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NUCLEAR ORIENTATION OF Tb^{156}

C.A. Lovejoy and D.A. Shirley

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ABSTRACT

Terbium-156 nuclei were oriented at low temperatures in an ethylsulfate lattice, and the anisotropies of several γ-rays in Gd^{156} were studied as functions of temperature, external magnetic field, and magnetic environment. The results were explained using a five-term spin-Hamiltonian with two adjustable parameters, the magnetic dipole and electric quadrupole moments, which were thereby determined. The spin of Tb^{156} was shown to be 3, with μ_{156} = 1.45 ± 0.18 nm and Q_{156} = 1.4 ± 0.5 barns. The spin assignments of several high-energy states in Gd^{156} were confirmed, and a new 3- state at 2091 kev in Gd^{156} was indicated. The electron-capture transitions to states at 1943 and 2091-kev in Gd^{156} are predominantly Gamow-Teller.

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I. INTRODUCTION

The decay of Tb^{156} had been studied by conventional techniques, including electron spectroscopy[1] and angular correlation.[2] A rather detailed level scheme had been constructed which incorporated most of the known transitions. Very little was known, however, about the ground state of Tb^{156} or of the multipolarity of the electron capture decay. In this experiment we have observed the directional anisotropies of several γ-rays in Gd^{156} following the decay of Tb^{156} nuclei oriented at low temperatures in a crystal of neodymium ethylsulfate. Analysis of these data yields information about the ground state moments of Tb^{156} as well as elucidating certain features of its decay.

II. RESULTS

The experimental procedures have been described elsewhere.[3] Heat leaks to the demagnetized neodymium ethylsulfate crystal were kept low enough to allow warm-up times of several hours, and counting was done only for a short time immediately following demagnetization, to minimize effects of temperature inhomogeneity. Data were taken both with and without a polarizing magnetic field along the c axis of the crystal. The temperature range covered was $0.02 < T < 1^{\circ}K$

Seventeen photopeaks were resolved, of which fifteen were definitely anisotropic. Two of the photopeaks, at 106 and 165 kev, arose from the decay of Tb^{155} which was produced as an impurity when the Tb^{156} was prepared by a (p, n) reaction on enriched Gd^{156}. Both peaks were anisotropic, but were not analyzed further, because of the preponderance of Gd^{156} γ-rays. The finite anisotropies rule out a spin of 1/2 for Tb^{155} or for the levels in Gd^{155} from which these γ-rays proceed.

Within the limits of statistical error of our measurements all the γ-rays studied had angular distributions which could be described by the expression

$$W(\theta) = 1 + X_2 P_2 (\cos\theta) \qquad (1)$$

where X_2 is temperature - dependent and is different for each γ-ray. The angular distribution of the 1417-kev γ-ray at $0.017^{\circ}K$ is shown in Fig. 1. The parameters X_2 for several γ-rays at $0.017^{\circ}K$ are tabulated in Table I. In Figure 2 is shown the temperature dependence of X_2 for the 535-kev γ-ray under several experimental conditions. The decay scheme is shown in Fig. 3. A γ-ray spectrum is shown in Fig. 4, to illustrate the anisotropies.

