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Excited Energy Levels in Dy^{160}

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EXCITED ENERGY LEVELS IN Dy^{160}

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Abstract: The transitions and levels of Dy^{160} populated by Tb^{160} beta decay have been investigated by the methods of sum coincidence, gamma-gamma coincidence, angular correlation and polarization-direction correlation. The results confirm the decay scheme proposed by G.T. Ewan *et al.* which differs in the negative parity levels from the schemes reported by other authors. The relative intensities of the gamma rays and the quadrupole admixtures of several transitions are given.

1. Introduction

The level structure of Dy^{160} has been repeatedly investigated by using the beta decay of Tb^{160} (half-life 73 d)[1-11]. The decay of Tb^{160} furnishes sufficient energy to excite states up to 1800 keV in the daughter nucleus. Level schemes have been proposed by Nathan [1]), Ofer [2]), Grigor'ev *et al.* [3]), Bäckström *et al.* [4]) and Ewan *et al.* [5]). On the basis of these works the existence of excited states at 87, 284, 964, 1047, 1262 and 1357 keV as well as the position of the transitions at energies of 87, 197, 215, 298, 393, 680, 763, 877, 960, 964, 1175 and 1270 keV seem to be well established. However, discrepancies still exist as to the relative intensities of several gamma rays and the existence or position of weak transitions observed by some authors at 62, 95, 157, 236, 310, 917, 1003, 1047, 1073, 1113, 1200 and 1310 keV. In various works the internal conversion [1, 3-8]) and the angular correlation of several cascades [2, 9-11]) are investigated. Spins and parities of the excited levels at 87, 284, 964 and 1262 keV seem to be certain as 2^+, 4^+, 2^+ and 2^-. For the 1047 keV level spin 3 and even parity are probable. Up till now it has never been attempted to measure the angular correlation of a cascade which involves this level (e.g. 215 keV-960 keV cascade). For the excited state at 1357 keV all authors but one quote spin 3 and odd parity. Ewan *et al.* [5]) assign spin 2 to this level. Inconsistencies finally exist as to the multipole character of the 877 keV transition. Ofer [2]) found a practically pure quadrupole radiation, whereas Arns [9]) and Klimentovskaya [11]) obtained a mixture of M1 and E2.

The present measurements were undertaken to resolve at least some of the remaining uncertainties in the level scheme of Dy^{160}.

2. Experimental Procedure

The gamma-rays following beta decay of Tb^{160} were studied using sum coincidence and gamma-gamma coincidence techniques. The angular correlation and polarization-direction correlation of cascades were investigated by means of an automatic angular correlation polarimeter. All measurements employed the principle of fast-slow coincidence. The detectors were NaI(Tl) crystals mounted on RCA 6810 A photomultipliers.

The angular correlation polarimeter consists of three scintillation detectors A, B and C. Counters A and B together with the source S define the θ-plane. Both detectors are insensitive to the polarization of the quanta γ_1 and γ_2 emitted in a gamma cascade. Double coincidences between A and B are used to determine the angular correlation $W(\theta)$. Detector A is fixed whereas B (together with C) step by step rotates around S. Counters B and C form a polarization-sensitive detector. C is located at angle ϕ in a plane perpendicular to the axis of B. Part of the photons γ_2 which enter crystal B project a Compton electron in the scintillator, thus producing a signal in this counter. If a scattered quantum γ_2' interacts in crystal C, either by photoelectric effect or another Compton collision, it causes a count in detector C. The differential cross section for Compton scattering $d\sigma_C$ depends upon the angle between the polarization vector and the scattering plane. A measurement of the triple-coincidence counting rate between the three counters A, B and C thus furnishes the polarization-direction correlation $W(\theta, \phi)$. The principle outlined here was successfully applied for the first time by Metzger and Deutsch [12]) for polarization investigations. The apparatus used for the experiments of the present work in two essential respects deviates from that of those two authors. First, it permits to determine simultaneously the polarization-direction correlation and the angular correlation. On the other hand, only the polarization of one of the two multipoles is measured.

Let $I_{\parallel}$ and $I_{\perp}$ be the intensities of linear polarization parallel and perpendicular to the θ-plane; then the polarization properties of the multipole radiation to be investigated can be characterized by the ratio $p = I_{\parallel}/I_{\perp}$. For this reason, it is prudent to measure only the triple-coincidence counting rates $N_{\parallel}$ and $N_{\perp}$ corresponding to (B-C) parallel and (B-C) perpendicular to the plane of the two gamma rays. The ratio $N_{\parallel}/N_{\perp}$ is connected with p by the relation

$$\frac{N_{\parallel}}{N_{\perp}}(\theta) = \frac{p(\theta)+R}{Rp(\theta)+1}, \tag{1}$$

where R, the so-called asymmetry ratio, is a measure of the sensitivity of the polarimeter.

The crystals of detectors A, B and C have the dimensions 3.8 cm × 5.1 cm. Lateral lead shielding of counters A and B is used to prevent counter-to-counter scattering. Detector C is shielded against direct irradiation from the source by an obtuse lead cone. Fig. 1 shows the block diagram of the spectrometer. A detailed description of the apparatus is given elsewhere [13]).

