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ANISOTROPY OF THE HALL EFFECT IN DYSPROSIUM

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The Hall effect was measured in single-crystal samples of dysprosium [$\rho(294°K)/\rho(4.2°K) = 10$] in the temperature range 4.2—350°K. The field and temperature dependences of the Hall emf were found to be anisotropic in the temperature range in which magnetically ordered structures existed, and an anisotropy of the Hall coefficients above the Néel point was observed.

MEASUREMENTS of the Hall effect of polycrystalline samples of rare-earth metals have indicated some singularities in the field and temperature dependences of the effect and it has been suggested that these singularities are related to the anisotropy of the crystal and magnetic structures.[1-6] The first measurements of the Hall effect in a single crystal of gadolinium[7] showed indeed of the magnitude and temperature dependence of the spontaneous Hall coefficient R_s, as well as the field dependence of the Hall emf along various crystallographic directions, are all strongly anisotropic.

The present paper reports the results of an investigation of the Hall effect in a dysprosium single crystal. In this case, a much stronger anisotropy of the Hall effect was expected because the magnetic anisotropy of dysprosium was much stronger than that of gadolinium.

According to the results of electrical, magnetic, thermal, and neutron-diffraction measurements,[8-11] dysprosium is paramagnetic at temperatures above 178°K. Below this temperature, it is an antiferromagnet with a helicoidal structure, in which the magnetic moments lie in the basal plane and the helicoid axis coincides with the hexagonal axis. Below 85°K, dysprosium becomes ferromagnetic but the magnetic moments remain in the basal plane. The easy magnetization direction is then the $[11\bar{2}0]$ axis. In the antiferromagnetic state, the critical field for the destruction of the antiferromagnetic structure varies from zero at 85°K to 11 kOe at 178°K.

SAMPLES AND MEASUREMENT METHOD

Samples were cut from a sufficiently pure dysprosium single crystal [99.9%, $\rho(294°K)/\rho(4.2°K) = 10$]. The measurements were carried out on two samples: sample b was cut so that its plane coincided with the basal plane, and sample c was cut so that its plane was parallel to the c_0 axis and passed through the a_0 axis. The designations of the samples indicated the axis along which the Hall effect was measured. In both cases, the primary current was directed along the a_0 axis. The magnetic field in sample b was directed along the c_0 axis and in sample c along the b_0 axis.

The samples were cut using an emery disk 0.3 mm thick; they were etched with nital. The correct alignment of the samples and the absence of stresses, which could appear during cutting, were checked by the x-ray diffraction method. It was established that after etching the samples were still as perfect in the crystallographic sense as the initial single crystal. The maximum deviation of the sample orientation from the directions just referred to amounted to 2—2.5°.

The Hall emf was measured in the same way as in[7], using magnetic inductions up to 28 kG and temperatures from 4.2 to 350°K. The results of the measurements at temperatures higher than 178°K were analyzed by the method described in[7]. The magnetic susceptibility data for a dysprosium single crystal along various crystallographic directions above the Néel temperature were taken from[12].

Unfortunately, the highest values of the magnetic induction that we were able to achieve in the samples were insufficient to produce magnetic saturation in the temperature range in which magnetically ordered structures existed, and this prevented our separating the Hall coefficients R_0 and R_s at temperatures below 178°K.

RESULTS OF MEASUREMENTS

Figures 1—3 give the dependence of the Hall emf, taken per unit current density ($e_H = E_d/I$,

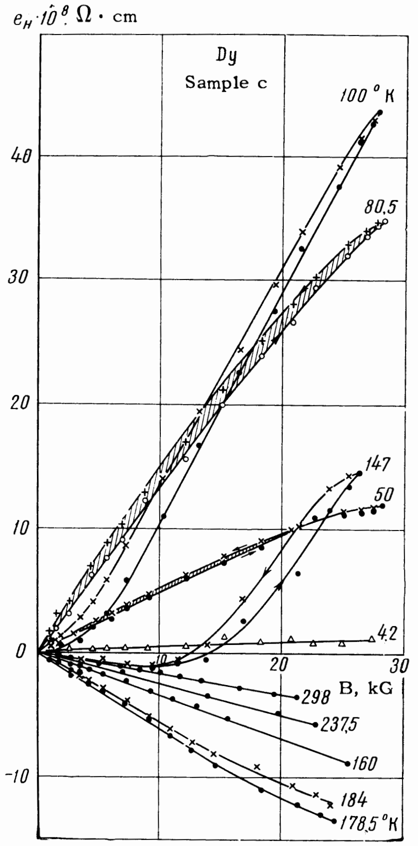

FIG. 1. Dependence of the specific Hall emf on the induction in sample c at some characteristic temperatures.

where E is the measured emf and d is the sample thickness), on the magnetic induction in the samples at certain characteristic temperatures.

