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Gamma Ray Intensity and Angular Correlation Measurements in ^{160}Dy

S. S. Bhati,[A] *Nirmal Singh,*[B] *P. D. Bajaj*[A] *and P. N. Trehan*[A]

[A] Department of Physics, Panjab University, Chandigarh-160014, India.
[B] Department of Applied Physics, Panjab Engineering College, Chandigarh, India.

Abstract

Gamma-ray intensity measurements in ^{160}Dy have been carried out using a Ge(Li) detector. In addition, γ–γ angular correlation measurements have been made on 10 cascades in ^{160}Dy using a Ge(Li)–NaI(Tl) fast coincidence arrangement. These cascades are 299→966, 299→879, 879→87, 197→87, 962→87, 215→962, 299→(879)→87, 299→(682)→197, 215→(962)→87 and 215→(765)→197 keV. Of these, the 215→(962)→87 and 215→(765)→197 keV cascades have been measured for the first time. The multipolarities of the 197, 215, 299, 879 and 962 keV transitions were found to be E2 $+(0\cdot2\pm0\cdot2)\%$ M3, E1 $+(2\cdot5^{+1\cdot5}_{-1\cdot0})\%$ M2, E1 $+(2^{+4}_{-2})\%$ M2, M1 $+(99\pm1)\%$ E2 and M1 $+(98\pm1)\%$ E2 respectively.

Introduction

The radioisotope ^{160}Tb decays to ^{160}Dy by β-emission with a half-life of 72·4 days. Dysprosium-160 is a doubly even nucleus in the deformed region and its level scheme has been studied by many workers (Nathan 1957; Ofer 1957; Arns *et al.* 1959; Ewan *et al.* 1961; Kundig 1961; Michaelis 1963; Gupta and Saha 1965) using scintillation, curved-crystal and magnetic spectrometers. Recently the decay scheme of ^{160}Tb has been investigated using a Ge(Li) spectrometer (Ludington *et al.* 1968; Keller and Zganjar 1970; McAdams and Ottesson 1972; Roehmer 1973). While several new γ rays proposed by Ludington *et al.* have been subsequently verified by Keller and Zganjar and by McAdams and Ottesson, there is some disagreement between the relative intensities of some of the γ rays as measured by these workers.

Spin and parity assignments to most of the levels in ^{160}Dy have been made using the angular correlation method (Nathan 1957; Ofer 1957; Arns *et al.* 1959; Kundig 1961; Michaelis 1963) and internal conversion measurements (Ewan *et al.* 1961). The angular correlation studies were carried out with scintillation detectors in all these investigations. Since then Jaklevic *et al.* (1967), Krane and Steffen (1971) and Zawislak *et al.* (1973) have made angular correlation measurements in the case of ^{160}Dy using Ge(Li)–NaI(Tl), Ge(Li)–Ge(Li) and Ge(Li)–NaI(Tl) combinations respectively. The results of these workers, however, are not in good agreement with each other. In addition, the angular correlation of some of the cascades has not been measured so far by scintillation or by Ge(Li) detectors.

In view of the above-mentioned discrepancies, it was thought worth while to re-investigate the decay scheme of ^{160}Tb. In the present work, the level scheme of ^{160}Dy has been studied using a Ge(Li) spectrometer in the singles mode. In addition, angular correlations for the following 10 cascades in ^{160}Dy, namely 299→966, 299→879, 879→87, 197→87, 962→87, 215→962, 299→(879)→87, 299→(682)→197, 215→(962)→87 and 215→(765)→197 keV, have been studied using Ge(Li)–NaI(Tl) detectors in the fast coincidence mode. From these studies, it has been possible to measure the relative intensities of various γ rays in ^{160}Dy and to assign multipolarities to the 197, 215, 299, 879 and 962 keV γ rays. Fig. 1 shows the decay scheme of ^{160}Tb, and the level scheme of ^{160}Dy which is consistent with the present measurements.

