Nuclear Orientation of La^{140}, Eu^{154}, Gd^{159}, Lu^{177}, and Lu^{177m} by Sternheimer Antishielding*

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Five rare-earth nuclei were oriented in neodymium ethyl sulfate and/or cerium magnesium nitrate lattices at very low temperatures, by utilizing the amplification of the crystal-field gradient (by a factor of $\sim 10^2$) provided by Sternheimer antishielding. The following quadrupole coupling constants P were obtained in the ethylsulfate lattice (units of 10^{-5} cm^{-1}): La^{140}, $-1.42(12)$; Eu^{154}, $-41.7(28)$; Gd^{159}, $-144(5)$; Lu^{177}, $-67(3)$; Lu^{177m}, $-13.0(12)$; and in the double nitrate lattice: La^{140}, $+1.10(16)$; Eu^{154}, $+1.5(1)$. The quadrupole moment for La^{140} was found to be $+0.127(13)$ b. The ratio of $Q(Lu^{177m})/Q(Lu^{177})$ is $+2.33(25)$. The 815-keV γ ray in Ce^{140} has $\delta(E2/M1)=-0.11(5)$, if taken *last* in cascade. The *signs* and magnitudes of (g_K-g_R) for the $\frac{7}{2}-[514]$ band and the $\frac{9}{2}+[624]$ band in Hf^{177} were determined. Of special interest is the retention of nuclear orientation through the $\sim$1-sec isomeric states in Hf^{177}.

I. INTRODUCTION

THE nuclei of paramagnetic ions in ionic crystals usually experience large hyperfine magnetic fields produced by the unpaired electrons of the ions. The resulting energy splitting of the nuclear-magnetic substates can often be used to achieve nuclear orientation at very low temperatures, the degree of orientation being governed by the temperature and the details of the electron-nucleus interactions.[1] This technique has been especially useful in orienting nuclei of rare-earth ions during the last decade. Indeed a combination of magnetic and quadrupole hfs arising from the $4f$-electron configuration should be adequate to orient eleven of the fifteen rare earths (La^{3+} through Lu^{3+}); the method has actually been used for ten of these eleven ions. The other four rare earths, La^{3+}, Eu^{3+}, Gd^{3+}, and Lu^{3+}, are not readily susceptible to this method because they show, in their usual trivalent states, either small hfs arising from $4f$ electrons [Eu^{3+},$4f^6(^7F_0)$; Gd^{3+}, $4f^7$ ($^8S_{7/2}$)], or none at all [La^{3+}, $4f^0$ ($^1S_0$); Lu^{3+}, $4f^{14}$ ($^1S_0$)]. It has been found that the quadrupole crystal-field gradient (usually denoted A_2^0) is adequate to orient nuclei of all four ions in the rare-earth ethyl sulfate lattice and that La^{3+} and Eu^{3+} can also be oriented in the "double-nitrate" lattice, because of the amplification of A_2^0 through "antishielding"[2] in the rare-earth ions. The cooling salts neodymium ethyl sulfate (NES) and cerium magnesium nitrate (CMN) were used. A detailed account of the Eu^{3+}-in-NES work has been given.[3] A preliminary report of some of the work reported here has also been made.[4] Applications of antishielded quadrupole crystal-field gradients for nuclear orientation have recently been made to Am^{3+},[5] and to Cs^+.[6] It appears that this method should permit orientation of nuclei of several other elements.

In this paper we give a detailed account of orientation experiments on La^{140} in NES and CMN, Eu^{154} in CMN, and Gd^{159}, Lu^{177} and Lu^{177m} in NES. Section II contains a brief description of the method. In Sec. III the data for each isotope are presented and discussed. Finally, in Sec. IV a short discussion is given of the applicability of this method for orienting nuclei.

II. EXPERIMENTAL

The angular distribution of gamma radiation from an oriented assembly of nuclei not subject to intermediate-state reorientation is given in general terms by

$$W(\theta)=\sum_{\nu \text{ even}} B_\nu U_\nu g_\nu F_\nu P_\nu(\cos\theta). \quad (1)$$

