Nuclear Orientation of Dy^{155} and Dy^{157}

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The isotopes Dy^{155} and Dy^{157} were aligned at low temperatures in a single crystal of neodymium ethylsulfate, using the magnetic hfs method. Angular distribution of gamma radiation following the decay of these isotopes was studied as a function of temperature in the region $0.02°K<T<1°K$. Spin assignments of $\frac{5}{2}-$ were made to states at 227 kev in Tb^{155} and at 327 kev in Tb^{157}. Assuming $I=\frac{3}{2}$ for both dypsprosium isotopes as well as pure $L=1$ beta decay to the $\frac{5}{2}-$ states, nuclear moments of $|\mu_{155}|=0.21\pm.05$ nm and $|\mu_{157}|=0.32\pm0.02$ nm were derived.

INTRODUCTION

IN recent years the technique of nuclear orientation has been used with remarkable success in studies of radioactive isotopes of the rare earths. Because of the extremely high sensitivity of the method, it offers a unique though indirect measurement of the magnetic moments of many radioactive nuclei. In this experiment, nuclear alignment techniques were used to determine the magnetic moments of Dy^{155} and Dy^{157} as well as to confirm previous work on the decay schemes of these isotopes.[1,2]

EXPERIMENTAL PROCEDURE

The dysprosium isotopes were obtained by bombarding natural gadolinium oxide powder (99.9% pure) with 48-Mev α particles accelerated at the Berkeley 60-in. cyclotron. This bombardment produced a mixture of Dy^{155} and Dy^{157}, the latter constituting the greater part of the activity.

The dysprosium fraction was purified and separated from the main Gd mass by the usual ion-exchange method, employing alpha-hydroxyisobutyric acid as eluant. The resulting Dy^{3+} isotopes were converted into the ethylsulfate and grown into a single crystal of $Nd(C_2H_5SO_4)_3\cdot 9H_2O$. The crystal was then mounted in a cryostat.

Alignment was obtained by cooling the crystal by adiabatic demagnetization. By demagnetizing from different fields extending up to 18 kgauss, temperatures ranging from 1.1°K (the helium bath temperature) down to 0.02°K were attained. The magnetic temperatures of the crystal after demagnetization were determined with mutual inductance coils and an ac bridge. Magnetic temperatures were converted into absolute temperatures by using the work of Meyer.[3]

Gamma-ray intensities at different temperatures were recorded by two counters: one parallel to the crystalline c axis and another perpendicular to it. Intensity distributions of the γ rays were also measured at different angles θ from the crystalline c axis at the lowest temperature attainable. Gamma-ray counting was done with 3×3-in. NaI(Tl) crystals in conjunction with 100-channel pulse-height analyzers. The sample was counted within a few minutes after demagnetization. Counts were normalized to 1.1°K, by warming up the crystal to the temperature of the bath (1.1°K) through introduction of helium exchange gas into the cryostat. When the crystal had warmed up, a normalization count was taken for the same length of time. Corrections were made for half-life, blocking time, solid angle, and back-

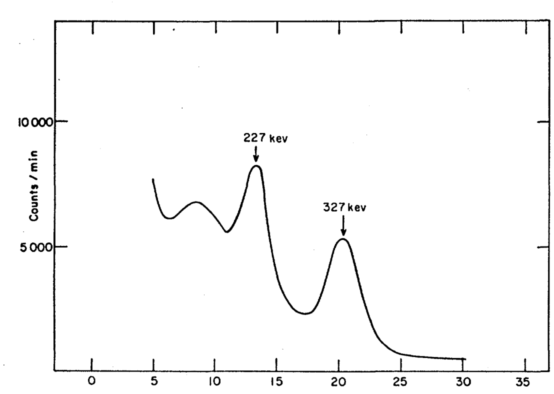

FIG. 1. Typical γ-ray spectrum of Dy^{155} and Dy^{157} mixture.

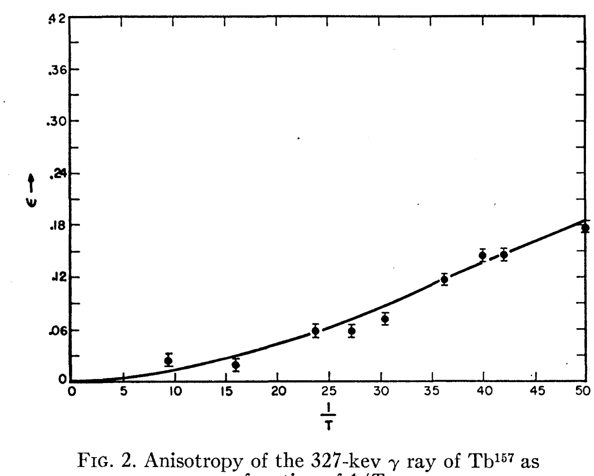

FIG. 2. Anisotropy of the 327-kev γ ray of Tb^{157} as a function of $1/T$.

