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NUCLEAR ORIENTATION OF Tb^{160}

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ABSTRACT

Nuclear orientation of Tb^{160} in a single crystal of neodymium ethylsulphate has been observed by the anisotropic intensity distribution of the γ-rays. The alignment arises from the coupling of the nuclear-magnetic and quadrupole moments with the crystal field. The spin of Tb^{160} is shown to be 3, and the spin of the 1360-kev level in Dy^{160} is 2. The nuclear moments of Tb^{160} are $|\mu| = 1.60 \pm 0.25$ nm and $Q = +1.9 \pm 0.5$ barns.

NUCLEAR ORIENTATION OF Tb^{160}*

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I. INTRODUCTION

Nuclear orientation has become a well-established technique for measuring nuclear moments and for studying the changes in angular momentum during radioactive decay. It is usually produced by the coupling between the nuclei and the local internal fields (hfs) in crystals, which may arise from one or more of the following mechanisms:

(a) the interaction between the nuclear magnetic moment and an externally applied magnetic field, via the intermediary of an electronic moment[1]

(b) the interaction between the nuclear magnetic moment and the crystalline electric field, via an electronic moment[2]

(c) the interaction between the nuclear electric-quadrupole moment and the electric-field gradient at the nucleus.[3]

In order to obtain enough orientation for the anisotropic emission from radioactive nuclei to be measured, it is usually necessary to cool the crystal to temperatures such that the thermal energy kT is comparable with the energy separations ΔE of the nuclear magnetic levels. These splittings are most often measured by paramagnetic or nuclear-resonance spectroscopy on a stable isotope. From such determinations the choice of a suitable crystal may be made.

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Mechanism (a) produces a polarization (i.e., an orientation in sense as well as direction) with respect to the applied field. Mechanisms (b) and (c) produce an alignment (orientation where parallel and antiparallel senses are equally populated) with respect to the crystal axes.

In the region of the rare earths and the actinides are found large nuclear quadrupole moments which are associated with the deformed nuclear core, as well as large electronic magnetic moments. Hence nuclear orientation may arise from a combination of magnetic and electric hfs interactions which may act together to increase or reduce the net nuclear orientation according to their relative signs.

In this paper, experiments on the nuclear alignment and polarization of Tb^{160} in a mixed crystal of terbium and neodymium ethyl sulphates are described. It was found that the magnetic interaction tended to align the nuclear spins along the c-axis of the crystal, and the quadrupole interaction tended to align them perpendicular to the axis. The net effect was a smaller degree of alignment than would be expected from either interaction alone. An analysis of the data obtained is used in conjunction with the results of other workers to give values for the magnetic and quadrupole moments of Tb^{160} and to assign angular momenta to some of the levels in the daughter nucleus, Dy^{160}.

II. EXPERIMENTAL

Terbium-160 was produced by irradiation of natural terbium (100% Tb^{159}) for 100 hr at a neutron flux of 2×10^{14} cm^{-2} sec^{-1} in the MTR reactor, Arco, Idaho. The terbium in the +3 state was incorporated into a 5-gm single crystal of neodymium ethylsulphate in a molar ratio $(Tb^{+3}/Nd^{+3}) < 10^{-6}$. The crystal contained 10 μC of Tb^{160}. The high specific activity ensured that the susceptibility measurements on the crystal were not affected by the Tb^{+3} ions.

The crystal was mounted in a demagnetization cryostat consisting of a glass chamber inside a glass dewar vessel containing liquid helium surrounded by another dewar containing liquid nitrogen. The crystal could be kept in thermal contact with or isolated from the liquid-helium bath by controlling the pressure of helium exchange gas in the chamber. By pumping away the vapor with a Kinney KMB-230 mechanical booster pump, the temperature of the liquid helium could be reduced to about 1.1°K. Magnetic fields up to 18 kgauss could be applied to the crystal by placing the cryostat between the pole-pieces of an iron-cored electromagnet energized by a 100-kw motor-generator set. The crystal was supported on a glass framework attached by a 2-mm-diam glass rod to the top of the chamber, and a pill of compressed manganous ammonium sulphate was attached halfway along the rod to act as a thermal guard. Radiation from parts of the apparatus at temperatures above that of the liquid helium was prevented from falling on the specimen by painting the chamber with Aquadag (colloidal graphite).

