TEMPERATURE DEPENDENCE OF THE ELECTRICAL CONDUCTIVITY AND HALL EFFECT OF DYSPROSIUM AND ERBIUM

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The electrical resistivity and Hall emf of Dy and Er were measured in the temperature range 4.2—350° K. The transition from the paramagnetic to antiferromagnetic state was clearly evident from the $\rho(T)$ curves of both Dy and Er. A study of the specific Hall emf of Dy showed that the extremal values of the Hall effect correspond to transitions from the paramagnetic to antiferromagnetic state and from the antiferromagnetic to ferromagnetic state. For Er only a maximum of the specific Hall emf was observed on transition from the antiferromagnetic to ferromagnetic state. The Hall effect of Dy in the ferromagnetic and antiferromagnetic regions exhibited "hysteresis" and reversed its sign from negative to positive in the temperature range 100—150° K. The sign of the Hall effect in Er was negative throughout the whole temperature range investigated and there was no "hysteresis."

INTRODUCTION

ANOMALOUSLY high values of the Hall emf, exceeding by one or two orders of magnitude the effects observed in nonferromagnetic metals, have been found experimentally [1-6] in the ferromagnetic metals Fe, Ni, and Co, as well as in the rare-earth metal Gd. It was therefore of interest to investigate the behavior of the Hall effect in the region of the transitions from the paramagnetic to antiferromagnetic and from the antiferromagnetic to ferromagnetic states in the rare-earth metals Dy and Er, whose magnetic structures are known from neutron-diffraction data. [7,8].

According to several theoretical treatments,[9,12] the anomalous Hall effect is due to the spin-orbit interaction, which should be different in metals of the iron group and in rare-earth metals. In metals with unfilled 3d-band the d- and s-bands overlap, while in rare-earth metals with unfilled 4f-band there is no overlap of the f- and s-bands. This difference between the two groups of metals may give rise to differences in the magnitude and temperature dependence of the anomalous Hall effect. In view of this there is interest in systematic measurements of the Hall effect of rare-earth metals in a temperature interval which includes the paramagnetic—antiferromagnetic and antiferromagnetic—ferromagnetic transitions.

The published work [13,14] reports measurements of the Hall effect of rare-earth metals only for temperatures above the magnetic transition points, i.e., in the paramagnetic region. In the present work we give the results of measurements of the electrical resistivity and the Hall effect in the temperature range from 4.2 to 350° K, which covers the regions of ferromagnetic and antiferromagnetic transitions, of the two rare-earth metals Dy and Er. Measurements were carried out using the technique described earlier. [15]

EXPERIMENTAL RESULTS

The results of measurements on Dy are given in Figs. 1—4. It is seen in Fig. 1 that the Hall emf per unit current density ($e_H = Ed/I$, where E is the measured Hall effect, and d is the sample thickness) in the paramagnetic region depends linearly on the magnetic induction up to 175° K. The latter temperature represents the Néel point of Dy and is clearly evident in the plot of the temperature dependence of the electrical resistivity (Fig. 2). In the temperature interval 77.5—175° K, i.e., in the region of the existence of antiferromagnetism, [7] there is a departure from the linear dependence referred to above at induction values greater than the threshold magnetic fields for a given temperature. [16] In this region the Hall effect reverses its sign from negative to positive as the temperature is reduced and the induction raised.

Moreover, there is the so-called "hysteresis" phenomenon. Values of the Hall emf obtained after

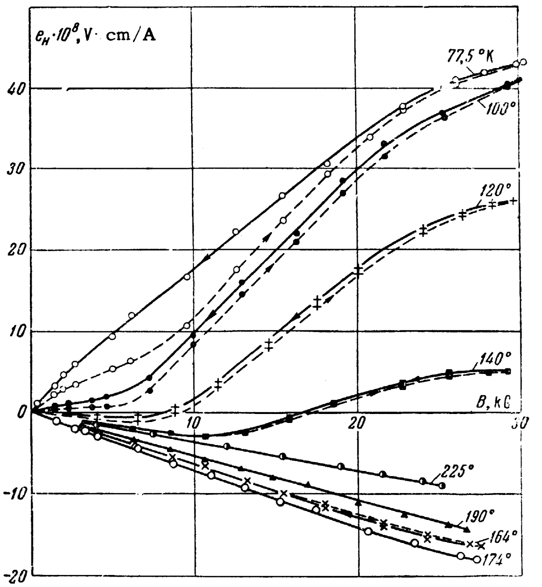

FIG. 1. Dependence of the specific Hall emf (e_H = Ed/I) of Dy on the magnetic induction at certain characteristic test temperatures.