[1] K. S. Toth and J. O. Rasmussen, Phys. Rev. **115**, 150 (1959).
[2] K. S. Toth and O. B. Nielsen (private communication).
[3] Horst Meyer, Phil. Mag. **2**, 521 (1957).

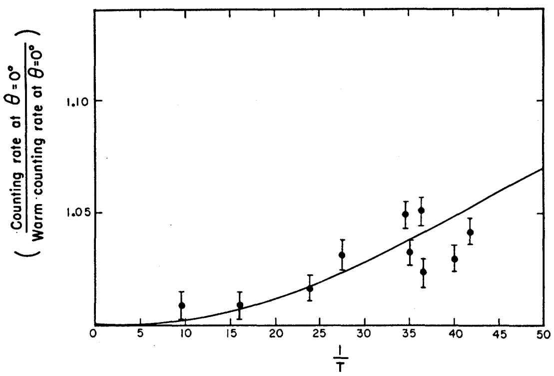

FIG. 3. $B_2U_2F_2$ for the 227-kev γ ray of Tb^{155} vs $1/T$.

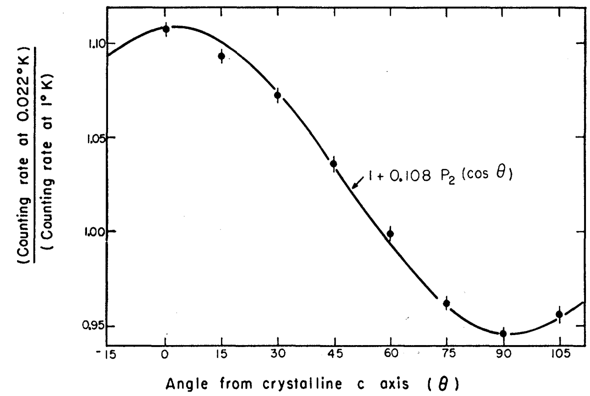

FIG. 4. Intensity distribution of the 327-kev γ ray of Tb^{157} at 0.022°K.

ground due mostly to Tb^{155}, the daughter of Dy^{155}, which has an anisotropy of opposite sign.[4]

RESULTS

The two most intense gamma rays, at 327 and 227 kev, had anisotropic distributions. These have been shown by Toth and Rasmussen,[1] Toth and Nielsen,[2] and Mihelich *et al.*[5] to belong to the decays of Dy^{157} and Dy^{155}, respectively. No other γ rays were examined for anisotropy, as these two were the only prominent ones.

A typical spectrum is shown in Fig. 1. The anisotropy $\epsilon(\equiv 1-[I(0)/I(\pi/2)])$ of the 327-kev γ ray of Dy^{157} plotted against $1/T$ is shown in Fig. 2. The 227-kev γ-ray anisotropy as a function of $1/T$ is plotted in Fig. 3. The intensity distribution of the 327-kev γ ray as a function of the angle θ between the direction of propagation and the crystalline c axis is shown in Fig. 4.

The experimental angular distribution at $T=0.022$°K were found to follow the equations

$W(\theta)=1+(0.108\pm 0.008)P_2(\cos\theta)$ for the 327-kev γ ray,

and

$W(\theta)=1+(0.060\pm 0.025)P_2(\cos\theta)$ for the 227-kev γ ray.

DISCUSSION

The angular distribution of gamma radiation from aligned nuclei is given by[6]

$$W(\theta)=1+\sum_{\text{even}} B_kU_kF_kP_k(\cos\theta), \quad (1)$$

where the B_k's are a measure of the degree of orientation of the parent nuclei. The U_k's are a measure of the amount of reorientation that takes place during any unobserved preceding transitions. The F_k's are constants determined by the mulitpolarity and the initial and the final spins of the observed γ transitions, and are identical to the F_k's used in angular correlation theory for two successive radiations. In this experiment only low orders of alignment were obtained, and only the term in $k=2$ was necessary in treating the data. In order to calculate B_2 it is first necessary to examine the form of the spin Hamiltonian.

Dy^{3+} has the configuration $4f^9$, and the ground term $^6H_{15/2}$. This term is split by the interaction of the electronic charge of the $4f$ electrons with the crystalline electric field into doublets which may be characterized in the first approximation by $|\pm J_z\rangle$. Elliott and Stevens have shown that there are two possible ground doublets: (a) a doublet which is mostly $|\pm 9/2\rangle$ with some admixtures of $|\mp\frac{3}{2}\rangle$ and $|\mp 15/2\rangle$ states, and (b) another doublet composed of a mixture of the states $|\pm\frac{7}{2}\rangle$ and $|\mp\frac{5}{2}\rangle$.[7]

The first doublet would have $g_\perp=0$ and $g_\parallel=10.3$; while the second would have $g_\parallel\approx g_\perp$. Paramagnetic resonance experiments have shown that resonance is observed at 14°K,[8] but not at helium temperatures.[9] This may be interpreted as evidence that the (nonresonant) doublet (a) lies lowest. The interpretation was confirmed by susceptibility measurements at helium temperatures,[10] which give for the ground doublet $g_\parallel=10.76\pm 0.1$ and $g_\perp=0$.