Here we have used the nomenclature of Frankel, Shirley, and Stone[7] where B_ν are the orientation parameters,[8] $P_\nu(\cos\theta)$ are the Legendre polynomials, and F_ν are the angular-correlation "F coefficients."[9] The U_ν describe the effect of the intermediate (unobserved) transitions, and g_ν are attenuation factors which account for the finite solid angle subtended by the detector. The terms in Eq. (1) usually fall off rapidly with increasing ν. For all cases we are to consider here the γ-ray distribution can be adequately described by the first two terms only, i.e.,

$$W(\theta)=1+B_2U_2g_2F_2P_2(\cos\theta). \quad (2)$$

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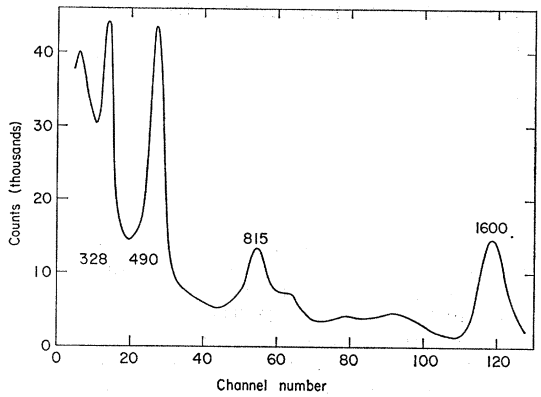

FIG. 1. Gamma-ray spectrum of La^{140} with NaI(Tl) detectors. Energies are indicated in keV.

Thus only one observation angle (usually chosen as $\theta=0$) is necessary. We usually placed an additional counter at $\theta=\pi/2$ as well. The factors U_2 and F_2 can be readily determined from the angular momenta involved in the decay and the factor g_2 has been calculated for NaI(Tl) scintillators.[10]

The energy levels of an ion governed by a spin Hamiltonian[11] $\mathcal{H}$ may be obtained from the matrix whose elements are

$$H_{ij}=\langle S_z^i I_z^i|\mathcal{H}|S_z^j I_z^j\rangle. \quad (3)$$

The orientation parameters are then defined by[8,12]

$$B_\nu=(2I+1)^{1/2}\sum_{j=1}^{N} W(E_j)$$

$$\times\{\sum_{i=1}^{N}(a_{ij})^2(-1)^{I-M_i}\langle IIM_i-M_i|II\nu 0\rangle\}. \quad (4)$$

Here E_j is the jth eigenvalue, a_{ij} is the ith coefficient of the jth eigenvector in the $|S_zI_z\rangle$ representation, and N is the size of the matrix. The population functions $W(E_j)$ are given by the Boltzmann expression

$$W(E_j)=e^{-E_j/kT}\Big/\sum_{i=1}^{N} e^{-E_i/kT}. \quad (5)$$

In practice we analyze the experiments implicitly, deducing $B_2(T)$ from the measured $W(\theta)$ and deriving hfs constants from B_2.

The samples, each consisting of a host cooling crystal of NES or CMN with the radioactive isotope isomorphously substituted into lattice sites, were cooled in a glass adiabatic demagnetization cryostat which has been described elsewhere.[13] The temperature of the crystal was determined from the susceptibility measured with a 20-cps mutual inductance bridge using the recently determined temperature scales of NES[14] and of CMN.[15] In a typical experiment, stray heating would warm the crystal from the lowest temperatures to the liquid-He bath temperature (about 0.96°K) in about 20 h in the case of NES and in about 90 min. in the case of CMN. For most nuclei, 3-in. by 3-in. NaI(Tl) detectors were used to detect the gamma rays. The extremely complex spectrum of 155-day Lu^{177m} required the use of lithium-drifted germanium detectors.

TABLE I. Gamma-ray anisotropies observed in the decay of La^{140} in CMN at $1/T=500$. The data are corrected for background, finite solid angle, and the short half-life of the source.

Gamma energy (keV)	$\frac{3}{2}B_2U_2F_2$
490	+0.0100(27)
815	−0.0180(26)
1597	+0.0194(10)

III. ALIGNMENT RESULTS

A. La^{140}

The γ-ray spectrum of La^{140} obtained with NaI(Tl) detectors is shown in Fig. 1. The quantity $\frac{3}{2}B_2U_2F_2$ in CMN at $1/T\cong 500$ is given in Table I for each of the 490, the 815, and the 1597-keV transitions. From the decay scheme (Fig. 2), it follows that the 490 and the 1597-keV transitions are pure $E2$ (with calculable F_2's of −0.448 and −0.597, respectively), while the 815-keV transition may be mixed $M1$ and $E2$. Now B_2 is the

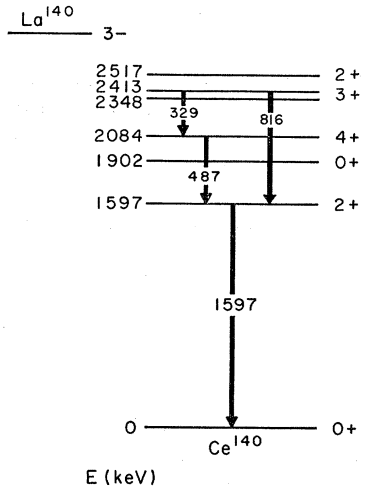

FIG. 2. Partial decay scheme of La^{140}.

