1.E.1: 3.A

Nuclear Physics **11** (1959) 411—418, ©*North-Holland Publishing Co, Amsterdam*

THE LEVEL STRUCTURE OF Dy^{160}

R G ARNS, R E SUND and M L WIEDENBECK

The Harrison M Randall Laboratory of Physics, University of Michigan, Ann Arbor, Mich †

Received 24 January 1959

Abstract: Gamma rays in Dy^{160} following beta decay of the 72 day Tb^{160} have been studied using coincidence and angular correlation methods The relative intensity and coincidence measurements confirm the principal features of the decay scheme proposed by Nathan [1]) Angular correlation measurements were made on six cascades The spin and parity of the 0 087 MeV, 0 964 MeV, and 1 262 MeV levels were found to be 2+, 2+, and 2− respectively The measurements favour spins of 4 and 3 for the 0 283 MeV and 1 359 MeV levels These assignments are in agreement with previous assignments by Ofer [2]) The multipolarities of the main gamma transitions are given

1. Introduction

The level structure of Dy^{160} following beta decay of the 72 day Tb^{160} has been the subject of several investigations [1–8]) The more recent of these studies have been in agreement on several features of the level structure However, conflicts still exist in regard to the relative intensities and multipolarities of certain strong gamma transitions The angular correlation of the 1 076 MeV—0 196 MeV cascade reported by Ofer [2]) was considerably different from that observed by Nathan [1]) In addition, Ofer found it necessary to postulate an attenuation [2,9]) in interpreting three of his angular correlation measurements (those involving the 0 087 MeV level) Under the circumstances an attenuation is difficult to understand and further study of this aspect would seem to be of value. Thus the present coincidence and angular correlation measurements were undertaken in the hope of resolving some of the incompatible aspects of previous research on this decay

2. Experimental Procedure

Qualitative coincidence measurements were carried out using a fast-slow coincidence circuit with multichannel recording of the "gray wedge" type (modified Beva Lab 210). The detectors were $1\frac{1}{2}'' \times 1''$ NaI(Tl) crystals mounted on RCA type 6342 phototubes

The quantitative coincidence measurements and angular correlation

† Supported in part by the Michigan Memorial Phoenix Project and the United States Atomic Energy Commission

measurements employed a conventional fast-slow coincidence circuit [10]) with an effective resolving time of 20 ns The scintillation counters consisted of 2″×2″ NaI(Tl) crystals mounted on RCA type 6342 phototubes Differential analyzers were used to provide energy selection Lateral lead shielding was used to prevent counter-to-counter scattering

Angular correlation data were taken in a double quadrant sequence A least-squares fit of the data was made to the function

$$W'(\theta) = \alpha_0+\alpha_2 P_2(\cos\theta)+\alpha_4 P_4(\cos\theta)$$

The resultant expansion coefficients were then normalized and corrected for finite angular resolution by a collimated beam method [11]) This yielded a correlation function of the form

$$W(\theta) = 1+(A_2\pm\sigma_2)P_2(\cos\theta)+(A_4\pm\sigma_4)P_4(\cos\theta)$$

The σ_2 and σ_4 are the root-mean-square errors as defined by Rose (ref [12]), eq (30))

High purity Tb_2O_3 powder was irradiated for 24 hour periods in The University of Michigan Ford Nuclear Reactor The activated powder was then dissolved in HCl and the solution was diluted No impurity activities were found to be present in the source material

3. Results

3 1 COINCIDENCE MEASUREMENTS

In order to determine the position of the various gamma rays in the decay scheme, measurements were made of the gamma rays coincident with the following energy regions

$$0\ 080 \text{ MeV} \leqq E \leqq 0\ 100 \text{ MeV}, \quad 0\ 160 \text{ MeV} \leqq E \leqq 0\ 240 \text{ MeV},$$
$$0\ 250 \text{ MeV} \leqq E \leqq 0\ 350 \text{ MeV}, \quad \text{and} \quad 0\ 830 \text{ MeV} \leqq E \leqq 1\ 00 \text{ MeV}$$

