GALVANOMAGNETIC EFFECTS IN FERRIMAGNETICS NEAR THE COMPENSATION POINT

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Starting from the symmetry properties of ferrimagnetic crystals, we list the galvano- and thermomagnetic effects, due to antiferromagnetic ordering, which can occur in ferrimagnetics near the magnetic compensation point. A qualitative explanation is proposed for the $\Delta\rho/\rho$ effect, which is odd with respect to the magnetic field and which has been observed experimentally near the compensation point in the ferrimagnetic compound Mn_5Ge_2 [6].

IN our earlier investigations [1,2] we predicted, on the sole basis of the conditions of crystallographic and magnetic symmetry in antiferromagnetic and ferrimagnetic crystals, several new kinetic effects due to the presence of a preferred antiferromagnetism axis. In these investigations we started from general kinetic relationships between the fluxes and the forces [3]:

$$E_i = \rho_{ik} j_k + \beta_{ik}\nabla_k T,$$
$$w_i = \gamma_{ik} j_k - \varkappa_{ik}\nabla_k T, \qquad i, k \equiv x, y, z. \tag{1}$$

Here j—density of electric current; $\mathbf{w} = \mathbf{q} - \varphi^*\mathbf{j}$, where q—energy flux density; $\varphi^* = \varphi + \xi_0/e$, where φ—electric potential and ξ_0—chemical potential (for $\varphi = 0$); $\mathbf{E} = \nabla\varphi^*$. The tensors ρ, β, γ, and κ are functions of the magnetic field $\mathbf{H}$, of the ferromagnetism vector $\mathbf{M} = \mathbf{M}_1 + \mathbf{M}_2$, and of the antiferromagnetism sector $\mathbf{L} = \mathbf{M}_1 - \mathbf{M}_2$ ($\mathbf{M}_1$ and $\mathbf{M}_2$ are the sublattice magnetizations), and satisfy, on the basis of the Onsager principle, the following symmetry relations:

$$\rho_{ik}(\mathbf{H}, \mathbf{M}, \mathbf{L}) = \rho_{ki}(-\mathbf{H}, -\mathbf{M}, -\mathbf{L}),$$
$$\varkappa_{ik}(\mathbf{H}, \mathbf{M}, \mathbf{L}) = \varkappa_{ki}(-\mathbf{H}, -\mathbf{M}, -\mathbf{L}),$$
$$\gamma_{ik}(\mathbf{H}, \mathbf{M}, \mathbf{L}) = T\beta_{ki}(-\mathbf{H}, -\mathbf{M}, -\mathbf{L}). \tag{2}$$

If these coefficients are expanded in the components of the vectors H, M and L, then the galvanomagnetic and thermomagnetic effects of interest to us, connected with the specific nature of antiferromagnetism, will be due only to the terms in the right half of (1), which are proportional to the product of the components of H and L.

The galvanomagnetic and thermomagnetic effects obtained in this manner in different types of antiferromagnetic and ferrimagnetic structures reduce to the following:

1) Characteristic additions to the usual coefficient of transverse (perpendicular to the flux) kinetic effects (Hall, Ettingshausen, transverse Nernst-Ettingshausen, and Righi-Leduc effects).

2) Effects that are longitudinal (along the flux) and odd in the magnetic field both in transverse and longitudinal magnetic fields (effects involving the change of resistance in the magnetic field, and the Nernst, longitudinal Nernst-Ettingshausen, and Maggi-Richi-Leduc effects)[1)].

3) Specific plane-parallel effects of the type of the 'plane Hall effect' (all of the three measured quantities, namely the effect itself, the flux, and the magnetic field, lie in the same plane).

Observation of all these effects is probably made complicated by the presence of domain structures in the antiferromagnets, since these effects, being linear in the vector L, will cancel each other out if domains with oppositely directed vectors L exist with equal probability. So far there are no definite methods for 'annihilating' the antiferromagnetic domains. In this connection, particular interest apparently attaches to ferrimagnets which have a point of magnetic compensation, whereby an antiferromagnetic compensated state is realized in these ferrimagnets.

By placing such a substance in a magnetic field at a temperature different from the point of compensation Θ_C, i.e., when $M \neq 0$, we specify by the same token a definite direction of the vector L in the specimen, since it is known that when $H_A < H \ll H_E$ (H_A—effective field of magnetic anisotropy and H_E—field of exchange forces) we have $\mathbf{L} \parallel \mathbf{M} \parallel \mathbf{H}$ [14] [2)]. This direction should be

[1)]In ordinary substances (without antiferromagnetic ordering, i.e., for $\mathbf{L} = 0$), such odd kinetic effects are forbidden by the Onsager principle.

[2)]Strictly speaking, the latter is not valid when the magnetic field is applied along the easy or difficult magnetization axis.

conserved in the majority of the domains also after the transition to the compensation point. In the very least we have a specific magnetic texture with a predominant direction L, which is either parallel to the treatment field or antiparallel to it, depending on the relations $M_1 > M_2$ or $M_1 < M_2$ in the initial state. By the same token, favorable conditions are created for an experimental observation of the foregoing galvanomagnetic and thermomagnetic effects (even in polycrystalline specimens).