The angular correlation data were fitted by the least-squares method to the function

$$W(\theta) = \sum_{\nu} A_{2\nu} P_{2\nu}(\cos\theta). \tag{2}$$

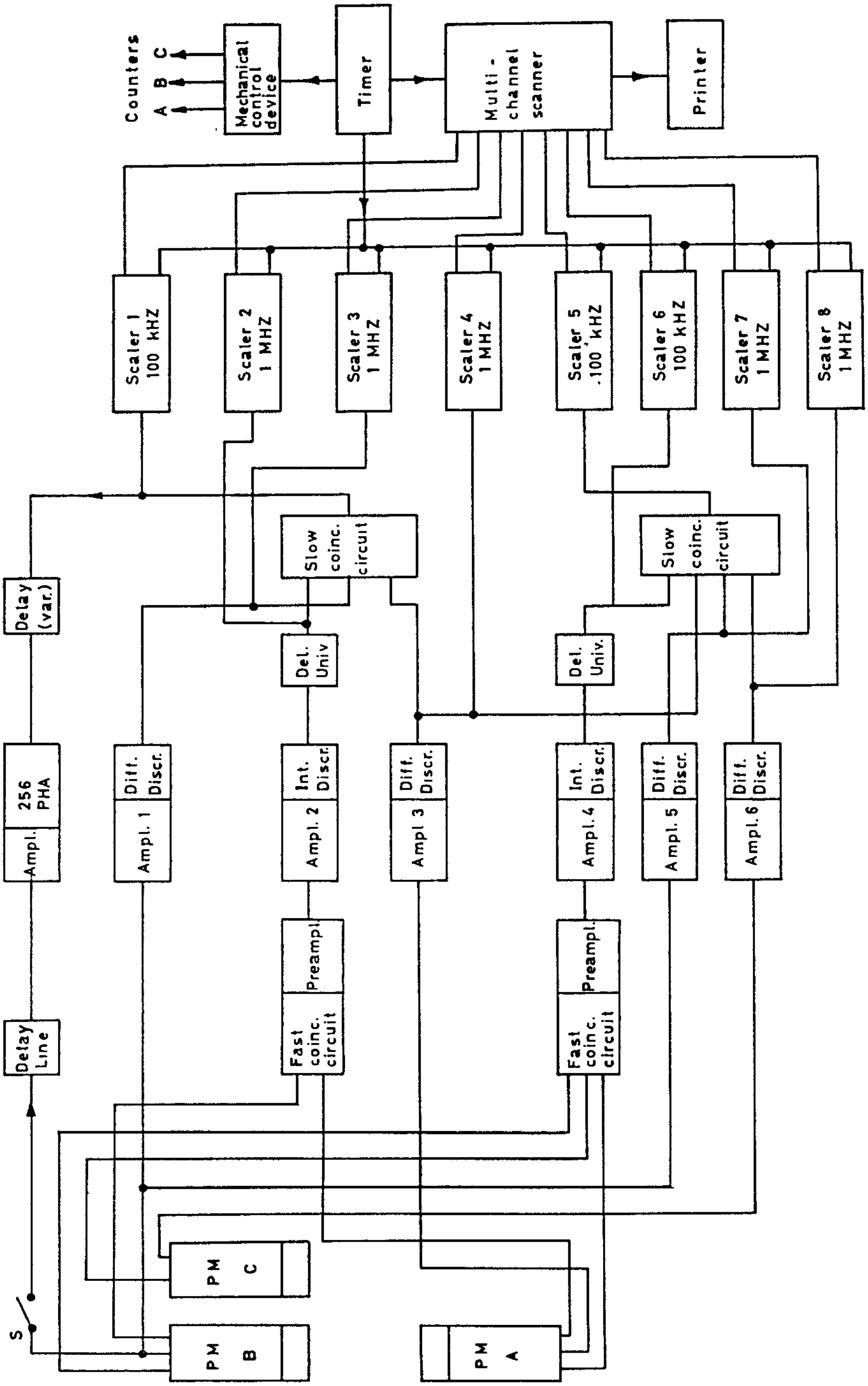

Fig. 1. Block diagram of the angular correlation polarimeter.

The expansion coefficients were corrected for geometrical effects and interactions in the source by a numerical method [14]).

Sum coincidence and gamma-gamma coincidence measurements were performed using the A-B fast-slow coincidence circuit of the angular correlation polarimeter. The resolving time was selected to 12 nsec. A Compton shield of 4 mm thick lead surrounded by 0.5 mm cadmium and 0.5 mm copper was placed between the detectors.

Sources were prepared from Tb-oxide powder of 99.9 per cent purity and irradiated in the Munich research reactor. For the angular correlation and polarization experiments the terbium oxide was treated with hot concentrated HCl over a longer period of time, and the solution was then diluted. No impurity activities were found to be present in the sources.

3. Results

3.1. COINCIDENCE MEASUREMENTS

A total of 26 sum coincidence and gamma-gamma coincidence measurements was carried out. The most significant spectra are shown in figs. 2 to 4 and will be briefly discussed here.