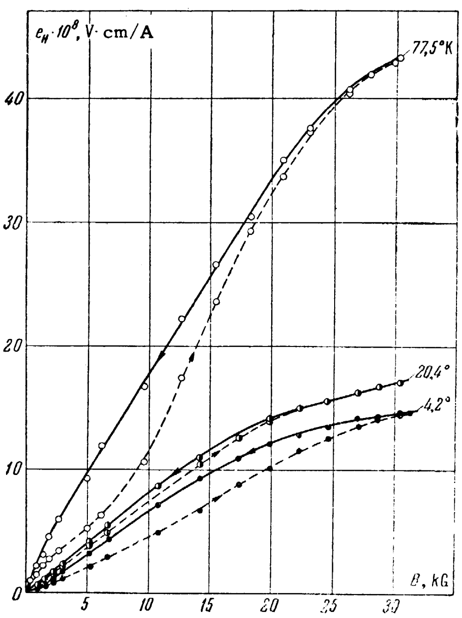

FIG. 3. Dependence of the specific Hall emf of Dy on the magnetic induction in the ferromagnetic region.

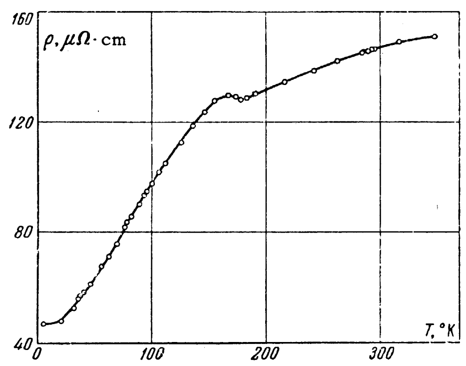

FIG. 2. Depencence of the electrical resistivity of Dy on temperature.

cooling outside a magnetic field are, on first measurement, lower than the values on second and subsequent measurements if there is no heating or if the sample is cooled in a magnetic field. On reduction of temperature this phenomenon becomes more noticeable and the maximum differences between the curves are displaced toward lower values of the magnetic induction. On reduction of temperature in this range the value of the Hall emf increases continuously (cf. the curves for T = 100° K and T = 120° K in Fig. 1).

The "hysteresis" is retained on cooling below 77.5° K, i.e., after transition to the ferromagnetic region (Fig. 3). The sign of the Hall effect remains positive at these temperatures and the value of e_H decreases with decrease in temperature.

Curves showing the temperature dependence of e_H for various values of the magnetic induction (Fig. 4) show clearly a maximum and a minimum corresponding to the paramagnetic—antiferromagnetic and antiferromagnetic—ferromagnetic transitions, as well as a change of sign of e_H in the temperature region where antiferromagnetism exists. The higher the value of the magnetic induction the higher the temperature at which e_H changes its sign.

The results of measurements on Er are given in Figs. 5—7. Figure 5 shows that at the Néel point the resistivity of Er has a clear inflection.

Figure 6 shows that at all the test temperatures the value of e_H has the same negative sign. At temperatures above and close to the Néel point the dependence of e_H on the magnetic induction B is linear, as for normal paramagnets. In the temperature range 20—60° K, i.e., in the region of the existence of antiferromagnetism, e_H(B) curves have a kink at values of B corresponding to the threshold magnetic fields for the given test temperature.[17] At higher values of the magnetic induction another kink is observed in the e_H(B) curve, in the same way as for Dy.

Cooling from 300 to 23° K produces a continuous increase of the absolute value of e_H at a fixed value of the magnetic induction. Further cooling, i.e., transition to the ferromagnetic region, reduces the value of e_H, as in the case of Dy, but the kink remains at low values of the magnetic induction. The "hysteresis" is not observed in Er at any temperature.

The curves of the temperature dependence of e_H for various values of the magnetic induction

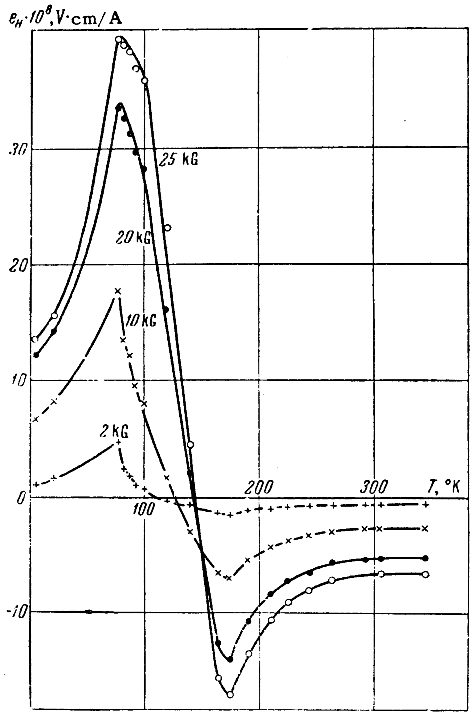

FIG. 4. Dependence of the specific Hall emf of Dy on temperature at various values of the magnetic induction in the sample.

