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# *TEMPERTURE DEPENDENCE OF THE HALL EFFECT OF PURE FERROMAGNETS*

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The paper presents results of the measurements of the Hall effects for 99.998% pure iron, nickel, and cobalt, over a wide temperature range from room temperature down to 4.2°K. It is shown that the existing theories are inadequate for a satisfactory explanation of the experimental data obtained for the temperature dependence of $R_0$ and $R_s$ over a wide temperature range.

MANY papers have been published recently on the Hall effect of ferromagnets.[1-7] In none of these investigations, however, were the Hall effect and the electric resistivity measured in materials of maximum purity and on the same samples, a factor of particular importance at low temperatures.

The Hall effect in ferromagnets is of interest primarily because it differs from the Hall effect in nonferromganetic metals by many "anomalies," due to the presence of spontaneous magnetization. Let us consider the principal of these anomalies.

1. While the Hall emf of nonferromagnetic metals varies linearly with the intensity of the magnetic field H, over a wide range of fields ($e_H = RH$, where R is the Hall constant), experiment shows that in ferromagnets the Hall emf depends not only on the intensity of the external field, but also on the magnetization I of the specimen. The dependence on I is due not to the induction B alone, but also to an added specific dependence on the magnetization. It is usually assumed[1,8] that

$$e_H = R_0 B + R_s 4\pi I,$$

where $R_0$ and $R_s$ are the ordinary and spontaneous Hall constants, respectively.

2. The absolute values of $R_0$ do not differ in order of magnitude from the corresponding values of the Hall constants of nonferromagnetic metals (see the table). The spontaneous constant $R_s$ may exceed $R_0$ in absolute value at room temperature by a factor of two or more (for example, in the case of iron, nickel, and the alloys $Fe_3Al$ and CrTe).*

| Nonferromagnetic materials | | Ferromagnets | | |
|---|---|---|---|---|
| | $R$* | | $R_0$ | $R_s$ |
| V | +0.82 | Fe | +0.23 | +7.22 |
| Mn | +0.84 | Ni | −0.46 | −6.05 |
| Cu | −0.5 | Co | −0.84 | +0.6 |
| | | $Ni_3Mn$ | −0.56 | +155 |
| | | $Fe_3Al$ | 0.0 | +470 |
| | | CrTe | — | ~ −5000 [9] |

*The Hall constants are given in units of $10^{-12}$ v-cm/amp-gauss.

3. Both $R_0$ and $R_s$ have a clearly pronounced temperature dependence, that of $R_s$ being greater. It is characteristic that in the region of low temperatures ($T \ll \Theta_f$, where $\Theta_f$ is the ferromagnetic Curie point) the temperature dependence of $R_0$ and $R_s$ can also be not monotonic.

In many theoretical papers the spontaneous Hall constant is associated with the electric resistivity. Some[10] give the relationship $R_s \sim \rho^2$ and others[11] $R_s = a\rho + b\rho^2$. Experimental data[4,5] show, however, that these relations are approximately correct, but only near the Curie point. At lower temperatures (below those of liquid nitrogen) there is no linear relation between $\log R_s$ and $\log \rho$ at all. In the region where a nonmonotonic temperature variation of $R_s$ is observed, the connection between $R_s$ and $\rho$ becomes in general meaningless.

We measured the Hall effect and the specific electric resistivity of pure ferromagnets

$$\mathrm{Fe}\,(\rho_{292°}/\rho_{4.2°} = 11.45), \quad \mathrm{Ni}\,(\rho_{292°}/\rho_{4.2°} = 57.2),$$

$$\mathrm{Co}\,(\rho_{292°}/\rho_{4.2°} = 66.3)$$

in the temperature range from 300°K to 4.2°K using a potentiometer setup and a method de-

*It should be noted that our measurements (see below) show that in the case of cobalt, in which the sign of $R_s$ is reversed, this constant reaches large values at higher temperatures than, for example, in nickel and iron.

