Gamma-Gamma Directional Correlations in the Decay of Tb^{160}

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Gamma-gamma directional correlation measurements have been made in the decay of Tb^{160}–Dy^{160}, for the cascades, 87–197 keV, 87–877 keV, 87–960 keV, 87–1175 keV, 197–680 keV, 197–1250 keV, and 298–877 keV. The corresponding angular correlation functions obtained are as follows:

$$W(\theta)_{87-197\,\mathrm{keV}}=1+(0.100\pm0.001)P_2(\cos\theta)+(0.0087\pm0.001)P_4(\cos\theta).$$
$$W(\theta)_{87-877\,\mathrm{keV}}=1-(0.092\pm0.001)P_2(\cos\theta)+(0.300\pm0.01)P_4(\cos\theta).$$
$$W(\theta)_{87-960\,\mathrm{keV}}=1-(0.07\pm0.003)P_2(\cos\theta)+(0.0009\pm0.001)P_4(\cos\theta).$$
$$W(\theta)_{87-1175\,\mathrm{keV}}=1+(0.133\pm0.04)P_2(\cos\theta)+(0.0700\pm0.012)P_4(\cos\theta).$$
$$W(\theta)_{197-680\,\mathrm{keV}}=1+(0.200\pm0.002)P_2(\cos\theta)+(0.089\pm0.001)P_4(\cos\theta).$$
$$W(\theta)_{197-1250\,\mathrm{keV}}=1+(0.09\pm0.001)P_2(\cos\theta)-(0.152\pm0.002)P_4(\cos\theta).$$
$$W(\theta)_{298-877\,\mathrm{keV}}=1-(0.126\pm0.02)P_2(\cos\theta)-(0.008\pm0.01)P_4(\cos\theta).$$

INTRODUCTION

THE Tb^{160} nucleus decays with a half-life of 73 days,[1,2] through beta disintegration to the excited states of Dy^{160}. Cork *et al.*[3] first resolved the beta spectrum into two components with energies 546 and 882 keV; later Benson *et al.*[4] resolved the same into three components with energies 860, 521, and 396 keV. Subsequently the same spectrum was shown to consist of four beta groups[1] of allowed shapes with energies 851, 557, 461, and 280 keV. Clark and Knowles[5] observed three beta groups with energies 560, 860, and 170 keV. Nathan[6] obtained four beta groups with end-point energies 555, 575, 870, and 1765 keV with relative intensities 22, 42, 36, and 0.4, respectively. These four beta groups give rise to the 1358-, 1264-, 966-, and 865-keV excited states of Dy^{160}. Many investigators[6–12] studied gamma rays from this source and the energies of these radiations obtained were 1270, 1175, 960, 877, 766, 680, 393, 298, 215, 197, and 87 keV.

Ofer[7] made angular correlation studies of the excited levels of Dy^{160} and expressed some doubt regarding the conclusions drawn by Bertollini *et al.*[8] in this direction. Arns *et al.*[9] investigated the cascade 1076–196 keV and discussed the postulate of attenuation suggested previously. In the present investigation, a detailed study of all the cascades in this isotope by the gamma-gamma angular correlation method is undertaken.

EXPERIMENTAL TECHNIQUE

The experimental setup used in the present investigation is a slow-fast–type triple coincidence scintillation spectrometer with NaI(Tl) scintillators coupled to Dumont 6292 photomultipliers. The fast channel consists of an EFP 60 transient amplifier limiter connected to a Bell-Graham-Petch type of fast coincidence unit; the coincidence output is connected to an amplifier and the amplified pulse is given to the triple coincidence unit. The slow channel consists of an OC170 transistor emitter follower coupled to a Beva model 155 non-overload amplifier. The amplified pulse is fed to a single-channel analyzer, the output pulse from which is fed to the triple coincidence unit. The time resolution of the spectrometer is 60 nsec.