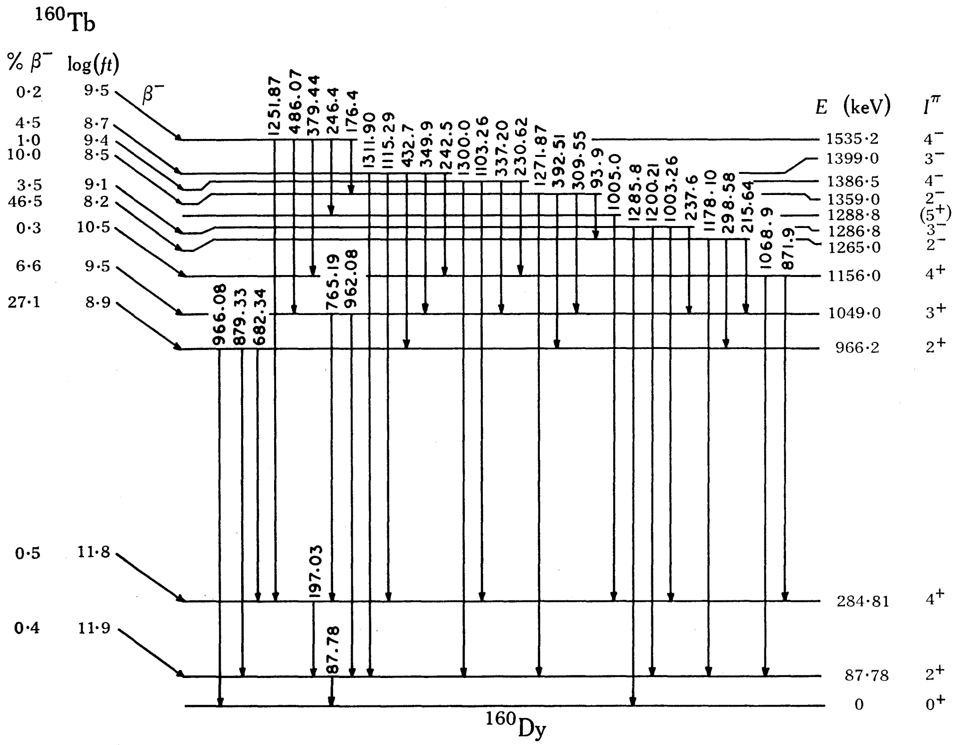

Fig. 1. Decay scheme of ^{160}Tb, and the level scheme of ^{160}Dy which is consistent with the present measurements. ^{160}Tb has $I^{\pi} = 3^{-}$.

Experimental Arrangement and Data Analysis

The ^{160}Tb radioactive source in the form of terbium chloride in dilute hydrochloric acid was obtained from the Bhabha Atomic Research Centre. From this active solution, sources of different strengths were prepared in cylindrical Perspex holders with central cavities of 1·5 mm diameter and 4 mm depth. A 7·77 cm^3 Ge(Li) detector and an ND-1100 multichannel analyser were used to measure the relative intensities of various γ rays. The calibration of the Ge(Li) spectrometer was performed by the method of Gehrke *et al.* (1971).

The directional correlation measurements were made employing a Ge(Li)–NaI(Tl) fast coincidence arrangement with an effective resolving time τ = 50 ns. The γ rays were detected by a 7·77 cm^3 Ge(Li) detector on one side and a 5×5 cm NaI(Tl) detector mounted on a Dumont 6292 photomultiplier on the other side. The NaI(Tl) detector was shielded with an anti-Compton graded lead cylinder and lead cone.

The source was located at a distance of 10 cm from the NaI(Tl) crystal and 6 cm from the Ge(Li) detector at the point of intersection of the axes of the two detectors. The NaI(Tl) detector could be moved to different angular positions whereas the Ge(Li) detector was kept fixed. The centring of the source was achieved to within 1% variation in the singles counting rate of the movable detector at various angular positions. Chance coincidences were recorded by introducing an appropriate delay in one channel of the fast coincidence setup.

The least squares fitting method of Rose (1953) was used to obtain the correlation functions. Solid angle corrections were made by using the correction factors calculated by Yates (1965) for NaI(Tl) crystals. The correction factors for the Ge(Li) detector were calculated using the technique of Camp and Vanlehn (1969).

The 87 and 299 keV γ rays were selected by the gate set on the NaI(Tl) detector side and the 197, 215, 879, 962 and 966 keV γ rays were selected by the gate set on the Ge(Li) detector side for the eight cascades that were studied which involved these γ rays. For the 215→962 and 215→(765)→197 keV cascades, the 215 keV γ ray was selected by the gate set on the NaI(Tl) side. All cascades were corrected for interference through Compton events from higher energy γ rays falling in the gates of the various lower energy γ rays by use of the intensity data given in Table 1. In analysing the correlation functions to obtain mixing ratios, the methods of Arns and Wiedenbeck (1958) and Taylor *et al.* (1971) were used.