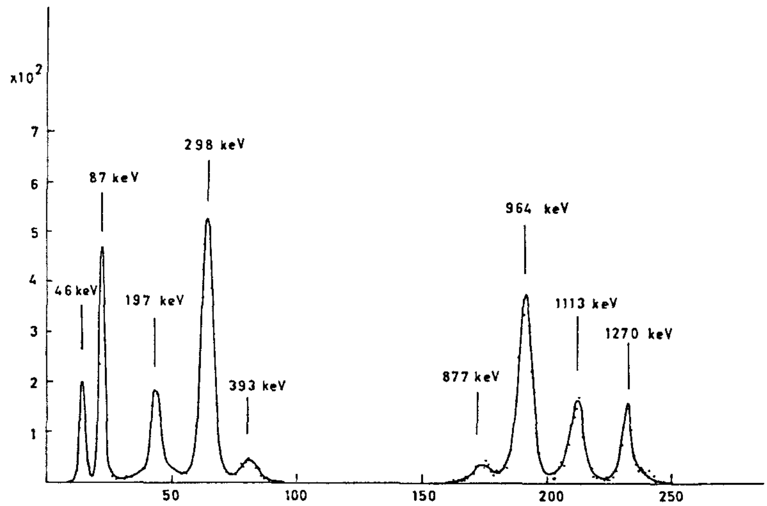

Fig. 2. Sum coincidence spectrum to the energy range from 1310 keV to 1340 keV.

The sum coincidence spectrum to the energy range from 1310 keV to 1340 keV (fig. 2) clearly indicates, along with the well-known cascades (1270+87) keV, (298+964) keV and (393+877) keV, the existence of the coincidence (1113+197) keV. Obviously, the 1113 keV gamma ray is not a transition from a level at 1200 keV to the first excited state at 87 keV, as was suggested by most previous authors, but a transition proceeding from a level at 1397 keV to the state at 284 keV.

The sum coincidence spectrum to the energy range from 1375 keV to 1415 keV is shown in fig. 3. In an evident way the pulse height distribution points to the cascade 1310 keV-87 keV which is interpreted as going from the 1397 keV level to the ground state. In addition, the measurement may indicate that a weak transition of about 1250 keV feeds the 284 keV level. The (393 + 964) keV coincidence is well established.

Fig. 4a illustrates the gamma-gamma coincidence spectrum to the energy range from 186 keV to 202 keV. In agreement with the results of previous workers gamma rays appear at 87, 215, 298, 393, 680 and 763 keV. The unambiguous presence of 1113 keV photons confirms the interpretation of fig. 2. Again, a weak line at about

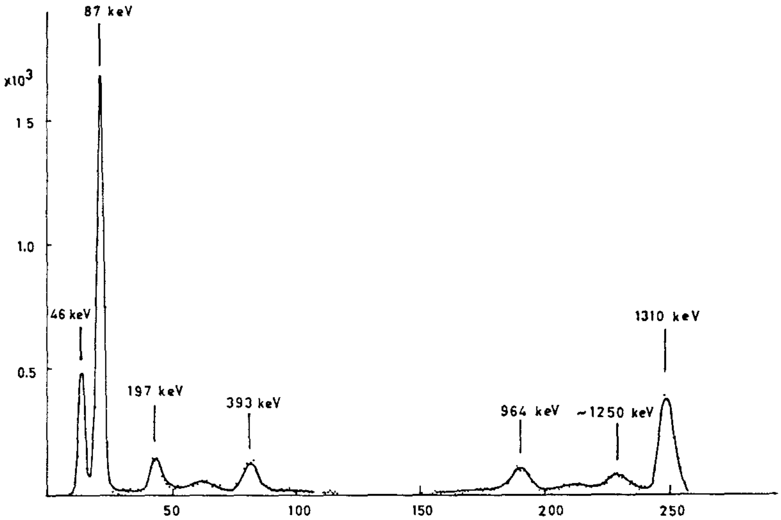

Fig. 3. Sum coincidence spectrum to the energy range from 1375 keV to 1415 keV.

1250 keV † is seen to be in coincidence with the 197 keV quanta. The lines at 877 keV and 960 keV are due to interference in the selector channel from the gamma rays at 215 keV and 298 keV. The high energy coincidence spectra to the energy ranges from 205 keV to 222 keV and 285 keV to 305 keV are shown in fig. 4b and fig. 4c, respectively. Using the relative gamma ray intensities from subsection 3.2, the channel settings and the known shapes of single gamma ray spectra in this energy region the pulse height distribution in fig. 4a was corrected by means of fig. 4b for interference of the 215 keV transition. The result is shown in fig. 4d. Following a similar procedure the remaining contribution of the 298 keV gamma ray was then eliminated. Fig. 4e illustrates the final result. There is a clear indication of a line at 1003 keV which is covered in fig. 4a by the much stronger 960 keV radiation. To explain the 1003 keV-

† The quoted energy is expected to be correct to within 3 %. This large error precludes a statement on the possible identity of this transition with the 1285 keV gamma ray observed by other authors in the Ho^{160} decay [15]).

197 keV coincidence a level must be postulated at 1287 keV. A transition of marked intensity at 1073 keV can be ruled out on the basis of fig. 4e. In previous gamma-gamma coincidence studies, due to poorer resolution, this transition most probably was simulated by the doublet containing 1003 keV and 1113 keV photons.