The crystal was cooled to temperatures between 0.02°K and 1.1°K by adiabatic demagnetization from fields applied along the c-axis. The heat influx to the crystal after cooling was of the order of 10 ergs min^{-1}, so that the temperature remained essentially constant for several minutes after demagnetization. Measurements of the intensities of the γ-radiation from the Tb^{160} were taken at a series of angles, θ, with the crystal axis. The susceptibility of the neodymium ethylsulphate was also measured in order to determine the temperature of the crystal. The effects of imhomogeneous heating of the crystal were studied and were found to be appreciable after a large change in temperature, even though the warming rate was slow. In order to minimize these effects, the observations were usually made for periods of not more than 5 min after demagnetization. The crystal was then warmed to 1.1°K by admitting

helium exchange gas to the chamber, and a further 5-min count of the γ-rays was taken for normalization. By demagnetizing from different initial fields, the whole range of temperatures between $0.02^{\circ}K$ and $1.1^{\circ}K$ was covered. Measurements were made in zero magnetic field and with external magnetic fields of 200 gauss and 400 gauss applied along the crystal axis.

Gamma-ray detection was done with two Na(Tl) I scintillation counters with 3-in. by 3-in. crystals and PENCO PA-4 100-channel pulse-height analysers. The intensities of all the γ-rays could thus be measured simultaneously. Corrections were applied for background, small changes in the gain of the photomultiplier tubes and amplifiers, and for the block time of the pulse-height analysers. In the experiments with a magnetic field, the photomultipliers were kept at a sufficient distance to be unaffected by the magnetic field.

The susceptibility measurements were made in a direction perpendicular to the c axis of the crystal. Neodymium ethylsulphate has $g_{\parallel} = 3.5$ and $g_{\perp} = 2.0$ which allows enough sensitivity even in the perpendicular direction.[4] A pair of mutual-inductance coils surrounded the specimen. Both ballistic and AC (20 cps) methods were used and agreed well with each other. The coils were calibrated between $4.2^{\circ}K$ and $1.1^{\circ}K$ against the helium vapor-pressure scale. The magnetic temperature $T_{\perp}^{*}$ obtained by extrapolating Curie's law to below $1.1^{\circ}K$ was corrected for the demagnetizing factor of the crystal, and the absolute temperature T was deduced from the data of Meyer.[5] In the experiments using an applied magnetic field H, the effects of saturation of the susceptibility were corrected by using the approximate formula

$$T_0^{\circledast} / T_H^{*} = \frac{\tanh g_{\parallel}\beta H/2kT}{g_{\parallel}\beta H/2kT} ,$$

where $T_0^{\circledast}$ has been corrected for the demagnetizing factor, and $g_{\parallel}$ refers to the neodymium ions.

III. RESULTS

The γ-ray peaks of Dy^{160} at 298, 880, 960, 1180, and 1270 kev were analyzed and found to be anisotropic, showing that the nuclei had been oriented. Peaks of energy lower than 298 kev were not studied, because of their large background, nor were peaks of low intensity. In alignment experiments, data were compiled for the angular distribution with respect to the crystalline c axis of all the γ-rays at the lowest temperature, $0.02^{\circ}K$, and for the temperature dependence of all γ-ray anisotropies ϵ defined by

$$\epsilon = \frac{I(\pi/2) - I(o)}{I(\pi/2)}$$

in the range $0.02^{\circ}K < T < 1.1^{\circ}K$. In polarization experiments, data were compiled for the temperature dependence of the anisotropy of the 298-kev γ-ray in the range $0.05^{\circ}K < T < 1.1^{\circ}K$ with magnetic fields of 200 and 400 gauss applied along the crystalline c axis. Several different crystals were used in the course of this investigation and the results were always consistent within experimental error.

The angular distributions of all γ-rays could be fitted to functions of the form

$$I(\theta) = 1 + X_2 P_2 (\cos\theta),$$

where X_2 for each γ-ray is given in Table I.

The values of X_2 for the 298-kev γ-ray as a function of field and temperature is shown in Fig. 1.

