ORIENTED OF Tb^{160} *NUCLEI IN METALLIC TERBIUM*

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Tb^{160} nuclei were polarized in a polycrystalline sample of metallic terbium which is ferromagnetic below 218°K. The sample was cooled to 0.03—0.04°K by adiabatic demagnetization of potassium chrome alum. Co^{60} was employed as the thermometer. Anisotropy of the angular distribution of 298-keV γ-rays was measured. The hyperfine splitting constant was determined, $A = 0.054 \pm 0.007$°K.

INTRODUCTION

RECENT investigations [1-4] have shown that the internal magnetic fields of ferromagnets can be used for polarization of nuclei at low temperatures. Since some rare-earth metals are ferromagnetic at low temperatures, it is to be expected that they, too, can be used in experiments on oriented nuclei. Recent experiments with metallic holmium [5,6] have confirmed this possibility. The Ho^{165} nuclei were polarized in metallic holmium, a fact detected by the scattering of the polarized neutrons.

In the present investigation we attempted to orient the nuclei of metallic terbium. The polarization of Tb^{160} nuclei was determined from the anisotropy of the angular distribution of 298-keV γ radiation. Terbium is a convenient object for investigation, since its magnetic properties have been sufficiently well investigated, and measurements of the nuclear specific heat yielded a large value of the effective magnetic field on the nucleus [7]. However, it must be kept in mind that unlike ferromagnets of the iron group, very large magnetic fields are necessary to saturate rare-earth elements.

THE SAMPLE AND ITS MAGNETIC PROPERTIES

The sample investigated was filed from a piece of metallic terbium in the form of a disc 3 mm in diameter and 0.3 mm thick. The terbium contained the following chemical impurities: Y—1.2%, Gd—0.8%, Ca < 0.004%, Cu—0.05%, and Fe—0.009%. The sample was irradiated in a reactor and the induced activity of Tb^{160} amounted to $\sim 50\,\mu$Ci.

To calculate the degree of polarization of the nuclei it is necessary to know the real magnetization of the sample in the working magnetic field. The magnetization curve of the investigated sample was measured at 4.2°K in fields up to 10 kOe[1)]. In recent measurements with terbium single crystal [8] it was observed that some magnetization anisotropy occurs in the terbium, and the direction of easiest magnetization is the crystal axis b $(10\bar{1}0)$. The maximum atomic magnetic moment along this direction is $\mu_a = 9.34\,\mu_B$. This quantity was used as the basis in the calculation of the real magnetization of the sample. The degree of magnetization of the sample, determined from the ratio to the saturation magnetization of the single crystal, amounted to $M/M_{sat} = 0.63$ in an external field of 10 kOe.

CRYOSTAT AND RECORDING APPARATUS

The cryostat, containing the paramagnetic salt and the sample, is shown in Fig. 1. A block of magnetic salt which serves to cool the sample is placed in a brass ampoule situated inside a Dewar with liquid helium. The sample is at the end of a cold duct comprising a copper rod 5 mm in diameter, the other end of which is pressed into the paramagnetic-salt block. To increase thermal contact between the salt and the cold duct, brass foil strips were soldered to the latter. Thermal contact between the salt and the helium bath was made by admitting into the ampoule helium gas, which was pumped out prior to demagnetization with the aid of an adsorption carbon pump. Usually in experiments of this type the sample is soldered to the

[1)]The measurements were made by V. Sokolov in the Laboratory of Prof. K. P. Belov in the Physics Department of Moscow State University.

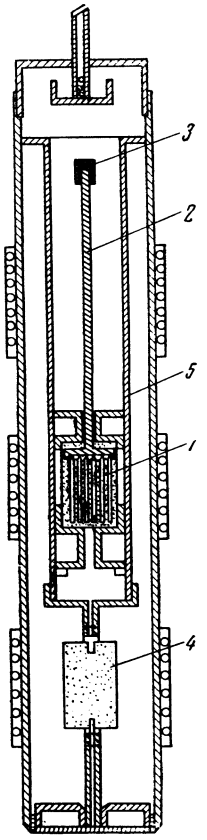

FIG. 1. Section through the ampoule: 1—cooling salt, 2—cold duct, 3—sample, 4—"guarding" salt, 5—Plexiglas holder.

cold duct. Since metallic terbium cannot be wetted with ordinary solders, the thermal contact with the cold duct was produced in the following manner: the sample was pressed against the end of the cold duct by means of a copper cup which fitted tightly over the cold duct and which was soldered with indium. The inside of the cup was also filled with molten indium.