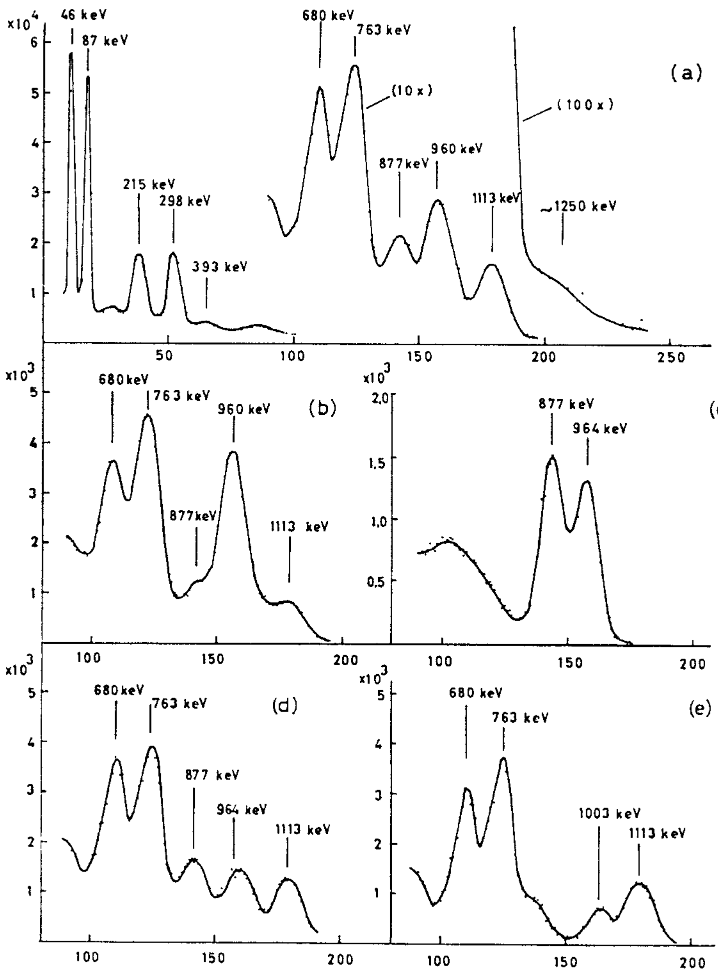

Fig. 4. (a) Spectrum of gamma rays coincident with the energy range from 186 keV to 202 keV (b) High energy coincidence spectrum to the energy range from 205 keV to 222 keV. (c) High energy coincidence spectrum to the energy range from 285 keV to 305 keV. (d) Spectrum (a) corrected for interference of the 215 keV transition. (e) Spectrum (d) corrected for the remaining contribution of the 298 keV gamma ray.

As the spectrum in fig. 4e points to a level at 1287 keV, it is obvious from energy considerations to assume that the 1200 keV gamma ray which was clearly observed by means of a three-crystal pair spectrometer corresponds to a transition from the

1287 keV level to the first excited state at 87 keV. The 1200 keV quanta do not appear in any sum coincidence and gamma-gamma coincidence spectrum. This is consistent with the above statement because the 1200 keV line then is always screened by the intense 1175 keV radiation.

TABLE 1
Summary of the coincidence measurements

Energy range (keV)	Coincident gamma ray energies (keV)																
	87	197	215	298	393	680	763	877	960	964	1003	1113	1175	1200	1250	1270	1310
a) Sum coincidences																	
910–990	+		+	+		+	+	+									
1025–1095	+				+	+			+								
1125–1205	+		+	+				+	+			+					
1248–1298	+			+	+			+		+			+				
1310–1340	+	+		+	+			+		+		+				+	
1375–1415	+	+			+					+					+		+
b) Gamma-gamma coincidences																	
65–96		+	+	+	+		+	+	+				+			+	
186–202	+		+	+	+	+	+				+	+			+		
205–222	+	+					+		+								
285–305	+	+						+		+							
375–425	+	+						+		+							
422–648	+	+	+	+	+												
640–690	+	+		+	+												
755–791	+	+	+														
846–886	+			+	+												
950–988	+		+	+	+												
1075–1125	+	+															
1140–1195	+																
1212–1262	+	+															
1290–1340	+																

In the energy range from 422 keV to 648 keV six gamma-gamma coincidence measurements were made with different discriminator settings. The pulse height distribution showed no characteristic changes which might give rise to the assumption of gamma rays of noticeable intensity in this region. All lines present in the spectra are caused by Compton processes of the high-energy quanta.

The results of the coincidence measurements which could be unambiguously interpreted are summarized in table 1.

3.2 GAMMA RAY RELATIVE INTENSITIES

The relative intensities of the observed gamma rays were determined from the photopeak areas in the measured spectra. Table 2 gives the results. The intensities are corrected for crystal efficiency, peak-to-total ratio, absorption between source and detector as well as at lower energies for changes in the coincidence efficiency.

TABLE 2

Relative intensities of the gamma rays

E_γ (keV)	Unconverted gamma ray relative intensity	E_γ (keV)	Unconverted gamma ray relative intensity
87	30 ± 3	964	83 ± 8
197	12 ± 1	1003	2.5 ± 0.8
215	11 ± 1	1113	6.2 ± 1.5
298	65 ± 13	1175	48 ± 5 †
393	2.9 ± 0.9	1200	7 ± 1 †
680	1.7 ± 0.7	1250	0.5 ± 0.3
763	2.5 ± 0.8	1270	20 ± 4 †
877	100	1310	7.3 ± 1.4 †
960	26 ± 5		

† Value deduced from the pulse height distribution of a three-crystal pair spectrometer

3.3. ANGULAR CORRELATION OF THE 298 keV-964 keV CASCADE AND POLARIZATION-DIRECTION CORRELATION OF THE 964 keV TRANSITION

Analysis of the experimental data yielded the angular correlation function

$$W(\theta) = (1 \pm 0.003) + (0.184 \pm 0.005) P_2(\cos\theta) + (0.013 \pm 0.008) P_4(\cos\theta) \tag{3}$$

Although the photopeaks at 877 keV and 964 keV are well resolved the result in eq. (3) still has to be corrected for contributions of the 298 keV-877 keV cascade. From the pulse height distribution and the discriminator settings this overlap was calculated to be $(16 \pm 3)\,\%$. When using eq. (6) and considering all uncertainties the true angular correlation function

$$W(\theta) = (1 \pm 0.006) + (0.242 \pm 0.020) P_2(\cos\theta) + (0.018 \pm 0.013) P_4(\cos\theta) \tag{4}$$

is obtained. In terms of a 2(D, Q) 2(Q) 0 spin sequence eq. (4) yields $Q_1 \leqq 0.002$. This result will be used in subsection 3.4.