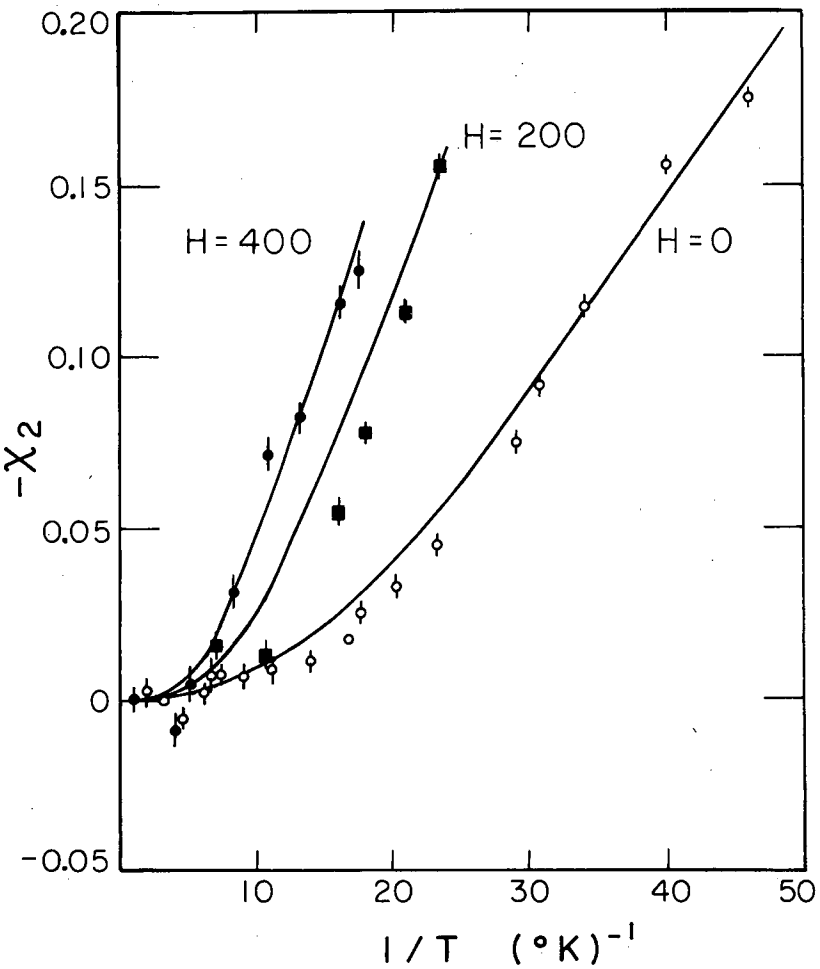

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Fig. 1. The coefficient X_2 of the 298-kev γ-ray of Dy^{160} vs reciprocal absolute temperature. Here 0, □, and ● denote data taken in external magnetic fields of 0, 200, and 400 gauss, respectively.

Table I

$X_2 = (B_2U_2F_2)$ of several gamma-rays at 0.02°K.

Gamma-ray energy (kev)	$B_2U_2F_2$ at 0.02°K
300	-0.200 ± .005
880	+0.105 ± .015
960	-0.152 ± .010
1180	-0.133 ± .040
1280	-0.124 ± .010

The limits of error on the data are the r.m.s. statistical errors. Corrections have been applied as explained in Section II. The maximum error introduced by the change in temperature during the counting period was only 0.1%.

Alignment experiments were also performed on Tb^{160} in cerium magnesium nitrate, but no anisotropy greater than 1% was observed at the lowest temperature, 0.003°K. We conclude that the lowest electronic state of Tb^{+3} in this crystal is a singlet.

IV. THE DECAY SCHEME OF Tb^{160}

Several investigations of the decay of 72-day Tb^{160} have been carried out.[6-12] Studies of the β spectrum agree on branches with end points at 1.71 Mev (log ft = 11.8), 0.86 Mev (log ft = 8.8), and 0.56 Mev (log ft = 8.1). However, the lower-energy branches were difficult to measure and led to uncertainties in the higher-energy levels in Dy^{160}. Recent conversion-electron spectroscopy by Bäckström et al.[10] has shown the existence of new γ transitions previously unobserved and has enabled accurate measurements of the conversion

coefficients to be made.[10] The results have considerably helped our understanding of the higher-energy levels in Dy^{160}. The data show that the most energetic peak in the γ-ray spectrum is composed of two E1 γ-rays of energies 1272 kev and 1312 kev and with a relative abundance of 7.7:2.3. The results of Ewan et al. confirm this,[9] giving a slightly different relative abundance of 10:4. The energy-level scheme shown in Fig. 2 fits all the available data best, and has been used in the interpretation of this experiment. The lower five levels are identical to those proposed by Nathan, who assigned the spins on the basis of internal-conversion measurements and explained the levels as members of K = 0 and K = 2 bands.[6] The spins of the upper levels have been assigned from the angular-correlation data of Ofer[7] and of Arns, Sund, and Wiedenbeck,[8] from the recent conversion-electron data,[9-12] and from this nuclear-orientation experiment.