It is evident from these figures that the field dependence of the Hall effect in dysprosium is strongly anisotropic. Above 178°K, the Hall effect in both samples is negative, but its absolute value is considerably larger for sample b. Moreover, while the dependence $e_H(B)$ for sample c becomes linear already at temperatures a little higher than the Néel point, for sample b it remains nonlinear up to 340°K.

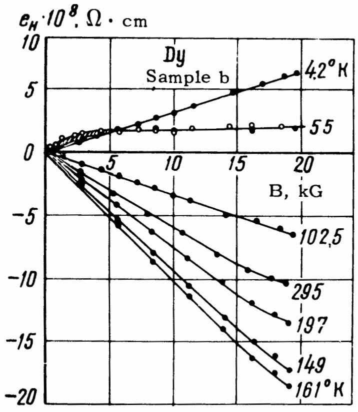

FIG. 2. Dependence of the specific Hall emf on the induction in sample b at some characteristic temperatures.

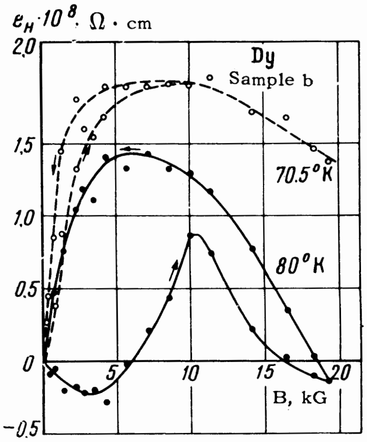

FIG. 3. Dependence of the specific Hall emf on the induction in sample b at temperatures close to the AFM → FM transition.

An even stronger anisotropy is observed in the temperature range in which magnetically ordered structures exist. In this range of temperatures, the dependence $e_H(B)$ for sample c is similar to the analogous dependence for polycrystalline dysprosium.[1] At temperatures close to the Néel point, $e_H(B)$ is negative and linear up to values of the induction close to the critical field which destroys the antiferromagnetism at a given temperature. At higher values of the induction, the curves $e_H(B)$ have kinks; below 150°K, the derivative de_H/dB changes its sign so that positive values of $e_H(B)$ correspond to higher values of the induction in the sample. Further cooling increases the Hall emf and, near the point of transition from the antiferromagnetic to the ferromagnetic state (AFM → FM), the emf reaches its maximum value and the kinks in the $e_H(B)$ curves disappear at low values of the induction. Further cooling reduces $e_H(B)$.

In the temperature range from ≈ 150°K to ≈ 40°K, the $e_H(B)$ curves exhibit "hysteresis," i.e., the values of e_H obtained when the induction is being increased differ from the values of e_H obtained when the induction is being reduced. We note that at higher temperatures the "hysteresis" is observed at higher values of the induction, while during cooling the "hysteresis" shifts to lower values of B and disappears at ≈40°K. Below this temperature the dependence $e_H(B)$ becomes linear.

The dependence $e_H(B)$ remains almost linear to ≈90°K for sample b in the antiferromagnetic state. In the temperature range 70–90°K, $e_H(B)$ becomes nonlinear and there is a fairly strong "hysteresis" which is most clearly observed near the AFM → FM transition point. We note that at these temperatures

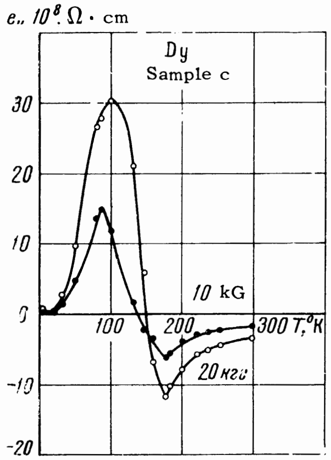

FIG. 4. Temperature dependence of the Hall emf of sample c for two values of the induction in the sample.

the derivatives de_H/dB for low values of the induction obtained in the first measurement, i.e., before the destruction of the antiferromagnetic state, and those obtained for B greater than the saturation induction in the ferromagnetic state, have the same negative, sign opposite to the sign of de_H/dB at moderate values of B at which the transition AFM → FM takes place. The initial part of the curve is unstable and disappears when the measurements are repeated without heating the sample.