In view of the fact that $g_\perp=0$, the effective spin Hamiltonian in zero field may be written as

$$\mathcal{H}=AI_zS_z. \quad (2)$$

A simple calculation based on the theory of Elliott and Stevens[11] shows that the quadrupole interaction should have negligible effect on nuclear alignment for the assumed ground doublet.

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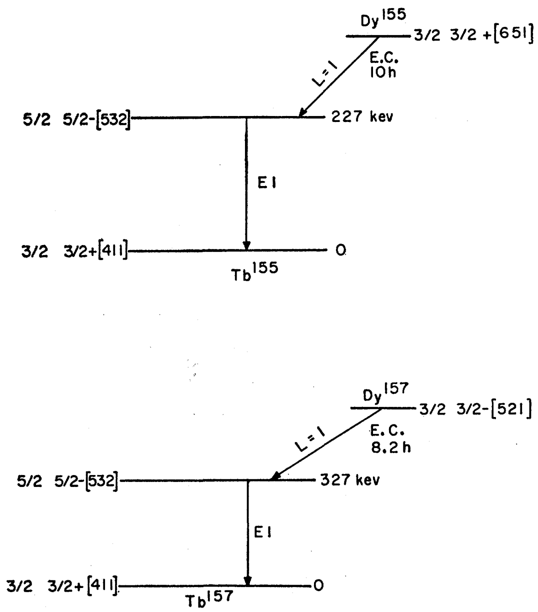

FIG. 5. Partial decay schemes of Dy^{155} and Dy^{157} relevant to this experiment.

The decay scheme of Dy^{157} has been fairly well established, and the portion of interest in this investigation is shown in Fig. 5. The ground-state assignment for Dy^{157}, according to the notation of Mottelson and Nilsson,[12] is $\frac{3}{2}-[521]$. The 327-kev γ ray has been found to have multipolarity $E1$. Just as in the case discussed below for Tb^{155}, if the ground-state spin and parity of Tb^{157} are $\frac{3}{2}+$, then the sign and magnitude of the γ-ray anisotropy preclude any assignment other than $\frac{5}{2}-$ for the 327-kev state. For the spin sequence $\frac{3}{2}-(L=1)\frac{5}{2}-(E1)\frac{3}{2}+$, the theoretical intensity distribution of the 327-kev γ ray may be expressed as

$$W(\theta)=1+0.280B_2P_2(\cos\theta). \qquad (3)$$

For Dy^{155}, the decay scheme is not so comprehensive, but these results can be used to assign spin $\frac{5}{2}-$ to the 227-kev level of Tb^{155} on the following arguments. Toth and others have assigned a spin of $\frac{3}{2}+$ to the ground state of Tb^{155} and have shown that the 227-kev γ ray is $E1$.[1,2] Thus the 227-kev state must have spin and parity $\frac{1}{2}-$, $\frac{3}{2}-$, or $\frac{5}{2}-$. But a spin of $\frac{1}{2}-$ would allow no anisortopy in this γ ray, while a spin of $\frac{3}{2}-$ would require $F_2=-0.40$, which would produce an anisotropy with sign opposite to that experimentally observed. Thus only a spin and parity assignment of $\frac{5}{2}-$ for this level is compatible with the experimental data. Again for spin sequence $\frac{3}{2}+(L=1)\frac{5}{2}-(E1)\frac{3}{2}+$, the theoretical

[12] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 1, 8 (1959).

TABLE I. Comparison of theoretical and observed nuclear moments of dysprosium and gadolinium.

Isotope	Ground state	μ_{theory} $\delta=0.28$ $g_R=0.32$ (nm)	μ_{observed} (nm)	Reference
Dy^{155}	$\frac{3}{2}+[651]$	-0.33	$\lvert 0.21\pm0.05\rvert$	This work
Dy^{157}	$\frac{3}{2}-[521]$	-0.49	$\lvert 0.32\pm0.02\rvert$	This work
Gd^{155}	$\frac{3}{2}-[521]$	-0.49	-0.30	17
			0.30 ± 0.05[a]	18[a]

[a] Corrected for $\langle r^{-3}\rangle=48.5(A)^{-3}$ (see reference 14).

intensity distribution of the 227-kev γ ray is given by Eq. (3).

