ON SOME GALVANO- AND THERMOMAGNETIC EFFECTS IN ANTIFERROMAGNETS

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Submitted to JETP editor July 9, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 2273—2276 (December, 1962)

A general phenomenological analysis of galvanomagnetic and thermomagnetic phenomena in antiferromagnetic crystals with different crystallographic and magnetic structures is carried out. A number of new effects connected with the presence of antiferromagnetic ordering are predicted.

SEVERAL effects [1] connected with the presence of a preferred axis of antiferromagnetic ordering $\mathbf{L} = \mathbf{M}_1 - \mathbf{M}_2$ in antiferromagnetic crystals were discovered and investigated during the last few years. Here $\mathbf{M}_1$ and $\mathbf{M}_2$ are the magnetizations of the sublattices, each of which consists of atoms (ions) having the same magnetic-moment directions [1)]. First among these effects is the appearance of a spontaneous weakly-ferromagnetic moment

$$M_\alpha^{(s)} \equiv M_{1\alpha} + M_{2\alpha} = D_{\alpha\beta} L_\beta, \tag{1}$$

accompanying the antiferromagnetic ordering, (i.e., the appearance of $\mathbf{L} \neq 0$) [2,3]. The second is the piezomagnetic effect [4], consisting of the production of magnetization in a fully compensated antiferromagnet by application of elastic stresses

$$M_\alpha^{(p)} = \Lambda_{\alpha\beta\gamma\delta}\sigma_{\beta\gamma}L_\delta. \tag{2}$$

Finally, there is the magnetoelectric effect—the magnetization of the antiferromagnet

$$M_\alpha^{(E)} = G_{\alpha\beta\gamma}E_\beta L_\gamma, \tag{3}$$

caused by the electric field $\mathbf{E}$ [5]. The explicit form of the tensors D, Λ, and G is determined from the condition of the invariance of relations (1)—(3) under all symmetry operations of the corresponding crystallographic space group [2)].

All the foregoing effects are static. The main purpose of the present work is to consider several kinetic effects due to the presence of antiferromagnetic ordering.

The kinetic effects of interest to us (the galvanomagnetic and thermomagnetic effects) are obtained if we separate in the right half of the general relation between the fluxes $\mathbf{j}$ and the forces $\mathbf{F}$

$$F_\alpha = \rho_{\alpha\beta}(\mathbf{H},\ \mathbf{M},\ \mathbf{L})\, j_\beta, \tag{4}$$

the terms that are linear in $\mathbf{L}$. For the sake of being definite we discuss the galvanomagnetic effect, taking $\mathbf{F}$ to mean the electric field $\mathbf{E}$ and $\mathbf{j}$ the electric current density. It is obvious that these effects can exist only in antiferromagnetic structures, the magnetic-symmetry elements of which retain all the translations and symmetry centers contained in the crystallographic space group. When determining the specific form of the expansion of $\rho_{\alpha\beta}$ in powers of $\mathbf{H}$, $\mathbf{M}$, and $\mathbf{L}$ it is necessary to take into account here, in addition to the invariance of relations (4) under the crystallographic-symmetry operations, also the Onsager relations for the kinetic coefficients.

We first consider the spontaneous Hall effect, connected with the existence of a spontaneous weak ferromagnetic moment. Let us illustrate this using as an example the structure of the type 2^+2^- in rhombic crystals (for example, in orthoferrites [3]) [3)]. For this structure, the spontaneous mag-

[1)]Here and throughout we refer to antiferromagnets with collinear or weakly noncollinear magnetic structure, in which all the magnetic atoms occupy crystallographically equivalent positions. Only such structures can be described by means of two magnetic sublattices.