Only spin and parity assignment of 3- for the ground state of Tb^{160} is in agreement with the experimental evidence. A spin of 4 has also been suggested,[11] but this is inconsistent with the log-ft value of 8.1 for the 0.56-Mev β branch and the assignment of spin and parity of 2- to the 1260-kev level of Dy^{160} to which this branch leads. It will be shown that the present experiment confirms this latter spin assignment.

V. ENERGY LEVELS OF Tb^{+3} IN $Tb(C_2H_5SO_4)_3 \cdot 9H_2O$.

Terbium ethylsulphate was chosen in this experiment because it is the only salt of terbium that (a) has shown paramagnetic resonance and (b) can be grown into a mixed crystal with a salt that may be cooled to the required low temperatures by adiabatic demagnetization. The coolant used was the isomorphous salt neodymium ethylsulphate, which had previously been used successfully in similar experiments on other rare earth isotopes.[13]

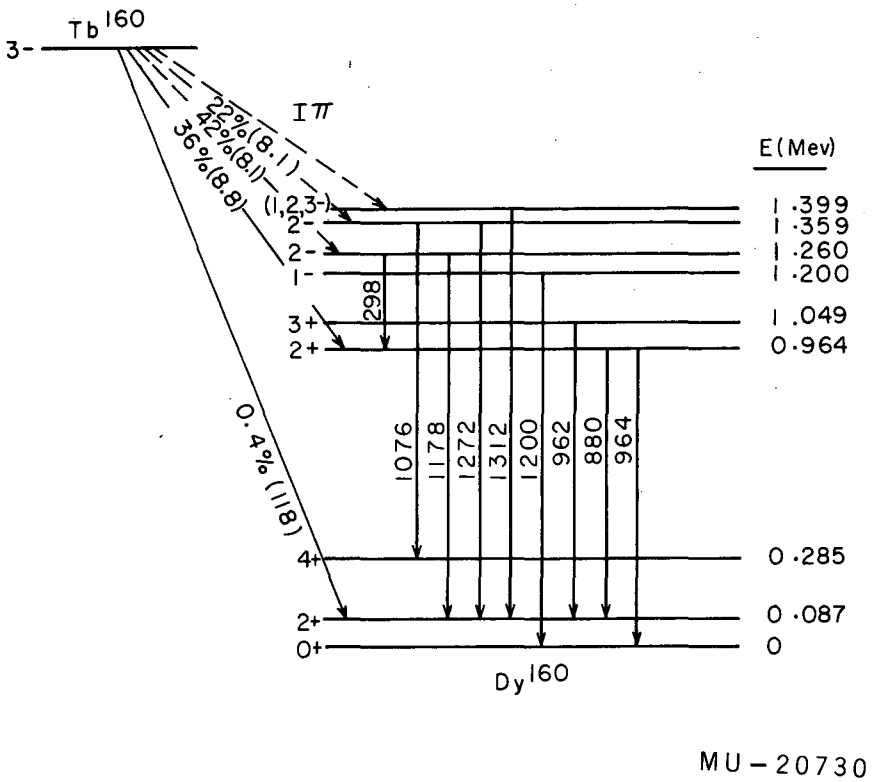

Fig. 2. Portion of the decay scheme of Tb^{160} which is relevant to this work.

The free Tb^{+3} ion has eight 4f electrons and the configuration $^7F_6$. In a crystalline electric field with trigonal symmetry this term is split into six doublets characterized by $|\pm J_z\rangle$ and a singlet $|J_z = 0\rangle$. Paramagnetic resonance data on terbium ethylsulphate magnetically diluted with yttrium ethylsulphate showed that at 20°K only the lowest level, $|\pm 6\rangle$, was appreciably populated.[14] This state was further split (Tb^{+3} being a non-Kramers ion) by the sixth-order crystal field potential V_6^6, which has nonvanishing matrix elements with the singlet $|J_z = 0\rangle$. The magnetic and electric hfs interactions further split the level, so that the system may be described by the following spin-Hamiltonian

$$\mathcal{H} = g_{\parallel}\beta HS_z + \Delta_x S_x + \Delta_y S_y + AS_z I_z + P[I_z^2 - \tfrac{1}{3}I(I+1)],$$