The experimental polarization-direction correlation of the 964 keV transition is shown in fig. 5. Using eq. (1) and the correlation functions given by Biedenharn and

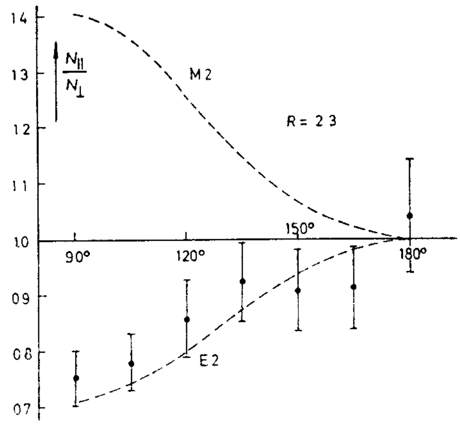

Fig. 5. Polarization-direction correlation of the 964 keV transition.

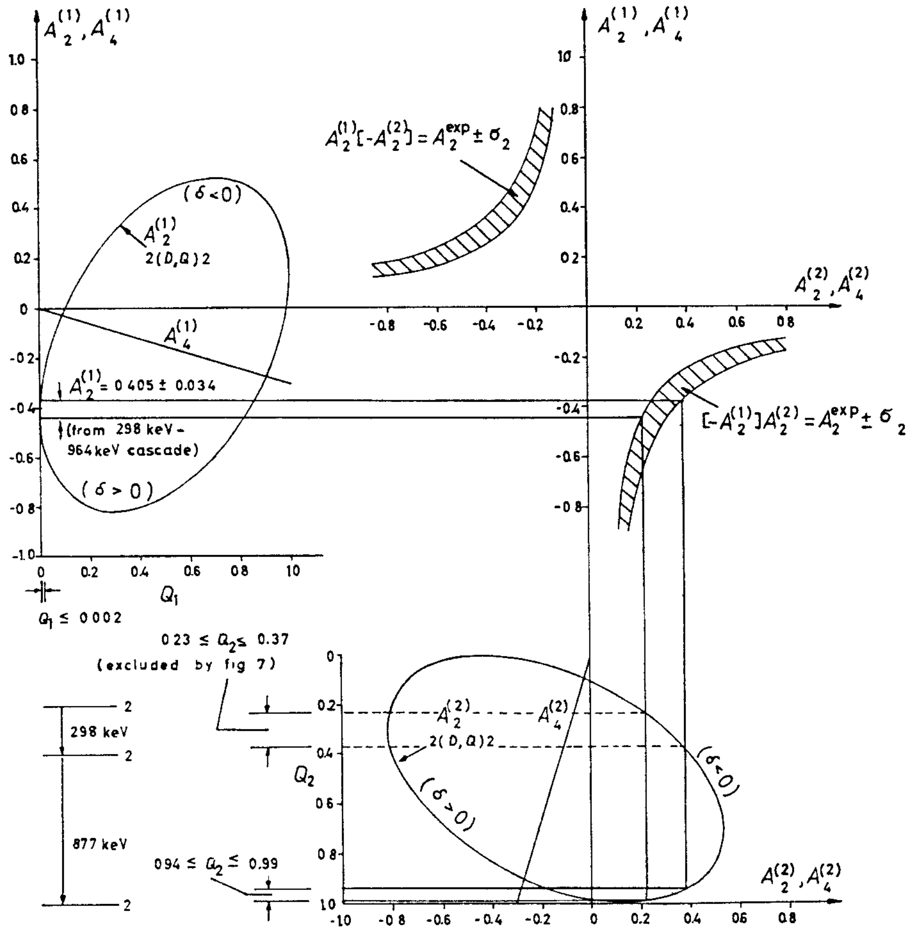

Fig. 6. Analysis of the 298 keV-877 keV angular correlation in terms of a 2(D, Q)2(D, Q)2 spin sequence.

Rose [16]) the theoretical ratio $N_{\|}/N_{\perp}(\theta)$ was calculated for both an E2 and a M2 transition. The results are also shown in fig. 5. Considering the well established E2 character of the 964 keV radiation the measurement provides an excellent check of the polarimeter.

3.4. ANGULAR CORRELATION OF THE 298 keV-877 keV CASCADE AND POLARIZATION-DIRECTION CORRELATION OF THE 877 keV TRANSITION

The angular correlation function was found to be

$$W(\theta) = (1\pm 0.003)-(0.055\pm 0.004)P_2(\cos\theta)-(0.004\pm 0.008)P_4(\cos\theta) \qquad (5)$$

Eq. (5) still contains an overlap of $(18\pm 3)\%$ from the 298 keV-964 keV cascade.

