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ABSTRACT

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 $0.02^\circ K < T < 1^\circ K$. Spin assignments of $5/2^-$ were made to states at 227 kev in Tb$^{155}$ and at 327 kev in Tb$^{157}$. Assuming $I = 3/2$ for both dysprosium isotopes as well as pure $L = 1$ beta decay to the $5/2^-$ states, nuclear moments of $|\mu_{155}| = 0.21\pm.05$ nm and $|\mu_{157}| = 0.32\pm.02$ were derived.
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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.\(^1,4\)

Experimental Procedure

The dysprosium isotopes were obtained by bombarding natural gadolinium oxide powder (99.9\% pure) with 48-Mev a particles accelerated at the Berkeley 60-inch 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$^{4+}$ 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 low-temperature cryostat.

\* This work was done under the auspices of the U.S. Atomic Energy Commission.
Alignment was obtained by cooling the crystal by adiabatic demagnetization. By demagnetizing from different fields extending up to 18 kg, temperatures ranging from $1.1^0 K$ (the helium bath temperature) down to $0.02^0 K$ 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 Horst Meyer.  

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 $\gamma$ rays were also measured at different angles $\theta$ from the crystalline c-axis at the lowest temperature attainable. Gamma-ray counting was done with 3x3-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 $1.1^0 K$, by warming up the crystal to the temperature of the bath ($1.1^0 K$) 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 background due mostly to Tb$^{155}$, the daughter of Dy$^{155}$, which has an anisotropy of opposite sign.

Results

The two most intense gamma rays, at 327 kev and 227 kev, were anisotropic. These have been shown by Toth and Rasmussen, Toth and Nielsen, and Mihelich et al to belong to Dy$^{157}$ and Dy$^{155}$, respectively. No other $\gamma$ rays were examined for anisotropy, as these two were the only prominent ones.
A typical spectrum is shown in Fig. 1. The anisotropy of the 327-kev γ-ray of Dy\textsuperscript{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

\[ W(θ) = 1 + (0.108±0.008) P_2(\cos θ) \] for the 327-kev γ ray,

and

\[ W(θ) = 1 + (0.060±0.025) P_2(\cos θ) \] for the 227-kev γ ray.

**Discussion**

The angular distribution of gamma radiation from aligned nuclei is given by \textsuperscript{6}

\[ W(θ) = 1 + \sum_{\text{even}} B_k U_k F_k P_k(\cos θ), \]  

where the B\textsubscript{k}'s are a measure of the degree of orientation of the parent nuclei. The U\textsubscript{k}'s are a measure of the amount of reorientation that takes place during any unobserved preceding transitions. The F\textsubscript{k}'s are constants determined by the multipolarity and the initial and the final spins of the observed γ transitions, and are identical to the F\textsubscript{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\textsubscript{2} it is first necessary to examine the form of the spin Hamiltonian.

Dy\textsuperscript{3+} has the configuration 4f\textsuperscript{9}, and the ground term \textsuperscript{6}H\textsubscript{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 $|\pm 3/2\rangle$ and $|\pm 15/2\rangle$ states, and (b) another doublet composed of a mixture of the states $|\pm 7/2\rangle$ and $|\pm 5/2\rangle$. 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 $g = 0$, the effective spin Hamiltonian in zero field may be written as

$$H = A I Z S_z.$$

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.

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 $3/2 - [521]$. The 327-kev $\gamma$ 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 $3/2^+$, then the sign and magnitude of the $\gamma$ ray anisotropy preclude any assignment other than $5/2^-$ for the 327-kev state. For the spin sequence $3/2 - (L = 1) 5/2 - (E1) 3/2^+$, the theoretical intensity distribution of the 327-kev $\gamma$ ray may be expressed as
\[ W(\theta) = 1 + 0.280 B_2 P_2(\cos \theta). \quad (3) \]