with $S = 1/2$ (effective), and where $g_{\parallel}$ is the component of the spectroscopic splitting factor along the crystalline axis. The terms in Δ_x and Δ_y represent the V_6^6 crystal-field splitting; A represents the magnetic hfs coupling between the nuclear magnetic moment, μ, and the electronic magnetic moment arising from the unpaired 4f electrons, and is given by

$$A = 4\beta\beta_n \mu/I \langle r^{-3} \rangle \langle + |N_z| + \rangle .$$

Here P represents the electric hfs coupling between the nuclear quadrupole moment, Q, and the gradient of the crystalline electric field. It is given by[15]

$$P = -9e^2 Q/4I(2I-1) \langle r^{-3} \rangle \langle J \| \alpha \| J \rangle \langle + |J_z^2 - \tfrac{1}{3} J(J+1)| + \rangle$$

for diagonal elements, where $\langle r^{-3} \rangle$ is the mean value of r^{-3} averaged over the 4f wave function and may be obtained from the calculations of Judd and Lindgren.[16] The reduced matrix element $\langle J \| \alpha \| J \rangle$ and the matrix element $\langle + |J_z^2 - \frac{1}{3} J(J+1)| + \rangle$ are calculated from a knowledge of the electronic ground state.

For stable Tb^{159}, Baker and Bleaney give $g_{\|} = 17.72 \pm 0.02$, $\Delta = (\Delta_x^2 + \Delta_y^2)^{1/2} = 0.387 \pm 0.001$ cm^{-1}, and $I = 3/2$. No information about the value of P was obtained from their measurement.

For Tb^{160}, assuming the spin $I = 3$, we have $|+\rangle = |J_z = +6\rangle$, $A/k = 0.078\ \mu\ ^{\circ}K$, and $P/k = 0.0032\ Q\ ^{\circ}K$. The splitting Δ depends on the crystal-field parameters V_2^0, V_4^0, V_6^0, and V_6^6, and is not due (as in other non-Kramers ions, e.g. Pr^{+3}) to random distortions of the crystal lattice. Hence it is expected that its value does not vary strongly with temperature or with the surrounding trivalent ions. Thus we shall assume that the value measured at $20^{\circ}K$ in a lattice of Y^{+3} is the same as the value in our experiment at $0.02^{\circ}K$ in a Nd^{+3} lattice. A further splitting which must be considered in our Tb-Nd ethylsulphate crystal is due to magnetic dipole-dipole interaction between the ions. To a good approximation only the two nearest Nd^{+3} neighbors affect the levels of the Tb^{+3} ion, and they add a term $cS_z(S_{1z} + S_{2z})$ to the spin Hamiltonian. Here we have $c = -2g_{\|Tb}\, g_{\|Nd}\, \beta^2/d^3$, where d denotes the distance to the nearest neighbor, S_{1z} and S_{2z} are the effective spin operators of the two nearest Nd^{+3} ions, and c is readily evaluated from paramagnetic resonance and X-ray data.[4,17] Since the g values of both Tb^{+3} and Nd^{+3} are large, this term becomes important at the low temperatures used in our experiment.

The significance of the positive sign of P is that the quadrupole coupling tends to align the nuclei so that the $|I_z = 0\rangle$ state lies lowest, i.e. so that the nuclei precess in the plane perpendicular to the crystal axis. This is in contrast to the magnetic hfs coupling described by A which tends to align the nuclei parallel and antiparallel to the crystal axis. Our results show that the magnetic effect predominates and that the lowest state is $|I_z = \pm 3\rangle$ for Tb^{160} in terbium ethylsulphate.

The energy levels are rather complicated and are given by

$$E = \pm 1/2 \left[\Delta^2 + (g_{\parallel} \beta H + Tc_z + AI_z)^2\right]^{1/2} + P[I_z^2 - \tfrac{1}{3} I(I+1)]$$

where T_z, the projection of the resultant spin of the two nearest neodymium neighbors on the z axis, takes the values -1, 0, and +1. In zero field, the levels consist of doublets $|\pm I_z\rangle$ and singlets $|I_z = 0\rangle$. The effect of the Δ term is to split the zero-field levels into two groups and to alter the spacing of the levels within the groups, compressing them closer together in the lower-energy group and spacing them further apart in the higher-energy group. This reduces nuclear alignment. When a magnetic field is applied along the direction of the z axis, the effect of the Δ term is partially overcome, and the separation of the lower levels increases. Hence the degree of nuclear orientation is increased, and because the degeneracy of the doublets is removed, a nuclear polarization is produced.