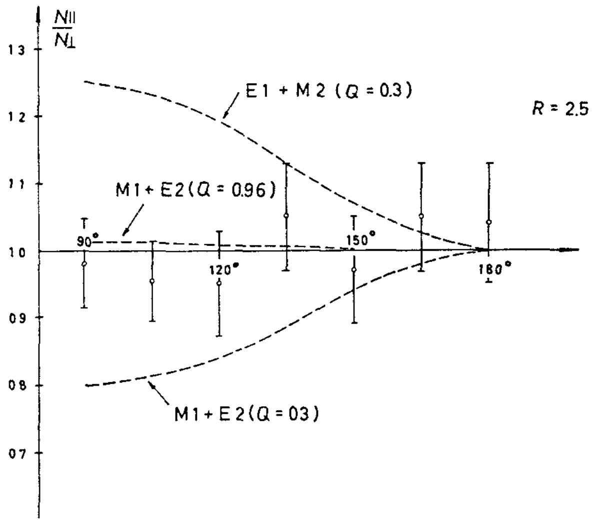

Fig. 7. Polarization-direction correlation of the 877 keV transition.

With eq. (4) the true angular correlation reads

$$W(\theta) = (1\pm 0.006)-(0.120\pm 0.023)P_2(\cos\theta)-(0.009\pm 0.014)P_4(\cos\theta) \qquad (6)$$

Fig. 6 shows the graphical analysis of eq. (6) in terms of a 2(D, Q) 2(D, Q) 2 spin sequence. When using the result $Q_1 \leqq 0.002$ from subsection 3.3 one obtains for the 877 keV radiation a quadrupole content of $Q_2 = 0.30\pm 0.07$ or $Q_2 = 0.965\pm 0.025$. The first of these interpretations which are possible according to eq. (6) is definitely excluded by the polarization-direction correlation of the 877 keV transition. Fig. 7 shows the experimental result as well as the theoretical correlations for the transitions† $M1+E2(Q_2 = 0.3)$, $M1+E2(Q_2 = 0.96)$ and $E1+M2(Q_2 = 0.3)$. As can be seen from figs. 6 and 7, the 877 keV radiation consists of $(3.5\pm 2.5)\%$ M1 and $(96.5\pm 2.5)\%$ E2 radiation.

† The case $E1+M2(Q_2 = 0.96)$ can be ruled out a priori.

3.5. ANGULAR CORRELATION OF THE 215 keV-960 keV CASCADE AND POLARIZATION-DIRECTION CORRELATION OF THE 960 keV TRANSITION

Evaluation of the experimental data yielded the angular correlation function

$$W(\theta) = (1 \pm 0.004) + (0.059 \pm 0.008) P_2(\cos\theta) - (0.012 \pm 0.014) P_4(\cos\theta). \quad (7)$$

Due to the relatively low intensity of the 215 keV and 960 keV gamma rays (cf. table 2) this result still contains some interfering coincidences the share of which

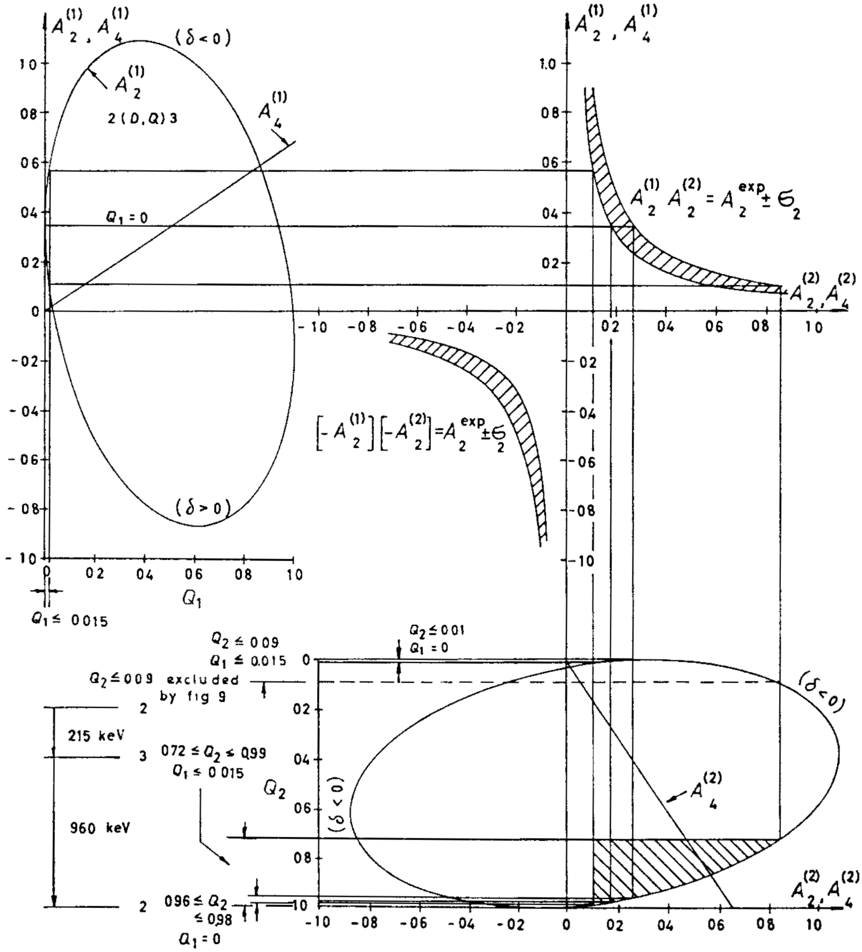

Fig. 8. Analysis of the 215 keV-960 keV angular correlation in terms of a 2(D, Q) 3 (D, Q) 2 spin sequence.