The salt and sample were magnetized with an electromagnet which produced a maximum field of 23 kOe at the location of the salt. Following demagnetization of the paramagnetic salt, the cryostat was lowered by means of a special mechanism, leaving the salt in the shield of the magnet and the sample in the gap between the pole.

The registration of the γ radiation was by means of three scintillation spectrometers with NaI(Tl) crystals 30 mm in diameter and 40 mm thick and an FÉU-13 photomultiplier. The photomultipliers were placed in channels cut in the cover of the magnet and in the pole pieces, and two of the multipliers registered the radiation parallel to the direction of the magnetic field (angle 0 and 180°), while one registered at an angle 90° to this direction. The photomultipliers were screened against the stray magnetic field by means of permalloy and iron shields.

The temperature of the salt was measured by a ballistic method, and the data of Daniels and Griffith's [9] were used to calculate the thermodynamic temperature of potassium chrome alum.

ANISOTROPY OF Tb^{160} γ RADIATION

To determine the degree of polarization of the Tb^{160} nuclei, the 298 keV ($2^- \rightarrow 2^+$) γ transition was chosen, being a pure E1 transition [10]. The Hamiltonian of the interaction for the hyperfine structure has the form $\mathcal{H} = A \langle J_z \rangle I_z$, where I is the spin of the nucleus and $\langle J_z \rangle$ the averaged value of the moment of the electron shell for the ferromagnetic state. The degree of polarization of the nuclei is described by the Brillouin function*

$$f_1 = B_I\left(\frac{A}{2T}\right) = \frac{2I+1}{2I}\,\mathrm{cth}\left(\frac{2I+1}{2}\beta\right) - \frac{1}{2I}\,\mathrm{cth}\left(\frac{\beta}{2}\right),$$

where $\beta = A/2T = \mu H/IkT$. Here μ—magnetic moment of the nucleus, H—effect of the magnetic field, k—Boltzmann's constant, and T—temperature.

The angular distribution of the 298 keV γ rays is described by

$$W(\theta) = 2\,(1 - {}^3/_2 B_2 K_2 f_2 P_2(\cos\theta)).$$

Here $f_2 = 2(I+1)/3I - 1/I \coth(\beta/2) \times f_1$, $K_2 = I/(I+1)$, and B_2 is a function that takes into account the depolarization of the nuclei as a result of the preceding β decay. Since the spins of the initial and final states of the nucleus are known, we can determine from the measured angular distribution the value of the orientation parameter f_2. In the calculation of B_2 it was assumed that an angular momentum L = 1 is carried away in the β decay (allowed β transition).

MEASUREMENT PROCEDURE AND RESULTS

Following the demagnetization of the paramagnetic salt, a magnetic field was applied to the sample and the intensity of the γ counts at angles 0° (180°) and 90° to the direction of the magnetic field was determined. The measurements were made for approximately 1 hour, the readings being taken every 90 or 150 seconds. The salt was then warmed up to the temperature of the helium bath (~ 1.3°K) and the normalization count was determined for a short period of time. Typical results of the measurement of the angular anisotropy of the γ rays are shown in Fig. 2. In the reduction

*cth = coth.

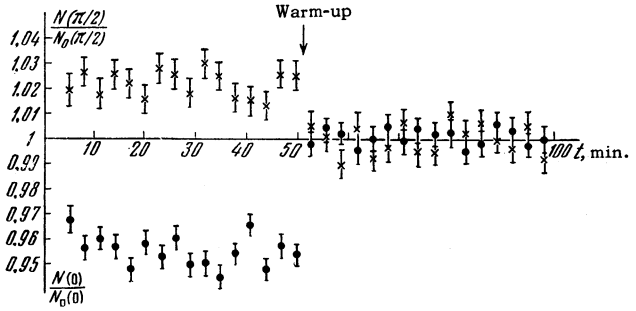

FIG.2. Measured anisotropy of the angular distribution of the 298 keV γ radiation of Tb^{160} as a function of the time following the demagnetization. H_{ext} = 10 kOe; ● – $\theta = 0°$, × – $\theta = 90°$.

of the results it was assumed that the sample temperature was equal to the salt temperature.

