We choose the anomalous representation in which T_{10} and T_{01} are respectively space and time inversions. Then T_{10}, T_{01}, T_{11} leave invariant only an extended 8-component Dirac equation

$$\Gamma_i \frac{\partial\psi}{\partial x_i} + m\psi = 0, \quad \Gamma_i = \begin{pmatrix} \gamma_i & 0 \\ 0 & -\gamma_i \end{pmatrix}, \tag{7}$$

whereas the second variant of the anomalous representation leaves invariant a 4-component Dirac equation. The first variant of the anomalous representation also leaves invariant the Dirac equation for 4-spinors of the second kind[2]

$$\gamma_i \partial\psi / \partial x_i + m\gamma_5 \psi = 0. \tag{8}$$

Fermions with $m \neq 0$ which are described by the anomalous representation are in some ways reminiscent of the longitudinal neutrino which obeys the 2-component Dirac equation.[3] According to the choice of representation, they satisfy either a 4-component or an 8-component equation, and in the latter case T_{11} plays the role of γ_5 in the 2-component theory. It is possible that the eight components of the Dirac equation which describes "anomalous" Fermions may be connected with the existence of isotopic spin.

In conclusion we observe that Schwinger[4] proposed a connection between the Pauli exclusion principle and the lack of invariance of the Dirac equation under time-inversion. Ordinary time-inversion interchanges the two equations

$$\gamma_i \partial\psi / \partial x_i + m\psi = 0 \text{ and } \gamma_i \partial\psi / \partial x_i - m\psi = 0,$$

In the case of spinor particles described by the anomalous representation of the full Lorentz group (using the second variant, with T_{10} and T_{01} for time and space inversion respectively) the Lagrangian of the system is a true scalar under T_{10}. In other words, changing the order of factors in it does not change its sign. The requirement that the Lagrangian be invariant under the inversion T_{10} does therefore not lead to any additional restriction on ψ, and consequently does not imply the Pauli principle.

I thank Professors D. D. Ivanenko and M. L. Tsetlin for discussions.

[1] I. M. Gel'fand and M. L. Tsetlin, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 1107 (1956), Soviet Phys. JETP **4**, 947 (1957).

[2] É. Cartan, "Leçons sur la Théorie des Spineurs" (2 vol., Hermann, Paris, 1938).

[3] L. D. Landau, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 59 (1957), Soviet Phys. JETP **5**, 101 (1957).

[4] J. Schwinger, Phys. Rev. **82**, 914 (1951).

Translated by F. J. Dyson
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GALVANOMAGNETIC PROPERTIES OF MANGANESE FERRITE

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Submitted to JETP editor July 30, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1517-1519 (December, 1957)

DATA on the galvanomagnetic properties of the ferromagnetic semiconductors — ferrites — are still quite scant. Yet a study of these properties is of interest from the point of view of clarifying the nature of the conductivity of materials of this type, and also from the point of view of establishing a connection between the electric properties and their antiferromagnetic state, since ferrites can be classified as "uncompensated" antiferromagnets.

We measured the temperature dependence of the galvanomagnetic effect in a ferrite consisting of 50% (mol.) MnO and 50% (mol.) Fe_2O_3. The resistance of this ferrite is not too high and the effect can therefore be measured with direct current over the range from room temperature to 350°C. The ferrite was prepared by the ordinary "ceramic" technology from chemically-pure oxides. The specimens were rods 52 mm long and 25 mm^2 in cross-section. Contacts were formed on the ends of the specimens for current carrying by burning-in a silver paste. The specimen was placed in a bifilarly-wound oven, placed in turn in a magnetized solenoid. The galvanomagnetic effect was measured with an unbalanced bridge. The same value dc current was passed through the specimen at all times. At each temperature, the specific magnetization σ was measured ballistically, in addition to measuring the electric resistivity and the galvanomagnetic effect $\Delta R/R$. All three quantities were determined practically simultaneously.

