for copper, the residual nucleus in our (α,p) experiment, we obtain $a=4.7$, which is very good agreement with the value of 4.4 obtained in this experiment.

$S(\alpha,E)$ is related to the level density of the residual nucleus. For (p,p') the residual nucleus is even-even, while for (α,p) the residual nucleus is odd-even. The odd-even nucleus has a level density estimated to be five times that of an even-even nucleus.[2] Thus $S(\alpha,E)$ for (p,p') shows much structure, while $S(\alpha,E)$ for (α,p) is very smooth. However, if we average the (p,p') data over 1-Mev energy intervals, most of the detailed structure is smoothed out and we may attempt to obtain level density information by applying statistical theory. Figure 7 is a plot of $S(\alpha,E)$ for (p,p') scattering on Ni as a function of $\sqrt{E}$. When this curve is fitted with a straight line, the result $a=2.4$ is obtained. This small value of a is consistent with smaller level densities that are observed for even-even nuclei.

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Nuclear Moment of Ce^{137m} by Nuclear Alignment*

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Nuclei of Ce^{137} and Ce^{137m} have been aligned at low temperatures in a single crystal of neodymium ethylsulfate nonahydrate by means of the magnetic hfs coupling with the electrons of the Ce^{+3} ions. The anisotropy of their gamma radiation has been observed. The magnetic moment of Ce^{137m} is $|\mu_N|=0.96\pm0.09$ nm. The spin of Ce^{137m} is established as 11/2.

1. INTRODUCTION

Cerium-137 is one of a large group of nuclides which has an $h_{11/2}$ isomeric state that decays by emission of $M4$ radiation to a $d_{3/2}$ ground state. Brosi and Ketelle[1] have studied this isomeric transition and the electron-capture decay of the ground state to La^{137} by gamma-ray, coincidence, and conversion-electron-spectroscopic techniques. Their results lead to the energy-level scheme shown in Fig. 1. A $g_{7/2}$ orbital was assigned to the ground state of La^{137} from its observde second-forbidden beta decay to Ba^{137} (spin 3/2), and a $d_{5/2}$ state to the first excited state from the $M1$ character of the 10-kev gamma ray. The shell model is in good agreement with these assignments, and further predicts that the 455-kev level is either in a $s_{1/2}$ or a $d_{3/2}$ state.

We have measured the magnetic moment of Ce^{137m} by aligning Ce^{137m} nuclei and measuring the anisotropic distribution of the gamma radiation. Further information was obtained about the decay scheme of Ce^{137}, which was also aligned.

2. EXPERIMENTAL PROCEDURE

Cerium-137m was prepared by a $(p,3n)$ reaction of 21-Mev protons on natural lanthanum (99.911% La^{139}) in the ORNL 86-inch cyclotron. Cerium was separated from the target material by oxidation to the +4 state, followed by solvent extraction,[2] which yielded about 10^{12} atoms of Ce^{137m}. The cerium was then reduced to the +3 state and grown into a single crystal of neodymium ethylsulfate nonahydrate so that it replaced some of the Nd^{+3} ions. The crystal was mounted in

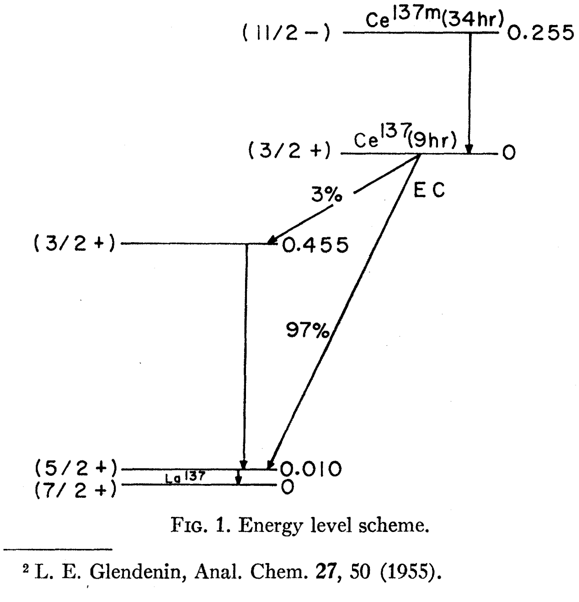

Fig. 1. Energy level scheme.