[2)]We point out also the principal possibility of existence of a thermal analog between the magnetoelectric effect, consisting of magnetization of the antiferromagnet

$$M_\alpha^{(T)} = P_{\alpha\beta\gamma}\nabla_\beta T L_\gamma,$$

due to the temperature gradient ∇T. The tensor $P_{\alpha\beta\gamma}$, which determines this magnetothermal effect, has the same asymmetry as the corresponding tensor G for the magnetoelectric effect. In particular, the magnetothermal effect, like the magnetoelectric effect, should appear in the antiferromagnetic compound Cr_2O_3.

[3)]We use here the symbols introduced in [3] for antiferromagnetic structures. Each symbol indicates the constituent crystallographic symmetry elements (in this case two rotation, screw, or inversion two-fold axes; the latter coincide with the symmetry planes, reflection or glide), and also the "parity" of the netic moment $M_x^{(s)} = D_1 L_y$, $M_y^{(s)} = D_2 L_x$ and $M_z^{(s)} = 0$ is connected with the following spontaneous transverse galvanomagnetic effect:

$$F_x^{(s)} = -R_1^s j_z L_x, \qquad F_y^{(s)} = -R_2^s j_z L_y,$$
$$F_z^{(s)} = R_1^s j_x L_x + R_2^s j_y L_y. \tag{5}$$

As particular cases we obtain from this the corresponding effects for uniaxial crystals: for structures of the type $n_z^+ 2_x^-$ (n = 3, 4, 6), which include, for example, $MnCO_3$ and α-Fe_2O_3—when $R_1^S = R_2^S$ and $D_1 = D_2$; for structures of the type $4_z^- 2_d^+$ (2_d is the diagonal axis or symmetry plane), which includes for example NiF_2, —when $R_1^S = -R_2^S$ and $D_1 = -D_2$.

Less obvious are the effects connected with the terms proportional to the product of the **H** and **L** components in the right half of (4). For example, for structures of the type $3_z^+ 2_x^-$ there will be added to the terms that are common to all uniaxial crystals, linear in **H**, and independent of **L**,

$$F_x = R_1 j_y H_z - R_2 j_z H_y, \quad F_y = R_2 j_z H_x - R_1 j_x H_z,$$
$$F_z = R_2 (j_x H_y - j_y H\ ), \tag{6}$$

additional terms that depend appreciably on the direction of the antiferromagnetism axis.

For a state with $\mathbf{L} \parallel \mathbf{z}$ (which is realized, for example, in hematite below 250° K or in $FeCO_3$ below 35° K) we have in addition to the right halves of (6)

$$F_x = \alpha_1 L (j_x H_x - j_y H_y) + \alpha_2 L j_z H_y,$$
$$F_y = -\alpha_1 L (j_x H_y + j_y H_x) - \alpha_2 L j_z H_x,$$
$$F_z = \alpha_2 L (j_x H_y - j_y H_x). \tag{7}$$

The terms with α_2 introduce in the coefficient R_2 in (6) corrections, such that for F_x and F_y we have $R_2 \to R_2' = R_2 - \alpha_2 L$ and for F_z we have $R_2 \to R_2'' = R_2 + \alpha_2 L$. This effect can be determined in pure form from the measured values of R_2' and R_2'', since $(R_2'' - R_2')/2 = \alpha_2 L$.

The terms with α_1 in (7) yield perfectly new effects. Let the current **j** and the field **H** lie in the basal plane, and let the direction of **j** in this plane be determined by an angle φ_j, while **H** makes an angle φ_{jH} with **j**. In this case the vector **F** also lies in the basal plane so that its longitudinal and transverse components relative to the **j** direction have the following respective forms:

$$F_{\parallel} = \alpha_1 L j H \cos (3\varphi_j + \varphi_{jH}),$$
$$F_{\perp} = -\alpha_1 L j H \sin (3\varphi_j + \varphi_{jH}). \tag{8}$$

The first formula in (8) gives an effect that is odd in **H**, the variation of the electric resistivity in a magnetic field. To exclude to the usual even effects it is necessary to determine the difference

$$\Delta\rho = [\rho(+\mathbf{H}) - \rho(-\mathbf{H})]/2 = \alpha_1 L H \cos (3\varphi_j + \varphi_{jH}).$$