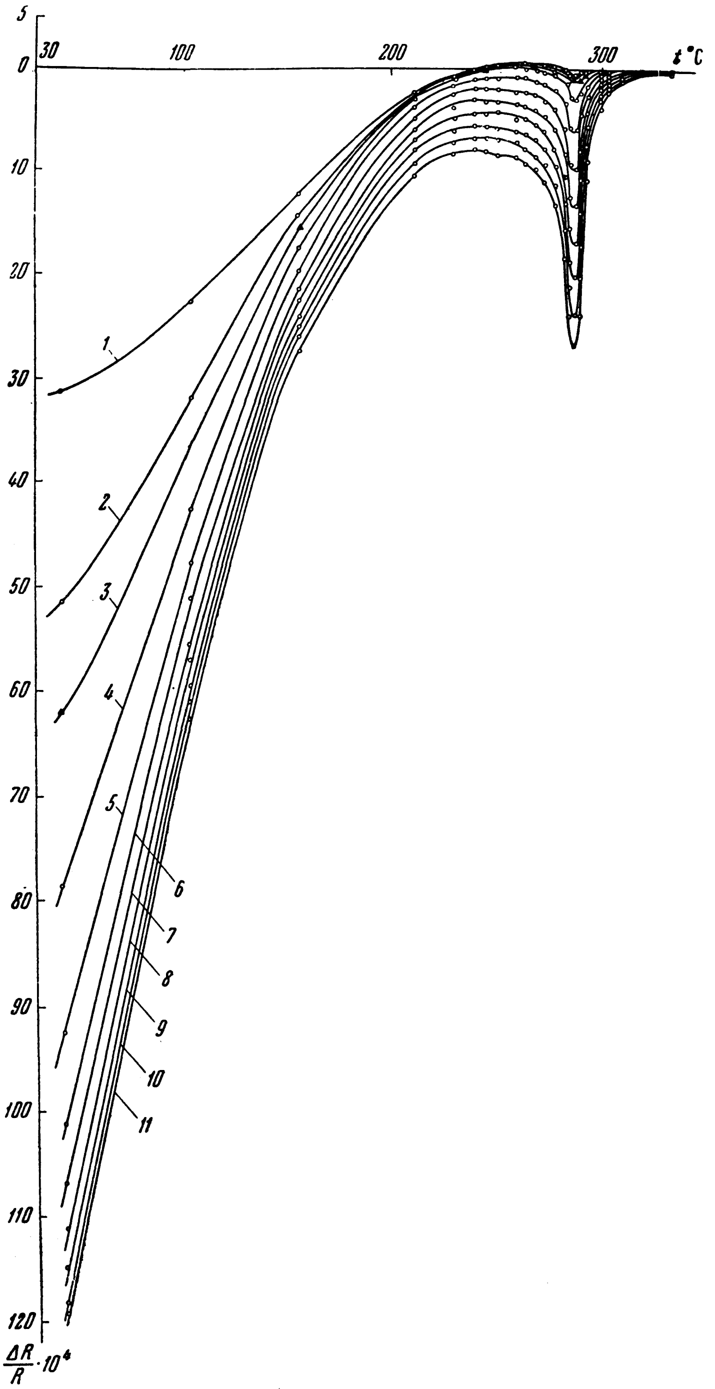

FIG. 1. Temperature dependence of longitudinal galvanomagnetic effect in manganese ferrite for different magnetic fields. 1 — 39.2; 2 — 65.4; 3 — 98.0; 4 — 196.0; 5 — 392.0; 6 — 654.0; 7 — 915.0; 8 — 1178.0; 9 — 1439.0; 10 — 1700.0; 11 — 1960.0 oersted.

Figure 1 shows curves of the temperature dependence of the longitudinal galvanomagnetic effect, plotted in weak and strong magnetic fields (above commercial saturation). It is seen that $(\Delta R/R)_{\parallel}$ has a negative sign and diminishes rapidly in magnitude, since the role of the displacement and rotation continuously diminishes with the temperature. Near the Curie point, however, the galvanomagnetic effect displays a sharp maximum, which owes its origin to the influence of the paraprocess. We note that Komar and Kliuskin[1] did not observe any influence of the paraprocess on the galvanomagnetic effect in nickel and nickel-zinc ferrites, probably because they did not make detailed measurements in the region of the Curie point. Our measurements have established that the dependence of the galvanomagnetic effect on σ and on H in the paraprocess region has approximately the same character as in metallic ferromagnets ($\Delta R/R$ linear with σ^2, $\Delta R/R$ linear with H in the region below the Curie point, $(\Delta R/R)_\Theta$ linear with $H^{2/3}$ directly at the Curie point itself, and $\Delta R/R$ linear with H^2 above the Curie point). It must be noted that the coefficient in the relation $(\Delta R/R)_\Theta = a_\Theta H^{2/3}$, which can serve as a quantitative characteristic of the influence of the paraprocess on the electric resistivity, has the same order of magnitude in manganese ferrite as in metals and alloys.[2] In manganese ferrite $a_\Theta \approx 20 \times 10^{-6}\ Oe^{3/2}$, while in nickel $a_\Theta \approx 21 \times 10^{-6}\ Oe^{3/2}$. In metallic ferromagnets, the value of a_Θ is determined by the conductivity of the tested ferromagnet. The greater the number of current carriers and the greater their mobility, the larger a_Θ (see Ref. 2). This explanation can apparently not be given for ferrites, since their conductivity is many times smaller than that of metallic ferromagnets, even at the Curie point.