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same for all transitions. Estimating $U_2 \cong 0.8$, we find $F_2(815) = +0.56 \pm 0.08$. We may compare this result with the angular correlation data for the same gamma ray. Since the 815-keV transition is the first in the cascade for angular correlations and "last" for nuclear orientation, it follows that agreement requires the same magnitude but opposite sign of the $E2/M1$ mixing ratio, δ.[12,16] The angular correlation results of various authors are shown in Table II. We observe fair agreement with Refs. 17 and 18 for our value of $\delta = -0.11(5)$. For Refs. 19, 20, and 21 no such agreement is possible, however. The absence of a large A_4 term in the angular-correlation data precludes the alternate choices of strong $E2$ mixing.

La^{3+} has no $4f$ electrons, thus no magnetic hfs interactions are possible. The spin Hamiltonian is simply

$$\mathcal{H} = P[I_z^2 - \tfrac{1}{3}I(I+1)]. \quad (6)$$

From this Hamiltonian and the value of B_2 measured for the 1597-keV transition we find $P = +0.110(16) \times 10^{-4}$ cm^{-1}. Using nuclear-magnetic-resonance techniques Edmonds[22,23] has determined P for La^{139} in the double nitrate at various temperatures and extrapolating his data to $T = 0°$K we find $|P_{139}| = 0.186 \times 10^{-4}$ cm^{-1}. Abragam and Chapellier[24] have measured $P_{139} > 0$ in the double-nitrate lattice. Combining this sign with our result, and noting that $P \propto Q/I(2I-1)$, we find $Q_{140} = +0.114(17)$ b. We have used $Q_{139} = +0.27$,[25] $I_{140} = 3$, and $I_{139} = \frac{7}{2}$.

Alignment of La^{140} in NES gave only a very small anisotropy, but with the aid of very fast stabilized counting apparatus we determined the anisotropy of the 1597-keV transition quite accurately. We find $\frac{3}{2}B_2U_2F_2 = -0.0045(4)$ at $1/T = 88$. This leads to $P = -1.42(12) \times 10^{-5}$ cm^{-1} when we use $U_2 \cong 0.8$ as before. Edmonds' value for La^{139} extrapolated to $T = 0°$K is $|P_{139}| = 1.98 \times 10^{-5}$ cm^{-1}. We thus find $Q_{140} = +0.140(19)$ b from the NES data. An average of the two results yields $Q_{140} = +0.127(13)$ b as the best value.

TABLE II. Mixing ratio for the 815-keV transition in Ce^{140} measured by angular-correlation techniques.

Reference	F_2	Acceptable values of δ	Agreement with nuclear alignment?
17	+0.166(15)	+0.045,	yes
19	+0.016(15)	−0.09,	no
20	−0.006(9)	−0.09,	no
21	+0.125(32)	$\lvert\delta\rvert < 0.02$,	no
18	+0.186	+0.06,	yes

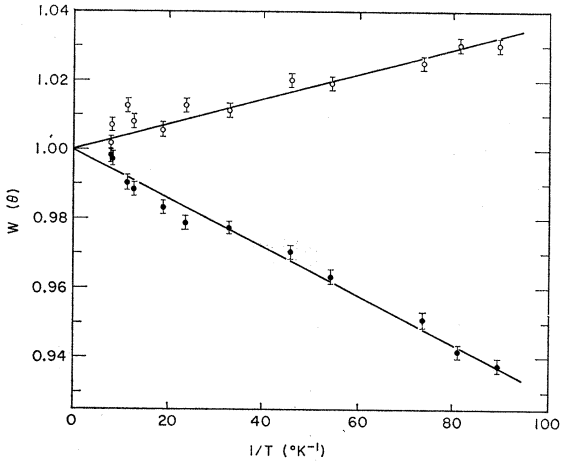

FIG. 3. $W(\theta)$ for Eu^{154} in NES at $\theta = 0°$ (filled circles) and $\theta = 90°$ (open circles). The linear dependence on $1/T$ is clearly illustrated.