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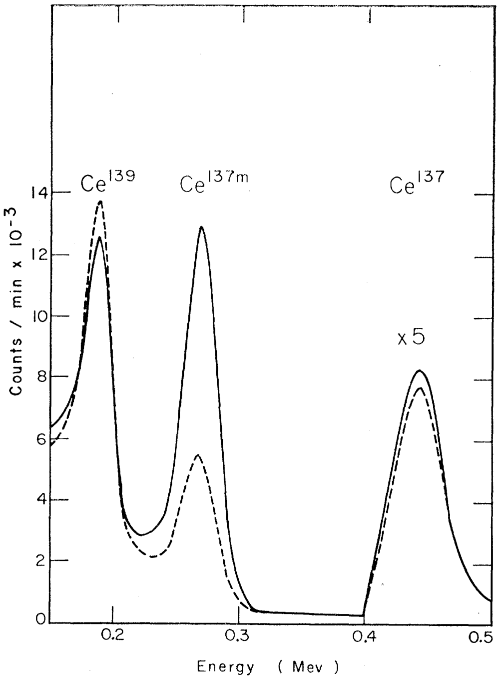

FIG. 2. Gamma-ray pulse-height spectrum at 1.1°K (solid line) and at 0.02°K (dashed line).

a demagnetization cryostat. Previous experiments[3,4] on Ce^{139} and Ce^{141} had shown that nuclear alignment of the cerium isotopes was produced by cooling such a crystal to very low temperatures.

The crystal was cooled by adiabatic demagnetization from 1.1°K and fields of up to 18 000 gauss. The intensity of the gamma radiation was measured at several temperatures between 0.02- and 1.1°K for a series of angles θ defined by the direction of propagation of the gamma radiation with respect to the trigonal axis of the crystal. The gamma rays were counted using 3-×3-in. NaI(Tl) crystals and 100-channel pulse-height analyzers. The spectrum obtained is shown in Fig. 2. The peaks due to the 255-kev isomeric transition of Ce^{137m}, the 445-kev gamma ray of La^{137}, and the 165-kev gamma ray of La^{139} (from the decay of Ce^{139}, which was present as an impurity) are clearly resolved. The decay of these gamma rays was followed over 10 half-lives of the Ce^{137m}, and no other peaks were observed.

The magnetic temperature of the crystal after demagnetization was determined by measuring the mutual inductance of a pair of coils surrounding the crystal, using a 20-cycle/sec ac mutual-inductance bridge. The coils were calibrated in the liquid helium range of 4.2 to 1.1°K against a helium vapor-pressure thermometer. From the data of Meyer,[5] the absolute temperatures T reached after an adiabatic demagnetization from an initial temperature $T_i = 1.1$°K, and various fields of H_i were known. A correlation between T and T^* was determined by extrapolating our value of the magnetic temperature T^* to the time of demagnetization.

The time taken for the temperature to rise from the lowest temperatures reached to that of the helium bath (1.1°K) was over an hour, but in order to avoid errors due to inhomogeneous heating of the crystal, the gamma-ray counting and the susceptibility measurements were continued for only one minute after the demagnetization. The crystal was then warmed to 1.1°K by the introduction of helium exchange gas. A further one-minute gamma-ray count at 1.1°K was then taken for normalization. The gamma radiation was isotropic within experimental error at this temperature. The gamma-ray counting rates were corrected for background and finite counter size effects,[6] and the anisotropies $\epsilon = 1 - I(0\ \text{deg})/I(90\ \text{deg})$, were evaluated as a function of temperature.

3. RESULTS

The anisotropy of the 255-kev gamma ray of Ce^{137m} plotted versus $1/T$ is shown in Fig. 3.

The intensity of the 255-kev gamma ray at 0.018°K is shown as a function of θ in Fig. 4. This angular distribution, expressed in Legendre polynomials, was found to be

$$I(\theta) = 1 - (0.70 \pm 0.06) P_2(\cos\theta) + (0.05 \pm 0.01) P_4(\cos\theta). \quad (1)$$

At the same temperature, the intensity angular distribution of the 445-kev gamma ray was

$$I(\theta) = 1 - (0.10 \pm 0.02) P_2(\cos\theta),$$

and the 165-kev gamma ray of Ce^{139} showed an anisotropy of approximately -0.13 ± 0.03. The latter result agrees with the data of Grace *et al.*[3]

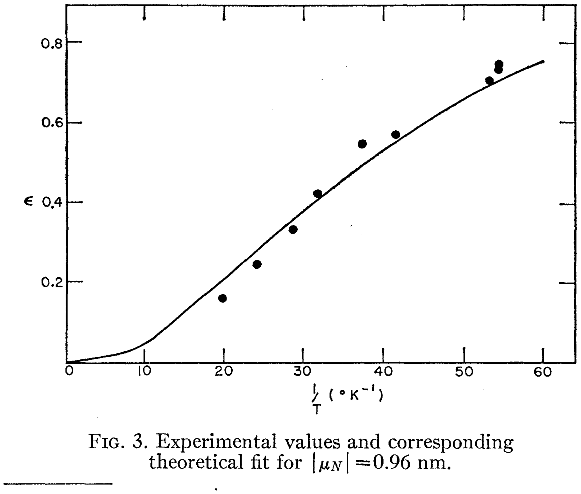

FIG. 3. Experimental values and corresponding theoretical fit for $|\mu_N| = 0.96$ nm.