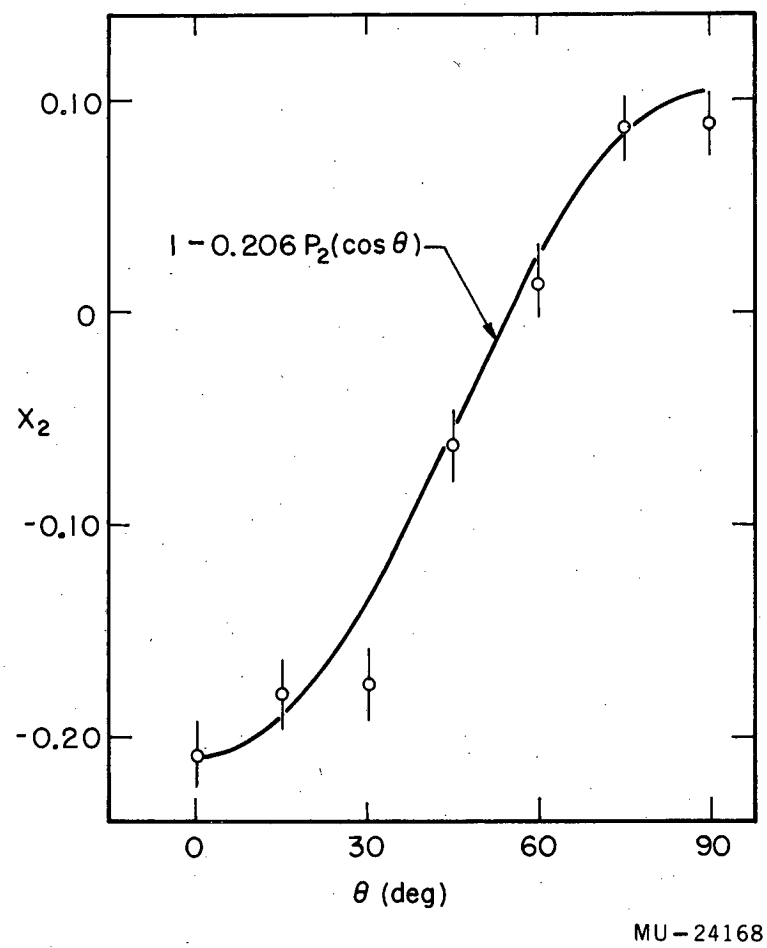

Fig. 1. Augular distribution of the 1417-kev γ-ray in Gd^{156} following the decay of oriented Tb^{156} in neodymium ethylsulfate at $0.017^{\circ}K$. The angle θ is measured from the crystalline c axis.