B. Eu^{3+}

The alignment of Eu^{154} and Eu^{152} in NES has been reported previously.[3] We have repeated the experiment, finding $\frac{3}{2}B_2U_2F_2 = -0.098(7)$ at $1/T = 90$ for the 1277-keV transition of Eu^{154}. The larger anisotropy reported earlier[3] arose from a combination of errors in the old temperature scale for NES and an unrealistically high background correction applied to the data. For Eu^{3+} the spin Hamiltonian is represented by Eq. (6) to a good approximation. The best evidence for this is the linearity of $B_2(T)$ in $1/T$. This is shown in Fig. 3. We find $P = -4.17(28) \times 10^{-4}$ cm^{-1} from the measured anisotropy.

The alignment of Eu^{154} in CMN similarly gave $\frac{3}{2}B_2U_2F_2 = +0.019(1)$ at $1/T = 500$ for the 1277-keV transition. The corresponding quadrupole coupling constant is $P = +0.15(1) \times 10^{-4}$ cm^{-1}.

C. Gd^{159}

The temperature dependence of the anisotropy of the prominent 362-keV gamma ray of Gd^{159} is shown in Fig. 4. This gamma ray is a pure $E1$, $\frac{5}{2}^- \rightarrow \frac{3}{2}^+$ transition in Tb^{159} preceded by a pure Gamow-Teller $\frac{3}{2}^- \rightarrow \frac{5}{2}^-$ beta decay from Gd^{159}. It is therefore simple to calculate $U_2 = +0.749$ and $F_2 = +0.374$. The spin Hamiltonian for Gd^{3+} in the ethylsulfate may be written as[26]

$$\mathcal{H} = g\beta \mathbf{H}\cdot\mathbf{S} + B_2^0P_2^0 + B_4^0P_4^0 + B_6^0P_6^0 + B_6^6P_6^6 + A\mathbf{S}\cdot\mathbf{I} + P[I_z^2 - \tfrac{1}{3}I(I+1)] + CS_zT_z. \quad (8)$$

[16] S. Ofer, Phys. Rev. **114**, 870 (1959).
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TABLE III. Gamma-ray anisotropies for Lu^{177m} in NES. The average temperature of the measurements was $1/T=81$. The error in the last figure is indicated in parentheses.

Hf^{177} gamma rays			Lu^{177} gamma rays		
Gamma energy (keV)	$B_2U_2F_2$ Uncorrected	$B_2U_2F_2$ Background corrected	Gamma Energy (keV)	$B_2U_2F_2$ Uncorrected	$B_2U_2F_2$ Background corrected
105.4	+0.091(5)	+0.37(16)	121.6	−0.055(6)	−0.24(14)
113.0	+0.016(5)	+0.048(24)	268.4	−0.175(20)	−0.175(20)
128.5	+0.154(6)	+0.46(23)	318.8	−0.197(18)	−0.197(18)
153.3	+0.210(6)	+0.48(13)	413.6	−0.230(21)	−0.230(21)
174.4	+0.121(7)	+0.27(9)			
208.4	−0.090(5)	−0.090(5)			
228.5	−0.220(8)	−0.220(8)			
249.7	−0.138(11)	−0.138(11)			
281.8	−0.216(11)	−0.216(11)			
296.1	−0.138(43)	−0.138(43)			
327.4	−0.210(16)	−0.210(16)			
378.2	−0.303(13)	−0.303(13)			
418.2	−0.223(18)	−0.223(18)			
465.0	−0.216(64)	−0.216(64)			

The energy spacing of the electronic levels is shown in Fig. 5. In the absence of a magnetic field all terms in Eq. (8) are negligibly small compared to B_2^0 which is given in Ref. 26 as $B_2^0=0.0067$ cm^{-1}. The operator P_2^0 is defined as $[3S_z^2-S(S+1)]$. With this Hamiltonian the doublet with $S_z=\pm\frac{1}{2}$ will lie lowest by 0.04 cm^{-1} as shown in Fig. 5. The Nd^{3+} neighbors set up a dipole-dipole field at the Gd^{3+} site which can be handled in a straightforward way,[12,13] through the term CS_zT_z in Eq. (8). This Hamiltonian has been used to calculate the temperature dependence of B_2 in terms of P. For this calculation we have used $A=0.5\times10^{-3}$ cm^{-1},[27] $g=1.99$, $S=\frac{7}{2}$, and $I=\frac{3}{2}$. An IBM 7094 computer performed the numerical calculations, giving a satisfactory fit to the experimental data for $P=-1.44(5)\times10^{-3}$ cm^{-1}.