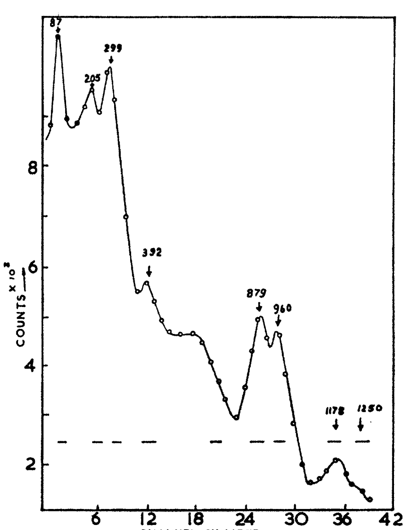

FIG. 1. Gamma spectrum of Tb^{160}.

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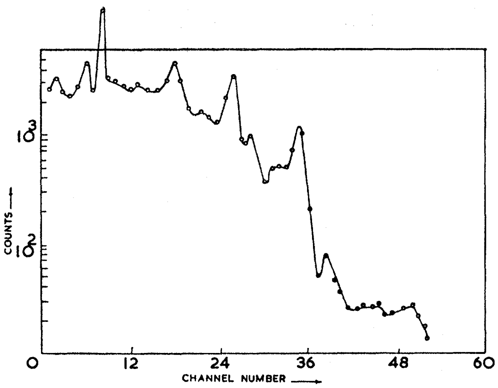

FIG. 2. Coincidence spectrum with 87-keV gamma component.

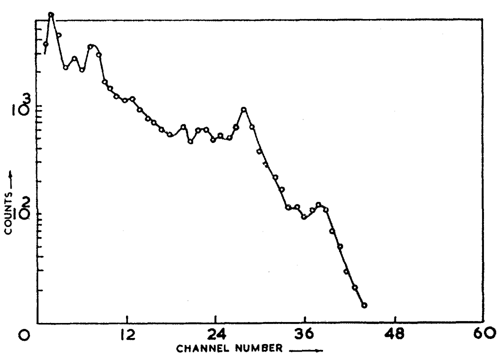

FIG. 3, Coincidence spectrum with 197-keV gamma radiation.

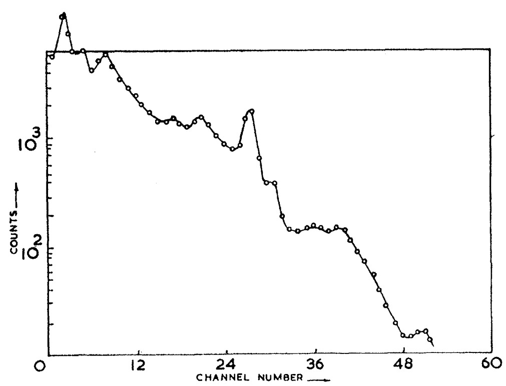

FIG. 4. Coincidence spectrum with 298-keV gamma ray.

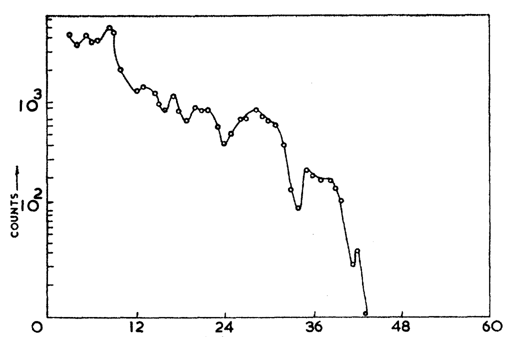

FIG. 5. Coincidence spectrum with 510-keV Compton peak.

RESULTS

The gamma-ray spectrum obtained in the present investigation is shown in Fig. 1. The gamma components with energies 87, 197, 298, 500, 877, 960, 1175, and 1250 keV are resolved in this spectrometer.

