THERMOMAGNETIC PHENOMENA IN FERROMAGNETIC METALS WITH MAGNETIC IMPURITIES

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The temperature and field dependences of the thermal emf and normal Nernst coefficient in ferromagnetic metals with magnetic impurities are found. The thermal emf decreases with increasing magnetic field strength, reverses sign, and vanishes in strong fields. Like the thermal emf, the Nernst coefficient is anomalously large and depends on temperature in a nonmonotonic manner. The Nernst coefficient decreases monotonically with increasing magnetic field strength.

In our earlier papers[1-3] we have shown that in ferromagnetic metals with magnetic impurities (the times of electron relaxation on such impurities depend on the electron spin direction, $\tau_\uparrow \neq \tau_\downarrow$) the thermal emf has anomalous properties; it depends nonmonotonically on the temperature and concentration of the impurities, it reaches at the maximum anomalously large values comparable with k/e (k is Boltzmann's constant and e is the electron charge), and the sign of the thermal emf is determined by the sign of the difference $\tau_\uparrow - \tau_\downarrow$. These results are in good agreement with the experimental data of[4]. In the present paper we consider, within the framework of the model employed in[3], thermomagnetic phenomena in ferromagnetic metals with magnetic impurities, and show that they also have a number of interesting distinguishing features.

The thermal emf $\alpha(H)$ decreases in absolute magnitude and reverses sign when $\omega_c^2\tau_\uparrow\tau_\downarrow \approx 1$ (H--magnetic field, ω_c—cyclotron frequency), reaches a maximum (minimum), and $\alpha(H)$ w H^2 at $\omega_c^2\tau_\uparrow\tau_\downarrow \gg 1$. The normal Nernst coefficient Q(H), like the thermal emf, is anomalously large in a weak magnetic field and depends nonmonotonically on the temperature. With increasing magnetic field, Q(H) decreases monotonically. At $\omega_c^2\tau_\uparrow\tau_\downarrow \gg 1$ we have $Q(H) \propto H^{-4}$.

The cause of these anomalies can be explained qualitatively in the following manner. We break up the electrons into two groups: the first (second) consists of electrons with spin $\downarrow(\uparrow)$ above the Fermi level and with spin $\uparrow(\downarrow)$ below the Fermi level ($\uparrow$—spin directed along the magnetic moment, $\downarrow$—opposite). The heat fluxes carried by the "hot" (energy $\epsilon - \epsilon_F > 0$) and "cold" ($\epsilon - \epsilon_F < 0$) electrons have opposite directions. Since $\tau_\uparrow \neq \tau_\downarrow$, the heat flux carried by each of the groups electrons in scattering by magnetic impurities differs from zero, but the total flux is equal to zero (accurate to small terms of the order of kT/ϵ_F, where T is the temperature.

Allowance for scattering by magnons changes the situation. At low temperatures, the scattering of electrons on magnons is negligible with respect to the momenta compared with scattering on impurities. Generally speaking, scattering with respect to the energies mixes "cold" and "hot electrons, thereby reducing the heat flux. Since an electron with spin $\uparrow(\downarrow)$ can only absorb (emit) a magnon, such mixing takes place only for electrons in the first group. Therefore in scattering of electrons by magnetic impurities and magnons, the total flux, together with the thermal emf, is different from zero already in the zeroth order in kT/ϵ_F and I/ϵ_F (I--energy of the s-d exchange interaction).

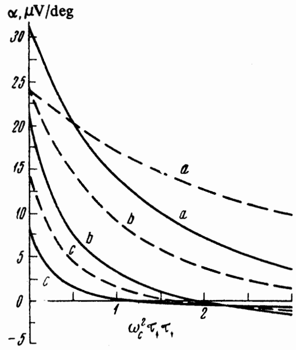
In a magnetic field, within each electron group, the heat flux of the electrons whose relaxation time is larger decreases more strongly. In some field, the heat fluxes carried by the electrons with spins $\uparrow$ and $\downarrow$ become commensurate, and the total flux vanishes. If the relaxation on magnetic impurities and on magnons (with respect to energy) is of the same order (this is precisely the case when the thermal emf in a zero magnetic field is maximal), then the heat flux and the thermal emf vanish at $\omega_c^2\tau_\uparrow\tau_\downarrow \gtrsim 1$, and reverse sign with further increase of the magnetic field. With increasing temperature, the magnon scattering becomes stronger and the field at which the thermal emf $\alpha(H)$ vanishes increases.

In very strong fields, the heat flux is proportional to the collision frequencies. Since the effective frequencies of collisions of electrons with spin $\uparrow$ and $\downarrow$ with magnons are the same in each group, and the heat flux carried by the electrons of the given group is equal to the difference of the fluxes carried by the electrons with spins $\uparrow$ and $\downarrow$, scattering by magnons drops out altogether from the expression for the heat flux, since both the thermal emf and the Nernst coefficients vanish.