No observable effect was seen when Gd^{159} was aligned in CMN. We can place an upper limit on the anisotropy of $|B_2U_2F_2|<0.004$ at $1/T=500$. It is possible, of course, that the Gd^{3+} actually does not grow substitutionally into the CMN lattice. For the heavier rare earths, there is always the possibility that most of the activity is merely incorporated in "brine holes" in the crystal interior rather than being an integral part of the lattice. In such a case, the ions would not feel the crystal field and no alignment would be expected.

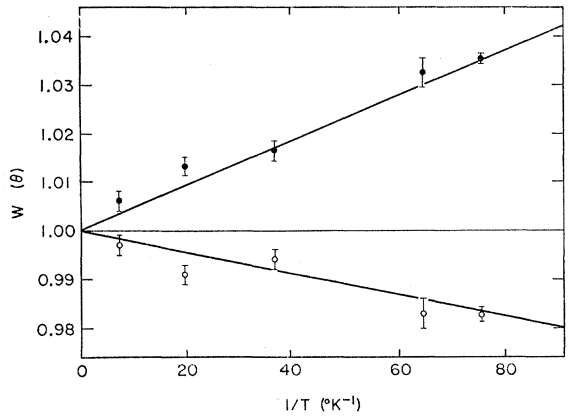

FIG. 4. $W(\theta)$ versus $1/T$ for Gd^{159} in NES at $\theta=0°$ (filled circles) and $\theta=90°$ (open circles).

D. Lu^{177} ($7d$)

The complete Lu^{177} decay scheme is shown in Fig. 6.[28,29] The temperature dependence of anisotropy of the

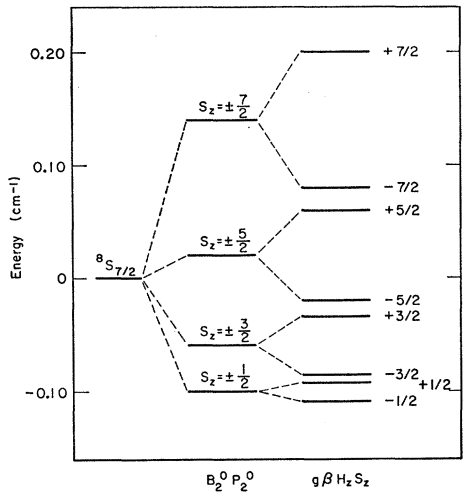

FIG. 5. Spacing of the electronic levels of the Gd^{3+} ion in an NES lattice. The terms of the spin Hamiltonian responsible for the splitting are indicated along the abscissa. Here, H_z represents the dipole-dipole field of 184 G due to the Nd^{3+} neighbors.

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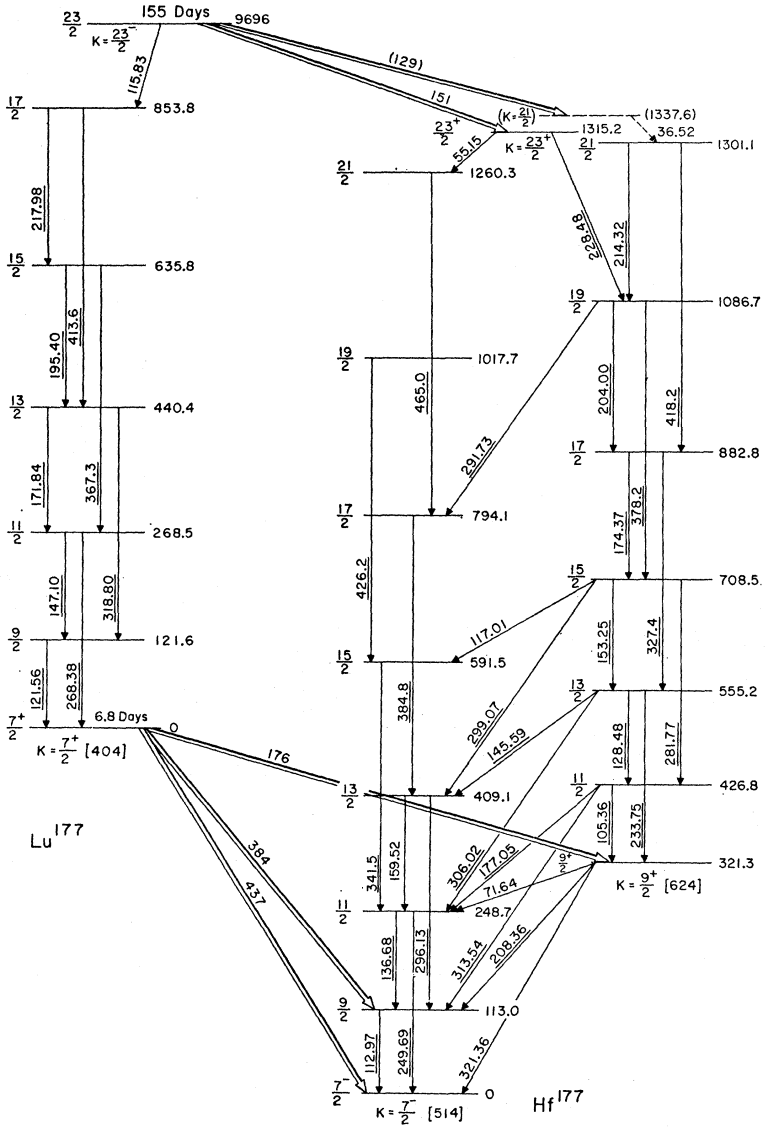