Measurements and Results

Our measurements of the relative intensities of the γ rays, as obtained with a $7 \cdot 77\ \mathrm{cm}^3$ Ge(Li) detector, are given in Table 1 along with those determined by Ludington *et al.* (1968). In general, there is good agreement between the two sets of results. Some of the very weak γ rays were not observed in the present experiment. Measurements of the angular correlation coefficients for some cascades in ^{160}Dy are compared in Table 2 with the results of Krane and Steffen (1971). These are considered in more detail in the following subsections.

(*a*) *299→996 keV Cascade*

The 299→966 keV cascade follows a spin sequence $2^-(D,Q)2^+(Q)0^+$. Assuming the 966 keV γ ray to be pure E2 (Ewan *et al.* 1961), we found the multipole admixture in the 299 keV γ ray by the method of Taylor *et al.* (1971). The two values of δ obtained are $-0 \cdot 07 \leqslant \delta_1 \leqslant 0 \cdot 03$ and $-2 \cdot 2 \leqslant \delta_2 \leqslant -1 \cdot 9$. The values Q_1 and Q_2 of $Q = \delta^2/(1+\delta^2)$ corresponding to δ_1 and δ_2 are given in Table 3. The second value Q_2 is not in agreement with internal conversion measurements (Ewan *et al.*), and so the mixing ratio in the 299 keV γ ray corresponds to Q_1 and is given by E1 $+(0 \cdot 2^{+0 \cdot 3}_{-0 \cdot 1})\%$ M2.

(*b*) *299→879 keV Cascade*

The 299→879 keV cascade follows a spin sequence $2^-(D,Q)2^+(D,Q)2^+$. Assuming the 299 keV γ ray to be E1 $+(0 \cdot 5 \pm 0 \cdot 5)\%$ M2, as determined by suitably averaging the results given in subsection (*a*) and subsection (*g*) below, the mixing ratio analysis of the 879 keV γ ray yields the values of Q given in Table 3. The Q_1 value is not in agreement with internal conversion measurements (Ewan *et al.* 1961), and so the 879 keV γ ray is M1 $+(99 \cdot 5 \pm 0 \cdot 5)\%$ E2 in character.

Table 1. Comparison of measured γ ray relative intensities in ^{160}Dy

γ ray energy (keV)	Relative intensity: Ludington *et al.* (1968)	Relative intensity: Present work	γ ray energy (keV)	Relative intensity: Ludington *et al.* (1968)	Relative intensity: Present work
86·78	13·7 ±2·0	14·7 ±2·5	871·90	0·17 ±0·035	0·28 ±0·025
197·03	5·22 ±0·29	5·12 ±0·52	879·33	30	30
215·64	3·93 ±0·22	3·95 ±0·31	962·08	10·2 ±0·7	10·37 ±0·83
230·62	0·071±0·007	0·061±0·007	966·08	24·7 ±1·5	25·80 ±1·74
298·58	27·1 ±1·6	27·2 ±1·9	1003·26	0·98 ±0·05	0·83 ±0·08
309·55	0·90 ±0·04	0·85 ±0·08	1103·26	0·50 ±0·09	0·39 ±0·04
337·32	0·33 ±0·03	0·34 ±0·04	1115·29	1·50 ±0·09	1·20 ±0·06
379·44	0·014±0·004	0·013±0·005	1178·10	14·80 ±0·50	14·84 ±1·46
392·51	1·36 ±0·05	1·12 ±0·11	1200·21	2·24 ±0·09	2·72 ±0·18
486·07	0·080±0·007	0·108±0·010	1251·87	0·094±0·008	0·092±0·009
682·34	0·545±0·050	0·621±0·050	1271·87	7·4 ±0·2	7·92 ±0·35
765·19	2·03 ±0·18	2·16 ±0·23	1311·90	2·79 ±0·17	3·09 ±0·03

Table 2. Comparison of measured angular correlation coefficients for γ ray transitions in ^{160}Dy