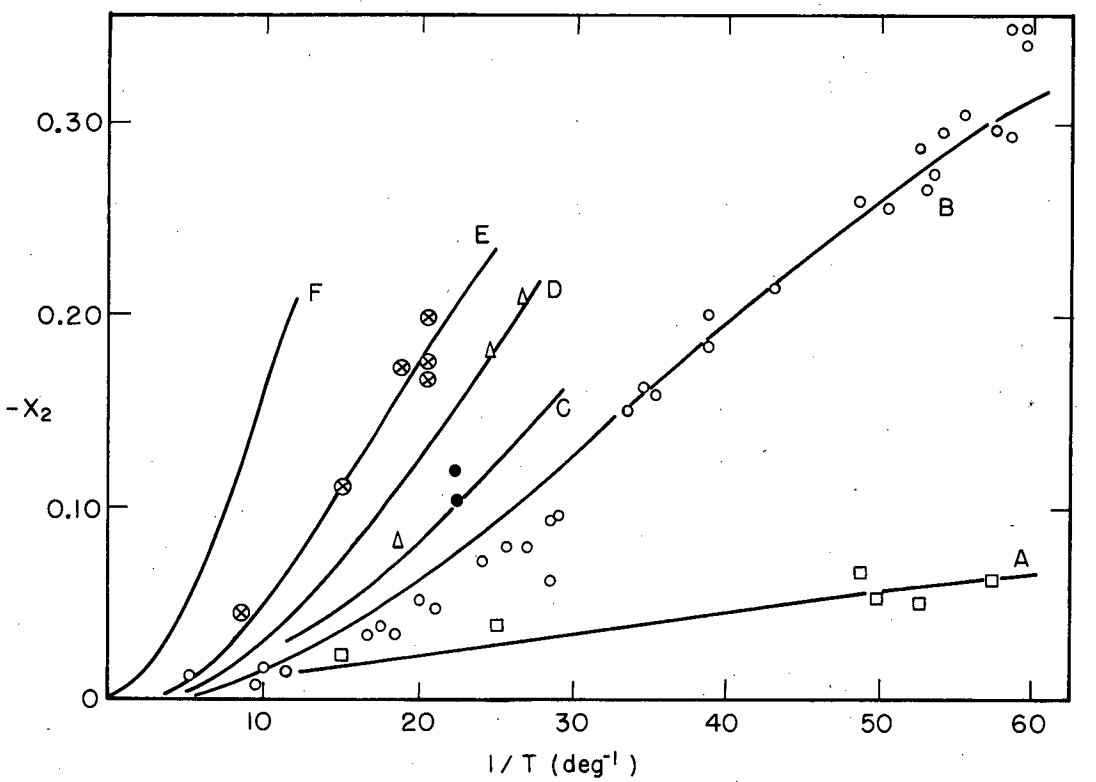

Fig. 2. Temperature dependence of X_2 for the 535-kev γ-ray in Gd^{156} following the decay of Tb^{156} oriented in the ethylsulfate lattice, under several experimental conditions (explained in text). The theoretical curves were calculated by using Eqs. (2), (4), and (6).

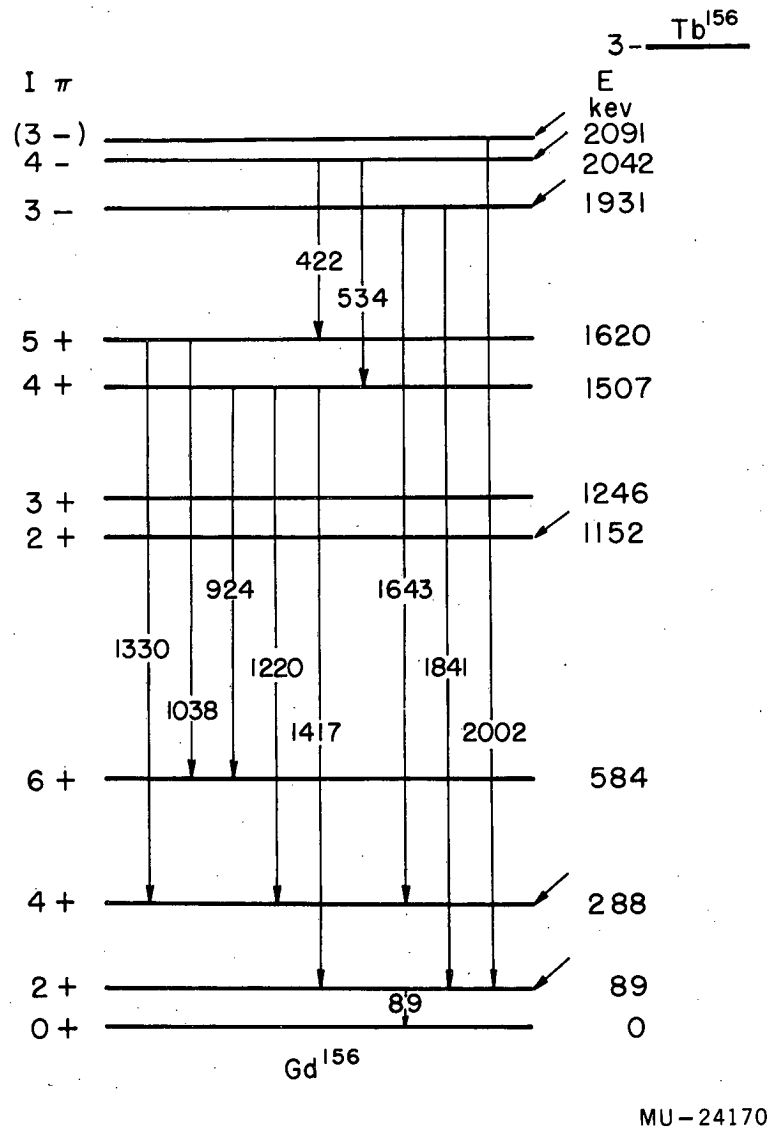

Fig. 3. Level scheme of Gd^{156} with transitions relevant to this work. A more complete decay scheme, with intensities, is given in ref. 1. The spins of the top five levels were studied in the present work.

