DIRECTIONAL CORRELATION MEASUREMENTS OF THE GAMMA RAYS

EMITTED IN THE DECAY OF ^{160}Tb

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Directional Correlation Measurements of the Gamma Rays

Emitted in the Decay of ^{160}Tb

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Abstract: The decay of ^{160}Tb to levels in ^{160}Dy has been investigated by measuring the gamma-gamma directional correlations using two 30 cc coaxial Ge(Li) detectors in conjunction with multichannel coincidence and routing apparatus. A detailed analysis was performed in order to correct for the effects on the measured correlations of Compton-scattered radiation. The result of the sixteen measured directional correlations served to verify the current spin assignments, and in addition yielded values for the E2/M1 and M2/E1 multipole mixing ratios of the gamma transitions, given in terms of explicitly defined reduced matrix elements. Values obtained for the mixing ratios $\delta(\gamma)$ are (energies in keV): $\delta(215) = -0.18 \pm 0.10$, $\delta(299) = +0.005 \pm 0.010$, $\delta(392) = +0.005 \pm 0.070$, $\delta(765) = - (7 \pm \frac{20}{5})$, $\delta(879) = -13.5 \pm 3.0$, $\delta(962) = -18.0 \pm 5.0$, $\delta(1178) = 0.02 \pm 0.02$, $\delta(1272) = -0.03 \pm 0.03$. The results are discussed in terms of collective rotational nuclear motion.

E

RADIOACTIVITY ^{160}Tb ; measured $\gamma\gamma(\theta)$. ^{160}Dy
deduced J, $\delta(\text{E2/M1})$, $\delta(\text{M2/E1})$.

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1. Introduction

The energy level scheme of the excited states of ^{160}Dy populated by the beta-decay of ^{160}Tb (72 days) has been well established through the efforts of a number of investigators¹⁻¹¹). The results of such measurements have led to the interpretation of the levels of ^{160}Dy in terms of collective rotations about a permanent equilibrium deformation. In particular, members of the ground-state rotational band and of the γ -vibrational band have been identified in support of this interpretation, along with a number of negative parity levels.

Although angular correlation measurements of gamma rays emitted in the decay of ^{160}Tb have been reported^{2,3,6-9}), the advent of large-volume, high-resolution Ge(Li) gamma detectors has permitted a more accurate investigation of the ^{160}Dy gamma rays. In particular, gamma-gamma directional correlation measurements yield information concerning the multipole admixtures present in the gamma transitions, which in turn provide information as to the details of the structure of the states involved in the transitions. High-resolution measurements allow the determination of the multipole mixing ratios with much greater accuracy than was possible using NaI(Tl) detectors; thus one can determine the magnitude of small multipole admixtures in the radiation field.

In the collective interpretation, transitions between members of the $K = 2$ γ -band and the $K = 0$ ground-state band must be of an electric quadrupole (E2) nature, and the existence of small magnetic dipole (M1) components is an indication that other effects may enter into the structure of the states involved. On the other hand, the uniqueness of the assignment

of the K quantum number to the negative parity levels (particularly in the case of $K = 2^-$) would be indicated by the observation of retarded $E1$ -components and enhanced $M2$ -components, in transitions for which both multipoles are allowed by angular momentum selection rules.

In order to measure accurately the $E2/M1$ and $M2/E1$ multipole mixing ratios of transitions following the decay of ^{160}Tb , γ - γ directional correlations have been measured, and the results are presented in terms of explicitly defined reduced matrix elements.

2. Decay scheme of ^{160}Tb

The decay scheme of ^{160}Tb to levels in ^{160}Dy is shown in fig. 1. The existence of the lower collective levels was established by early spectroscopic investigations ^{1,2}), and directional correlation measurements ^{2,3}) served to verify the spins of the lowest three members of the ground-state rotational band, the two lowest members of the γ -band, and additional negative parity levels at 1264 keV (2^-) and 1358 keV (2^- , originally identified as 3^-). An additional pair of states of spins 3^- were established by coincidence measurements at 1287 keV and 1399 keV ^{4,6}). The 4^+ member of the γ -band (1155 keV) and a 4^- state at 1386 keV have also been reported ⁵). High-resolution measurements ¹²) of the complex decay scheme of ^{160}Ho to ^{160}Dy have identified states of the ground-state band and the γ -band up to 6^+ , two members of the β -band, and a number of negative parity states, as well as a plethora of additional rotational bands built on various modes of excitation. The existence of the 6^+ state of the ground-state band and the 5^- level at 1408 keV have been confirmed by

inelastic deuteron scattering ¹³). Levels not observable from the decay of ¹⁶⁰Tb have been included in fig. 1.