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4. DISCUSSION

Determination of the Magnetic Moment of Ce^{137m}

The angular distribution of gamma radiation from aligned nuclei is given[7] by

$$I(\theta)=1+B_2U_2F_2P_2(\cos\theta)+B_4U_4F_4P_4(\cos\theta)+\cdots. \quad (2)$$

The B_k's are a measure of the degree of orientation of the parent nucleus. The U_k's describe the amount of nuclear re-orientation that takes place during any unobserved beta or gamma transitions preceding the observed gamma ray. The F_k's are constants determined by the multipolarity and the initial and final spins of the observed gamma transition.

The crystal field-theory of Ce^{+3} in the ethylsulfate lattice has been worked out in detail by Elliott and Stevens,[8] and only a brief account will be given here.

The free ion Ce^{+3} has the configuration $4f^1$ and the ground term is $^2F_{5/2}$. In a trigonal crystalline field this term is split into doublets which may be characterized in the first approximation by $|\pm J_z\rangle$. In the ethylsulfate lattice, however, the lowest Kramers' doublet which is made mostly of the state $|\pm 5/2\rangle$, contains in addition, admixtures of other states from the $^2F_{5/2}$ ground term as well as from the next term $^2F_{7/2}$. It is, of course, essential that these admixtures be taken into account in calculating the nuclear magnetic-moment from hyperfine-structure constants.

The effective spin-Hamiltonian for the lowest Kramers' doublet of Ce^{137m} in the ethylsulfate is

$$\mathcal{H}=AS_zI_z+B(S_xI_x+S_yI_y)+P[I_z^2-\tfrac{1}{3}I(I+1)].$$

The last term can be shown to have a negligible effect on nuclear alignment in this case, by using the theory of Elliott and Stevens[9] to calculate P and by using $Q=0.3$ barn for an $(h_{11/2})^9$ neutron configuration.[10] The terms in B alter the energy levels of the hyperfine-structure multiplet slightly, and this has been taken into account. The energy levels of this multiplet then given approximately by twelve doublets $|\pm I_z\rangle$, separated by $A/2$. In going from 1.1 to 0.02°K the percentage of the Ce^{137m} nuclei occupying the lowest doublet changes from 8.3% to 37%.

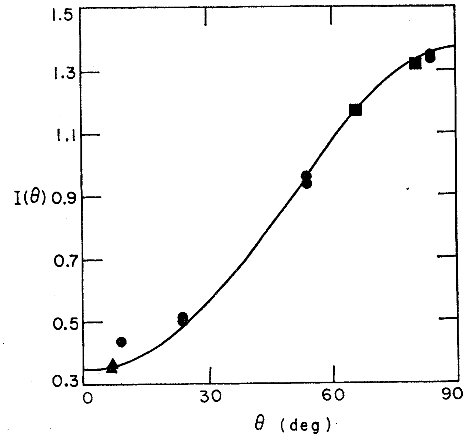

FIG. 4. Angular distribution of the 255-kev γ ray at 0.018°K. The line corresponds to $I(\theta)=1-0.70\ P_2(\cos\theta)+0.05\ P_4(\cos\theta)$. ● 1st quadrant, ■ 2nd quadrant, ▲ 4th quadrant.

For the 255-kev isomeric transition in Ce^{137m} there are no unobserved preceding transitions, and $U_2=U_4=1$. Thus, Eq. (2) becomes

$$I(\theta)=1-0.8890B_2P_2(\cos\theta)+0.4434B_4P_4(\cos\theta),$$

for the spin sequence $11/2 \xrightarrow{M4} 3/2$ or

$$I(\theta)=1-0.7444B_2P_2(\cos\theta)+0.1693B_4P_4(\cos\theta)$$

for the spin sequence $9/2 \xrightarrow{M4} 3/2$. The functions B_2 and B_4 depend on the single parameter $\beta=A/2kT$, and by varying A it is possible to fit the temperature dependence of the anisotropy for either spin sequence. Using the values of A which best fit the temperature dependence, we have calculated the angular distribution of the 255-kev γ ray at 0.018°K from each of the above expressions. The results are:

$$I(\theta)=1-0.65P_2(\cos\theta)+0.04P_4(\cos\theta), \quad \text{for } I=11/2, \quad (3)$$

$$I(\theta)=1-0.60P_2(\cos\theta)+0.02P_4(\cos\theta), \quad \text{for } I=9/2. \quad (4)$$

Comparison with Eq. (1) shows that (4) is in disagreement with it. Thus the spin possibility of 9/2 is eliminated for Ce^{137m}. We are not aware of any direct measurements of the spin of 11/2 for the $h_{11/2}$-$d_{3/2}$ isomers, therefore this measurement offers the most direct evidence available for this spin assignment.