The qualitative results are summarized in table 1

A knowledge of the relative intensities of the 0 877, 0 960 and 0 964 MeV lines is necessary in order to interpret the angular correlation data. Hence a careful measurement was made by means of the 0 298 MeV coincidence spectrum After correction for detector efficiency and the slight overlap of the lines, the intensity ratio 0 877 0 964 0 960 was found to be 1 0 73±0 06 0 29±0 06 This ratio was confirmed by measurements in the 0 087 MeV coincidence spectrum although the presence of interfering cascades prevented reliable quantitative results The present results are in good agreement with the ratio 1 . 0 68±0 10 0 35±0 10 found by Nathan A ratio of 1 0 90±0 18 0 05±0 01 has been quoted by Ofer

TABLE 1

Gamma-gamma coincidence measurements

Energy Region (MeV)	Transitions Selected (MeV)	Coincident Transitions (MeV)	Remarks
0 080≦E≦0 100	0 087	0 196+0 215, 0 298, 0 877, 0 960, 1 175, 1 272	The photopeak at 0 960 MeV was found to be about $\frac{1}{3}$ as strong as the 0 876 MeV photopeak after subtraction of interfering cascades
0 160≦E≦0 240	0 196, 0 215	0 087, 0 196+0 215, 0 298, 0 681, 0 764, 0 960, 1 076	The 0 681 MeV transition was found to be about $\frac{1}{2}$ as strong as the 0 764 MeV transition No gamma ray was found at 1 047 MeV thus ruling out the presence of a strong ground state transition from the 1 047 MeV level
0 250≦E≦0 350	0 298	0 087, 0 196, 0 877, 0 964	The 0 964 MeV transition was found to be about $\frac{2}{3}$ as strong as the 0 877 MeV transition
0 830≦E≦1 00	0 877, 0 960, 0 964	0 087, 0 159, 0 215, 0 298	

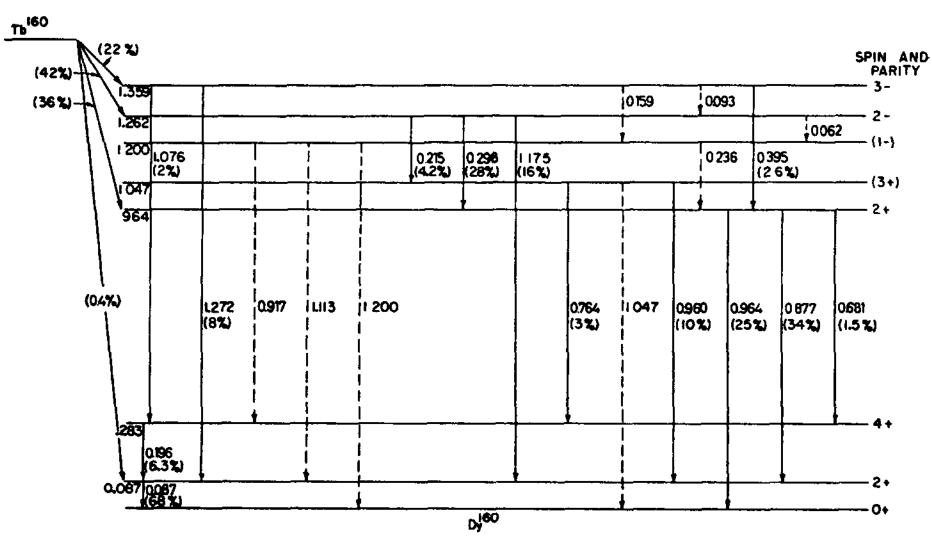

Fig 1 Decay scheme of Tb^{160} The beta decay data and gamma ray energies (in MeV) are according to Nathan The relative intensities are due to Nathan except where directly measured in the present research A number of weak transitions observed by Gregor'ev *et al* [7]) (relative intensities unknown) have been included

The decay scheme shown in fig 1 is due to Nathan [1]) The relative intensities of some transitions have been modified to agree with the present measurements An additional level at 1 200 MeV and several weak transitions have been added to the scheme on the basis of internal conversion measurements by Grigor'ev *et al* [7])