The interpretation of the states of the ground-state band ($K = 0$) and the γ -band ($K = 2$) are well known on the basis of the systematics of rotational levels in deformed nuclei. Such an interpretation predicts that M1 radiation is strictly forbidden to exist in transitions from the γ -band to the ground-state band, since the radiation must carry away two units of angular momentum projection along the nuclear symmetry axis. The existence of small M1 admixtures indicates additional interactions entering into the structure of these levels. In addition, the deviations from the rotational $I(I+1)$ -rule for the spacings of the energy levels are considerable; successful attempts have been made to calculate the energy levels of these two bands from the asymmetric rotor model ¹⁴) and from the rotational-vibrational coupling model ¹⁵), and reasonably good agreement has been obtained for the energy levels and for E2 transition rates. However, the calculation of small M1 transition probabilities is highly sensitive to the degree of approximation used in the calculation, and thus such calculations are difficult at best.

It has been calculated by Gallagher and Soloviev ¹⁶) that the lowest two-quasiparticle states in ¹⁶⁰Dy occur at about 1.4 MeV of excitation, with two rotational bands having $K^\pi = 1^-$ and 2^- built on a pair of states at that excitation energy; thus it is unlikely that such effects enter into the structure of the 2^+ and 3^+ states of the γ -band considered in this work, which occur at about 1 MeV above the ground state. This tends to support the collective interpretation for the positive parity states.

The interpretation of the negative parity levels is considerably more difficult. The collection of these levels can be grouped into two bands, built on the 1^- state at 1285 keV and the 2^- state at 1264 keV, but the energy spacing of the states of these bands precludes their interpretation as rotational bands, since they deviate considerably from the $I(I+1)$ rule. Calculations of reduced E1 transition probabilities from these states to the positive-parity states of the γ -band and ground-state band have indicated an unambiguous assignment of $K = 2$ to the 1264 keV state, while a unique assignment for the other states is not possible^{9,10}). On this basis the $2^- - 2^+$ transition from the 1264 keV state to the ground-state band ($\Delta K = 2$) might be expected to show an enhancement of the M2 component relative to the E1 component; in the absence of collective effects, such M2 admixtures are vanishingly small.

The propinquity of the two negative-parity bands indicates a strong possibility of interference between the states of these bands. Günther, Ryde, and Krien¹⁷) have considered Coriolis coupling of $K = 0, 1$, and 2 bands, and obtained good agreement with the observed energy levels of the negative-parity states. The calculation of Gallagher and Soloviev¹⁶) justifies the occurrence of the 1^- and 2^- bands as two-quasiparticle excitations, although at a somewhat higher energy, and the inclusion of the 0^- octupole band improves the calculation for the odd-spin levels.

It should be noted that any interpretation which allows the inclusion of a $K = 1$ component into the negative-parity states would lead to a prediction of a normally strongly forbidden M2 component in $2^- - 2^+$ transitions to both the γ -band and the ground-state band.

3. Experimental procedure

Radioactive ^{160}Tb was obtained from Nuclear Equipment Chemical Corporation in the form of TbCl_3 in HCl solution, and a source of approximately 30 μCur strength was prepared in a glass cylindrical ampule of approximately 1.5 mm diameter and 8 mm length.

Two coaxial $\text{Ge}(\text{Li})$ detectors were employed for the directional correlation measurements; the coincidence circuitry used a time-to-amplitude converter system having a resolving time of approximately 50 nsec. The apparatus has been described in a previous paper¹⁸). In order to correct for coincidences arising from the considerable amount of Compton-scattered radiation lying beneath the gamma peaks of interest, spectra were accumulated in coincidence with the gamma peak (including the background under the peak) and with the Compton background distribution. The point-by-point subtraction of the two spectra allowed extraction of coincidence events that are caused by the gamma peak only; integration of such events over peaks of interest in the spectrum allowed the measurement of the directional correlations by accumulating such spectra at various angles between the detectors. (Such a measurement is referred to as an indirect measurement, as opposed to a direct measurement, which consisted of the direct counting of coincidences between two gamma transitions that are selected by single channel analyzers).