When determining the orientation parameters f_1 and f_2 it is necessary to take into account the fact that the sample is not magnetized to saturation, and the results must therefore be corrected for the incomplete magnetization. Actually, $f_k = \langle f_k \rangle / K$, where K is the degree of magnetization of the sample, $\langle f_k \rangle$ the effective nuclear polarization, and f_k the polarization existing inside the domain. In addition, a correction was introduced for the contribution of the harder γ quanta in the investigated portion of the spectrum, and the value of f_2 was then calculated. The resultant value of f_2 was used to determine the hyperfine splitting constant A, which was found to be equal to 0.056 ± 0.006°K (the error given here does not include the inaccuracy in the determination of the thermodynamic temperature of the salt).

MEASUREMENTS WITH Co^{60}

In experiments of this type there are always doubts whether the temperature of the sample was correctly determined from the temperature of the cooling salt. To monitor the temperature directly on the sample, permendur (alloy of 50% cobalt and 50% iron) was placed directly on the surface of the terbium sample, in the form of a disc 3 mm in diameter and 0.1 mm thick, which was then clamped by means of a copper cup as in the experiments with terbium alone. The activity of the Co^{60} source amounted to 15 μCi. By measuring simultaneously the anisotropy of the γ rays of Co^{60} and the 298-keV γ quanta, it is possible to eliminate the temperature and obtain immediately the ratio of the hyperfine splitting constants A.

The pulses from the photomultiplier registering the intensity of the γ rays at 0° were fed to two pulse analyzers, and different sections of the spectra corresponding to Tb^{160} and Co^{60} were registered simultaneously. The measured angular distributions are shown in Fig. 3. The permendur sample was magnetized in the given magnetic field to saturation, and suitable corrections were introduced into the Tb^{160} results.

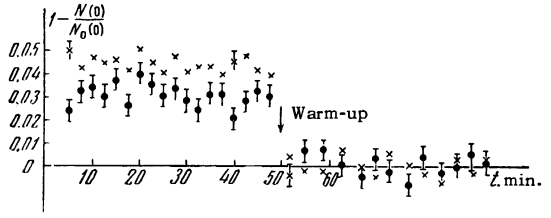

FIG. 3. Results of simultaneous measurement of the anisotropy of the angular distribution of the γ radiation of Tb^{160} Co^{60}: $\theta = 0°$, H_{ext} = 6.8 kOe, ● – Tb^{160}, × – Co^{60}.

If it is assumed that the effective magnetic field acting on the Co^{60} nucleus in permendur is 2.5×10^5 Oe [2] and that the magnetic moment of Co^{60} is $\mu = 3.8\ \mu_{nuc}$ [10], which corresponds to a hyperfine splitting constant $A_{Co} = 0.014°K$, then we obtain for this constant in terbium $A_{Tb} = 0.052 \pm 0.008°K$.

DISCUSSION OF THE RESULTS

The results obtained offer evidence that the hyperfine splitting in metallic terbium is sufficiently large and can be used for orientation of the nuclei at low temperatures. However, the value obtained for the hyperfine splitting turned out to be smaller than expected. If we use the value of the magnetic moment of Tb^{160} [11] we can calculate the effective magnetic field acting on the nucleus of this element. Assuming $\mu = 1.6 \times \mu_{nuc}$, we obtain $H_{eff} = (1.4 \pm 0.15) \times 10^6$ Oe from the first series of measurements, and we get $H_{eff} = (1.3 \pm 0.2) \times 10^6$ Oe from the second series (with Co). The effective magnetic field obtained by measuring the nuclear specific heat [7] is $H_{eff} = 5.7 \times 10^6$ Oe. The cause of such a discrepancy is still not clear. It is possible that it is due to insufficient purity of the terbium which we used, since it is known that the magnetic properties of rare earths are strongly affected even by small impurities. We also disregarded in the calculation the quadrupole interaction of the nuclear quadrupole moment with the inhomogeneous electric field of the crystal.

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71