were calculated from the transition intensities except for the first excited state where the value obtained by Nathan [4]) was used.

TABLE 5

Ratios of E2 reduced transition probabilities from the $K = 2$ gamma vibrational level to the $K = 0$ ground state rotational band

Level energy (keV)	$\frac{B(\mathrm{E2}; I_\mathrm{i}K_\mathrm{i} \rightarrow I_\mathrm{f}K_\mathrm{f})}{B(\mathrm{E2}; I_\mathrm{i}K_\mathrm{i} \rightarrow I_\mathrm{f}K_\mathrm{f})}$	Experimental ratio [a])	Pure rotation	Z_2 [a])
966.1	$\frac{B(\mathrm{E2}; 22 \rightarrow 00)}{B(\mathrm{E2}; 22 \rightarrow 20)}$	0.51 (3)	0.70	0.053(10)
966.1	$\frac{B(\mathrm{E2}; 22 \rightarrow 40)}{B(\mathrm{E2}; 22 \rightarrow 20)}$	0.065(6)	0.05	0.020(8)
1048.9	$\frac{B(\mathrm{E2}; 32 \rightarrow 40)}{B(\mathrm{E2}; 32 \rightarrow 20)}$	0.62 (7)	0.40	0.038(9)
1155.7	$\frac{B(\mathrm{E2}; 42 \rightarrow 40)}{B(\mathrm{E2}; 42 \rightarrow 20)}$	7.0 (20)	2.95	0.06 (2)

[a]) The uncertainties in the last figures are given in parentheses.

The ground state rotational band with excited states at 86.8(2^+) and 283.8(4^+) keV and the gamma-vibrational band with excited states at 966.2(2^+) and 1049.0(3^+) keV have been well established by previous investigators. On the basis of the 197-872 keV coincidence, we establish the feeding of a level at 1155.8 keV in this decay. On the basis of the 231-1069 keV coincidence data, the 1069 keV transition has been placed as proceeding from this state to the first excited state. This 1155.8 keV state is most likely the same state that has been determined to be the 4^+ member of the gamma-vibrational band from a study of the ^{160}Ho decay. The intensity ratio of the 1069 keV to the 872 keV transition is roughly the same as that measured in the ^{160}Ho decay. The ratios of the reduced transition probabilities (RTP) from the three $K^\pi = 2^+$ levels are presented in table 5, where these transitions are assumed to be pure E2. The pure rotational values are given in column 4, and in column 5 are the values of Z_2 obtained by comparing the experimental results with the band mixing predictions [32]). Although there is some disagreement for two Z_2 values from the 966 keV level, the four values are in reasonable agreement with the experimental values given by Marshalek [33]) for this nucleus (average $Z_2 = 0.039 \pm 0.004$) and with his calculations which he obtained using a microscopic model.

The level at 1535.2 keV is now well established on the basis of energy fits and coincidence results. From fig. 2, the 1251 keV transition is established to be in coincidence with the 197 keV transition. Fig. 3 shows the 486 keV transition to be in coincidence with the 962-966 keV doublet. The 486 keV transition was not observed to be in coincidence with the 879 keV gamma ray thereby establishing the 486 keV gamma ray to be in coincidence with the 962 keV transition. In addition, the 379 keV gamma ray was observed in the spectrum coincident with the 879 keV transition. The intensity values were consistent with the interpretation that the 379 keV transition was in coincidence with the 872 keV gamma ray which was also in the gate. The 176.5 keV transition has been placed as depopulating this 1535.2 keV level only on the basis of energy fit. The presence of the 246-1005 keV coincidence and the 197-246 keV coincidence indicates that the 197, 246 and 1005 keV gamma rays are in cascade. This result is most easily incorporated into the decay scheme by the addition of a new level at 1288.7 keV This state is populated by the 246 keV transition which proceeds from the level at 1535.2 keV and would depopulate via a 1004.9 keV transition to the 283.8 keV (4^+) state. A 246-1202 keV coincidence was not observed, but the low coincidence rate in the 246 keV gate coincidence run allows us only to place a relative intensity limit on a possible 1202 keV gamma ray of $I_\gamma(1202) \leqq 0.15\, I_\gamma$ (1005). Therefore, the feeding from this 1288.7 keV state to the 87.8 keV (2^+) level is much less than the feeding to the 284 keV (4^+) level. This 1288.7 keV state could possibly be the 5^+ member of the gamma-vibrational band. A similar interpretation has been given a state observed with about this same energy in the ^{160}Ho decay. The possible 709 keV transition from this state to the 6^+ state of the ground state rotational would be a factor of two or more less intense than the 1005 keV transition to the 4^+ state and would not have been observed in the present work.