Indirect measurements were performed at 90° , 135° , 180° , and 210° , with spectra accumulated in a Victoreen SCIPP 1600 - channel analyzer. Direct measurements were made at nine angles between 90° and 270° . Corrections were made for chance coincidences and for effects of Compton -

scattered radiation, and a least-square fit of the coincidence counting rates $W(\theta)$ was performed to a sum of Legendre polynomials P_Λ of the form:

$$W(\theta) = \sum_{\Lambda=0}^{\Lambda_{\max}} A_{\Lambda\Lambda} Q_{\Lambda\Lambda} G_{\Lambda\Lambda} P_\Lambda(\cos \theta) \quad (1)$$

in which only even values of Λ are allowed and $\Lambda_{\max} = 4$ for the transitions considered in this work. The directional correlation coefficients $A_{\Lambda\Lambda}$ are defined in terms of the mixing ratio δ in a previous paper¹⁸⁾. The mixing ratio for quadrupole - dipole transitions is defined in terms of Bohr and Mottelson¹⁹⁾ emission matrix elements:

$$\delta(\gamma_n) = \pm k_n \frac{\sqrt{3}}{10} \frac{\langle I_{n+1} \| \mathfrak{M}(\pi' 2) \| I_n \rangle}{\langle I_{n+1} \| \mathfrak{M}(\pi 1) \| I_n \rangle} \quad (2)$$

for a mixed quadrupole - dipole transition γ_n of energy k_n (in natural units $\hbar = m_e = c = 1$), in which the lowest - order multipole has character π (electric or magnetic) and the next allowed multipole has character π' . The + sign is employed in the E2/M1 case, and the - sign for mixed M2/E1 radiation. The geometric correction factors $Q_{\Lambda\Lambda}$ were applied to correct for the finite angular resolution of the detectors and for the finite size of the source¹⁸⁾.

The attenuation coefficients $G_{\Lambda\Lambda}$ which describe the effects of extranuclear perturbations constitute an important correction to the data, and an accurate knowledge of these coefficients is necessary to achieve an accurate extraction of the mixing ratio²⁰⁾. It is expected that the effects of external perturbations would be considerable on the 87 keV state,

due to the long lifetime of that state (2 nsec), and that perturbations of the other states involved in the measurement would be negligible. The source of this perturbation was expected to be the interaction of the nuclear electric quadrupole moment with the electric field gradient in the liquid sources used, and in addition the interaction of the nuclear magnetic dipole moment with the large paramagnetic field due to the unfilled 4f-electron shell of the dysprosium atom. The coupling of these two modes of interaction is not clear, and since the relative magnitudes of the interactions cannot be determined, it was not possible to calculate the factors $G_{\Lambda\Lambda}$. It was thus necessary to rely on empirical methods to determine them, by measuring correlations having known coefficients and comparing the measured value with the expected value. The $4^+ - 2^+ - 0^+$ correlation was used to determine G_{22} and the $2^{+1} - 2^+ - 0^+$ correlation to obtain an estimate of G_{44} .

An additional factor which tended to distort the measured results was the influence of radiation scattered from one detector to the other. This factor becomes especially significant when a crossover transition competes with a $\gamma - \gamma$ cascade under investigation, and when one of the gamma rays of the cascade has an energy in the neighborhood of 200 - 300 keV. In this case, the radiation backscattered by one detector gives rise to spurious coincidences having a strongly anisotropic angular distribution when it is absorbed by the second detector. The placing of lead absorbers blocking a direct path between the detectors eliminated this effect.