γ ray cascade	Krane and Steffen (1971) A_2	Krane and Steffen (1971) A_4	Present work A_2	Present work A_4
299→966	0·246±0·010	−0·017±0·015	0·284±0·017	0·035±0·015
299→879	−0·089±0·011	−0·015±0·017	−0·062±0·009	0·029±0·015
879→87	0·002±0·017	0·324±0·025	−0·026±0·006	0·325±0·039
197→87	0·102±0·025	−0·019±0·038	0·129±0·026	−0·031±0·014
962→87	−0·247±0·044	−0·057±0·033	−0·294±0·021	0·015±0·012
215→962	0·00 ±0·05	0·00 ±0·05	0·060±0·008	0·037±0·015
299→(879)→87	−0·056±0·013	−0·012±0·026	−0·057±0·012	−0·004±0·003
215→(962)→87	—	—	−0·083±0·012	0·00 ±0·04
299→(682)→197	0·115±0·027	0·047±0·038	0·109±0·016	0·053±0·028
215→(765)→197	—	—	−0·075±0·009	0·007±0·005

Table 3. Experimental multipole mixing ratios for γ ray transitions in ^{160}Dy

γ ray cascade	E_γ (keV)	Q_1	Q_2	Mixing ratio
299→966	299	$0{\cdot}002^{+0{\cdot}003}_{-0{\cdot}001}$	$0{\cdot}80^{+0{\cdot}04}_{-0{\cdot}02}$	E1 + $(0{\cdot}2^{+0{\cdot}3}_{-0{\cdot}1})$% M2
299→879	879	0·18 ±0·02	0·99 ±0·01	M1 + (99·5±0·5)% E2
879→87	879	0·13 ±0·01	0·995±0·005	M1 + (99±1)% E2
197→87	197	0·002±0·002	0·68 ±0·06	E2 + (0·2±0·2)% M3
962→87	962	0·06 ±0·02	0·98 ±0·01	M1 + (98±1)% E2
215→962	215	0·015±0·005	0·985±0·005	E1 + (1·5±0·5)% M2
299→(879)→87	299	0·01 ±0·01	0·79 ±0·08	E1 + (1±1)% M2
215→(962)→87	215	$0{\cdot}02^{+0{\cdot}04}_{-0{\cdot}02}$	0·84 ±0·06	E1 + (2^{+4}_{-2})% M2
299→(682)→197	299	0·06 ±0·03	0·64 ±0·08	E1 + (6±3)% M2
215→(765)→197	215	$0{\cdot}025^{+0{\cdot}015}_{-0{\cdot}010}$	0·85 ±0·03	E1 + $(2{\cdot}5^{+1{\cdot}5}_{-1{\cdot}0})$% M2

(c) 879→87 keV Cascade

The 879→87 keV cascade involves the 87 keV state as the intermediate state whose half-life is 2·0 ns. Due to this long half-life, the observed angular correlation coefficients of the 879→87 keV cascade are attenuated and have to be corrected. The values of the attenuation coefficients G_{22} and G_{44} as determined by Gunther *et al.* (1965) for a similar source of $TbCl_3$ in HCl solution were used for this correction, namely, $G_{22} = 0{\cdot}74 \pm 0{\cdot}02$ and $G_{44} = 0{\cdot}594 \pm 0{\cdot}025$. These values were also used to correct the correlation coefficients of the 197→87, 962→87, 299→(879)→87 and 215→(962)→87 keV cascades, which also involve the 87 keV state as the intermediate state. The 879→87 keV cascade follows a spin sequence $2^+(D,Q)2^+(Q)0^+$. Assuming the 87 keV γ ray to be pure E2, the mixing ratio analysis for the 879 keV γ ray yields $0{\cdot}36 \leqslant \delta_1 \leqslant 0{\cdot}38$ and $-16{\cdot}0 \leqslant \delta_2 \leqslant -13{\cdot}0$. The value δ_1 is not supported by the experimental value for A_4. The corresponding Q values are listed in Table 3. The mixing ratio of the 879 keV γ ray is given by δ_2, and its character is M1 $+(99{\cdot}0 \pm 1{\cdot}0)\%$ E2. This value is in good agreement with that obtained by Jaklevic *et al.* (1967).

(d) 197→87 keV Cascade

The angular correlation coefficients for the 197→87 keV cascade given in Table 2 have been corrected for attenuation due to the half-life of the 87 keV level. This cascade follows a spin sequence $4^+(Q,0)2^+(Q)0^+$. Assuming the 87 keV γ ray to be pure E2, the mixing ratio analysis yields for the 197 keV γ ray $0{\cdot}004 \leqslant \delta_1 \leqslant 0{\cdot}06$ and $1{\cdot}30 \leqslant \delta_2 \leqslant 1{\cdot}65$, which give the two values of Q listed in Table 3. The Q_2 value does not agree with the internal conversion measurements (Ewan *et al.* 1961), so that the mixing ratio of the 197 keV γ ray is E2 $+(0{\cdot}2 \pm 0{\cdot}2)\%$ M3.