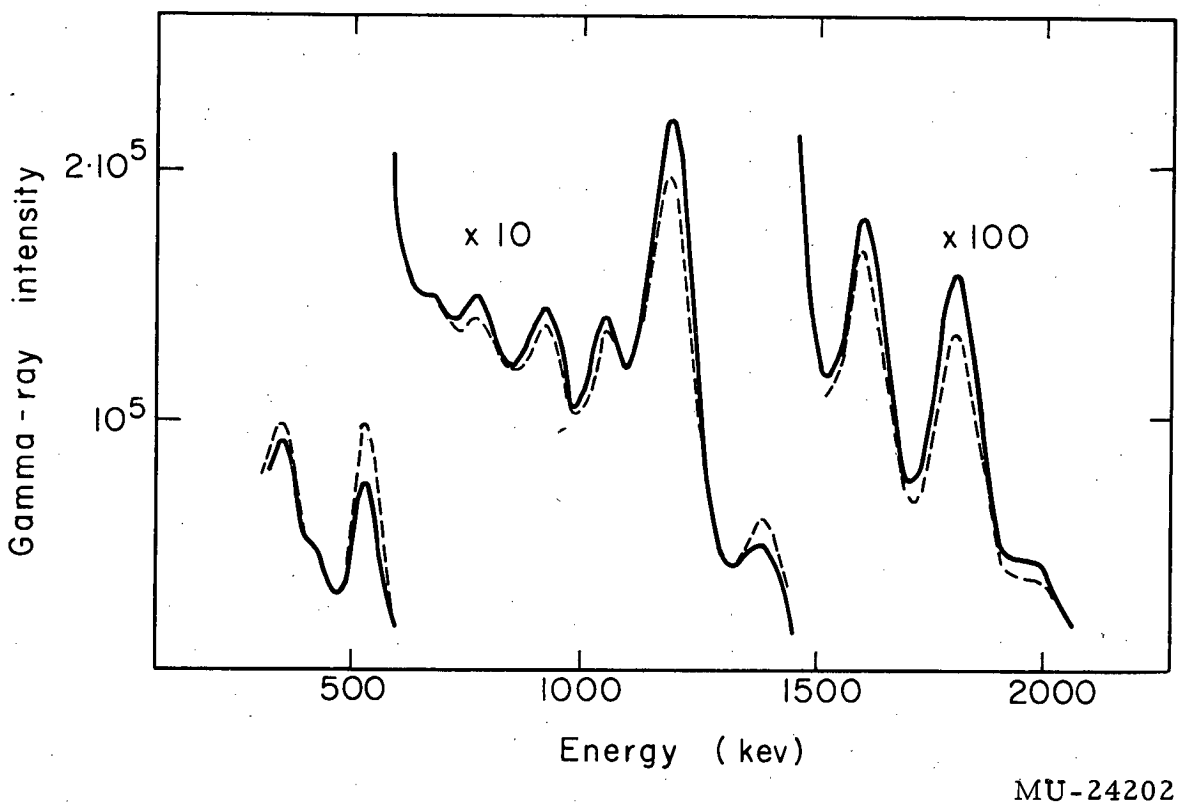

Fig. 4. High-energy portion of the γ-ray spectrum of Tb^{156} taken along the crystalline c axis. The solid line represents intensities at 0.02°K, and the dashed line represents intensities at 1.1°K.

III. DISCUSSION

A. The Spin Hamiltonian

In order to interpret a nuclear orientation experiment reliably, it is necessary to know the form of the spin Hamiltonian governing the hyperfine-structure energy levels. Both paramagnetic resonance[4] and nuclear orientation[3,5] experiments have been performed on Tb^{3+} in the ethylsulfate lattice. In the latter work, the angular distribution of γ-radiation had a unique temperature dependence which was, however, explained using the Hamiltonian[3]

$$H = g\,\beta H_z S_z + \Delta_x S_x + \Delta_y S_y + A S_z I_z + P\,[I_z^2 - 1/3\,I(I+1)] + c S_z T_z \qquad (2)$$

