ANISOTROPY OF THE HALL EFFECT IN GADOLINIUM

N. V. VOLKENSHTEĬN, I. K. GRIGOROVA, and G. V. FEDOROV

Institute of Metal Physics, Academy of Sciences, U.S.S.R.

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The Hall effect in gadolinium single-crystal samples ($\rho(292°K)/\rho(4.2°K) = 20$) was measured at temperatures between 4.2° and 370° K. The field dependence of the specific Hall emf and the temperature dependence of the spontaneous Hall coefficient R_S were found to be anisotropic.

MEASUREMENTS of the Hall effect in polycrystalline samples of rare-earth metals has shown that there are special features in its temperature and field dependences in the region where magnetically ordered states exist. These features are obviously associated with the uniqueness of their crystalline and magnetic structures.

It is well known that all heavy rare-earth metals have very complex magnetic structures. Even gadolinium has certain properties that distinguish it from the ferromagnets of the iron group. In particular, above 248°K and up to the Curie point (292° K) the magnetic moment of gadolinium is directed along the c_0 axis—[0001]. Below this temperature, it makes a certain angle with the c_0 axis, attaining a maximum value of 75° at 195° K. At this temperature the magnetic moment makes the smallest angle with the b_0 axis—$[11\bar{2}0]$—in the basal plane. At 4.2° K, the angle between the magnetic moment and the c_0 axis is 30°.[1]

In connection with the anisotropy of the magnetic properties of the rare-earth metals it is of great interest to investigate the temperature dependence of the Hall effect in different crystallographic directions, since measurements performed on polycrystalline samples give only average values. However, such measurements have not as yet been performed.

The present paper presents the results of an investigation of the Hall effect in single-crystal specimens of gadolinium.

SAMPLES AND MEASUREMENT METHOD

The temperature measurements were carried out in the interval 4.2–370° K both in liquid nitrogen, hydrogen, and helium boiling at normal pressure and in a cryostat of the type described by Borovik-Romanov and Kreĭnes.[2] Temperatures above room temperature were obtained by means of a U8 ultrathermostat (Webster type).

The single crystal of gadolinium from which the samples were cut was quite pure: $\rho(292° K)/\rho(4.2° K) = 20$. The samples were cut from the single crystal in two mutually perpendicular directions. Sample b was cut so that its plane coincided with the basal plane, sample c, so that its plane was parallel to the c_0 axis and passed through the a_0 axis.

In the measurements on sample b the primary current was directed parallel to the a_0 axis, the magnetic field parallel to the c_0 axis, and the Hall field was measured in the direction of the b_0 axis. For sample c the primary current was directed as in sample b, the magnetic field was parallel to the b_0 axis, and the Hall field was measured along the c_0 axis.

The samples were cut with an emery wheel to a thickness of 0.3 mm and then pickled in nital for 30 min. X rays were used to check the orientation of the samples and the absence of strains, which might have appeared as a result of the cutting. It was established that the samples were just as perfect as the original monocrystal from which they were cut. The maximum deviation of the orientation of the samples from the above indicated directions amounted to about 3.5°.

Measurement of the Hall emf was accomplished by the method described in [3], by which inductions in the samples of up to 30 kG could be obtained. The results were analyzed by the same method as in [4]: below the Curie temperature ®, according to the relation

$$e_H = R_0 B + R_s \cdot 4\pi M(H, T), \tag{1}$$

and above this temperature, according to the relation

$$R_0^* = R_0 + R_s' \cdot 4\pi\varkappa / (1 + 4\pi\varkappa), \tag{2}$$

where e_H is the Hall emf per unit current density ($e_H = Ed/I$), B is the induction in the sample, R_0