The parity of the 1386 keV state can be deduced from the following considerations. In table 3 upper limits on the electron intensities for the 231, 337 and 1103 keV transitions were obtained from limits placed on transitions of 238, 350 and 1113 keV in the work of Ewan *et al.* [13]). These data combined with the gamma-ray intensities reduced by one standard deviation were used to obtain upper limits on the K-conversion coefficients of the transitions from the 1386 keV level. These limits are consistent only with E1 transitions, and thus these data lead to a negative-parity assignment for this level. If the 1300 keV transition seen only in the 35 cm^3 singles spectrum is correctly placed, then the decays to the 2^+ and 4^+ members of the ground state band would indicate a spin of 3. An upper limit of 0.01 was placed on a 420 keV transition to the 966 keV 2^+ level, but this intensity limit is not inconsistent with a strong retardation of the 1300 keV transition to the first excited 2^+ state (see table 6).

Unfortunately, the gamma-ray intensities of the transitions from the 1535 keV level are too weak and the intensity limits on the conversion electron lines too uncertain to use arguments similar to the above to determine the parity of this level. The spin is 3, 4 or 5 on the basis of the pattern of gamma rays leaving this level. To have beta population of such a high energy level from the 3^- ground state of ^{160}Tb would suggest odd parity for the 1535 keV level. With this assumption of odd parity, the relative E1 transition rates to the 4^+ gamma-vibrational and 4^+ ground state bands were calculated and are presented in table 6. The results are consistent with an odd-parity assignment.

Table 6 also gives the retardation factor of the higher energy E1 transition to a member of the ground state rotational band relative to the transition to the member

TABLE 6

Relative hindrance factors for E1 transitions to the $K = 0$ ground state rotational band relative to the $K = 2$ gamma vibrational band

Level energy (keV)	J_i; J_fK_f	E_γ	Relative hindrance factor
1265	2; 22	298.6	112 ±8
	2; 20	1178.1	
1359	2; 22	392.5	6.3 ±0.2
	2; 20	1272.0	
1386	–; 42	230.6	15 ±2
	–; 40	1102.9	
	–; 22	420	<90
	–; 20	1300	
1399	3; 42	243.2	0.26±0.19
	3; 40	1115.2	
	3; 22	432.7	0.12±0.04
	3; 20	1312.0	
1535	–; 42	379.4	5.3 ±1.6
	–; 40	1251.4	

TABLE 7

Ratios of reduced E1 transition probabilities

Level energy (keV)	$\frac{B(\mathrm{E1}; I_iK_i \to I_fK_f)}{B(\mathrm{E1}; I_iK_i \to I_fK_f)}$	$\frac{E(I_i \to I_f)}{E(I_i \to I_f)}$	Observed ratio [a]	Calculated		
				$K = 0$	$K = 1$	$K = 2$
1264.7	$\frac{B(\mathrm{E1}; 2\mathrm{K} \to 32)}{B(\mathrm{E1}; 2\mathrm{K} \to 22)}$	$\frac{216}{299}$	0.38(3)	2 [b]	2	0.5
1286.8	$\frac{B(\mathrm{E1}; 3\mathrm{K} \to 40)}{B(\mathrm{E1}; 3\mathrm{K} \to 20)}$	$\frac{1003}{1200}$	0.75(5)	1.33	0.75	0.75 [b]
1358.7	$\frac{B(\mathrm{E1}; 2\mathrm{K} \to 32)}{B(\mathrm{E1}; 2\mathrm{K} \to 22)}$	$\frac{310}{393}$	1.34(6)	2 [b]	2	0.5
1399.9	$\frac{B(\mathrm{E1}; 3\mathrm{K} \to 40)}{B(\mathrm{E1}; 3\mathrm{K} \to 20)}$	$\frac{1115}{1312}$	0.58(5)	1.33	0.75	0.75 [b]

[a] Numbers in parentheses are the uncertainties.