4. Results

A singles gamma ray spectrum is shown in fig. 2. The resolution of

the 962 keV - 966 keV doublet was not necessary for the experiment, since the two transitions are in coincidence with none of the same gamma transitions. Indirect measurements were performed by accumulating spectra in coincidence with the 87 keV, 299 keV, 879 keV, 962 keV, and 966 keV transitions. In addition, direct measurements were made on the 879 keV - 87 keV, 299 keV - 966 keV, 299 keV - 879 keV, 1178 keV - 87 keV, and 1272 keV - 87 keV cascades. In several cases, directional correlations having an unobserved intermediate transition were measured; the analysis of such measurements is discussed in Reference 18. The results for the directional correlation coefficients determined from direct and indirect measurements are shown in table 1, along with the mixing ratio $\delta(\gamma)$ derived from each correlation. All applicable corrections have been applied, including the attenuation across the 2 nsec state.

The figures quoted for the error limits of the indirect measurements are based on the inherent statistical uncertainty of each measurement and the errors associated with the subtraction of background events, with the latter the dominant source of error.

The results for the G_{22} and G_{44} coefficients were derived, respectively, from the A_{22} coefficient of the $4^+ - 2^+ - 0^+$ correlation and the A_{44} coefficient of the $2^+ - 2^+ - 0^+$ correlation. Comparing the measured value of the correlation coefficients to the expected value, we obtain:

$$G_{22} = 0.72 \pm 0.17$$

$$G_{44} = 0.64 \pm 0.06$$

These results are in good agreement with those of Günther et al.⁸⁾

($G_{22} = 0.740 \pm 0.020$, $G_{44} = 0.597 \pm 0.025$) for a similar source of TbCl_3 in HCl solution.

The large attenuations observed were due to the nature of the combined electric quadrupole and magnetic dipole interactions acting on the 2 nsec state. Assuming the total interaction to be of a random, time-dependent nature, the coefficients $A_{\Lambda\Lambda}$ are expected to be attenuated in time as $e^{-\lambda_{\Lambda} t}$; the relaxation constants λ_{Λ} may then be derived from the measured time-integrated attenuation coefficients, yielding:

$$\lambda_2 = (0.13 \pm 0.11) \times 10^9 \text{ sec}^{-1}$$

$$\lambda_4 = (0.19 \pm 0.05) \times 10^9 \text{ sec}^{-1}$$

and thus we obtain for the ratio of the relaxation constants

$$\frac{\lambda_4}{\lambda_2} = 1.4 \pm 1.2$$

This value must be compared with the value $\lambda_4/\lambda_2 = 3.3$ for a pure magnetic dipole interaction, and $\lambda_4/\lambda_2 = 0.6$ for a pure electric quadrupole interaction. The measured value lies between these two extremes, and thus it is reasonable to assume that a combination of these two effects is present.

As expected, no perturbations were observed for the higher excited states, since for example, the 2^+ state of the γ -vibrational band has a lifetime of approximately 1 picosecond²¹).

The mixing ratio of the $2^{+'} - 2^+$ transition (879 keV) was determined from the A_{22} -coefficient of the 299 keV - 879 keV correlation; the

large relative error of the A_{22} - coefficient of the 879 keV - 87 keV correlation made the extraction of the mixing ratio from the latter measurement unreliable. Good agreement in both magnitude and sign is obtained with previous work. The present value for $\delta(879)$ is consistent with the results of the 879 keV - 87 keV correlation (with the calculated value $A_{22} = 0.021$) as well as the 299 keV - (879 keV) - 87 keV correlation (calculated $A_{22} = -0.053$). These figures provide a good internal test for the results.

The transitions from each of the two 2^- states to the 2^+ state of the γ - band (299 keV and 392 keV) both show vanishingly small M2 admixtures in the predominantly E1 transitions. However, there is some disagreement with previous results as to the sign of the M2/E1 mixing ratios for these two transitions. In the present work, two independent determinations of this parameter for the 392 keV transition disagree in sign, although the error limits are large enough to allow overlap of the two values.

The analysis of the directional correlation data for the 962 keV transition was difficult because of the substantial corrections it was necessary to apply to the measured coefficients. Since the 962 keV transition could not be completely resolved from the 966 keV transition, the 962 keV - 87 keV directional correlation measurement included a considerable number of chance coincidences due to the 966 keV transition. In addition, it was necessary to correct for the influence of Compton-scattered radiation due to the 299 keV transition; such events accepted in the 87 keV energy window were in coincidence with the 966 keV transition.