Further cooling destroys the "hysteresis" and the curves retain only one kink at inductions of the order of 3—5 kG, while below 30—40°K the dependence $e_H(B)$ becomes linear.

Figures 4 and 5 show the temperature dependence of the Hall emf for several values of the induction in the samples. It is evident from these figures that, although in the paramagnetic region the temperature dependence of e_H is almost the same for both samples and the only differences are in the value of e_H, in the antiferromagnetic and particularly in the ferromagnetic state the differences are more considerable. While sample c has a clear $e_H(T)$ maximum near the temperature of the AFM → FM transition, for sample b such a maximum, or more exactly a kink, is observed in the $e_H(T)$ curves only at low values of the induction in the sample. At high inductions, these curves show no singularities.

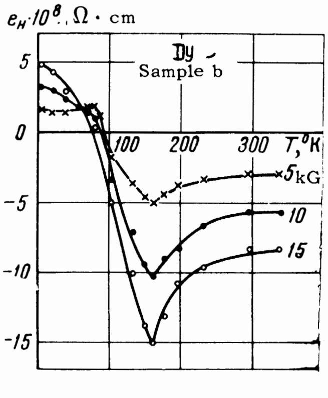

FIG. 5. Temperature dependence of the Hall emf of sample b at three values of the induction in the sample.

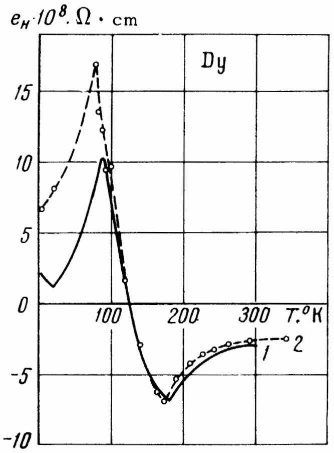

FIG. 6. Comparison of the temperature dependence of the Hall emf for 10 kG induction in a polycrystalline sample (curve 2) with the dependence calculated from the relationship $e_{H.tot} = (2/3)e_{Hc} + (1/3)e_{Hb}$ (curve 1).

Figure 6 compares the temperature dependence $e_H(T)$ at 10 kG for polycrystalline dysprosium, taken from[1], with the temperature dependence obtained by averaging the results of the present study using the relationship

$$e_{H\ \mathrm{tot}} = {}^2/_3 e_{Hc} + {}^1/_3 e_{Hb}$$

It is evident that in the paramagnetic and antiferromagnetic regions the curves agree quite well. A considerable difference between the values of the Hall emf and its temperature dependences is observed below 90°K, i.e., in the ferromagnetic region. This may be associated with the different purities of the dysprosium samples.

Above 178°K, R_0 and R_s' were calculated for both samples in the same way as in[4]. The values of these coefficients also exhibit an anisotropy: for sample c, we have $R_s' = -32.6 \times 10^{-12}\ \Omega \cdot \mathrm{cm} \cdot \mathrm{G}^{-1}$, $R_0 = -1 \times 10^{-12}\ \Omega \cdot \mathrm{cm} \cdot \mathrm{G}^{-1}$; for sample b, $R_s' = -25.5 \times 10^{-12}\ \Omega \cdot \mathrm{cm} \cdot \mathrm{G}^{-1}$, $R_0 = -5.7 \times 10^{-12}\ \Omega \cdot \mathrm{cm} \cdot \mathrm{G}^{-1}$.

DISCUSSION OF RESULTS

The characteristic features of the field and temperature dependences of the Hall effect of single-crystal dysprosium samples may be compared with the features of its magnetic structure.

In sample c, the magnetic field is directed parallel to the basal plane, i.e., it acts in the plane in which the magnetic moments are located. Any variation of an external magnetic field and of the temperature alters the magnetic state of the sample and this is reflected in the field and temperature dependences of the Hall effect. The first kink in the $e_H(B)$ curves in the temperature range 90–178°K corresponds to the beginning of the destruction of the antiferromagnetic structure and to the rotation of the magnetic moments in the basal plane toward the magnetic field direction. Since the Hall effect of dysprosium in the ferromagnetic state is positive, this leads to a gradual change in the Hall emf when the magnetic field intensity is increased. The lower the temperature of the measurement, the lower the critical field for the destruction of the antiferromagnetic structure and the earlier the change in sign of the emf.