For arbitrary coupling parameters, A and P, a series of curves for the variation of nuclear orientation with temperature may be calculated. The parameters may be determined by fitting the experimental data to these. From the above relations the nuclear magnetic and quadrupole moments may be deduced.

VI. THE NUCLEAR MOMENTS OF Tb^{160}

The theoretically expected angular distribution of γ-radiation from oriented nuclei may be written[18]

$$I(\Theta) = 1 + B_2 U_2 F_2 P_2 (\cos \Theta),$$

where U_2 is a function of the spins of the initial and final states in the preceding β transition and of the angular momentum carried away by the electron-neutrino system, F_2 depends on the initial and final spins in the γ transition and on the multipolarity, and B_2, the degree of orientation of the nuclei, may be calculated from the Boltzmann population distribution,

which depends on the energy levels and the temperature. Conversely, a measurement of the temperature dependence of B_2 enables one to determine the spin-Hamiltonian parameters and hence the nuclear magnetic and quadrupole moments.

The nuclear moments of Tb^{160} were determined from a study of the anisotropy of the 298-kev γ-ray. This is the best understood and most intense of the peaks studied. In all previous investigations, there is agreement that it is a pure E1 radiation, and in most, that it has the spin sequence $2 \xrightarrow{1} 2$. This experiment confirms this spin sequence and eliminates the alternative of $3 \xrightarrow{1} 2$, which has also been suggested,[11] because the latter would give a positive value of $B_2U_2F_2$, whereas a negative value was observed. Hence the spin of the 1260-kev level in Dy^{160} must be 2, and, as remarked in Section II, it immediately follows that the spin of Tb^{160} must be 3. The alternative, 4, would require the β transition to the 1260-kev level to be at least second-forbidden, which is inconsistent with its observed log-ft value of 8.1.

Thus the 298-kev γ-ray is emitted after the spin sequence $3 \xrightarrow{L=1} 2 \xrightarrow{E1} 2$, and from this U_2 and F_2 may be calculated. From the data of Fig. 1, the temperature variation of B_2 in different fields was deduced and was fitted to the spin Hamiltonian to determine the parameters A and P. The alignment data alone do not uniquely determine these quantities but give the following relation between them:

$$P/k = 0.112\ |A|/k - 0.00784^{\circ}K.$$

This relation is more accurate than the separate values of A and P which are derived from it. Because of the relative insensitivity of the anisotropies in zero field to the value of A, these data allow acceptable fits for $0.105 < |A|/k < 0.250^{\circ}K$. The polarization experiments were performed in order to enhance the sensitivity of the anisotropy to A, and can be fitted to theoretical curves for $0.095 < A < 0.145^{\circ}K$. Thus we have $|A|/k = 0.125 \pm 0.020^{\circ}K$

and $P/k = +0.0061 \pm 0.0022^{\circ}K$. The curves in Fig. 2 have been derived using these values. For the moments of Tb^{160} we find $|\mu_{160}| = 1.60 \pm 0.25$ nm and $Q_{160} = 1.9 \pm 0.5$ barns.

VII. THE GAMMA-RAYS OF Dy^{160}

The temperature dependence of the anisotropies of all the γ-rays from the aligned nuclei was found to be the same. This anisotropy is proportional to $B_2U_2F_2$, and since B_2 may be determined from the data on the 298-kev γ-ray (for which U_2 and F_2 are known) at the same temperature, the product U_2F_2 may be determined for each γ-ray and may be used to obtain information about the angular-momentum changes in the decay scheme. In each cascade, U_2 may be calculated from the spins given in Fig. 2, using $L = 1$ in all the β-decays, which follows from the log-ft values.

A. The 1280-kev Peak

Conversion-electron measurements show that this peak is composed of two γ-rays of energies 1272-kev and 1312-kev in the ratios 10:4 or 7.7:2.3, both of which are pure E1 radiations. The coefficients U_2F_2 which are expected theoretically for the various possible values of the spins of the parent levels are listed in Table II. Comparison with the experimental data shows that the spin of the 1360-kev level must be 2; a spin of 3 would give an anisotropy of opposite sign to that measured. The spin of the 1399-kev level which best fits our data is 1.