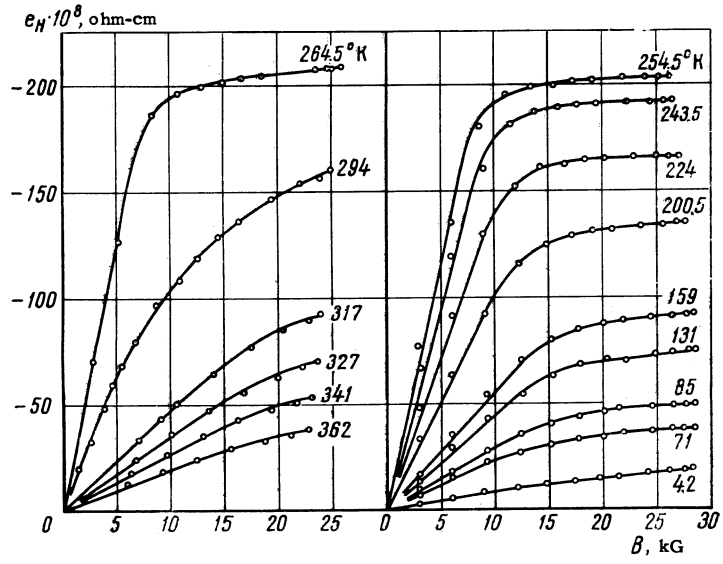

FIG. 1. Dependence of the specific Hall emf on the induction of sample c.

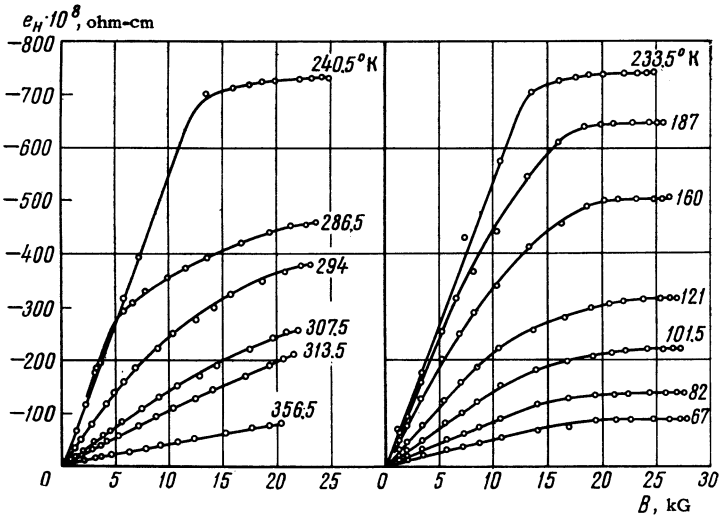

FIG. 2. Dependence of the specific Hall emf on the induction of sample b.

is the ordinary Hall coefficient, R_s is the spontaneous Hall coefficient below the Curie point, R_0^* is the effective Hall coefficient, equal to the slope of the curves $e_H(B)$ above the Curie point, and R_s' is the magnetization-dependent Hall coefficient, above the Curie point.

RESULTS AND DISCUSSION

Figures 1 to 3 show the dependence of the Hall emf per unit current density on the induction in both samples at several representative temperatures. It is clear from the figures that the field dependence of the Hall effect in gadolinium already shows a marked anisotropy. At temperatures above the Curie point, e_H depends linearly on the induction in the sample. However, if for sample b this linearity begins from temperatures above 310° K, then for sample c there is still a marked deviation from linearity at 360° K.

At temperatures below the Curie point but close to it, the curves of e_H at inductions greater than the saturation induction do not depart from a

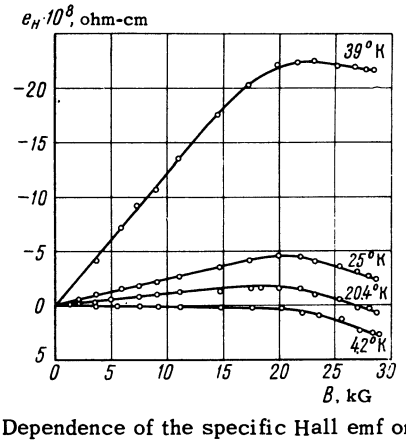

FIG. 3. Dependence of the specific Hall emf on induction of sample b at low temperatures.

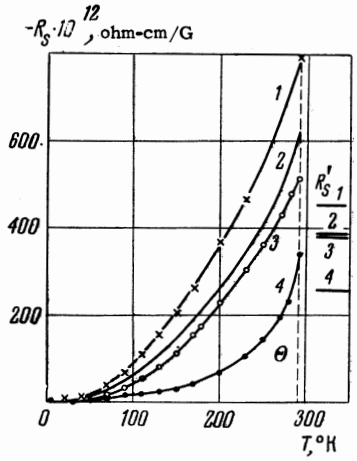

FIG. 4. Temperature dependence of the spontaneous Hall coefficient R_s: curve 1—sample b; 2—calculated curve for a polycrystalline sample; 3—experimental curve for a polycrystalline sample, from[4]; 4—sample c. The line segments labeled 1–4 are values of R'_s calculated according to Eq. (2) for temperatures above the Curie point.

straight line; for sample b this phenomenon is observed above 253° K, and for sample c only above 274° K.