In the case of uniaxial crystals (rhombohedral, tetragonal, hexagonal) and for class T_d, O, and O_h cubic crystals with two non-equivalent magnetic sublattices, the following kinetic effects occur for the state with $L \parallel z$, owing to the preferred antiferromagnetism axis (see the appendix in [2]; for the sake of simplicity the result is illustrated with galvanomagnetic effects in the presence of a temperature gradient) [3)]

1. Case $\mathbf{H} \parallel z$.

a) $j \perp z$:

$$E_x = \alpha L_z j_x H_z, \qquad E_y = \alpha L_z j_y H_z, \qquad E_z = 0 \tag{3}$$

or in other words

$$\mathbf{E}_{(xy)} = \alpha L_z \mathbf{j}_{(xy)} H_z, \tag{3'}$$

where the indices (xy) denote that the given vector lies in the plane (xy);

b) $\mathbf{j} \parallel z$:

$$E_x = E_y = 0, \qquad E_z = \alpha_1 L_z j_z H_z. \tag{4}$$

2. Case $\mathbf{H} \perp z$.

a) $j \perp z$:

$$E_x = E_y = 0, \qquad E_z = \alpha_2 L_z (j_x H_x + j_y H_y) \tag{5}$$

or

$$E_{\perp}^{(z)} = \alpha_2 L_z j H \cos \varphi_{jH}, \tag{5'}$$

where φ_{jH} is the angle between $\mathbf{j}$ and $\mathbf{H}$;

b) $\mathbf{j} \parallel z$:

$$E_x = \alpha_2 L_z j_z H_x, \quad E_y = \alpha_2 L_z j_z H_y, \qquad E_z = 0 \tag{6}$$

or

$$E_{\perp} = \alpha_2 L_z j_z H \cos \varphi_{EH}, \tag{6'}$$

where φ_{EH} is the angle between the measured field $\mathbf{E}$ and $\mathbf{H}$.

Formulas (3) and (4) give us an effect that is odd in $\mathbf{H}$, wherein the resistance changes in both the transverse and longitudinal magnetic fields. Expressions (5) and (6) are particular cases of plane-transverse effects—these are the so-called 'Hall effect in longitudinal field' and 'longitudinal Hall effect,' respectively [2].

For crystals of the rhombic system and for crystal classes T and T_h of the cubic system, the analogous formulas have a somewhat more complicated form [2]. For rhombohedral crystals there will occur in case 2a) [in addition to the effect described by formula (5)] also the following effects:

$$E_{\parallel} = \alpha' L_z j H \sin (3\varphi_j + \varphi_{jH}) \tag{5''}$$

which is the odd $\Delta\rho/\rho$ effect and

$$E_{\perp}^{(xy)} = \alpha' L_z j H \cos (3\varphi_j + \varphi_{jH}) \tag{5'''}$$

which is a plane Hall effect. The angle φ_j determines the direction of j relative to the crystallographic axes in the (xy) plane.

The considered ferrimagnets with a compensation point are of interest also because the foregoing effects can be observed apparently also in polycrystalline specimens subjected to the aforementioned magnetic treatment, for the already mentioned uniaxial magnetic texture can appear in such specimens. Levina, Novogrudskiĭ, and Fakidov [5] investigated galvanomagnetic phenomena on polycrystalline specimens of the ferrimagnetic compound Mn_5Ge_2, which has a compensation point ($\Theta_c \approx 122°C$). In this case, by subjecting the specimens to preliminary magnetic treatment at temperatures $T \neq \Theta_c$, they observed a $\Delta\rho/\rho$ effect which was odd with respect to H near Θ_c (both in transverse and longitudinal magnetic fields) [6]. Qualitatively this experiment can be described by formulas (3′) and (4).

The experiment is also in good agreement with the conclusion drawn from (3) and (4) that these effects are odd not only with respect to H, but also with respect to the vector L. Applying a treatment field of fixed direction first below Θ_c and then above Θ_c, we get specimens with two different states, having different signs of L. The signs of the considered effects should also be different in this case. Measurements carried out in this way have fully confirmed this prediction of the theory.

Great interest attaches to experiments from the measurement of transverse (with respect to j) galvanomagnetic effects, determined by formulas

[3)] We note that a ferrimagnet at the point of compensation differs from an ordinary antiferromagnet in the fact that its magnetic sublattices are crystal-chemically nonequivalent. Since there are no crystallographic operations of symmetry in this case translating the sites of one magnetic sublattice into the sites of the other, the tensors ρ, β, γ, and $\varkappa$ have, of course, different forms for the ferrimagnets and antiferromagnets.

(5) and (6), and further investigation of the remaining similar galvanomagnetic and thermomagnetic phenomena, both in the same substance and in other ferrimagnetic compounds which have a point of magnetic compensation. Such experiments, of course, are best carried out, from the point of view of theoretical treatment, with single-crystal specimens.

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