3 2 ANGULAR CORRELATION OF THE 0 298 MeV—0 877 MeV and 0 298 MeV—0 964 MeV CASCADES

Although the 0 877 MeV photopeak and the 0 960 MeV and 0 964 MeV combined photopeak were easily resolved by the scintillation counters, there remains a small overlap of these lines which must be considered in analyzing the angular correlation data Two angular correlation measurements were made In each measurement one of the differential analyzers was set to accept the upper half of the photopeak of the 0 298 MeV gamma ray In one case the second differential analyzer was set to accept a narrow range of pulses in the upper half of the 0 964 MeV photopeak In the other measurement, the second differential analyzer selected a narrow range of energies centered on the 0.877 MeV photopeak

Using the measured relative intensities (without the detector efficiency correction), the 0 877 MeV and 0 964 MeV photopeaks were constructed from known shapes of single gamma rays in this energy region The integrated contribution of both gamma rays to each correlation function was then determined The two correlation functions were combined with special attention to the errors in the relative intensities, channel settings, and the correlation functions themselves In this manner the 0 298 MeV—0 964 MeV angular correlation yielded expansion coefficients $A_2 = +0\ 259 \pm 0.042$ and $A_4 = -0\ 031 \pm 0\ 030$ These are in good agreement with the theoretical coefficients for a pure 2(D)2(Q)0 cascade, i e , $A_2 = +0\ 250$, $A_4 = 0$ If the cascade is of the form 2(D, Q)2(Q)0, the limits of error will allow a maximum of 0 5 % quadrupole content in the 0 298 MeV transition This assignment is supported by the measured K-conversion coefficients [1, 7]) which indicate an E1 multipolarity for the 0 298 MeV gamma ray and E2 for the 0 964 MeV transition It seems safe to assign a spin and parity of 2+ to the 0 964 MeV level on the basis of the conversion data. The expansion coefficients for this sequence are also consistent with a 3(D, Q)2(Q)0 cascade with a quadrupole content Q_1 for the first transition of $0\ 21 \leqq Q_1 \leqq 0\ 65$ An M2 content of this magnitude is inconsistent with experience and with the measured K-conversion coefficients Thus a spin assignment of 3 must be ruled out for the 1 262 MeV level

In the manner described above the corrected expansion coefficients for the 0 298 MeV—0 877 MeV sequence were found to be $A_2 = -0\ 126 \pm 0\ 026$ and $A_4 = +0\ 015 \pm 0\ 020$ The first excited state (at 0 087 MeV) can almost certainly be characterized as 2+ If the 0 298 MeV transition is assumed to be pure dipole, the data are then consistent with a 2(D)2(D, Q)2 sequence with $0\ 95 \leqq Q_2 \leqq 0\ 99$ or $0\ 25 \leqq Q_2 \leqq 0\ 35$ The latter possibility can be ruled out by the angular correlation data from the 0 877 MeV—0 087 MeV cascade which is given below The possibility of a small M2 admixture in the 0 298 MeV transition cannot be ruled out The graphical analysis [13]) of the data for a doubly mixed cascade is shown in fig 2 in which the range of

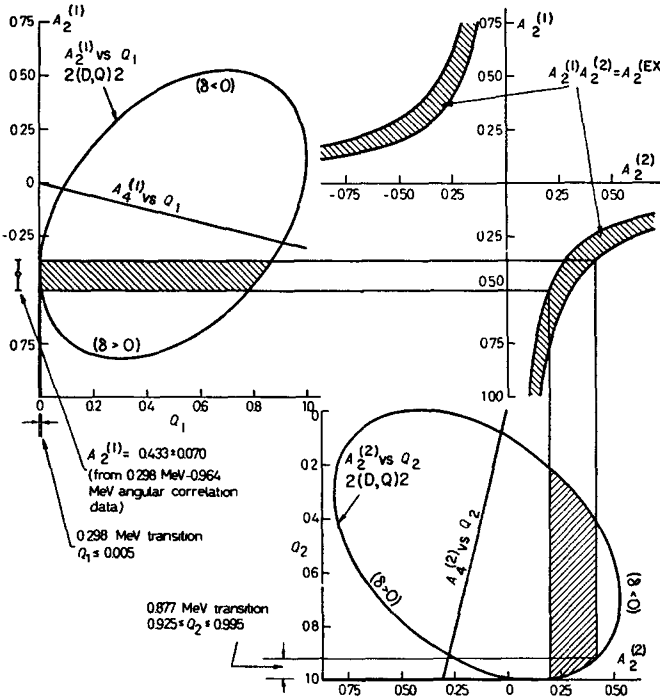

Fig 2 Analysis of the 0 298 MeV—0 877 MeV angular correlation in terms of a 2(D, Q)2(D, Q)2 sequence The limits of quadrupole content for the first step of the cascade are known from the 0 298 MeV—0 964 MeV angular correlation