FIG. 6. Decay scheme of Lu^{177} from Refs. 28 and 29. Only the underlined transitions were observed in the Ge (Li) spectrum.

208-keV and the 113-keV gamma rays from 7-day Lu^{177} aligned in NES are shown in Figs. 7 and 8. We note that the 208-keV peak has pure $E1$ multipolarity, while the

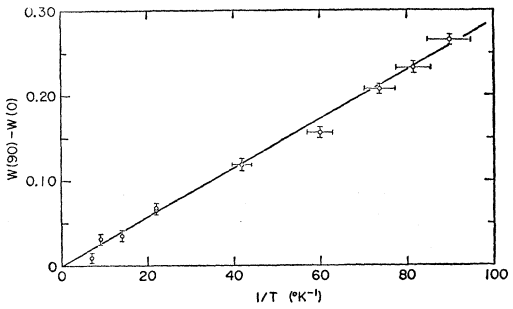

FIG. 7. $-\frac{3}{2}B_2U_2F_2$ for the 208-keV gamma ray of Lu^{177} aligned in NES. The linear dependence on $1/T$ is evident.

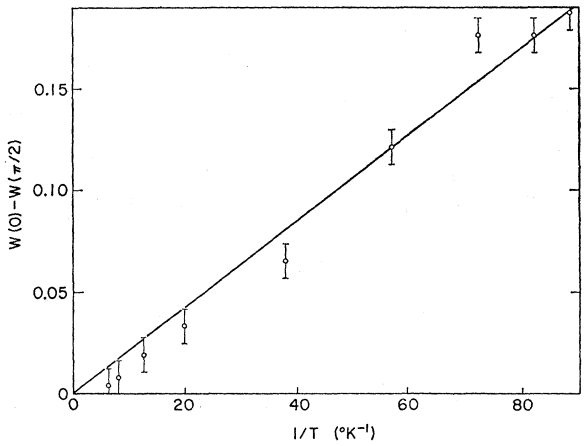

FIG. 8. $\frac{3}{2}B_2U_2F_2$ for the 113-keV gamma ray of Lu^{177} aligned in NES showing the characteristic linear dependence on $1/T$.

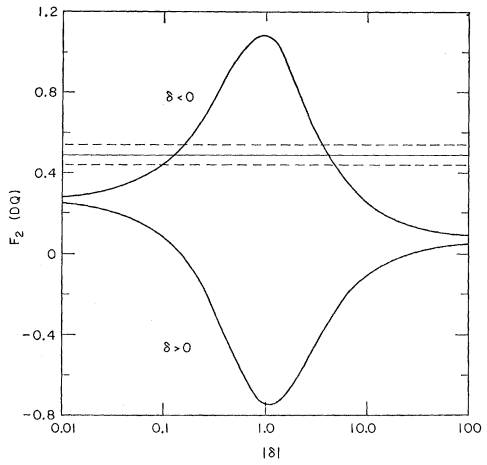

FIG. 9. Theoretical F_2 versus δ for the mixed transition $9/2^-(M1,E2)7/2^-$, in Hf^{177}. The experimental F_2 is shown as a horizontal line with error limits indicated by the dashed lines.