For Dy\textsuperscript{155}, the decay scheme is not so comprehensive, but these results can be used to assign spin 5/2\textsuperscript{-} to the 227-kev level of Tb\textsuperscript{155} on the following arguments. Toth and others have assigned a spin of 3/2\textsuperscript{+} to the ground state of Tb\textsuperscript{155} and have shown that the 227-kev \( \gamma \) ray is El.\textsuperscript{1,4} Thus the 227-kev state must have spin and parity 1/2\textsuperscript{-}, 3/2\textsuperscript{-}, or 5/2\textsuperscript{-}. But a spin of 1/2\textsuperscript{-} would allow no anisotropy in this \( \gamma \) ray, while a spin of 3/2\textsuperscript{-} 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 5/2\textsuperscript{-} for this level is compatible with the experimental data. Again for spin sequence 3/2\textsuperscript{+} (L=1) 5/2\textsuperscript{-}(El) 3/2\textsuperscript{+}, the theoretical intensity distribution of the 227-kev \( \gamma \) ray is given by Eq. (3).

The function \( B_2 \) depends on the single parameter \( \beta = A/2kT \).\textsuperscript{13} From the experimentally determined value of the anisotropy, which in turn is proportional to \( B_2 U_2 F_2 \), one can calculate the value of \( A \).

The results are
\[
\left| \frac{A}{k} \right|_{157} = 0.048 \pm 0.003^0K,
\left| \frac{A}{k} \right|_{155} = 0.032 \pm 0.008^0K.
\]

From the theory of Elliott and Stevens,\textsuperscript{11} and using the value of \( \left< \frac{1}{r^3} \right> \) by Judd and Lindgren,\textsuperscript{14} we obtain for Dy\textsuperscript{3+}

\[ \frac{A}{k} = 0.227 \mu_1^0K. \quad (4) \]

A comparison of Eq. (4) with the experimentally determined value of \( A \) yields for the nuclear moments
\[ \left| \mu_{155} \right| = 0.21 \pm 0.05 \text{ nm}, \]
$|\mu_{157}| = 0.32 \pm 0.02$ nm.

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

By using the values 0.28 and 0.32 respectively for the deformation parameter $\delta$ 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, $^{15}$ 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 magnitude 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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References

3. C. A. Lovejoy, private communication to the authors.
4. K. S. Toth and O. B. Nielsen, private communication to the authors.
9. J. G. Park, quoted from Ref. 10.


Table I

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

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Ground state</th>
<th>$\mu_{\text{theory}}$ (nm)</th>
<th>$\mu_{\text{observed}}$ (nm)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dy$^{155}$</td>
<td>$3/2^+ \ [651]$</td>
<td>-0.33</td>
<td>0.21±0.05</td>
<td>This work</td>
</tr>
<tr>
<td>Dy$^{157}$</td>
<td>$3/2^- \ [521]$</td>
<td>-0.49</td>
<td>0.32±0.02</td>
<td>This work</td>
</tr>
<tr>
<td>Gd$^{155}$</td>
<td>$3/2^- \ [521]$</td>
<td>-0.49</td>
<td>0.30</td>
<td>17</td>
</tr>
</tbody>
</table>

0.30±0.05$^a$ 18$^a$

$^a$Corrected for $\langle r^{-3} \rangle = 48.5(A)^{-3}$ (see Ref. 14).
Figure Captions

Fig. 1. Typical γ-ray spectrum of Dy\textsuperscript{155} and Dy\textsuperscript{157} mixture.

Fig. 2. Anisotropy of the 327-kev γ ray of Tb\textsuperscript{157} as a function of 1/T.

Fig. 3. B\textsubscript{2}U\textsubscript{2}F\textsubscript{2} for the 227-kev γ ray of Tb\textsuperscript{155} vs 1/T.

Fig. 4. Intensity distribution of the 327-kev γ ray of Tb\textsuperscript{157} at 0.022\textdegree K.

Fig. 5. Partial decay schemes of Dy\textsuperscript{155} and Dy\textsuperscript{157} relevant to this experiment.
Fig. 1.
Fig. 2.
Fig. 3.
Fig. 4.

The graph shows the counting rate at 0.022 K normalized to the counting rate at 1 K as a function of the angle from the crystalline c-axis. The formula $1 + 0.108 P_2(\cos \theta)$ is plotted alongside the data points.
Fig. 5.
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