The coincidence spectra obtained by setting one of the peaks fixed in one channel and the other scanned over the entire energy region are observed as shown in Figs. 2 to 9. It can be seen that the 87-keV gamma component is in coincidence with nearly all the radiations. The 197-keV gamma ray is coincident with 87-, 298-, 960-, and 1250-keV gamma rays; of these the coincidence with the 960-keV component is very prominent. The 298-keV gamma component has coincidences at 640 and 760 keV in addition to the prominent peak at 960 keV. Figure 5. shows the coincidence spectrum with the fixed channel set at the center of the 500-keV broad peak; the coincidences show a broad peak that covers the 877- and 960-keV radiations. The 500-keV peak can be considered as the Compton peak arising from the 877- and 960-keV gamma rays. The 877-keV component is in coincidence with 393-, 298-, and 87-keV radiations while no peak is observed at 200 keV. The 1175-keV gamma ray is in coincidence with 87- and 197-keV gamma components. The 1250-keV gamma component is in coincidence with 87-, 197-, and 298-keV gamma rays.

On the basis of the data mentioned above, a level scheme is drawn and is shown in Fig. 14. Ofer[7] obtained the coincidence spectrum with the 87-keV gamma ray focused in one channel; from his coincidence study he showed that the 970-keV gamma component is not in coincidence with the 87-keV gamma ray while others[6,10] indicated coincidences with the same. The 197-keV (Fig. 3) radiation has a coincidence peak at 1250 keV, suggesting an excited level at 1550 keV. In the coincidence spectrum with 298 keV (Fig. 4) a peak is obtained at 680 keV, while in the singles spectrum this peak is not resolved. A similar peak coincident with 197 keV is observed at 263 keV in Fig. 3; this cascade can be explained by the inclusion of the 215-keV gamma ray within the gate set for 197 keV. The broad peak obtained in the region of 500 keV (Fig. 1) may be attributed to the Compton peak of the intense radiations at 877 and 960 keV.

The 87–197-keV cascade has been studied for angular correlation and the correlation function $W(\theta)$ obtained after making the least-squares analysis and employing an angular resolution correction is

$$W(\theta)_{87-197\text{ keV}} = 1 + (0.100\pm0.001)P_2(\cos\theta) + (0.0087\pm0.001)P_4(\cos\theta).$$

The values of the theoretical angular correlation coefficients for the $4(Q)2(Q)0$ sequence are 0.102 for A_2 and 0.0091 for A_4. The experimentally obtained values are slightly below the theoretically computed values. This discrepancy may be attributed to the presence of the

216-keV gamma component in the unresolved peak at 197 keV.

Then the 87–877-keV cascade is investigated for angular correlations in order to verify the spin assignment of the first excited level. The correlation function $W(\theta)$ obtained in this case is

$$W(\theta)_{87\text{–}877\text{ keV}}=1-(0.092\pm0.001)P_2(\cos\theta)+(0.030\pm0.01)P_4(\cos\theta).$$

Similarly the 87–960-keV cascade is studied for angular correlations, and the correlation function after applying the necessary corrections is

$$W(\theta)_{87\text{–}960\text{ keV}}=1-(0.07\pm0.003)P_2(\cos\theta)+(0.0009\pm0.001)P_4(\cos\theta).$$

The 87–1175-keV cascade correlation yields the correlation function

$$W(\theta)_{87\text{–}1175\text{ keV}}=1+(0.133\pm0.04)P_2(\cos\theta)+(0.07\pm0.12)P_4(\cos\theta).$$

The gate of the first spectrometer is set to accept the 197-keV gamma ray, whereas the other is scanned in the region of 680 keV setting this gate at maximum coincidences. With this arrangement the angular correlation of the cascade 197–680 keV is investigated and the correlation function obtained is

$$W(\theta)_{197\text{–}680\text{ keV}}=1+(0.200\pm0.002)P_2(\cos\theta)+(0.089\pm0.001)P_4(\cos\theta).$$

From the level scheme (Fig. 10) it can be seen that the 215-keV transition is neither in coincidence nor in cascade with the 680-keV gamma ray.