An interesting feature of the galvanomagnetic effect in ferrites is that the longitudinal and transverse effects have the same sign, both being negative, while in metallic ferromagnets the longitudinal galvanomagnetic effect is positive in fields up to commercial saturation, while the transverse one is negative (exceptions to this rule exist).[3,4] In the case of manganese ferrite, however, we observed along with a negative galvanomagnetic effect also a positive component of the longitudinal effect, which appears in weak fields. Figure 1, and particularly Fig. 2, display clearly this positive component. It is seen from Fig. 2 that the greater portion of the galvanomagnetic effect is due to the paraprocess; the effect is negative and it is characterized by an exact fulfilment of the relation $\Delta R/R = c\sigma^2$. At lower magnetization, a "struggle" takes place between the negative galvanomagnetic effect (due to displacement, rotation, and the paraprocess) and the positive component of the longitudinal effect; this leads to a strong distortion of the galvanomagnetic-effect curve in this region. Cooling and repeated heating do not eliminate this anomaly. The presence of a positive component in the longitudinal galvanomagnetic effect is apparently due to our ferrite having a phase, in which it has a "quasimetallic" behavior with respect to the galvanomagnetic effect. The presence of this phase is also seen on the temperature vs. electric resistivity curves. In accordance with previous experimental[1,5] and theoretical[6] data, the straight line log R(1/T) displays in our case a break in the region of the Curie point, corresponding to the fundamental "ferrite" phase. However, unlike the results reported in Refs. 1 and 5, manganese ferrite displays in the same region of temperatures an additional break, which apparently must be ascribed to the second phase.

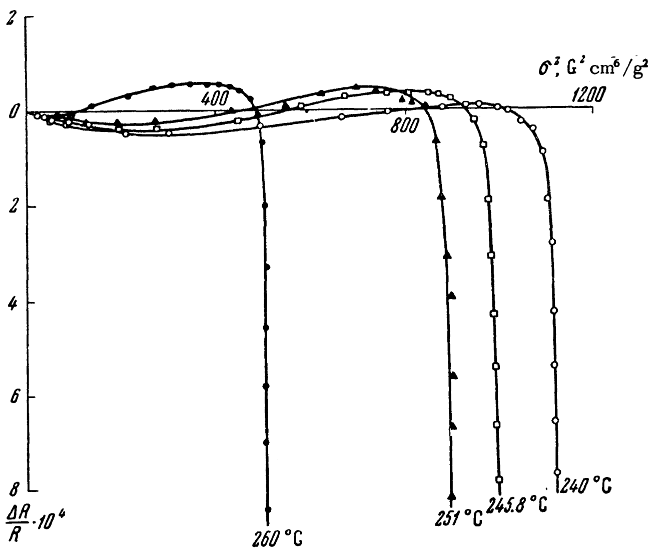

FIG. 2. Dependence of the longitudinal galvanomagnetic effect on the square of the magnetization in manganese ferrite.

[1] A. P. Komar and V. V. Kliushin, Izv. Akad. Nauk SSSR, ser fiz. **18**, 400, 403 (1954).

[2] K. P. Belov and G. A. Zaitseva, Физика металлов и металловедение (Physics of Metals and Metal Research) **1**, 404 (1955).

[3] L. Bates, Proc. Roy. Soc. **58**, 153 (1946).

[4] V. I. Drozzhina and Ia. S. Shur, J. Tech. Phys. (U.S.S.R.) **18**, 149 (1948).

[5] M. Foex, Bull. Soc. Chim. France, No. 3 — 4, 373 (1952).

[6] Iu. P. Irkhin and E. A. Turov, Физика металлов и металловедение (Physics of Metals and Metal Research) **4**, 9 (1957).

Translated by J. G. Adashko
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