The values quoted in table 1 for the directional correlation coefficients include all necessary corrections, and the E2/M1 mixing ratio derived differs in both magnitude and sign from a previous result.

Within the accuracy of the measurement, the anisotropy of the 215 keV - 962 keV correlation is vanishing. This lack of anisotropy can nevertheless allow conclusions to be drawn regarding the multipole admixtures of the 215 keV transition which would give rise to such an effect, assuming the result for $\delta(962)$ measured from the 962 keV - 87 keV correlation. The M2/E1 mixing ratio derived is in excellent agreement with the results of previous work.

The small M2/E1 mixing ratios measured for the high-energy 1178 keV and 1272 keV transitions are likewise in good agreement with the results of previous work. The magnitudes of the present results are somewhat smaller, but the relative phases are identical. The choice of phase is unambiguous, since the 1178 keV transition consistently yielded A_{22} - coefficients below the value for zero mixing of $A_{22} = 0.250$, while those for the 1272 keV transition were consistently above that value.

The E2/M1 mixing ratio for the 765 keV transition has not been measured previously. The measurement is difficult not only due to the low intensity of the 765 keV transition, but also due to its position in the gamma-ray spectrum on the Compton edge of the 962 keV - 966 keV doublet. The gated-spectrum indirect measurement allowed a separation of the events in a peak from those of the Compton background, and thus an unambiguous measurement of the coincidences between the 765 keV transition and the 87 keV transition was possible; however, the relatively low counting rates

and substantial background corrections resulted in poor statistics for this measurement.

The gamma transition at 682 keV is likewise of low intensity, and occurs on the Compton edge of the 879 keV transition. However, its intensity was too low to permit even a gated-spectrum measurement of the angular correlation. In this case it was necessary to analyze this transition as an unobserved intermediate transition between the high-intensity 299 keV and 197 keV transitions. The power of this technique is illustrated by the fact that, even though the 682 keV transition is barely visible in the gamma spectrum, the properties of that transition were measured with a relatively small statistical uncertainty in a measurement which did not involve the detection of the 682 keV transition. The measured correlation coefficients are consistent with the value $A_{22} = 0.140$ for the $E2$ 682 keV transition.

The last three measurements reported in table 1 involve high-energy, low-intensity transitions from the 3^- states. The analysis of the correlation data was unambiguous, but the low intensity was responsible for the large statistical spread of the directional correlation coefficients. The data were all consistent with the 3^- assignments for the 1287 keV and 1399 keV levels. The 1115 keV - (197 keV) - 87 keV angular correlation has an expected directional correlation coefficient of $A_{22} = -0.140$, while each of the $3^- - 2^+ - 0^+$ correlation would be expected to have $A_{22} = -0.072$. These values are within the large experimental uncertainties of the measured values. These large uncertainties made the extraction of $M2/E1$ mixing ratios for these transitions unreliable.

5. Discussion

The directional correlations measured in this work served to verify the accepted angular momentum assignments for the ^{160}Dy excited states^{10,17}). The magnitudes of the E2/M1 and M2/E1 mixing ratios as measured in this work are in qualitative agreement with the predictions of the rotational model. The large E2/M1 mixing ratios of the $2^{+1} - 2^{+}$ and $3^{+} - 2^{+}$ transitions indicate a strong collective nature for these states. The negative phase of the $2^{+1} - 2^{+}$ transition is consistent with the predictions of Greiner²²), as well as with measured results of $2^{+1} - 2^{+}$ transitions in other nuclei, which seem to show a systematic trend toward negative phases. Tamura and Yoshida²³) likewise predict a negative phase, and estimate the value $\delta \sim -10$.

All of the M2/E1 mixing ratios of transitions from the 2^{-} states to the 2^{+} states were determined to be vanishingly small, thus giving grounds for rejecting the $K = 2$ assignment for the 1264 keV state, and supporting the assumption of K-mixing as previously discussed. However, there are no consistent trends either in the phases or magnitudes of the measured M2/E1 mixing ratios of the four $2^{-} - 2^{+}$ transitions. The M2/E1 mixing ratio of the 215 keV transition to the 3^{+} level shows a somewhat larger magnitude, and allows the presence of approximately 4% of the M2 multipole in the primarily E1 transition. In view of the small magnitude of the M2/E1 mixing ratio for the 299 keV transition, which proceeds from the same 2^{-} level to the 2^{+} level of the γ -band, this result seems unusually large. At present, no explanation can be offered for this apparent anomaly.