113-keV peak is a mixed $M1$-$E2$, $\frac{9}{2}^- \rightarrow \frac{7}{2}^-$ transition. Using $U_2=+0.925$ for the 208-keV transition and $U_2=+0.870$ for the 113-keV transition, we find on comparing the anisotropies a value $F_2^{(113)}=+0.343(34)$. In Fig. 9 is plotted F_2 as a function of the mixing ratio for this transition. Since transitions in the $\frac{7}{2}^-$ rotational band of Hf^{177} are characterized by a large degree of $E2$ character,[28] we select the branch giving the larger $\delta(E2/M1)=-4.7_{+0.4}{}^{-0.8}$. From the expression[28]

$$\frac{1}{\delta^2}=\frac{(g_K-g_R)^2}{Q_0^2}\frac{(2I+2)(2I-2)}{E_\gamma{}^2}(2.87\times10^5). \quad (9)$$

We calculate $(g_K-g_R)^2=0.0012(2)$ using $Q_0=6.74$.[30] Since the sign of (g_K-g_R) is the same as that of δ,[31] we find $(g_K-g_R)=-0.034(1)$ for the $\frac{7}{2}^-[514]$ rotational band.[32] Using $g_R=+0.215(14)$ we find $g_K=+0.18(2)$ in good agreement with Bernstein and de Boer's value of $g_K=0.162(10)$,[31] but with the sign determined.

The Lu^{3+} ion has a completely filled $4f$ shell so no magnetic interactions are possible. The Hamiltonian is thus the same as for La^{3+}, and from the anisotropy of the 208-keV gamma ray we find $P=-6.7(3)\times10^{-4}$ cm^{-1}.

For Lu^{177} aligned in CMN the γ-ray anisotropy, if any, was too small to measure. If the activity actually grew into the rare-earth lattice sites, we may set $|B_2U_2F_2|<0.003$ at $1/T=500$ as an upper limit.

E. Lu^{177m} (155 day)

We have aligned the long-lived isomer of Lu^{177} in NES using Ge (Li) detectors to measure the anisotropy of many of the gamma rays in this complex spectrum.[29]

In Table III we show the quantities $B_2U_2F_2$ obtained by counting with one Ge (Li) detector parallel to the crystal axis. We note that there is no noticeable difference in anisotropy between the Hf^{177} and the Lu^{177} gamma rays. The decay scheme (Fig. 6) requires the cascades to go through two isomeric high-K states in Hf^{177}. A technique involving rapid chemical separation from Lu^{177m} has shown that at least one of these has a half-life of $t_{1/2}=1.06$ sec.[33] It is interesting that there is no reorientation in this isomeric Hf^{177} intermediate state during its 1-sec lifetime.

From the anisotropy of the 413-keV gamma ray we have calculated the ratio of the nuclear quadrupole moments of Lu^{177m} and of the 7-day ground state, Lu^{177g}. For the 413-keV gamma ray of Lu^{177m} we have $B_2U_2F_2=-0.230(21)$ at $1/T=81$. From this value we calculate $P=-1.30(12)\times10^{-4}$ cm^{-1} using $U_2=+0.937$ and $F_2=-0.378$. Since we found $P=-6.7(3)\times10^{-4}$ cm^{-1} for the 7-day ground state, we obtain

$$\frac{Q^m}{Q^g}=\frac{[PI(2I-1)]_m}{[PI(2I-1)]_g}=\frac{-1.30}{-6.7}\frac{(23/2)22}{\frac{7}{2}\times6}=2.33(25).$$

Using $Q_0{}^g=7.8$ estimated by Townes[34] we find $Q^g=3.6$. On this basis the quadrupole moment of the 23/2 level becomes

$$Q^m=2.33\times3.6=8.4(10)\text{ b},$$

from which $Q_0{}^m=10.8(13)$ b.

A comparison of the anisotropies of the $I\rightarrow I-2$ and the $I\rightarrow I-1$ transitions originating from the same state will yield the $M1-E2$ mixing ratio for the $I\rightarrow I-1$ transition. Since B_2 and U_2 are the same for the cascade and the crossover transitions, the ratio of

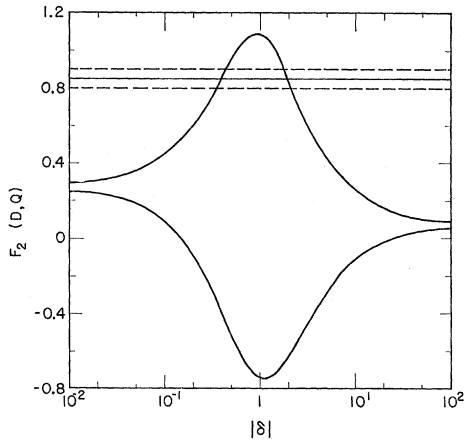

FIG. 10. Theoretical F_2 versus δ for the $15/2^+(M1,E2)13/2^+$ transition in Hf^{177}. The experimental F_2 with limits of error is shown as in Fig. 9.