Here Δ_x and Δ_y describes a V_6^6 crystal field splitting in the ground state doublet, the term in c describes nearest-neighbor spin-spin interactions, and the other terms have their usual meanings. All of the terms in Eq. (2) are given except A and P (and sometimes I), which vary from isotope to isotope, being proportional to the nuclear magnetic and quadrupole moments, respectively. Thus A and P may be varied in Eq. (2) until values are found which fit the anisotropy data best, and these values may be used to calculate the nuclear moments, using the relationships[3]

$$\begin{aligned} |A|/k &= 0.078\,|\mu|\,{}^{\circ}K \\ P/k &= +\,0.0032\,Q\,{}^{\circ}K \end{aligned} \qquad (3)$$

B. The Decay Scheme

For this experiment the theoretical angular distribution of γ-radiation may be described by an expression of the form[6]

$$W(\theta) = 1 + B_2 U_2 F_2 P_2(\cos\theta) \qquad (4)$$

where the orientation parameter B_2 alone is temperature dependent and also contains the entire dependence on the spin Hamiltonian. Each γ-ray has a distinct U_2 and F_2, but B_2 is common to all. Only X_2 in Eq. (1) is measured,

and in order to obtain $B_2(T)$ and thus the nuclear moments it is necessary to know U_2 and F_2 for at least one γ-ray. We shall use the 535-kev γ-ray, on which we have the most accurate data, for this purpose.

The multipolarity of the 535-kev γ-ray must be accurately known in order to obtain a reliable value for F_2. Hansen et al.[1] report a K conversion coefficient, $\alpha_k(535)$, of 0.0030±0.0008. Comparison with the theoretical values of 0.0038 for an E1 transition and 0.0632 for an M2 transition, calculated from the tables of Sliv and Band indicates that this γ-ray is pure E1. An M2 admixture of up to 6% would be consistent with most of Ofer's data[2], which were considerably less accurate. We shall use E1 multipolarity in our interpretation.

Next we wish to establish the spin of the 2042 kev energy level of Gd^{156}, from which the 535-kev γ-ray proceeds. Both Hansen et al. and Ofer have tentatively assigned spin 4 to this level. This assignment is confirmed in this experiment by the sign of the anisotropy of the 535-kev γ-ray alone. The quantity U_2 must be positive unless the multipolarity, L, of the preceding unseen (electron capture) transition is comparable to the spins of the initial and final states in the unseen transition. In this case the smallest possible nuclear spin involved is 3, and L is 0 or 1. While it is possible for a nucleus whose hyperfine structure is given by a Hamiltonian of the form of Eq. (2) to have a negative B_2, only a positive B_2 will increase in magnitude with the isothermal application of an axial magnetic field, as is the case here. The product $B_2U_2(535)$ is thus positive. But X_2 is negative (Table I); therefore F_2 is negative. The 535 kev γ-ray accompanies de-excitation to the 4+ level at 1507 kev, and its multipolarity restricts the possible spin and parity assignments for the 2042-kev level to 4-, 3-, or 5-, of which the

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latter two would require $F_2 > 0$. Hence the 4- assignment is definitely established.

Hansen et al. found that a 10% electron capture branch directly populates the 2+ level at 1152 kev in Gd^{156}. Thus the spin of Tb^{156} must be 3, which alone allows strong electron capture branches to states of spins 4 and 2. An examination of Table II shows that spin 3 also fits our data best. Here we have tabulated the ratios $U_2(535)/U_2(1841)$ for all the possible "pure" multipolarities in the electron capture branches to the 4- level at 2042 kev and the 3- level at 1931 kev in Gd^{156}. The experimental range of 1.30 ± 0.16 lies just outside the spin 4 range and thus excludes this possibility. We can also set limits of $0 \lesssim \lambda \lesssim 0.23$ on the Fermi fraction, λ, of the electron capture branch to the 1931-kev level.

A ground state spin and parity of 3- for Tb^{156} might be expected on the collective model. This state can be formed by combining the proton state 3/2 + [411] with the neutron state 3/2 - [521] according to the Gallagher-Moszkowski rules.[7] A 4- state cannot be formed, using these rules, from close-lying Nilsson orbitals.[8] Terbium-159 has a measured spin of 3/2[4] and the 3/2 - [521] neutron state is found in Dy^{161} at 75 kev.[9] The spin of Tb^{160} is 3[3,5,10,11] and spin 3 is consistent with the available data on Tb^{158}.[12]

Previous work had left the spin of the positive parity 1620-kev state in Gd^{156} in doubt. In this experiment a positive X_2 was found for the 422-kev transition. This is consistent with the sequence 4-(E1) 4+. Thus the spin of the 1620 kev state is established as 5+.