(e) 962→87 keV Cascade

After correcting for attenuation due to the long half-life of the 87 keV state, the angular correlation coefficients of the 962→87 keV cascade are those given in Table 2. This cascade follows a spin sequence $3^+(D,Q)2^+(Q)0^+$. Assuming the 87 keV γ ray to be pure E2, the mixing ratio analysis of the cascade yields for the 962 keV γ ray the values of Q_1 and Q_2 given in Table 3. The Q_1 value is not in agreement with the internal conversion measurements (Ewan *et al.* 1961), and hence the multipole admixture in the 962 keV γ ray is M1 $+(98 \pm 1)\%$ E2.

(f) 215→962 keV Cascade

The 215→962 keV cascade follows a spin sequence $2^-(D,Q)3^+(D,Q)2^+$. Assuming the 962 keV γ ray to be M1 $+(98 \pm 1)\%$ E2 as determined in subsection (*e*), the mixing ratio analysis of the cascade yields the values of Q_1 and Q_2 for the 215 keV γ ray given in Table 3. The Q_2 value is not supported by internal conversion measurements (Ewan *et al.* 1961), so that the 215 keV γ ray is E1 $+(1{\cdot}5 \pm 0{\cdot}5)\%$ M2 in character.

(g) 299→(879)→87 keV Cascade

The 299→(879)→87 keV cascade is a 1→3 cascade, with the 879 keV γ ray as the unobserved transition. The experimental angular correlation coefficients for such a cascade are given by

$$A_{kk}(\exp) = A_k^{(1)}\, U_k(\text{unobs})\, A_k^{(3)},$$

where $k = 2$ or 4. The values of the coefficients U_k for the 879 keV γ ray were taken from the tables of Rose and Brink (1967). The spin sequence for the cascade is $2^- \rightarrow (2^+ \rightarrow 2^+) \rightarrow 0^+$. Assuming the 87 keV γ ray to be pure E2 and the 879 keV γ ray to be M1 $+(99 \cdot 0 \pm 1 \cdot 0)\%$E2 (subsection *c*), the mixing ratio analysis of the 299 keV γ ray yields the Q values given in Table 3. The Q_2 value is not compatible with the internal conversion measurements (Ewan *et al.* 1961), and therefore the 299 keV γ ray is E1 $+(1 \pm 1)\%$M2. This result is in good agreement with that derived in subsection (*a*).