We proceed to calculate the thermal emf and the normal Nernst coefficient. We start from the system of kinetic equations (2) of[3] for the distribution functions of the electrons with spins $\uparrow$ and $\downarrow$, and include the magnetic field in the field terms of these equations in the usual manner. We consider the temperature region $T \gg \mu H$ (μ is the effective magneton), so that the magnon spectrum does not depend on the magnetic field. We direct the z axis along the magnetic field, while the electric field **E** and the temperature gradient lie in the x, y plane. It is convenient to introduce the complex drift velocities

$$u^{\uparrow,\downarrow} = u_x^{\uparrow,\downarrow} + iu_y^{\uparrow,\downarrow}. \quad (1)$$

The system of kinetic equations for $u^{\uparrow\downarrow}$ in a magnetic



Dependence of the thermal emf on the magnetic field. Solid curve—Θ = 1, dashed—Θ = 2. For curves a, b, and c we have respectively β = 0.5, 2 and 8.

field coincides with the system (2) from[3], if we replace E by $E_x + iE_y$ and $1/\tau_{\uparrow,\downarrow}$ by $1/\tau_{\uparrow,\downarrow} + i\omega_c$. By solving this system by the same method as in[3], we obtain the following expressions for the longitudinal and transverse components of the thermal emf tensor:

$$\alpha_{xx}(H) = \frac{\pi^2}{6e}\frac{\tau_\uparrow - \tau_\downarrow}{t_s}\frac{\Lambda(\Theta) - \omega_c^2\tau_\uparrow\tau_\downarrow}{[\Lambda(\Theta) - \omega_c^2\tau_\uparrow\tau_\downarrow]^2 + \omega_c^2\tau_\uparrow\tau_\downarrow\Psi^2(\Theta)}, \quad (2)$$

$$\alpha_{xy}(H) = \frac{\pi^2}{6e}\omega_c\sqrt{\tau_\uparrow\tau_\downarrow}\frac{\tau_\uparrow - \tau_\downarrow}{t_s}\frac{\Psi(\Theta)}{[\Lambda(\Theta) - \omega_c^2\tau_\uparrow\tau_\downarrow]^2 + \omega_c^2\tau_\uparrow\tau_\downarrow\Psi^2(\Theta)}, \quad (3)$$

$$\Lambda(\Theta) = 1 + \frac{1}{2}\frac{\tau_\uparrow + \tau_\downarrow}{t_{ph}} + A(\Theta)\frac{\tau_\uparrow + \tau_\downarrow}{t_s} + \frac{\tau_\uparrow\tau_\downarrow}{t_s}\left[\frac{B(\Theta)}{t_s} + \frac{C(\Theta)}{t_{ph}}\right], \quad (4)$$

$$\Psi(\Theta) = \frac{\tau_\uparrow + \tau_\downarrow}{\sqrt{\tau_\uparrow\tau_\downarrow}} + 2A(\Theta)\frac{\sqrt{\tau_\uparrow\tau_\downarrow}}{t_s} + \frac{\sqrt{\tau_\uparrow\tau_\downarrow}}{t_{ph}}; \quad (5)$$

$\Theta = V/T_0$ is the dimensionless temperature, where kT_0 is the minimal magnon energy that can be absorbed or emitted in a one-magnon process; t and t_{ph} have the meaning of the times of electron energy relaxation on magnons and phonons, respectively: $A(\Theta)$, $B(\Theta)$, $C(\Theta)$ are certain functions that vary with Θ more slowly than t_s. Their explicit form, and also the dependence of the times t_s and t_{ph} on Θ, are given in[3].

It can be shown that at all temperatures we have $\Lambda(\Theta) < \Psi^2(\Theta)/2$. With increasing magnetic field, $|\alpha(H)|$ decreases and $\alpha(H)$ reverses sign at $\Lambda(\Theta) = \omega_c^2\tau_\uparrow\tau_\downarrow$. With further increase of the magnetic field, $|\alpha(H)|$ increases and reaches the second maximum at $\omega_c^2\tau_\uparrow\tau_\downarrow = \sqrt{\Lambda(\Theta)}[\sqrt{\Lambda(\Theta)} + \Psi(\Theta)]$. At this maximum, the thermal emf is equal to

$$\alpha_{max(min)}(H) = -\frac{\pi^2}{6e}\frac{\tau_\uparrow - \tau_\downarrow}{t_s}\frac{1}{\Psi(\Theta)[\Psi(\Theta) + 2\sqrt{\Lambda(\Theta)}]}, \quad (6)$$

with

$$|\alpha(H)|_{max} < |\alpha(0)|/2(1 + \sqrt{2}). \quad (7)$$

At $\omega_c^2\tau_\uparrow\tau_\downarrow \gg \Lambda(\Theta)$, $\Psi(\Theta)$, the thermal emf is equal to

$$\alpha(H) = -\frac{\pi^2}{6e}\frac{\tau_\uparrow - \tau_\downarrow}{t_s}\frac{1}{\omega_c^2\tau_\uparrow\tau_\downarrow}. \quad (8)$$