has been determined to be (25±5)%. Essentially, the interfering coincidences should have an isotropic angular correlation. Thus, one obtains the corrected correlation function

$$W(\theta) = (1 \pm 0.004) + (0.079 \pm 0.016) P_2(\cos\theta) - (0.016 \pm 0.021) P_4(\cos\theta). \quad (8)$$

Presuming spin 2 for the excited states at 87 keV and 1262 keV eq. (8) is consistent with spin 3 for the 1047 keV level. Fig. 8 shows the analysis of eq. (8) in terms of a 2(D, Q) 3(D, Q) 2 spin sequence. Starting from the assumption that the 1047 keV level has positive parity the multipolarity E1(+M2) results for the 215 keV transition. The 215 keV gamma ray therefore is predominantly dipole radiation. For one thing, this assumption is supported by the K-conversion data [5, 6]) which indicate an E1 multipolarity; moreover, the spin 3 of the 1047 keV level gives rise to the conclusion that this level is the first rotational state to the 2^+ level at 964 keV and thus also shows even parity. For pure dipole radiation of the 215 keV transition ($Q_1 = 0$) fig. 8 indicates a quadrupole content of $Q_2 \leqq 0.01$ or $Q_2 = 0.97 \pm 0.01$ for the 960 keV radiation. From the K-conversion coefficient the value 0.015 can be determined

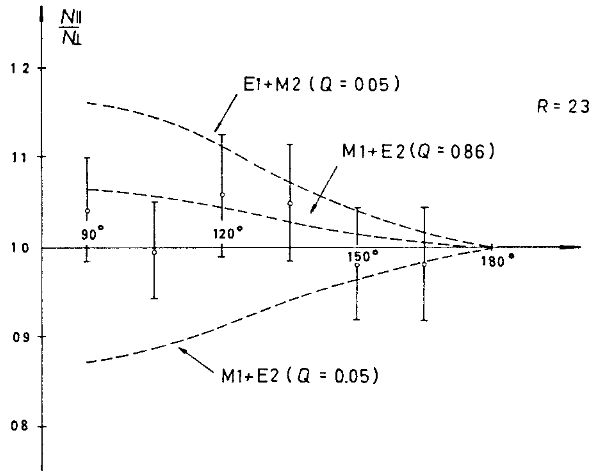

Fig. 9. Polarization-direction correlation of the 960 keV transition.

as upper limit of Q_1. With $Q_1 \leqq 0.015$ eq. (8) gives $Q_2 \leqq 0.09$ or $Q_2 = 0.855 \pm 0.135$. By the measured polarization-direction correlation of the 960 keV transition (fig. 9) the possibility $Q_2 \leqq 0.09$ is ruled out. As can be seen, the measurement moreover logically points to the (M1+E2) character of the 960 keV radiation. As the result $Q_2(E2) = 0.97 \pm 0.01 (Q_1 = 0)$, or $Q_2(E2) = 0.855 \pm 0.135$ ($Q_1 \leqq 0.015$), respectively, is in good agreement with the statement $Q_2(E2) \geqq 0.8$ which can be derived from K-conversion data [5, 6]), it seems safe to assign a spin and parity of 3^+ to the 1047 keV level.

4. Discussion

The level scheme based on the present results is shown in fig. 10. It confirms the scheme proposed by Ewan *et al.* [5]) and differs from those reported by Nathan [1]), Ofer [2]), Grigor'ev *et al.* [3]) and Bäckström *et al.* [4]) in the negative parity levels.

A level at about 1550 keV has been added in order to explain the observed weak 1250 keV transition to the second excited state (cf. footnote to subsection 3.1). From the weak lines quoted in section 1 those at 1003, 1113, 1200 and 1310 keV could be clearly observed. Their position in the decay scheme may be regarded as