[30] O. Hansen, M. C. Olesen, O. Skilbreid, and B. Elbek, Nucl. Phys. **25**, 634 (1961).
[31] E. M. Bernstein and J. de Boer, Nucl. Phys. **18**, 40 (1960).
[32] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **29**, No. 16 (1955).
[33] E. Bodenstedt, P. Meyer, L. Schanzler, M. Forker, H. Wagner, and J. Radeloff, Physikal. Verhandlungen **5**, 87 (1965).
[34] C. H. Townes, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 381, p. 377.

the anisotropies equals the ratio of the F_2's. Although in principle one can do this for each pair of transitions in each of the three rotational bands populated in the decay of Lu^{177m}, the experimental resolution is such that only the 153–281 pair and the 174–327 pair have both members sufficiently well resolved to measure the anisotropy with good reliability. For the 153 keV, $15/2 \rightarrow 13/2$ transition we have

$$F_2(153)=\frac{+0.478}{-0.216}F_2(281)$$

$$=\frac{+0.478}{-0.216}(-0.3856)=+0.853(54).$$

Figure 10 shows the ranges of δ satisfied by this value of F_2. The transition is expected to be largely $M1$ from a comparison with the analogous state in Hf^{179}; thus we favor the smaller value of δ. We thus find $\delta=-0.39(4)$ and from Eq. (9) we calculate $(g_K-g_R)/Q_0=-0.049(5)$. Using $Q_0=6.85$ from the analogous state in Hf^{179}, we find $(g_K-g_R)=-0.335(34)$.[30] Taking $g_R=+0.203(34)$ from Bernstein and de Boer for Hf^{179} yields $g_K=-0.13(5)$. The theoretical value for this $\frac{9}{2}+[624]$ band based on the Nilsson model is $g_K=-0.35$. Theory and experiment can be brought into agreement if we choose an effective spin g factor which is 50% of the free neutron value as suggested by Rasmussen and Chiao.[35]

For the 174 keV, $17/2 \rightarrow 15/2$ transition we obtain in analogous fashion

$$F_2(174)=\frac{+0.274}{-0.210}F_2(327)$$

$$=\frac{+0.274}{-0.210}(-0.3776)=+0.493(52).$$

[35] J. O. Rasmussen and L. W. Chiao, *Proceedings of the International Conference on Nuclear Structure, Kingston, Canada* (University of Toronto Press, Toronto, 1960), p. 646.

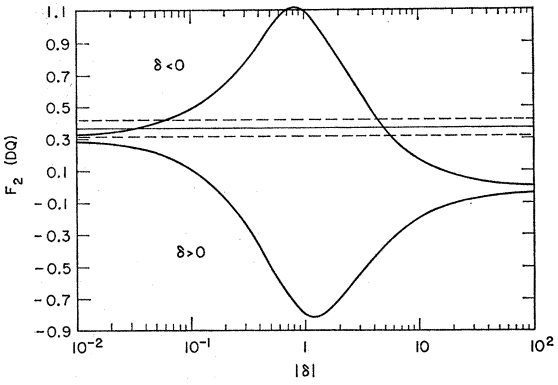

FIG. 11. Theoretical F_2 versus δ for the $17/2^+(M1,E2)15/2^+$ transition in Hf^{177}. The experimental F_2 with limits of error is shown as in Fig. 9.

Figure 11 shows the ranges of δ satisfied by this value of F_2. Again using only the smaller value of δ we have $\delta=-0.13(3)$ from which $(g_K-g_R)/Q_0=-0.047(11)$. Using $Q_0=6.85$ and $g_R=+0.203(34)$ as above we find $g_K=-0.12(8)$.

All members of a rotational band should have the same value of g_K. For the two cases calculated above we find that this is indeed the case for the $\frac{9}{2}^+[624]$ rotational band in Hf^{177}, to within the accuracy of our measurements.

IV. DISCUSSION

The specifically nuclear results are discussed above. Systematic trends for rare-earth ethyl sulfates are discussed elsewhere.[36] We conclude from the foregoing that quite appreciable quadrupole coupling constants can be expected for heavy ions through antishielding of the external crystal-field gradient in noncubic crystals. This nuclear-orientation mechanism[37] is thus of considerably more practical importance than it was previously thought to be.

[36] J. Blok and D. A. Shirley, Phys. Rev. **143**, 278 (1966).
[37] R. V. Pound, Phys. Rev. **76**, 1410 (1949).