Ofer included a 1935 kev transition in the decay scheme which connected the levels at 2042 and 89 kev. His gamma ray energies were consist-

ently lower than those found in the electron spectroscopy measurements of Hansen et al., which we have accepted as correct. In particular, these latter workers found evidence for conversion electrons in the range 1990-2030 kev. Unfortunately the electron intensity was so low that they couldn't determine whether there was one transition or several. We found a high energy photopeak, apparently due to a single γ-ray, at 2002±10 kev, using the lower energy photopeaks for energy calibration. Another peak of comparable intensity at a lower energy would have been obscured by the 1841 kev peak, but any other peak in the range 2000-2030 kev is present in extremely low abundance. In the absence of any convincing evidence to the contrary, we shall assume that this 2002 kev peak is due to a single γ-ray. It must decay to the 89-kev level in Gd^{156}, as it has been observed in coincidence with only the 89-kev γ-ray.[12] We infer, then, that this γ-ray depopulates a level at ~2091 kev which is populated directly in the electron capture decay of Tb^{156}. If the 2002 kev γ-ray is E1 in character as suggested by Hansen et al., the 2091 kev state can have only spins 1, 2, or 3 with negative parity. These spins would require F_2's of (+.071), (-0.418), and (+.340), respectively, for the 2002 kev γ-ray.

The experimental U_2F_2 of 0.195±0.045 is consistent with only the last value of F_2. Thus the state at 2091 kev must be 3-. Comparison with theoretical U_2F_2's of 0.340 and 0.254 for pure Fermi and pure Gamow-Teller electron-capture transitions to the 2094 kev level shows that this decay is probably mostly Gamow-Teller.

Care must always be taken in interpreting experiments involving the anisotropies of γ-rays following the electron capture decay of oriented nuclei, because of the possibility of attenuation in intermediate states caused electromagnetic fields in the vicinity of the nucleus. This problem is expected

Table.I.

The parameter X_2 for several γ-rays in Gd^{156} following the decay of Tb^{156} oriented in neodymium ethylsulfate at $0.017^{o}K$.

Gamma-ray energy (kev)	X_2
535	-0.317±0.011
1220	0.134±0.005
1417	-0.206±0.016
1643	0.095±0.005
1841	0.205±0.025
2002	0.154±0.040

to be expecially serious in the case of electron capture decay, because of the disruption of the electronic orbitals following the creation of a vacancy in the K-shell.[13] On the other hand there is no conclusive evidence for this effect in intermediate states with lifetimes shorter than about one nanosecond, and γ-ray anisotropies have been observed in nuclei in which the intermediate states have lifetimes of several nanoseconds.[14] In order to minimize the importance of attenuation effects we have restricted our interpretation to include only the anisotropies of high energy, primary E1 γ-rays (by "primary" we mean proceeding from levels which are populated only by direct electron capture transitions). This procedure also has the advantage of eliminating the effects of unresolved features of the decay scheme, such as the exact intensities of intermediate transitions, which affect the reorientation parameter U_2. The 1643 kev γ-ray also proceeds from a primary E1 transition,

from the 3- 1935-kev state to the 4+ 288-kev state. Since it has the same parentage as the 1841-kev γ-ray, the factors B_2 and U_2 for these two γ-rays will be the same, and $F_2(1643)/F_2(1815) = X_2(1643)/X_2(1815)$. This ratio is 0.46±0.08 experimentally and 0.416, calculated from the proposed decay scheme. Thus the E1 multipolarity assignments and the 3- spin and parity assignment for the 1931-kev state are borne out by this experiment.

C. Magnetic Interactions and The Nuclear Moments

The technique of nuclear orientation is a highly sensitive method for the determination of nuclear moments. Unfortunately it is not a method which is capable of high accuracy, and few moments have been determined to better than about ten percent in this way. The main advantage of the method is its high sensitivity, which allows it to be used to determine nuclear moments which could not be measured in any other way.