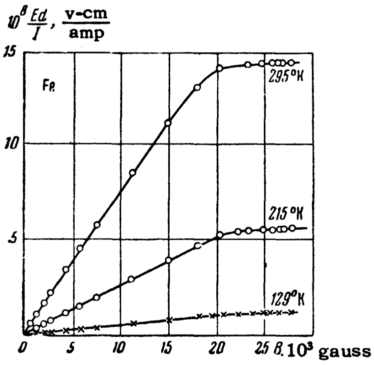

FIG. 1

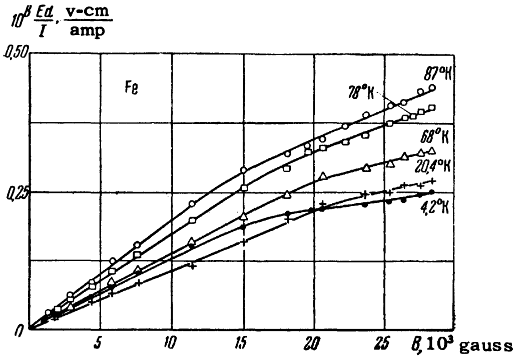

FIG. 2

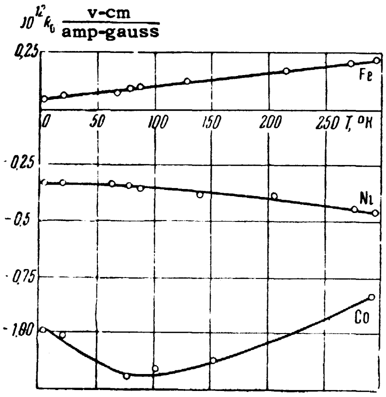

FIG. 3

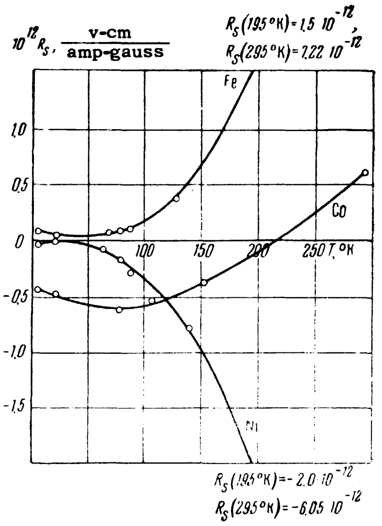

FIG. 4

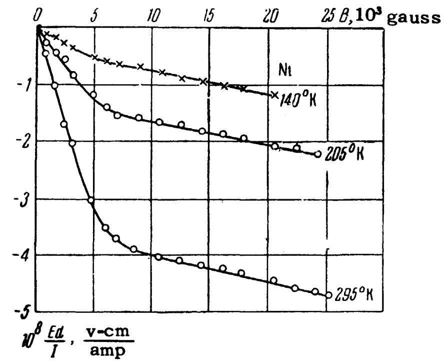

FIG. 5

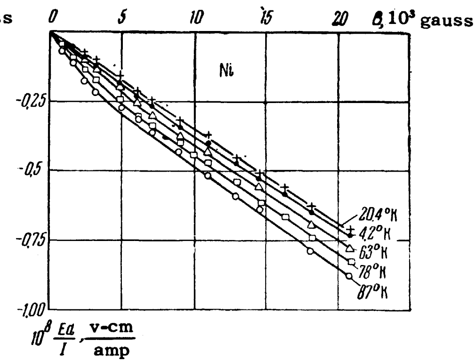

FIG. 6

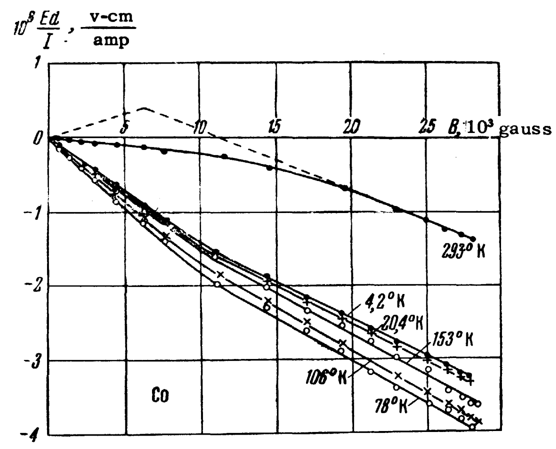

FIG. 7

scribed previously,[12] at the boiling temperatures of liquid nitrogen, hydrogen, and helium, as well as at intermediate temperatures, in a cryostate of the type described in the paper of Borovik-Romanov and Kreĭnes.[13]

We give the measurement results for each of the ferromagnets investigated.