E1+M2 mixture for the 0 298 MeV transition is assumed from the results of the 0 298 MeV—0 964 MeV correlation Again in accord with the results of the 0 877 MeV—0 087 MeV angular correlation, the data still require a quadrupole content of $0\ 925 \leqq Q_2 \leqq 0\ 995$ for the 0 877 MeV transition

In summary, it has been shown that the 0 298 MeV gamma ray proceeds from a 2— level at 1 262 MeV to a 2+ level at 0 964 MeV by radiation which is predominantly electric dipole ($\leqq 0\ 5\ \%$ M2) The 0 964 MeV level decays by pure E2 radiation to the 0+ ground state and by $96 \pm 3\ 5\ \%$ E2 and $4 \mp 3\ 5\ \%$ M1 radiation (0 877 MeV gamma ray) to the 2+ first excited state at 0 087 MeV

3 3 ANGULAR CORRELATION OF THE 0 877 MeV—0 087 MeV CASCADE

The 0 877 MeV gamma ray is a transition from the 2+ level at 0 964 MeV to the first excited state (spin and parity of 2+) at 0 087 MeV Angular correlation measurements on this cascade can provide information on the multipolarity of the 0 877 MeV transition, assuming that the 0 087 MeV transition is pure E2 An accurate measurement is not possible, however, due to the presence of the Compton distributions of interfering cascades The chief contributions to this background, i e , the 1 272 MeV—0 087 MeV, 1 175 MeV—0 087 MeV, 0 960 MeV—0 087 MeV and 0 298 MeV—0 877 MeV cascades, comprise nearly 50 % of the real coincidences measured by accepting a small portion of the 0 087 MeV and 0 877 MeV photopeaks in alternate differential analyzers However, the range of multipolarities possible for the 0 877 MeV gamma ray is already known from the 0 298 MeV—0 877 MeV angular correlation measurement Thus, despite the large errors introduced by the interference subtraction, the 0 877 MeV—0 087 MeV data can be used to distinguish between the two allowable ranges The corrected data showed the negative A_2 and large positive A_4 characteristic of a 2(D, Q)2(Q)0 sequence with a large (> 90 %) quadrupole content in the first transition

The angular correlation of this cascade was also measured by Ofer [2]) In that measurement the experimental data were corrected for interference from the 1 272 MeV—0 087 MeV and 1 175 MeV—0 087 MeV cascades and the resultant coefficients were considerably smaller than would be expected for the large quadrupole admixture present in the 0 877 MeV transition The present measurements indicate that it is not necessary to postulate an attenuation if all interference is considered However, the presence of some attenuation cannot be ruled out Ofer and Cohen [9]) were unable to achieve a completely satisfactory explanation for the large attenuation proposed It will be seen below that the results of the 1 272 MeV—0 087 MeV and 1 175 MeV—0 087 MeV angular correlations can be more readily understood if no attenuation is present

3 4 ANGULAR CORRELATION OF THE 1 272 MeV—0 087 MeV AND 1 175 MeV—0 087 MeV CASCADES

The 1 175 MeV and 1 272 MeV photopeaks are barely resolved in the scintillation spectrum, and an analysis similar to that outlined in section 3 2 must be applied in order to obtain the corrected angular correlation functions The errors involved are large due to a poor knowledge of the relative intensities and are reflected in the increased error limits of the expansion coefficients The corrected expansion coefficients for the 1 175 MeV—0 087 MeV angular correlation were found to be $A_2 = +0\ 133 \pm 0\ 041$ and $A_4 = +0\ 008 \pm 0\ 083$ Similarly the 1 272 MeV—0 087 MeV cascade yielded $A_2 = +0\ 148 \pm 0\ 065$ and $A_4 = -0\ 09 \pm 0\ 14$