[b] Calculated from the reduced transition probability for a *K*-forbidden E1 transition as given in ref. [34].

of the gamma-vibrational band with the same spin. The large retardation of the transition from the 1265 keV level to the ground state 2^+ level relative to the one to the gamma-band level has been used to argue that the 1265 keV state is a $K = 2$ level, and the small retardation factors for similar transitions from the 1359 and 1399 keV levels suggest $K = 0$ or $K = 1$ for them. This same argument suggests that the 1386 and 1535 keV levels are $K = 2$ and $K = 0$ or 1, respectively. However, it should be noted that a $I^{\pi}K = 4^{-}2$ assignment for the 1535 keV state is also consistent with the data.

The relative reduced E1 transition probabilities from the odd-parity levels to the gamma and ground state bands have been discussed previously [13, 20]). These data also were used to assign K quantum numbers to the 1265, 1287, 1359 and 1399 keV levels as shown in the decay scheme. The results from our improved intensities are presented in table 7. The point of interest is that with our improved limits of error there remains disagreement between the calculated values and our results in three cases. Ewan *et al.* [13]) have suggested these differences can be explained in terms of mixing of the two close-lying 2^- levels and of the two 3^- levels. It seems difficult, however, to arrive at a unique interpretation of these negative-parity levels in ^{160}Dy at present as has been pointed out recently [20]).

It may be noted that the K-conversion coefficient of the 765 keV transition is larger than the theoretical E2 value. An M1 admixture is not expected, since the M1 admixtures in the decay of gamma-vibrational bands to the ground state are small (< few percent). The difficulty probably arises from underestimation of the intensity of the gamma line which sits on a Compton edge. Also, it should be noted that the α_K of the 93.9 keV transition obtained from averaging the electron intensities of Ewan *et al.* [13]) and Bohm and Rogers [15]) (normalized relative to the 87 keV K-lines), and our gamma-ray intensities lead to a nearly pure E2 assignment for the 93.9 keV transition. This E2 assignment (but not M1) also fits the measured K/M and inferred K/L ratios as obtained by Ewan *et al.* [13]). Thus, the earlier predominantly M1 assignment [15]) appears to be in error.

The 1287 keV transition has been tentatively placed as the ground state transition from the 1286 keV level. As a result, one has the case of an E3 transition competing with two E1 transitions in depopulating this state. However, Elbek *et al.* [35]) have determined that the B(E3) associated with this state is enhanced by a factor of 11 over the single-particle value. Since E1 transitions are in general hindered [35]) often by factors of 10^5 or more, it is not unlikely that the E3 transition can compete with the E1 transitions.

Finally, it should be noted that no evidence was obtained with either the large volume detectors or the Compton suppressed system for population of any $K^{\pi} = 0^+$ beta-vibrational levels from the decay of ^{160}Tb as might be expected from a 3^- ground state decay. Such levels are expected to start around 1100 keV.