The 197-keV gamma component is studied for angular correlations with the other channel fixed at the coincidence peak observed over the 1250-keV region. The correlation function $W(\theta)$ obtained in this case is

$$W(\theta)_{197\text{–}1250\text{ keV}}=1+(0.126\pm0.02)P_2(\cos\theta)-(0.008\pm0.01)P_4(\cos\theta).$$

The correlation functions given above are plotted versus the angle subtended between the movable detector and the fixed one, and the respective plots are given in Figs. 10 and 11.

DISCUSSION

The 1765-keV energy beta disintegration from Tb^{160} gives rise to the 87-keV level of Dy^{160}. It may be pointed out that this intense 87-keV gamma ray is in coincidence with all other gamma radiations. This situation may be considered as arising out of the transition from the first excited state at 87 keV.[6–10] The angular correlation measurements are carried out for the cascades 87–197, 87–877, 87–960, and 87–1175 keV in order to assign the spin of this level and the multipolarity of the transition from it. The angular correlation study of the 87–197-keV cascade gives the value of 0.1±0.001 for A_2 and

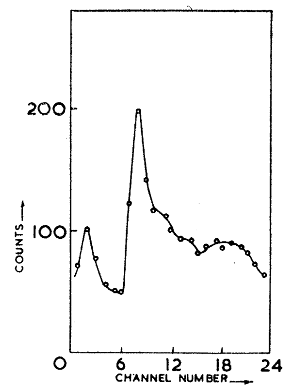

FIG. 6. Coincidence spectrum with 877-keV gamma radiation.

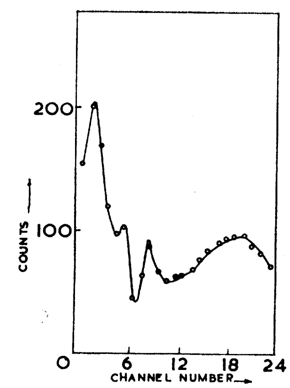

FIG. 7. Coincidence spectrum with 960-keV gamma component.

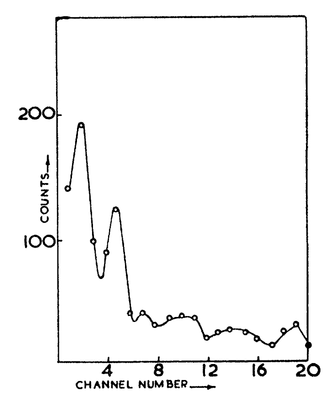

FIG. 8. Coincidence spectrum with 1178-keV gamma ray.

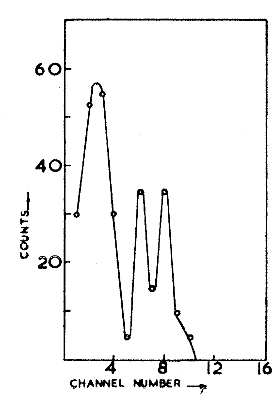

FIG. 9. Coincidence spectrum with 1250-keV gamma component.

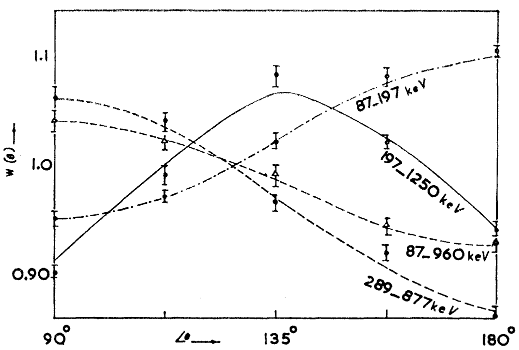

FIG. 10. Plots of $W(\theta)$ versus 'θ' for the cascades 87–197, 197–1250, 87–960, and 289–877 keV.