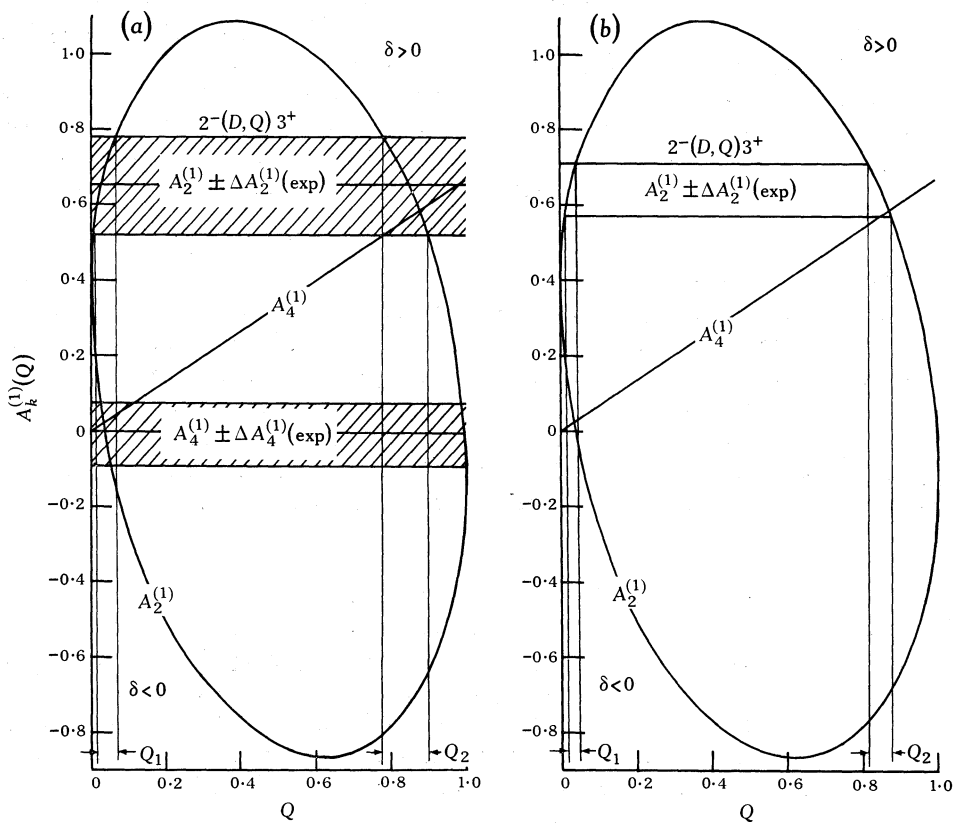

Fig. 2. Experimental angular correlation coefficients $A_k^{(1)}(Q)$ for determining multipole mixing in the 215 keV transition from the analysis of (*a*) the 215→(962)→87 and (*b*) 215→(765)→197 keV cascades.

(h) 215→(962)→87 keV Cascade

The measurement of the angular correlation of the 215→(962)→87 keV cascade was attempted for the first time. The angular correlation coefficients, after correcting for the attenuation due to the half-life of the 87 keV state are as given in Table 2. The cascade follows the spin sequence $2^- \rightarrow (3^+ \rightarrow 2^+) \rightarrow 0^+$ and is a 1→3 cascade, with the 962 keV γ ray as the unobserved transition. The coefficients U_k for the 962 keV transition were taken from the tables of Rose and Brink (1967) assuming the 962 keV γ ray to be M1 $+(98 \pm 1)\%$E2 in character (subsection *e*). Assuming the 87 keV γ ray to be pure E2, the mixing ratio analysis of the cascade yields the values of Q for the 215 keV γ ray given in Fig. 2*a*. The Q_2 value is not supported by the value of $A_4^{(1)}$(exp) as well as internal conversion measurements (Ewan *et al.* 1961). Therefore the 215 keV γ ray is E1 $+(2^{+4}_{-2})\%$ M2 in character. This result is in good agreement with the values derived in subsection (*f*) and subsection (*j*) below.

(i) 299→(682)→197 keV Cascade

The 299→(682)→197 keV cascade is a 1→3 cascade, with the 682 keV γ ray as the unobserved transition. The coefficients U_k for the 682 keV transition in this cascade were determined from the table of Rose and Brink (1967) assuming the 682 keV γ ray to be pure E2 in character. The transition follows the spin sequence $2^- \to (2^+ \to 4^+) \to 2^+$. Assuming the 197 keV γ ray to be E2 $+(0\cdot2\pm0\cdot2)\%$ M3 in character, as found in subsection (*d*), the mixing ratio analysis yields the Q values given in Table 3 for the quadrupole content of the 299 keV transition. The Q_2 value is not in agreement with internal conversion measurements (Ewan *et al.* 1961). Therefore the mixing ratio of the 299 keV γ ray is E1 $+(6\pm3)\%$ M2.

(j) 215→(765)→197 keV Cascade

The measurement of the angular correlation of the 215→(765)→197 keV cascade was attempted for the first time. Assuming a spin sequence of $2^- \to (3^+ \to 4^+) \to 2^+$ for the cascade and an E2 $+(0\cdot2\pm0\cdot2)\%$ M3 admixture for the 197 keV γ ray, and with the coefficients U_k for the 765 keV γ ray taken from Rose and Brink (1967) assuming this γ ray to be pure E2, we obtained the Q values for the 215 keV transition that are given in Table 3. The Q_2 value is not supported by internal conversion measurements (Ewan *et al.* 1961). Hence the 215 keV transition is E1 $+(2\cdot5^{+1\cdot5}_{-1\cdot0})\%$ M2 in character (Fig. 2*b*). This is in good agreement with results obtained in subsections (*f*) and (*h*).

Thus, in summary, our measurements for the relative intensities of γ rays in ^{160}Dy are found to be in good agreement with those obtained by Ludington *et al.* (1968). We have established the multipolarities of the 197, 215, 299, 879 and 962 keV γ rays to be E2 $+(0\cdot2\pm0\cdot2)\%$ M3, E1 $+(2\cdot5^{+1\cdot5}_{-1\cdot0})\%$ M2, E1 $+(2^{+4}_{-2})\%$ M2, M1 $+ (99\pm1)\%$ E2 and M1 $+(98\pm1)\%$ E2 respectively.

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