The angular correlation work of Arns et al. was interpreted on the assumption that this peak was due to a single γ-ray emitted from a 3^- level and led to a mixing ratio $\delta(M2/E1)$ of 0.30. This would require a 300% error in the K-conversion coefficient measurement. Table II also shows the theoretically expected values for the angular-correlation coefficient A_2 [i.e. the coefficient of $P_2(\cos\Theta)$ in the angular-correlation function]. Here the spins

Table II

Angular-correlation and nuclear-alignment parameters for several spin assignments in Dy^{160}.

Spin of 1360-kev level	Spin of 1399-kev level	A_2 theor.	A_2 exptl. ASW[8]	A_2 exptl. Ofer[7]	U_2F_2 theor.	U_2F_2 exptl.
3-	1-	-0.123			+0.201	
3-	2-	+0.021			+0.038	
3-	3-	-0.072	+0.148 ±0.065	+0.115 ±0.002	+0.260	-0.232 ±0.019
2-	1-	+0.107			-0.232	
2-	2-	+0.250			-0.346	
2-	3-	+0.159			-0.136	

of Fig. 2 are assumed. Again the results are consistent only with a spin 2 for the 1360-kev level, but a spin of 1 or 3 is possible for the 1399-kev level. It should be noted that in calculating the theoretical angular-correlation functions, we assumed that the observed peak consisted of the 1272- and 1312-kev gamma rays in the relative abundances 10:4. This may not have been the case in the experiments of references 7 and 8.

B. The 1180-kev peak

This peak is also complex, consisting of 1178-kev and 1200-kev γ-rays in relative intensities 18:3. Correcting for the small effect of the 1200-kev branch (using the spins of Fig. 2) we have for the 1178-kev γ-ray $U_2F_2 = -0.247 \pm .080$. This sets an upper limit of 0.7% on the M2 character of this transition.

Arns et al. give a 2.5 ± 1.5% M2 admixture for this γ-ray, in slight disagreement with our result.[8]

C. The 960-kev peak

This peak is due to transitions of 962-kev (29%) and 966-kev (71%) energies. The latter goes from a 2^+ state to a 0^+ ground state and must be pure E2. When its effect is subtracted from the observed anisotropy, the result indicates that the 962-kev radiation has $\approx 3.2 > \delta\,(E2/M1) > -7.2$, i.e. it is 94.7 ± 3.5% E2.

D. The 880-kev peak

The experimental value for F_2 is +0.310 ± 0.045 and shows that $-4.7 > \delta\,(E2/M1) > -8.4$, i.e. the transition is 97.0 ± 1.5% E2. This is in excellent agreement with the value of 96.0 ± 3.5% given by Arns et al.

VIII. DISCUSSION

A spin and parity assignment of 3- for Tb^{160} follows naturally from the proton state 3/2+ [411] and the neutron state 3/2- [521] coupled together so that the intrinsic spins are parallel.[10,19] These states are found in Tb^{159} as the ground state and in Dy^{161} at 75 kev. Using the detailed wave functions due to Nilsson[20] (with $\eta = +6$) and neglecting interactions between the odd nucleons, we can calculate a value of +2.0 nm for the magnetic moment. This is slightly higher than the experimental value.[14] We note that this is also the case for Tb^{159}, where the experimental value[14] after correcting for the new value of $\langle r^{-3} \rangle$,[16] becomes $|\mu| = 1.92 \pm 0.10$, whereas the theory predicts $\mu = +2.2$ nm.[21] Thus the slight discrepancy in the case of Tb^{160} may not be due to odd-nucleon correlation. At any rate, the agreement is quite good, and suggests that the Nilsson wave functions may be used to calculate magnetic moments of strongly deformed odd-odd nuclei rather accurately. By comparison with neighboring nuclei, it is possible to estimate the intrinsic quadrupole moment, $Q_o \tilde{=} 6$ b. Then we have $Q_{sp} = \frac{I}{I+1} \frac{2I-1}{2I+3} Q_o \tilde{=} 2.5$ b, again slightly higher than the experimental value.

The almost pure E2 character of the 880-kev and 962-kev radiations is expected from the assignment of K quantum numbers given by Nathan. These γ-rays originate from states in a K = 2 band and decay to the 2+ state in a K = 0 band. By the selection rule, $\Delta K \leq L$, the γ-ray would be expected to carry away an angular momentum of at least 2, even though the spins of the levels change by only 0 and 1, respectively, during the transition.

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