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# *DEGREE OF LOCALIZATION OF MAGNETIC ELECTRONS AND THE NERNST-ETTINGSHAUSEN EFFECT IN FERROMAGNETIC METALS*

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The results are given of an experimental study of the Nernst-Ettingshausen field and of the electrical resistance of ferromagnetic metals and of some of their alloys, carried out in order to find the degree of localization of electrons which act as spontaneous magnetization carriers ("magnetic" electrons). The results obtained confirm the correctness of the theory developed in [1] and lead to the conclusion that spontaneous magnetization carriers (electrons) in iron, nickel and cobalt take part in charge transport while in gadolinium they are bound to ions.

THE electric field $E_N$, which appears at right angles to a temperature gradient in magnetized ferromagnets (the Nernst-Ettingshausen (NE) effect), is given by the empirical formula

$$\mathbf{E}_N = -[(Q_0\mathbf{B} + 4\pi Q_s\mathbf{I}) \nabla T]_{j=0}, \quad (1)$$

where **B** and **I** are, respectively, the magnetic induction and magnetization, and $Q_0$ and $Q_s$ are the NE coefficients. The coefficient $Q_s$, in particular, represents the spontaneous NE field which appears in ferromagnets.

Kondorskiĭ[1] has shown that the cause of the spontaneous NE field is the spin-orbit interaction of the current carriers with the lattice ions, and has obtained the following theoretical formula for the ferromagnetic NE coefficient:

$$Q_s = -(\alpha + \beta\rho)\, T, \quad (2)$$

where $\rho$ is the electrical resistivity, T is the absolute temperature, and $\alpha$ and $\beta$ are parameters depending on the degree of localization of the magnetic electrons and on the nature of the current carriers. From the sign of the parameter $\alpha$ we can find whether localized or nonlocalized electrons make the principal contribution to the spontaneous magnetization [cf. Eqs. (27)–(42) in [1]].

To check the formula (1) and to determine the sign of $\alpha$ we measured the NE field at various temperatures for iron, cobalt and gadolinium. These measurements were carried out by the method described in [2]. The experimental data for nickel and iron-nickel alloys were taken from the same work.

Figure 1 gives plots of $Q_s/T$ against $\rho$ for pure metals, and Fig. 2 gives the dependence of $\alpha$ on the composition of iron-nickel alloys with fcc structure. From the graphs in Fig. 1 and from similar graphs plotted for the iron-nickel alloys, it is evident that the formula (2) describes well the observed dependence of $Q_s$ on $\rho$ and T between room temperature and temperatures close to the Curie point in the case of iron, cobalt and

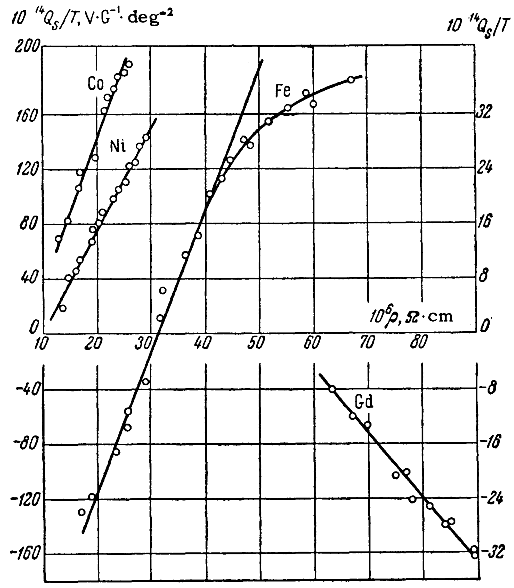


FIG. 1. Dependence of $Q_s/T$ on $\rho$ for pure metals. The right-hand scale applies to iron.

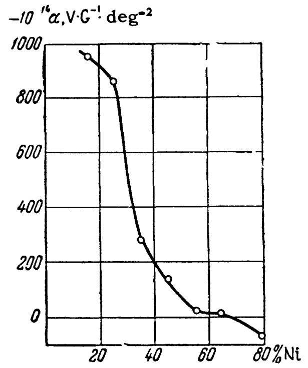


FIG. 2. Dependence of the parameter $\alpha$ in Eq. (2) on the alloy composition.

nickel, and in the temperature range from $-120°C$ to the ferromagnetic transition point in the case of gadolinium. The deviation of the observed dependence of $Q_s/T$ on $\rho$ from linearity at high temperatures in the case of iron may be due to errors made in separating the quantities B and I at temperatures above 400°C.

From the graphs given in Fig. 1 it is clear that the constant $\alpha$ is positive for iron, cobalt and nickel and negative for gadolinium. Hence we conclude that in ferromagnetic metals of the iron group the magnetic-moment carriers, which are obviously the d-electrons, take part in conduction. The negative sign of $\alpha$ for gadolinium (cf. Fig. 1) indicates that in this metal $M_e < M_i$. Thus, as expected, the f-electrons, which are the principal carriers of the magnetic moment in gadolinium, either do not take part in conduction or do so only slightly. Figure 2 shows that when the concentration of the components in iron-nickel alloys is varied the parameter $\alpha$ changes sign. If it is assumed that the formulas (2)—(5), deduced for metals, apply also to alloys, we can conclude from this graph that an increase in the number of iron ions in the fcc lattice increases the average magnetic moment of the electrons which participate weakly in conduction.

It has been shown in [1] that the ferromagnetic Hall coefficient $R_s$ also depends on the quantity $\Delta M$. In particular, if on reversal of the sign of $\Delta M$ the nature of the majority carriers (electrons or holes) is not affected then the sign of $R_s$ should change at the same time as the sign of $\Delta M$. The experimental data [3] confirm this conclusion. The quantity $R_s$ of iron-nickel alloys changes sign at a nickel concentration of $\approx 85\%$, i.e., where, according to our data, there is a change of sign of $\alpha$. The sign of the field Hall coefficient $R_0$, which gives information on the nature of the current carriers, remains unchanged at these concentrations (according to the data given in [3], $R_0$ remains negative at nickel concentrations from 50 to 100%). Thus the different signs of the Hall coefficient $R_s$ of iron-nickel alloys with fcc structure should be explained not by a change in the nature of the majority carriers but by a change in the degree of localization of the magnetic electrons.

Concluding, we note that the dependence of the sign of the ferromagnetic NE and Hall coefficients on the sign of $\Delta M$, which follows from quantum theory, has also an obvious classical interpretation. In particular when an electron with a magnetic moment $M_e$ moves about an ion with a magnetic moment $M_i$, this electron, possessing an orbital moment, is acted upon, apart from the Lorentz force, by a force proportional to grad $M_i H_e$, where $H_e$ is the magnetic field of the moving electron charge, and by a force proportional to grad $M_e H_i$, where $H_i$ is the magnetic field of the ion charge in the system of coordinates moving with the electron. The direction of the resultant of these forces depends on the magnitude and mutual orientations of the magnetic moments $M_e$ and $M_i$. Thus if the electron velocity is directed along the x axis, and the magnetic moments $M_e$ and $M_i$ are parallel and directed along the z axis, the resultant of these forces is directed along or opposite to the y axis, depending on whether $M_e > M_i$ or $M_e < M_i$.

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[3] W. Jellinghaus and M. P. de Andres, Naturwissenschaften **45**, 508 (1958); Berichte d. Arbeitgemeinschaft d. Ferromagnetismus, Riederer-Verlag, Stuttgart, 1958, p. 19; Ann. Physik **5**, 187 (1960).

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