The function B_2 depends on the single parameter $\beta=A/2kT$.[13] From the experimentally determined value of the anisotropy, which in turn is proportional to $B_2U_2F_2$, one can calculate the value of A.

The results are

$$|A/k|_{157}=0.048\pm0.003°\text{K},$$
$$|A/k|_{155}=0.032\pm0.008°\text{K}.$$

From the theory of Elliott and Stevens,[11] and using the value of $\langle 1/r^3\rangle$ by Judd and Lindgren,[14] we obtain for Dy^{3+}

$$A/k=0.227(\mu/I)°\text{K}. \qquad (4)$$

A comparison of Eq. (4) with the experimentally determined value of A yields for the nuclear moments

$$|\mu_{155}|=0.21\pm0.05 \text{ nm},$$
$$|\mu_{157}|=0.32\pm0.02 \text{ nm}.$$

Wide limits of error have been given for Dy^{155} because of uncertainty involved in the background correction for the 227-kev γ ray.

By using the values 0.28 and 0.32, respectively, for the deformation parameter δ and the gyromagnetic ratio of the core g_R given by Nilsson and Prior,[15] theoretical values of the magnetic moments of the two isotopes may be calculated. These are given in Table I based on ground-state assignments similar to the isotonic Gd isotopes,[16] together with the present experimental results and the known magnetic moment of Gd^{155}. It seems reasonable to infer that the signs of the magnetic moments of both Dy^{155} and Dy^{157} are negative. Then the magni-

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[14] B. R. Judd and I. P. K. Lindgren, Lawrence Radiation Laboratory Report UCRL-9188, 1960 (unpublished).
[15] S. G. Nilsson and O. Prior, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. (to be published).
[16] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Skrifter 1, No. 8 (1959).
[17] David R. Speck, Phys. Rev. 101, 1725 (1956).
[18] W. Low, Phys. Rev. 103, 1309 (1956).

tude may be compared with those calculated theoretically. In all these cases the theoretical magnitudes are too large, quite outside of experimental error. Thus, although the theory provides a good approximation to the magnetic moments, exact agreement is not obtained. The discrepancy may presumably be attributed to second-order effects, such as polarization of the core by the odd particle, which have not been included in the theory. Rasmussen and Chiao have shown that the theoretical magnetic moments of several deformed nuclei may be brought into better agreement with experiment by assigning quenched g factors for the intrinsic spin of the odd particle.[19] We note that use of quenched g factors for the odd neutron in Dy^{155} and Dy^{157} would improve the agreement between experiment and theory in both cases.

ACKNOWLEDGMENT

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Positron Spectra of Co^{56}†

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The positron spectrum of Co^{56} has been carefully studied with a magnetic spectrometer. Two positron groups were observed. The maximum energies and intensities of the two groups are 1.464 ± 0.015 Mev and 0.440 ± 0.030 Mev and $\geqslant 90\%$ and $\leqslant 10\%$, respectively. No evidence for any other groups was found. In particular, an upper limit of 1% was set for the presence of any group with maximum energy 0.9–1.0 Mev. The high-energy spectrum has essentially an allowed shape. However, the inclusion of a shape factor such as $(1+0.3/W)$ offers a more consistent fit to all the data.

INTRODUCTION

THE decay of Co^{56} to Fe^{56} has been studied by Kienle and Segel who report that all the Co^{56} positron-emission and electron-capture transitions, which are allowed on the basis of spins and parities of the levels, have relatively high ft values.[1] The intense positron decay ($E_0\simeq1.5$ Mev) from the 4+ ground state of Co^{56} to the 4+ second excited state of Fe^{56} has a $\log ft$ of 8.7. This is markedly higher than those of the other allowed transitions in Co^{56} (with $\log ft$ from 6.1 to 7.3). All these transitions have ft values which are larger than those of normal allowed decays.

Recently, the beta-gamma directional correlation between the 1.46-Mev positron group and the two cascade gamma rays which de-excite the second excited state of Fe^{56} was measured.[2] A maximum anisotropy of 2.5–3.3% for $A=[n(\pi)-n(\pi/2)]/n(\pi/2)$ was observed (n is the coincidence counting rate at the given angle). This is only the third anisotropy reported in allowed beta decay and this is much larger than the other two[3,4] (0.2% and 1%, respectively, for Na^{22} and F^{20}).

The unusually high ft value and the anisotropic beta-gamma directional correlation of the 1.46-Mev positron group suggest that deviations from the normal allowed beta-decay theory might also be observed in the shape of the beta spectrum. No detailed investigation in search of possible subtleties in the shape of the spectrum has been made. Indeed, there are disagreements among previous investigators as to the existence and characteristics of other possible positron groups from the Co^{56} decay.[1,5–10]

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