0.0087 ± 0.001 for A_4; these correlation coefficients can be said to follow the sequence $4(Q)2(Q)0$. The slight discrepancy between the experimental and theoretical values may be attributed to the interference of the 216-keV gamma component on the unresolved 197-keV peak. The 877-keV gamma component is a transition from the 964-keV level to the 87-keV level. The observed cascade 877–87 keV provides information on the 87-keV level. The 960–87-keV cascade interferes with the 877–87-keV cascade and the experimental values of A_2 and A_4 corrected for this interference are obtained

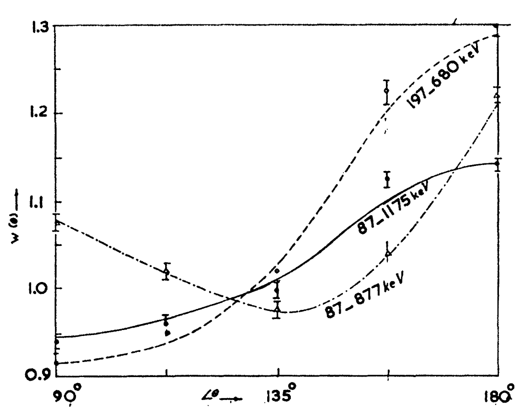

FIG. 11. Plots of $W(\theta)$ versus 'θ' for the cascades 197–680, 87–1175, and 87–877 keV.

as $A_2=-(0.092\pm0.001)$ and $A_4=+(0.30\pm0.01)$. It may be pointed out that the negative A_2 and large positive A_4 are the characteristics of $2(DQ)2(Q)0$ sequence with a quadrupole admixture of 18% in the 877-keV radiation as can be seen from Fig. 12. The 960-keV gamma ray arises out of the transition from the 1047-keV level to the 87-keV level. The angular correlation study of the 960–87-keV cascade after applying the corrections gives for the correlation coefficients the values $-(0.07\pm0.003)$ for A_2 and $+(0.0009\pm0.001)$ for A_4. Here the small A_4 and negative A_2 are the characteristics of the sequence $3(D)2(Q)0$. The slight discrepancy in the values can be explained as due to a small (1%) admixture of quadrupole in the 960-keV transition. From this cascade it can be established that the spin of the 87-keV level is 2 units and this is the case for the excited states of all even-even nuclei.

With a view to assigning the spin of the 284-keV level, the gamma components that are in cascade with the 197-keV gamma ray are studied for angular correlations. The cascades studied are 87–197, 197–680, and 197–1250 keV. The 87–197-keV cascade follows the

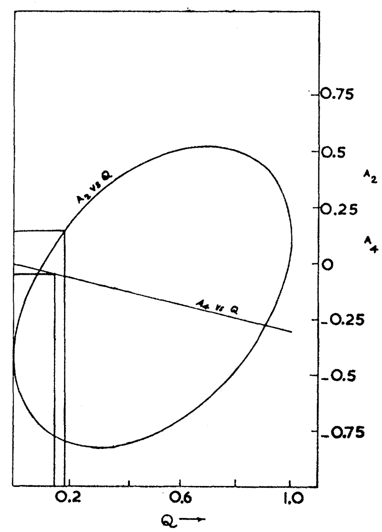

FIG. 12. Multipole admixture plot for the 877-keV transition.

sequence $4(Q)2(Q)0$ as already mentioned. The cascade 197–680 keV follows the $2(Q)4(Q)2$ sequence for which the experimental coefficients are $A_2=+(0.2\pm0.002)$ and $A_4=+(0.089\pm0.001)$ and the corresponding theoretical values are $A_2=+0.204$ and $A_4=+0.0926$. The 197–763 keV cascade is not attempted for angular correlation study since the transition above 763 keV is 216 keV and the one below is 197 keV, and these two gamma rays are not sufficiently resolved in the present

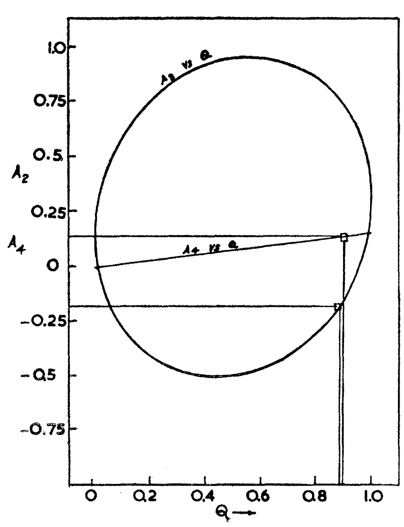

FIG. 13. Multipole admixture plot for the 1250-keV transition.

spectrometer. Since the two cascades 216–763 and 197–763 keV interfere with one another to a considerable extent, an angular correlation study on any one of these could not be performed.