In the case of Tb^{156} the γ-ray anisotropy depends on two unknown hyperfine-structure parameters, A and P. These parameters are proportional to the nuclear magnetic and quadrupole moments, respectively, and can be determined by adjusting A and P in Eqs. (2) and (4) to reproduce the experimental angular distribution and particularly its temperature dependence. By fitting the zero-field temperature dependence of anisotropy (curve B in Fig. 2) in this way we obtained the relationship between A and P

$$\frac{|A|}{k} = (9.1\pm0.1)\ P/k+(0.071\pm0.005) \qquad (5)$$

as well as reducing the allowable ranges to $0 < P/k < .012^{\circ}K$ and $0.07 < |A|/k < 0.18$. While Eq. (5) represents the most accurate result of this research, more information is required to determine the values of the two moments separately. Fortunately the temperature dependence of anisotropy becomes much more

sensitive to A in the presence of an axial magnetic field. Comparison of our data taken in external fields of 200 and 400 gauss (curves D and E in Fig. 2) with Eqs. (2) and (4) allows us to reduce the allowable ranges of $|A|$ and P and obtain the best values.

$$|A|/k = 0.113 \pm 0.014\,^{\circ}K$$
$$P/k = +0.0045 \pm 0.0015\,^{\circ}K \qquad (6)$$

comparison with Eq. (3) yields

$$|\mu_{156}| = 1.45 \pm 0.18 \text{ nm}$$
$$Q_{156} = +1.4 \pm 0.5 \text{ barns}$$

To demonstrate the effect of spin-spin interaction, data were also taken using a "layered" crystal prepared by growing a crystal of the following composition (from the inside): (a) yttrium ethylsulfate containing Tb^{156}; (b) inactive yttrium ethylsulfate; (c) a thin transition layer wherein the composition varied from (100% Y, 0% Nd) to (0% Y, 100% Nd) ethylsulfate; and (d) a thick layer of neodymium ethylsulfate, comprising about 80% of the mass. The T-T* relationship for such a crystal is somewhat uncertain, but should not differ greatly from that of neodymium ethylsulfate. The spin Hamiltonian for Tb^{3+} in this crystal should be given by Eq. (2), but without the term in c, and curve A was calculated on this basis, using the values of $|A|$ and P given in Eq. (6). Unfortunately, the data were not accurately reproducible using this arrangement, and we can only conclude that there is semiquantitative agreement. This technique is fraught with cryogenic difficulties, mostly involving the possibility of poor thermal contact between the Tb^{3+} spins and the Nd^{3+} spins. We also performed experiments in which a 200

gauss polarizing field was applied along the axis of the layered crystal. Here the data were fitted with curve c, using the appropriate Hamiltonian and the parameters derived above.

It is interesting to note that curves A-E represent cases in which the total average magnetic field on a Terbium ion is 0, ~100, 200, ~400, and ~600 gauss, respectively. This total average field is given by the sum of the external and internal (dipole-dipole) fields:

$$\vec{H} = \vec{H}_e + \vec{H}_i$$

In neodymium ethylsulfate $|H_i|$ takes the values 0 and 180 with equal probability, depending on whether $|T_z|$ is 0 or 1, in the absence of an external field. When a field is applied along the c axis the states with $H_i = 180$ are much more heavily populated. In the layered crystal H_i is always zero. Thus as the local field is increased the anisotropy increases monotonically because the effect of the off-diagonal elements is lessened. In the high field limit only the terms in A and P in the Hamiltonian should affect nuclear orientation. Curve F was calculated for the infinite-field limit.

Table II.

Possible U_2 ratios for the spin sequences Tb^{156} $(L_I)I$, where I is the spin of a state in Gd^{156} populated by electron-capture decay of multipolarity L from Tb^{156}.