At sufficiently low temperatures, t_s and t_{ph} are large, so that

$$\Lambda(\Theta) \approx 1, \quad \Psi(\Theta) \approx (\tau_\uparrow + \tau_\downarrow)/\sqrt{\tau_\uparrow\tau_\downarrow}. \quad (9)$$

In this case the thermal emf is written in the form

$$\alpha(H) = \frac{\pi^2}{6e}\frac{\tau_\uparrow - \tau_\downarrow}{t_s}\frac{1 - \omega_c^2\tau_\uparrow\tau_\downarrow}{(1 + \omega_c^2\tau_\uparrow^2)(1 + \omega_c^2\tau_\downarrow^2)}. \quad (10)$$

Formula (10) can also be obtained from the initial system of kinetic equations if the integrals of electron-magnon collisions are considered as perturbations[1)].

The thermal emf reverses sign when $\omega_c^2\tau_\uparrow\tau_\downarrow = 1$; The position of the second maximum is determined by the condition

$$\omega_c^2\tau_\uparrow\tau_\downarrow = 1 + (\tau_\downarrow + \tau_\uparrow)/\sqrt{\tau_\downarrow\tau_\uparrow} \geqslant 3, \quad (11)$$

and the ratio of the thermal emf's in the second and first maxima is equal to

$$\frac{|\alpha(H)|_{max}}{|\alpha(0)|} = \frac{\tau_\uparrow\tau_\downarrow}{(\tau_\uparrow + \tau_\downarrow)(\sqrt{\tau_\uparrow} + \sqrt{\tau_\downarrow})^2} \leqslant \frac{1}{8}. \quad (12)$$

If the relaxation times $\tau_\uparrow$ and $\tau_\downarrow$ differ strongly (for concreteness we shall assume that $\tau_\uparrow \gg \tau_\downarrow$) then, as seen from (10), the absolute magnitude of the thermal emf decreases with increasing H like H^{-2}, starting with fields $\omega_c^2\tau_\uparrow \gg 1$. After reversal of the sign, the thermal emf changes little with the field in fields $\omega_c^2\tau_\downarrow^2 \ll 1 \ll \omega_c^2\tau_\downarrow\tau_\uparrow$, and in fields $\omega_c^2\tau_\downarrow^2 \gg 1$ it again decreases in absolute magnitude[2)], like H^{-2}. With increasing temperature, the zero of the thermal emf and the second maximum of its absolute value shift towards stronger fields.

The figure shows a plot of $\alpha(H)$ at the temperatures $\Theta = 1$ and $\Theta = 2$ for the following values of the parameters: $r = 5$, $\gamma = 0$, and $\beta = 0.5$, 2, and 8 (the notation is the same as in[3]).

The normal Nernst coefficient $Q(H) = \alpha_{xy}(H)/H$ decreases monotonically with increasing magnetic field. In a weak magnetic field $\omega_c^2\tau_\uparrow\tau_\downarrow \ll \Lambda(\Theta)$, $\Lambda^2(\Theta)/\Psi^2(\Theta)$, we have

$$Q(0) = \frac{\omega_c\sqrt{\tau_\uparrow\tau_\downarrow}}{H}\alpha_{xx}(0)\frac{\Psi(\Theta)}{\Lambda(\Theta)}. \quad (13)$$

The function $\Psi(\Theta)/\Lambda(\Theta)$ decreases monotonically with increasing temperature. At low temperatures, when $|\alpha_{xx}(0)|$ increases rapidly with temperature, we have $\Psi(\Theta)/\Lambda(\Theta) \approx$ const. Thus Q(0), like $\alpha_{xx}(0)$, is a nonmonotonic function of the temperature. The maximum of $|Q(0)|$ is shifted relative to the maximum of $|\alpha_{xx}(0)|$ towards lower temperatures, and $|Q(0)|$ decreases more rapidly beyond the maximum than $|\alpha_{xx}(0)|$.

1) An analogous formula for the diffusion thermal emf in ferromagnetic metals with nonmagnetic impurities, $\tau_\uparrow = \tau_\downarrow = \tau$, was obtained in [5]. However, the thermal emf for the case of nonmagnetic impurities contains the small parameter I/ϵ_F.

2) The here-described field dependence in strong magnetic fields corresponding to reversal of the sign of the thermal emf and to the second maximum of its absolute value, may not be observed, since in such fields the thermal emf is small and relaxation mechanisms not accounted for in the present paper (see [3]), as well as the terms $\sim kT/\epsilon_F$, I/ϵ_F discarded by us, may become significant.

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124