The "hysteresis" indicates that the process of rotation of the magnetic moments in the antiferromagnetic state lags behind the variation of the magnetic field. The fact that at higher temperatures this "hysteresis" is observed at higher values of the induction, is obviously related to the value of the critical field for the destruction of the antiferromagnetic structure. It is not quite clear why the "hysteresis" appears below 90°K, i.e., in the ferromagnetic state.

In sample b, the magnetic field is directed at right angles to the magnetic moments. Since the magnetic anisotropy of dysprosium is strong, at temperatures above the FM → AFM transition point the variation of the external magnetic field cannot rotate the magnetic moments and cannot alter the magnetic state of the sample. This is manifested by the almost linear field dependence of the Hall emf in this range of temperatures.

On approach to the AFM → FM transition point, the critical field for the destruction of the antiferromagnetic state tends to zero and, therefore, even a small inaccuracy in the sample orientation, giving rise to a component of the magnetic field in the basal plane, rotates the magnetic moments in that plane and alters the magnetic state of the sample. That is why the field dependence of the Hall emf exhibits kinks in the temperature range 70–90°K and, as in the case of sample c, a "hysteresis" is observed.

At lower temperatures, the field dependences of the Hall emf of both samples are approximately the same and they differ only in the magnitude of the emf.

In the paramagnetic state, the field dependences of the Hall emf of both samples are also approximately the same and differ only in the magnitude of the emf. Evidently, in the paramagnetic and ferromagnetic states, the anisotropy of the Hall effect is mainly associated with the anisotropy of the crystal structure of dysprosium.

The temperature dependence of e_H for sample c below 90°K is similar to the analogous dependence for the ferromagnetic metals of the 3d-group below the Curie point. For sample b, the dependence $e_H(T)$ in the same range of temperatures at high values of the induction in the sample resembles the analogous dependence for the antiferromagnetic moments of the 3d-group, for example chromium.[13]

The change in sign of the Hall effect of dysprosium on going from the paramagnetic to the ferromagnetic state is very interesting. At present, there is no theoretical explanation of this change. The reversal of the sign of the Hall emf may be associated with a change in the lattice parameters of dysprosium, which occurs in the same temperature range (80–180°K) in which the sign of the Hall effect is reversed,[14] and it may make a Brillouin zone approach the Fermi surface when the former is compressed.

Thus, the results of the measurements of the Hall effect of single-crystal dysprosium samples indicate clearly that the anisotropy of this effect is associated with the crystal and magnetic anisotropies. A discussion of the features of the magnetic structure along various crystallographic directions makes it possible to account qualitatively for the features of the field and temperature dependences of the Hall effect.

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[1] N. V. Volkenshteĭn and G. V. Fedorov, JETP 44, 825 (1963), Soviet Phys. JETP **17**, 560 (1963).

[2] N. V. Volkenshteĭn, G. V. Fedorov, and V. E. Startsev, Izv. AN SSSR, ser. fiz., **28**, 540 (1964), Bull. USSR Acad. Sci. 28, 447 (1964).

[3] N. V. Volkenshteĭn and G. V. Fedorov, FMM **20**, 508 (1965).

[4] N. V. Volkenshteĭn and G. V. Fedorov, FTT **7**, 3213 (1965), Soviet Phys. Solid State **7**, 2599 (1966).

[5] N. V. Volkenshteĭn and G. V. Fedorov, FMM 18, 26 (1964).

[6] N. V. Volkenshteĭn and G. V. Fedorov, FTT 8, 1895 (1966), Soviet Phys. Solid State 8, 1500 (1966).

[7] N. V. Volkenshteĭn, I. K. Grigorova, and G. V. Fedorov, JETP **50**, 1505 (1966), Soviet Phys. JETP **23**, 1003 (1966).

[8] R. V. Colvin, S. Legvold, and F. H. Spedding, Phys. Rev. **120**, 741 (1960).

[9] J. F. Elliott, S. Legvold, and F. H. Spedding, Phys. Rev. **94**, 1143 (1954).

[10] M. Griffel, R. E. Skochdopole, and F. H. Spedding, J. Chem. Phys. **25**, 75 (1956).

[11] M. K. Wilkinson, W. C. Koehler, E. O. Wollan,

and J. W. Cable, J. Appl. Phys., **32**, 488 (1961).

[12] D. R. Behrendt, S. Legvold, and F. H. Spedding, Phys. Rev. **109**, 1544 (1958).

[13] G. de Vries and G. V. Rathenau, J. Phys. Chem. Solids **2**, 339 (1957).

[14] J. R. Banister, S. Legvold, and F. H. Spedding, Phys. Rev. **94**, 1140 (1954).

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