The expression for $F_\perp$ defines a unique transverse effect, which can be called plane-transverse, since all the three measured vector quantities **j**, **H**, and **F** lie in one plane. The quantities $F_\parallel$ and $F_\perp$ are determined by the same parameter $\alpha_1 L$, and consequently are not independent, with

$$(F_\parallel / jH)^2 + (F_\perp / jH)^2 = (\alpha_1 L)^2 = \text{const}.$$

For the case $L \perp z$ (which is realized, for example, in α-Fe_2O_3 in the temperature interval 250° < T < 950° K, and also in $MnCO_3$ and CrF_3) we have in addition to the already considered spontaneous transverse effect (which can be obtained by extrapolation to **H** = 0) several new effects linear in **L** and **H**. We consider only one case, when $\mathbf{L} \perp z$, $\mathbf{j} \parallel \mathbf{z}$, and $\mathbf{H} \perp z$, with $\mathbf{H} \perp \mathbf{L}$ (this can always be attained if **H** is made sufficiently large [1]). In this case the components of **F** along and transverse to the current $\mathbf{j} \equiv j_z$ have the form

$$F_\parallel = \alpha_3 L j H, \quad F_\perp = \alpha_4 L j H \sin (3\varphi_F + 2\varphi_{FH}), \tag{9}$$

where φ_F is the angle determining the direction of the field **F** transverse to the current, and φ_{FH} is the angle between **F** and **H**. In particular, when $\mathbf{F} \parallel \mathbf{H}$ ($\varphi_{FH} = 0$) the second formula in (9) determines the potential difference transverse (to the current) in the longitudinal direction (with respect to H).

We do not present here the rather long list of formulas describing the other possible (both galvanomagnetic and thermomagnetic effects), analogous to those considered above, for structures of the type $3_z^+ 2_x^-$ as well as for all other structures that admit in the expansion of the right half of (4) in **L** terms that are linear with respect to this vector (such a list will be published later). We note merely that suitable objects for investigation of these effects are, apparently, the antiferromagnetic compounds of the nickel-arsenide group (for example CrSb), which have an antiferromagnetic structure of the type $6_z^- 2_x^+$ [3,6]. For this structure

structure relative to these symmetry elements. The plus index denotes that the given structure is even relative to this symmetry element, i.e., the latter connects the magnetic sites belonging to one and the same magnetic sublattice, while the minus index corresponds to the symmetry elements that connect sites of different sublattices (i.e., the structure is odd relative to such a symmetry element).

there should occur, in particular, effects determined by formulas (8) in which φ_{jH} is replaced by $\varphi_{jH} + \pi/2$. Because of the relatively good electric conductivity of these compounds, it becomes possible to observe in them both the odd effect of variation of electric resistivity in the magnetic field, and the plane-transverse galvanomagnetic effect (the plane Hall effect). In the case of poor conductors, it is possible that it is simpler to deal with analogous thermomagnetic effects.

In conclusion the following remarks must be made.

1. The effects considered above are odd in **H** only if the reversal of the field **H** is not accompanied by a reversal of the vector **L**. In the presence of sufficiently large fields it is possible to reverse the direction of **H** in such a way that **L** is simultaneously reversed. The indicated effects, although linear, will then be even with respect to **H**. Thus, these effects make it actually possible to distinguish between antiferromagnetic states that differ only in the direction of the vector **L**.

2. The observation of all these effects may be made difficult by the existence of a domain structure in the antiferromagnets, since these effects, being linear in **L**, will mutually cancel out if domains with oppositely directed vectors **L** exist with equal probability. By the same token, an investigation of these effects can incidentally help solve the problem of the existence of 180° boundaries in uniaxial antiferromagnets with **L** ∥ **z**.

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Translated by J. G. Adashko
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