As the temperature is lowered the slope of the straight-line portion of the e_H curves at inductions above the saturation induction (for sample b) is greatly diminished, and at about 60° K, the lines run parallel to the abscissa axis. Further lowering of the temperature leads to a change in sign of the slope of these linear portions. This causes the Hall effect in sample b to change sign at 4.2° K. A similar phenomenon is not observed for sample c.

It should be mentioned that the same phenomenon was observed by Babushkina[5] in a polycrystalline sample of gadolinium, which probably had a suitable grain size.

The anisotropy of the Hall effect appears even more pronounced when one considers the Hall coefficients. Figure 4 shows the dependences on temperature of the spontaneous Hall coefficient R_S for samples b and c, and that calculated from the relation

$$R_{s\,\mathrm{poly}} = {}^1/_3 R_{sc} + {}^2/_3 R_{sb} \qquad (3)$$

for a polycrystalline sample. In the same figure is plotted the curve $R_S(T)$ for a polycrystalline sample, taken from data in [4].

It follows from Fig. 4 that R_S of sample b is much greater than that of sample c and has a different temperature dependence. The averaged values $R_{S\,\mathrm{poly}}$ have magnitudes and character of temperature dependence close to that measured on the polycrystalline sample. It is also clear from

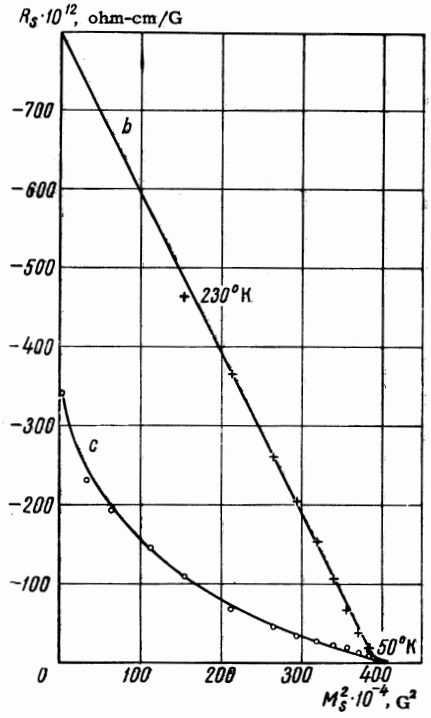

FIG. 5. Dependence of the spontaneous Hall coefficient R_s of samples b and c on the square of the spontaneous magnetization.

this figure that the anisotropy of the quantities R'_S is maintained even above the Curie temperature, and averaging also gives a magnitude for $R'_{S\,\mathrm{poly}}$ that is close to that obtained experimentally on a polycrystalline sample. We have (in units of 10^{-12} ohm-cm/G): $R'_S(b) = -454$, $R'_S(c) = -257$, $R'_{S\,\mathrm{poly}} = -388$, $R'_{S\,\mathrm{exp}} = -384$.

The theory[6] gives, by considering scattering by spin inhomogeneities, a temperature dependence of R_S of the form

$$R_s = K[M_s^2(0,0) - M_s^2(0,T)], \qquad (4)$$

which should be satisfied at temperatures close to the Curie temperature. The graphs in Fig. 5 show the dependence of the Hall coefficients R_S of both samples on the square of the spontaneous magnetization. From Fig. 5 it is seen that for sample b this relation is fulfilled rather well in the temperature interval 50 to 230° K. Extrapolation of the linear portion to the abscissa axis yields $M_S(0, 0) = 1985$ G, which agrees well with the value of this quantity known from other measurements. Equation (4) is not satisfied for sample c.

It may be noted that a dependence of the form of Eq. (4) for sample b is satisfied in that temperature interval in which the b_0 axis is the axis of easy magnetization. But the c_0 axis becomes the axis of easy magnetization only above 248° K,

i.e., near the Curie temperature, where one could hardly expect Eq. (4) to be valid.

Thus, the experimental results obtained in this work allow us to conclude that even in gadolinium, which has a simpler magnetic structure than the other rare-earth metals, there is significant anisotropy of the Hall effect due to the difference in the magnetic properties in different crystallographic directions.

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