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References

1) J. M. Cork, C. E. Branyan, W. C. Rutledge, A. E. Stoddard and J. M. LeBlanc, Phys. Rev. **78** (1950) 304
2) S. B. Burson, W. C. Jordan and J. M. LeBlanc, Phys. Rev. **94** (1954) 103
3) C. M. Fowler, AECU-3194 (1956)
4) O. Nathan, Nucl. Phys. **4** (1957) 125
5) S. Ofer, Nucl. Phys. **5** (1957) 331
6) R. G. Arns, R. E. Sund and M. L. Wiedenbeck, Nucl. Phys. **11** (1959) 411
7) G. Bäckström, J. Lindskog, O. Bergman, E. Bashandy and A. Bäcklin, Ark. Fys. **15** (1959) 121
8) E. P. Grigor'ev, A. V. Zolotavin and B. Kratsik, Izv. Akad. Nauk SSSR (ser. fiz.) **23** (1959) 183
9) E. P. Grigor'ev, B. S. Dzhelepov, A. V. Zolotavin, B. Kratsik and G. Bitterlikh, Izv. Akad. Nauk SSSR (ser. fiz.) **23** (1959) 859
10) N. A. Voinova, B. S. Dzhelepov, N. N. Zhukovskii and Yu. V. Khol'nov, Izv. Akad. Nauk SSSR (ser. fiz.) **24** (1960) 856
11) M. A. Clark, Can. J. Phys. **38** (1960) 262
12) C. E. Johnson, J. F. Schooley and D. A. Shirley, Phys. Rev. **120** (1960) 2108
13) G. T. Ewan, R. L. Graham and J. S. Geiger, Nucl. Phys. **22** (1961) 610
14) D. G. Douglas, Nucl. Phys. **33** (1962) 485
15) F. Boehm and J. Rogers, Nucl. Phys. **41** (1963) 553
16) W. Michaelis, Nucl. Phys. **44** (1963) 78
17) V. V. G. Sastry, V. Laskshminarayana and Swami Jnanananda, Indian J. Pure Appl. Phys. **2** (1964) 307
18) K. V. Reddy, B. B. Venkatapathi Raju, R. V. Rama Mohan and Swami Jnanananda, Phys. Rev. **138** (1965) B33
19) J. F. W. Jansen, J. H. Hamilton and E. F. Zganjar, in Internal conversion processes, ed. by J. H. Hamilton (Academic Press, New York, 1966) p. 257
20) J. M. Jaklevic, E. G. Funk and J. W. Mihelich, Nucl. Phys. **A99** (1967) 83
21) J. J. Reidy, M. A. Ludington and M. L. Wiedenbeck, Bull. Am. Phys. Soc. **12** (1967) 1202
22) D. J. McMillan, J. H. Hamilton and J. J. Pinajian, Bull. Am. Phys. Soc. **13** (1968) 249
23) L. L. Reidinger, N. R. Johnson and J. H. Hamilton, Phys. Rev. Lett. **19** (1967) 1243
24) J. J. Reidy and M. L. Wiedenbeck, Nucl. Instr. **33** (1965) 213
25) J. J. Reidy and M. L. Wiedenbeck, Nucl. Physics **70** (1965) 518
26) J. J. Reidy and M. L. Wiedenbeck, Nucl. Phys. **79** (1966) 193
27) D. P. Donnelly, H. W. Baer, J. J. Reidy and M. L. Wiedenbeck, Nucl. Instr. **57** (1967) 219
28) A. V. Ramayya, C. Restor and J. H. Hamilton, private communication
29) J. F. W. Jansen, Ph. D. thesis, Amsterdam (1967)
30) A. V. Ramayya, B. van Nooijen, H. K. Carter and J. H. Hamilton, Nucl. Instr. **43** (1966) 379
31) R. S. Hager and E. C. Seltzer, Nucl. Data **4A** (1968) 1
32) B. R. Mottelson, Proc. Int. Conf. on nuclear structure, Tokyo (1967), J. Phys. Soc. Japan Suppl. **24** (1968);
S. G. Nilsson, in Alpha-, beta-, and gamma-ray spectroscopy, ed. by K. Siegbahn (North-Holland Publ. Co., Amsterdam, 1965) p. 601
33) E. R. Marshalek, Phys. Rev. **158** (1967) 993
34) A. Bohr and B. R. Mottelson, Sov. J. Atom. Energy **14** (1963) 41
35) E. Elbek, T. Grotdal, K. Nybo, P. O. Tjom and E. Veje, Proc. Int. Conf. on nuclear structure, Tokyo, 1967, J. Phys. Soc. Japan Suppl. **24** (1968)
36) L. A. Sliv and I. M. Band, in Alpha-, beta-, and gamma-ray spectroscopy, ed. by K. Siegbahn (North-Holland Publ. Co., Amsterdam, 1965) p. 1639