The 1250-keV gamma component is of the highest energy in the spectrum and it is partially resolved from the 1175-keV peak. The gate of the channel that accepts the 1250-keV gamma ray is set from the peak of this gamma component towards the high-energy side of the spectrum as can be seen from Fig. 1. The 1175-keV gamma ray is not in coincidence with the 197-keV gamma ray. The correlation coefficients obtained experimentally for the 197–1250-keV cascade are $A_2=+(0.09\pm0.001)$ and $A_4=-(0.152\pm0.002)$. From the large negative value of A_4, the sequence may be of the type $3(DQ)4(Q)2$. When analyzed for multipole admixture in the 1250-keV transition, it resulted in 90% quadrupole content in the same as can be seen from the Fig. 13. From these considerations a spin of 4 units is assigned to the second excited level of Dy^{160} at 284 keV.

From the angular correlation study of the 298–877-keV cascade the spin of the 964-keV level can be assigned. The cascade 298–877 keV has for its correlation coefficients. $A_2=-(0.126\pm0.002)$ and $A_4=-(0.008\pm0.01)$. The large negative A_2 and vanishingly small A_4 values are the characteristics of a $2(DQ)2(DQ)2$ sequence. The experimentally obtained angular correlation coefficients A_2 and A_4 for the cascade 960–87 keV are $A_2=-(0.07\pm0.003)$ and $A_4=+(0.0009\pm0.001)$. After making the necessary corrections for the interference from the 877-keV gamma ray a $3(D)2(Q)0$ sequence is suggested, and the slight discrepancy in the values of the coefficients obtained theoretically and experimentally may be attributed to a small admixture of quadrupole content in the 960-keV transition. A spin of 3 units is assigned to the level at 1047 keV.

From the weak 1250–197-keV cascade observed, it can be seen that a $3(DQ)4(Q)2$ sequence is probable from which a spin of 3 units may be assigned to the level at 1550 keV. The measurement of the energy of the 1250-keV gamma ray by the scintillation spectrometer is not accurate enough. There is a possible identity of this gamma ray with that arising from the 1565-keV level in the study of Dy^{160} from the decay of Ho^{160}. However, from a study of the beta groups from Tb^{160} employing magnetic spectrographs[1] it is suggested that there exists a level at 1565 keV in Dy^{160}. Similarly another group[13] investigated and reported a beta component which might result in an excited level at 1565 keV in Dy^{160}. Michealis[14] reported a level at 1550 keV which is exactly the value obtained in the present investigation. In the present investigation a spin of 3 units is assigned to this level at 1550 keV from angular correlation data. The reported[15,16] level at 1565 keV in the decay of Ho^{160} is identified with the level at 1550 keV observed in the present investigation.

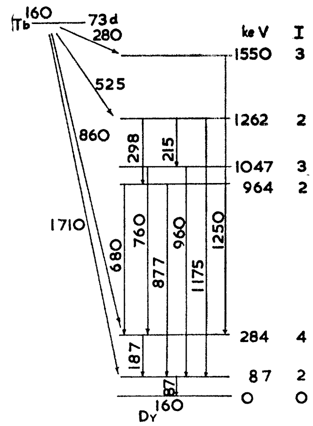

FIG. 14. Decay scheme of Tb^{160}.

The final decay scheme with spins and multipolarities is shown in Fig. 14. The first 0, 2, 4 levels comprise the $K=0$ ground-state rotational band, and the levels 2 and 3 at 964 and 1047 keV are the members of the $K=2$ vibrational band.

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