The 1 175 MeV gamma ray proceeds from the 2− level at 1 262 MeV to the first excited state The cascade is certainly of the form 2(D, Q)2(Q)0 The expansion coefficients are then consistent with an E1+M2 mixture for the 1 175 MeV gamma ray with 97 5±1 5 % E1 and 2 5∓1 5 % M2 This is in agreement with the K-conversion coefficient measurements of Nathan and of Grigor'ev *et al* If a perturbation were present, a larger M2 content could not be ruled out Assuming an attenuation, Ofer's data [2]) would require an M2 content of about 65 % This would contradict the conversion measurements and also constitute a much larger M2 admixture than is normally encountered Hence the results tend to favor the present interpretation

The 1 272 MeV gamma ray is a transition from a level at 1 359 MeV to the first excited state Of the spin assignments logically available for the 1 359 MeV level, the angular correlation data is consistent only with 2 or 3 As will be shown below, the 1 076 MeV—0 196 MeV angular correlation rules out a spin assignment of 2 for the 1 359 MeV level For a 3(D, Q)2(Q)0 sequence the data require $0\ 04 \leqq Q_0 \leqq 0\ 18$ or $0\ 66 \leqq Q_1 \leqq 0\ 86$ The K-conversion coefficient measured by Nathan favors an E1 multipolarity for the 1 272 MeV transition Hence the 1 359 MeV level is most naturally characterized as 3− and the 1 272 MeV gamma ray is an E1+M2 mixture with 89±7 % E1 and 11∓7 % M2 Ofer, assuming a perturbation, found a quadrupole content of between 27 % and 50 % for the 1 272 MeV transition

3 5 ANGULAR CORRELATION OF THE 1 076 MeV—0 196 MeV CASCADE

The 1 076 MeV gamma ray is a transition from the 1 359 MeV level to the second excited state at 0 283 MeV The 0 196 MeV gamma ray is a transition between the second and first excited states Both gamma rays involved are very weak The window of one differential analyzer was set to accept the 0 205 MeV photopeak and the other was set with a narrow window in the region where the 1 076 MeV gamma ray should occur It was found that interference was present due to the high energy tails of the 0 960 MeV and 0 964 MeV gamma rays as the 0 215 MeV—0 960 MeV and the 0 298 MeV—0 964 MeV cascades No adequate method could be found for subtracting out this interference

It seems highly probable that the second excited state can be characterized as 4+ Of the possible sequences 4(D, Q)4(Q)2, 2(Q)4(Q)2, and 3(D, Q)4(Q)2, the first two require a positive A_4 coefficient The present data, even with the large interference, require an A_4 which is negative or at worst vanishing Thus a spin of 3 must be assigned to the 1 359 MeV level but the multipolarity of the 1 076 MeV transition remains undetermined

4. Discussion

Nathan [1]) has discussed the level structure of Dy^{160} in terms of the unified model His spin and multipolarity assignments were based on internal conversion and relative intensity measurements The present angular correlation measurements confirm his assignments when interpreted in accord with the internal conversion data

References

1) O Nathan, Nuclear Physics **4** (1957) 125
2) S Ofer, Nuclear Physics **5** (1958) 331
3) Burson, Jordan and LeBlanc, Phys Rev **94** (1954) 103
4) Keshishian, Kruse, Klotz and Fowler, Phys Rev **96** (1954) 1050
5) Bertolini, Bettoni and Lazzarini, Nuovo Cimento **3** (1956) 754, and Nuovo Cimento **3** (1956) 1162
6) M A Clark and J W Knowles, Bull Am Phys Soc **4** (1957) 231
7) Grigor'ev, Dželepov, Zolotavin, Kraft, Kratsik and Peker, Izv Akad Nauk SSSR, Ser Fiz **22** (1958) 101
8) Avotina, Grigor'ev, Zolotavin and Kratsik, Doklady Akad Nauk SSSR, **119** (1958) 1127
9) S Ofer and S G Cohen, Proc Rehovoth Conf Nucl Structure (North Holland Publishing Co 1958) p 479
10) Stewart, Scharenberg and Wiedenbeck, Phys Rev **99** (1955) 691
11) Arns, Sund and Wiedenbeck, University of Michigan Research Institute Technical Report 2375-4-T (January, 1959)
12) M E Rose, Phys Rev **91** (1953) 610
13) R G Arns and M L Wiedenbeck, Phys Rev **111** (1958) 1631