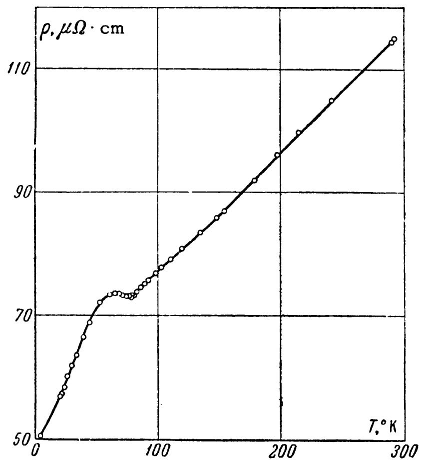

FIG. 5. Dependence of the electrical resistivity of Er on temperature.

(Fig. 7) show clearly a maximum corresponding to the Néel point.

DISCUSSION OF RESULTS

Comparison of the results on the Hall effect of the rare-earth metals Gd, [6] Dy and Er shows that the variations of their Hall emf's with increase of the magnetic induction in the antiferromagnetic and ferromagnetic regions differ considerably, apparently due to the differences and complexity of their magnetic structures. [7,8] In the paramagnetic region the nature of the dependence of e_H on the magnetic induction is the same for all these metals and does not differ from that for normal paramagnets.

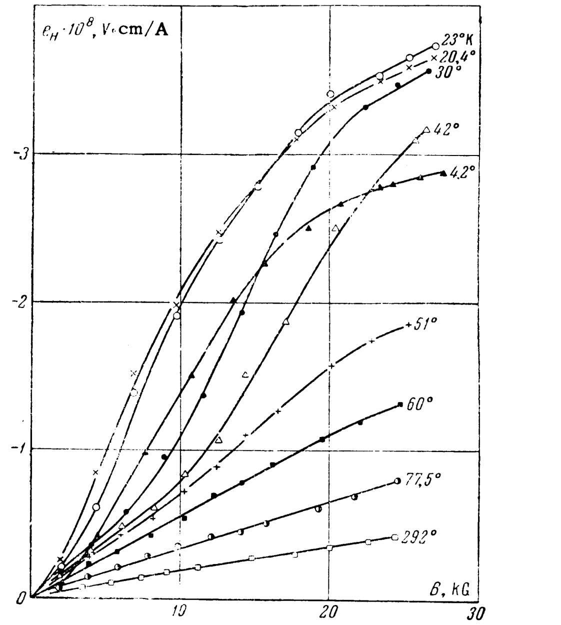

FIG. 6. Dependence of the specific Hall emf of Er on the magnetic induction at certain characteristic test temperatures.

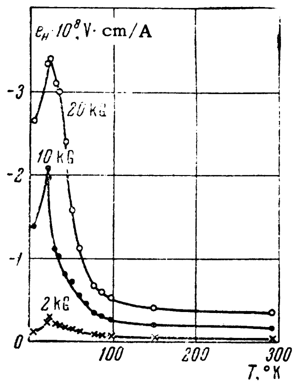

FIG. 7. Dependence of the specific Hall emf of Er on temperature at various values of the magnetic induction in the sample.

Examination of the $e_H(B)$ curves in the antiferromagnetic and ferromagnetic regions shows that for the rare-earth metals studied it is not possible to represent the Hall effect in the form of two terms, as is done for metals of the iron group; for the latter, the $e_H(B)$ curves can be split into two clearly marked linear portions allowing separation of the spontaneous (R_s) and the ordinary (R_0) Hall coefficients. Consequently to discuss the results obtained we must use only the temperature dependence e_H at one and the same value of the magnetic induction.

Moreover, the shape of the $e_H(B)$ curves is also complicated by the fact that, due to the low values of the threshold fields (from 0 to 10 kOe) which destroy the antiferromagnetic ordering, in fields up to 30 kOe one and the same curve may extend over different magnetic states.

While the transition of Dy and Er from the antiferromagnetic to the ferromagnetic state appears very clearly in the temperature dependence of the Hall effect, the transition from the paramagnetic to antiferromagnetic state appears clearly only in Dy. Er shows clearly only the ferromagnetic—antiferromagnetic transition. This becomes understandable if we remember that the paramagnetic—antiferromagnetic transition is one from complete disorder in spin distribution to the ordered state, which is important in the case of electrical conduction, while the Hall effect is also governed by the type of ordering, which is different for different magnetic structures. It should also be noted that the transition of Dy from the paramagnetic to the antiferromagnetic state is accompanied by a change of its crystal structure, [18] which may also exert a considerable influence on the temperature dependence of the Hall effect.

The "hysteresis" of the Hall effect has been observed [19] in a study of the Ni_3Mn alloy in its disordered state in which, according to magnetic measurements, the ferromagnetic and antiferromagnetic states can coexist. It is natural to expect that in Dy also the ferromagnetic and antiferromagnetic states may coexist in a certain range of temperatures.

In conclusion we wish to mention that the studies carried out on polycrystalline samples give average values of the measured effect and, therefore, analysis is difficult, especially if the complexity of the magnetic structure of rare-earth metals is taken into account. To make a more reliable judgment about the influence of the magnetic structure on the Hall effect and its temperature dependence it is necessary to study perfect single crystals. Such studies should assist in developing a theory of galvanomagnetic phenomena in rare-earth metals with complex magnetic structure.

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139