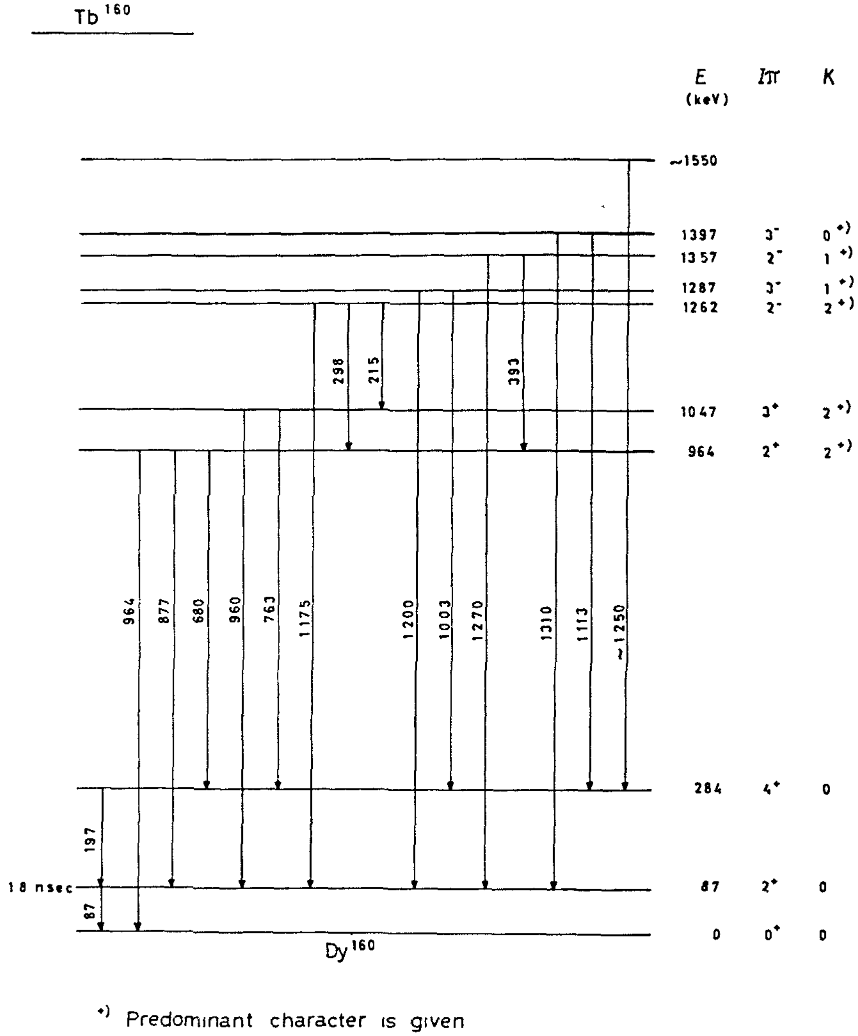

Fig. 10. Level scheme of Dy^{160} based on the results of the present investigation.

well established. However, there were no indications of the existence of gamma rays at 62, 157, 236, 917, 1047 and 1073 keV. Weak lines at 95 keV and 310 keV corresponding to transitions from the 1357 keV state to the levels at 1262 keV and 1047 keV should be expected on the basis of the observed level order. It is highly probable that these transitions were screened in the coincidence measurements by the strong lines at 87 keV and 298 keV.

TABLE 3
Reduced gamma ray transition probabilities

$\frac{B(EL; E_\gamma^{(1)})}{B(EL; E_\gamma^{(2)})}$	Theory: Unified model K=0	K=1	K=2	K=3	Theory: Asymmetric rotor theory	Experiment: Nathan [a]	Clark [b]	Ewan [c]	Present [d] measurements
964 keV level									
$\frac{B(E2; 964)}{B(E2; 877)}$	0.70	2.78	0.70	—	0.48	0.42	0.54 ± 0.08	0.53 ± 0.05	0.52 ± 0.05
$\frac{B(E2; 877)}{B(E2; 680)}$	0.56	0.44	20	—	10	> 20	> 18	10.5 ± 3	20 ± 8
1047 keV level									
$\frac{B(E2; 763)}{B(E2; 960)}$	—	2.5	0.4	0	0.9	0.77	$0.25^{+0.25}_{-0.10}$	0.81 ± 0.08	0.35 ± 0.15
1262 keV level									
$\frac{B(E1; 298)}{B(E1; 215)}$	—	0.5	2.0	—	—	2.6	3.1 ± 0.6	2.4 ± 0.2	2.3 ± 0.6
1287 keV level									
$\frac{B(E1; 1200)}{B(E1; 1003)}$	0.75	1.33	—	—	—	—	—	1.7 ± 0.35	1.9 ± 0.8
1357 keV level									
$\frac{B(E1; 393)}{B(E1; 310)}$	—	0.5	2.0	—	—	—	—	0.8 ± 0.15	—
1397 keV level									
$\frac{B(E1; 1310)}{B(E1; 1113)}$	0.75	1.33	—	—	—	—	—	0.96 ± 0.1	0.80 ± 0.33

a) See ref. [1]). Values calculated from conversion line intensities and directly measured gamma ray intensities
b) See ref. [6]). Values derived from conversion line intensities. Limit for 680 keV transition and intensity of 763 keV gamma ray obtained from 2 in. × 2 in. NaI spectrometer.
c) See ref. [5]). All values deduced from conversion line intensities.
d) All values calculated from directly measured gamma ray intensities.

The spin and parity assignments to the levels at 1047, 1287, 1357 and 1397 keV are based on the gamma ray multipolarities deduced from conversion data [5,6]) and on the observed pattern of transitions from these levels. A spin value of 3 for the 1357 keV level can almost certainly be ruled out. The assignment 3^+ to the level at 1047 keV is confirmed by the angular correlation and polarization experiment described in subsection 3.5.

The quadrupole content observed for the 877 keV transition is in contrast to the result found by Ofer [2]). However, it is in agreement with the measurements carried out by Arns *et al.* [9]) and Klimentovskaya and Chandra [11]).

Using table 2 and assuming pure E1 and E2 radiation, the ratios of reduced transition probabilities from the excited energy levels were calculated. The results are compared in table 3 with the predictions of the unified model [17]) and the asymmetric rotor theory [18]). The values given by Nathan [1]), Clark [6]) and Ewan *et al.* [5]) have also been included. The experimental transition probability ratios indicate that the levels at 964, 1047, 1262, 1287, 1357 and 1397 keV are predominantly K = 2, 2, 2, 1, 1 and 0, respectively. A possible K = 0 admixture in the K = 2 gamma-vibrational band and the possibility of interaction between the negative parity levels are discussed in the paper of Ewan *et al.*

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