The value for A obtained in (3) above is $|A|=0.0129$ cm^{-1}. By use of the theory of Elliott and Stevens for the ground doublet, together with the value of $\langle r^{-3}\rangle$ obtained by Judd and Lindgren,[11] we calculate

$$A=0.074\ \mu_N/I\ \text{cm}^{-1}, \quad B=0.002\ \mu_N/I\ \text{cm}^{-1}.$$

Comparison with our value for A yields

$$|\mu_N|=0.96\pm0.09\ \text{nm}.$$

The limits of error were obtained from the scatter of the experimental points.

Because this is the first nucleus with $I=11/2$ for which the magnetic moment has been measured, we have included (Fig. 5) the Schmidt diagram for even-

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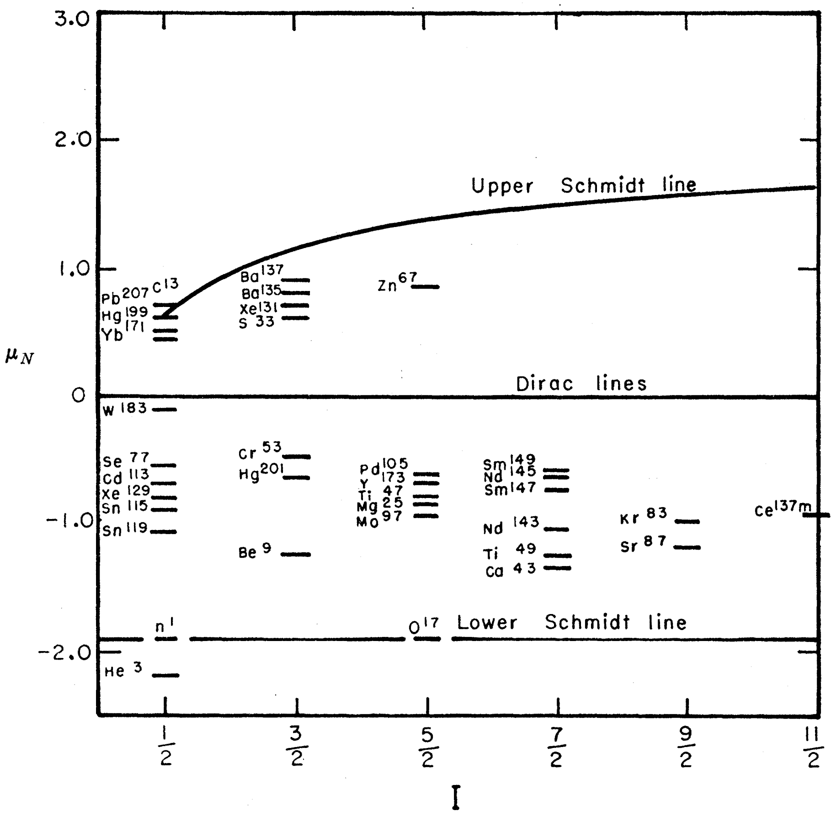

FIG. 5. Schmidt diagram for nuclei with an unpaired neutron.

odd nuclei. The moments for nuclei with $j<11/2$ were taken from the Table of Isotopes.[12] We note that Ce^{137m} follows the trend in that the magnetic moment is about halfway between the Schmidt limit and the Dirac limit.

Nuclear Alignment of Ce^{137}

Since the half-life of Ce^{137} (9 hours) is long compared with the nuclear spin-lattice relaxation time, the anisotropy of its gamma radiation does not depend on the preceding isomeric transition of Ce^{137m}.

Our observation of an anisotropy in the 445-kev gamma ray immediately shows that the 455-kev state of La^{137} cannot have a spin of 1/2, because this would show an isotropic gamma-ray distribution. Thus the spins 3/2 or 5/2 are consistent with our data. This spin assignment and a determination of the magnetic moment of Ce^{137} could be made from a measurement of the plane polarization of the 445-kev gamma ray in addition to its anisotropy. From the present data it is concluded that if the 455-kev level has a spin of 3/2, then the gamma ray must be a mixed $M1$-$E2$ radiation with $\delta(E2/M1)<0$.

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