Iron. As can be seen from Figs. 1 — 4, which show the variation of the specific Hall emf $e_H = Ed/I$ (d — thickness of specimen, I — current in the specimen) with the magnetic induction B in the specimen for different temperatures, as well as the temperature dependence of $R_0$ and $R_s$. The spontaneous Hall constant $R_s = (de_H/dB)_{B=0} - R_0$, and the ordinary Hall constant $R_0 = (de_H/dB)_{B=H+4\pi I_s}$ are positive over the entire interval of temperatures. $R_s$ diminishes sharply with decreasing temperature, becomes comparable with $R_0$ at hydrogen temperature, and has an extremum at $\sim 40°$ K.

Nickel. As can be seen from Figs. 3 — 6, $R_0$ and $R_s$ have the same sign (negative), but in all other respects nickel is analogous to iron in the behavior of the Hall emf and of $R_0$ and $R_s$. The extremal value of $R_s$ is reached at $\sim 30°$ K.

Cobalt. The temperature dependence of the Hall emf of cobalt (Figs. 3, 4, and 7) differs substantially from the temperature dependence of $e_H$ observed for iron and nickel. At room temperature $R_s$ is positive and $R_0$ is negative, the latter having the greater modulus. At the temperature of liquid nitrogen $R_S$ becomes negative and does not differ much from $R_0$ in magnitude. The extremal value of $R_S$ is reached at $\sim 80°$ K. The overall variation of the effect, from room temperature down to liquid helium temperature, is considerably less than in iron or nickel.*

An examination of the dependence of $R_S$ on the reduced temperature $T/\Theta_S$, shown in Fig. 8, indicates that the extremum is characteristic of all the investigated ferromagnets, and is observed at reduced temperatures ranging from 0.04 to 0.06.

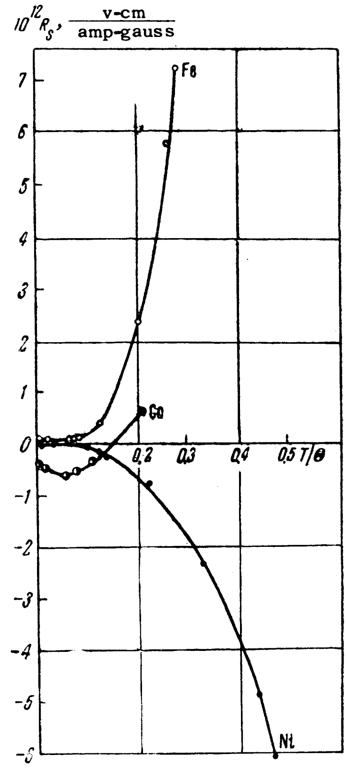


FIG. 8

An analysis of the experimental temperature dependence of the ordinary Hall constant $R_0$ (see Fig. 3) shows that $R_0$ changes substantially with temperature for all the investigated ferromagnets, and that in the case of cobalt this dependence is nonmonotonic.

The question of the temperature dependence of $R_0$ was recently investigated theoretically† and it was shown than an evaluation of the singularities in the energy spectrum and in the carrier scattering mechanism in ferromagnets (polarization of the conduction electrons, scattering by the inhomogeneities of the magnetic moment, etc.) explains qualitatively not only the temperature dependence of $R_0(T)$ at low temperatures, but also its nonmonotonic character.

To gain a better idea of the nature of the Hall constant $R_0$ in ferromagnets, a more detailed experimental investigation is necessary over an even wider temperature range (from infra-low up to temperatures above the Curie point), along with investigations of single-crystal specimens.

As first noted by Rudnitskiĭ,[14] the spontaneous Hall constant $R_S$ is apparently due to the spin-orbit interaction between the current carriers in the ferromagnets. However, not one of the existing theoretical papers[10,11,14-17] offers a satisfactory explanation of the magnitude and the temperature dependence of the observed effect.

The authors are grateful to S. V. Vonsovskiĭ for continuous interest and attention to this investigation.

*See first footnote of this article.

†See paper by S. V. Vonsovskiĭ, Yu. P. Irkhin, E. A. Turov, and V. G. Shavrov, 6-th All-Union Conference on Low-Temperature Physics, June 1959, Sverdlovsk, and also the paper by Irkhin and Petrova, Conference on the Theory of Metals and Alloys, June 1959, Kiev.

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