At the present time calculations of transitions from rotational states built on quasiparticle excitation have not been refined sufficiently to permit the calculation of small $M2$ amplitudes. It is hoped that the present data will prove of value for such calculations.

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TABLE 1

Results of directional correlation measurements of ^{160}Dy gamma transitions

cascade (E in keV)	spin sequence	A_{22}	A_{44}	$\delta(\gamma)$ present work	$\delta(\gamma)$ previous work	
197 - 87	$4^+-2^+-0^+$	0.102 ± 0.025	-0.019 ± 0.038	-	-	
879 - 87	$2^+-2^+-0^+$	0.002 ± 0.017	0.324 ± 0.025	-	-	
299 - 966	$2^--2^+-0^+$	0.246 ± 0.010	-0.017 ± 0.015	$\delta(299) = +0.005 \pm 0.010$	$\delta(299) = +0.029 \pm 0.005$	a)
					$\delta(299) = -0.02 \pm 0.02$	b)
299 - 879	$2^--2^+-2^+$	-0.089 ± 0.011	-0.015 ± 0.017	$\delta(879) = -13.5 \pm 3.0$	$\delta(879) = -(17.7 \pm 2.8)$	a)
					$\delta(879) = -(11 \pm 13)$	b)
299-(879)-87	$2^--(2^+-2^+)-0^+$	-0.056 ± 0.013	-0.012 ± 0.026	-	-	
392 - 879	$2^--2^+-2^+$	-0.095 ± 0.027	-0.019 ± 0.045	$\delta(392) = -0.02 \pm 0.08$	$\delta(392) = +0.023 \pm 0.007$	a)
392 - 966	$2^--2^+-0^+$	0.230 ± 0.033	0.042 ± 0.052	$\delta(392) = +0.03 \pm 0.05$	-	
962 - 87	$3^+-2^+-0^+$	-0.247 ± 0.044	-0.057 ± 0.033	$\delta(962) = -18.0 \pm 5.0$	$\delta(962) = +7.9 \pm 6.1$	b)
					-2.4	
215 - 962	$2^--3^+-2^+$	0.00 ± 0.05	0.00 ± 0.05	$\delta(215) = -0.18 \pm 0.10$	$\delta(215) = -0.199 \pm 0.049$	b)
1178 - 87	$2^--2^+-0^+$	0.232 ± 0.015	-0.007 ± 0.016	$\delta(1178) = +0.02 \pm 0.02$	$\delta(1178) = +0.040 \pm 0.043$	b)
1272 - 87	$2^--2^+-0^+$	0.272 ± 0.020	0.027 ± 0.040	$\delta(1272) = -0.03 \pm 0.03$	$\delta(1272) = -(0.063 \pm 0.086)$	b)
					-0.070	
765-(197)-87	$3^+-(4^+-2^+)-0^+$	0.14 ± 0.10	0.11 ± 0.13	$\delta(765) = -(7 \pm 20)$	-	
					-5	
299-(682)-197	$2^--(2^+-4^+)-2^+$	0.115 ± 0.027	0.047 ± 0.038	-	-	
1115-(197)-87	$3^+-(4^+-2^+)-0^+$	-0.09 ± 0.08	0.02 ± 0.10	-	-	
1200 - 87	$3^--2^+-0^+$	-0.10 ± 0.05	0.03 ± 0.06	-	-	
1312 - 87	$3^--2^+-0^+$	-0.05 ± 0.03	0.02 ± 0.04	-	-	

a) Reference 8

b) Reference 9

Figure captions

Figure 1.

Level scheme of ^{160}Dy populated by the decay of ^{160}Tb .
Numbers in brackets are values of E2/M1 or M2/E1 mixing
ratios measured in the present work.

Figure 2.

Gamma-ray spectrum from the decay of ^{160}Tb , measured
with 30 cc Ge(Li) detector. Transition energies are
indicated in keV.

3- $\frac{72d}{160Tb}$