Spin of Tb^{156}	L_{2042}	L_{1931}	$U_2(535)/U_2(1841)$
3	0	1	1.104
3	1	1	0.939
4	1	0	0.905
4	1	1	1.208

Using Nilsson wave functions (with $\eta = +6$) for the 3/2 + [411] proton state and the 3/2 - [521] neutron state,[8] and assuming no correlation between the odd particles, we obtain a theoretical magnetic moment of 2.0 nm. An alternative approach, involving the use of "quenched" g-factors for the intrinsic spins of the odd proton and neutron,[15] yields a moment of 2.1 nm., in no better agreement with experiment (using "g_p" = 4.0, g_n = -2.4). Of course in odd-odd nuclei with intrinsic spins parallel, a modest quenching of both intrinsic spins has little effect on the moment.

A useful empirical comparison is obtained by calculating the magnetic moments of Tb^{156} and Tb^{160} [3] from the measured magnetic moments of odd nucleons in the two states involved, in neighboring nuclei. The measured moment of +1.92±0.10 for Tb^{159} [4,3] provides the value for the 3/2 + [411] proton state, while the 3/2 - [521] neutron magnetic moment is obtained from the measured moments of -0.30 [16,17,18] for Gd^{155}, and (-) 0.32±0.02 for Dy^{157}. [18] Thus we would calculate μ = +1.61±0.12 for both Tb^{156} and Tb^{160} (neglecting slight differences in nuclear deformation), in good agreement with the experimental values of 1.45±0.18 for Tb^{156} and 1.60±0.25 for Tb^{160}. From this we may conclude that odd-particle correlations do not significantly affect the magnetic moments of these odd-odd deformed nuclei.

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REFERENCES

1. P. Gregers Hansen, O. B. Nielsen, and R. K. Sheline, Nuclear Physics 12, 389 (1959).
2. S. Ofer, Phys, Rev. 115, 412 (1959).
3. C. E. Johnson, J. F. Schooley, and D. A. Shirley, Phys. Rev. 120, 2108 (1960).
4. J. M. Baker and B. Bleaney, Proc. Roy. Soc. (London) A245, 156 (1958).
5. H. Postma, Miss M. C. Eversdijk Smulders, and W. J. Huiskamp, Physica 27, 245 (1961).
6. R. J. Blin-Stoyle and M. A. Grace, Handbuch der Physik, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. XLII, p.555.
7. C. J. Gallagher and S. A. Moszkowski, Phys. Rev. 111, 1282 (1958).
8. S. G. Nilsson, Kgl. Danske. Videnskab. Selskab. Mat.-fys. Medd 29, No. 16 (1955).
9. B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat-fys. Skrifter 1, No 8 (1959).
10. Amado Y. Cabezas, Ingvar Lindgren, and Richard Marrus, Phys. Rev. 122, 1796 (1961).
11. G. Bäckstrom, J. Lindskog, O. Bergman, E. Bashandy, and A. Bäcklin, Arkiv fur Fysik 15, 121 (1959).
12. H. R. Lewis, Jr., R. A. Naumann, and J. L. Power, Bull Am. Phys. Soc, 6, II, 238 (1961).
13. For a discussion of this problem, with references to other work, see Wm. Steyert, Ph.D. Thesis, California Institute of Technology, 1959.
14. For example, γ-ray anisotropies have been observed following the electron-capture decay of Sm^{145} (M. Kaplan and D. A. Shirley, unpublished data). No attenuation was observed in recent nuclear polarization experiments on Co^{57} in iron, although the intermediate state has a half-life of 10^{-7} seconds (J. G. Dash, R. D. Taylor, D. E. Nagle, P. P. Craig, and W. M. Visscher, Phys. Rev. 122, 1116 (1961).
15. J. O. Rasmussen and L. W. Chiao, in Proceedings of the International Conference on Nuclear Structure, Kingston, Canada, August 29 - Sept. 3, 1960.
16. David R. Speck, Phys. Rev. 101 1725 (1956).

REFERENCES (Con't)

17. W. Low, Phys. Rev. 103, 1309 (1956).

18. Q. O. Navarro and D. A. Shirley "Nuclear Orientation of Dy^{155} and Dy^{157}," Phys. Rev. (to be published, 1961).

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