Thermomagnetic effects in mercury selenide alloyed with iron

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We present the results of our measurements of the Nernst–Ettingshausen (NE) effects in HgSe samples with different iron content, 1×10^{18} cm^{-3} $<N_{\rm FE}<4\times10^{20}$ cm^{-3}, in the 9–40 K temperature range. We have found that the NE coefficients change their sign at low temperatures and when the iron content is fairly high ($N_{\rm Fe}>4.5\times10^{18}$ cm^{-3}). We show that the unusual dependence of NE effects on iron content in HgSe:Fe crystals at low temperatures is caused by electron scattering on the aggregate of the charged donors Fe^{3+}, an aggregate that constitutes a weakly correlated system in the range of low iron concentrations ($N_{\rm Fe}<4.5\times10^{18}$ cm^{-3}) and a strongly correlated Coulomb liquid in the range of high iron concentrations ($N_{\rm Fe}>4.5\times10^{18}$ cm^{-3}).

1. INTRODUCTION

The dependence of the electron mobility μ in HgSe:Fe crystals on the concentration $N_{\rm Fe}$ of iron substitution impurities was studied in Ref. 1. There it was shown that the anomalous nature of this dependence is explained by the combined effect of electron scattering on correlatively positioned donors Fe^{3+} and alloy scattering. It was also established that in the system of Fe^{3+} ions the inter-ionic correlations are fairly weak at low temperatures and low iron concentrations, $(N_{\rm Fe}-N_{\rm Fe^{3+}})/N_{\rm Fe}\ll1$, so that on the whole the aggregate of Fe^{3+} ions resembles a low-density gas. For higher iron concentrations, $(N_{\rm Fe}-N_{\rm Fe^{3+}})/N_{\rm Fe}>1$, there remains a rather large space for electron redistribution in the Fe^{2+}–Fe^{3+} system of ions, and Coulomb repulsion between the charged donors Fe^{3+} leads to strong correlations in their positions. Thus, when the iron concentration $N_{\rm Fe}$ is high, the system of Fe^{3+} ions resembles a Coulomb liquid in its properties. Note that the mobility calculations done by Wilamowski, Swiatek, Dietl, and Kossut[2] correspond to the case of a weakly correlated gas of Fe^{3+} ions and can be used only for the initial segment of the mobility growth curve $\mu(N_{\rm Fe})$, that is, up to approximately $N_{\rm Fe}=(5.5\text{–}6)\times10^{18}$ cm^{-3}.

As is well known (see, e.g., Ref. 3), thermomagnetic phenomena are exceptionally sensitive to changes in the mechanism of electron scattering. The transverse and longitudinal Nernst–Ettingshausen (NE) effects constitute much more subtle indicators of the scattering mechanism than electron mobility. Studies of mobility μ make it possible to verify the nature of scattering only by the value of μ, while in studies of the NE effects it is sufficient to determine the sign of the effects in order to establish the scattering mechanism predominant in the given conditions. The sign of the NE effects is determined by the dependence of the electron relaxation time τ on the energy ε. When $\tau(\varepsilon)$ is an increasing function, both NE effects are negative. The scattering of electrons on the disordered system of impurity ions corresponds precisely to this case. When τ as a function of ε decreases (scattering on acoustic phonons), the NE effects are positive. Here we are speaking of the case of a parabolic band.

The transverse NE effect consists in the emergence of an electric field $E=(0,E_y,0)$ in the direction perpendicular to the temperature gradient $\nabla T=(\nabla_x T,0,0)$ in the sample and to the magnetic field $H=(0,0,H_z)$ (Ref. 3):

$$E_y=Q_\perp H_z\nabla_x T. \qquad (1)$$

The longitudinal NE effect consists in the emergence of an electric field parallel to the temperature gradient or, what is the same thing, in the variation of the thermopower in a magnetic field:

$$E_x(H)-E_x(0)=[\alpha(H)-\alpha(0)]\nabla_x T=\Delta\alpha(H)\nabla_x T. \qquad (2)$$

In the case of a parabolic band, algebraic dependence $\tau\propto(\varepsilon/k_{\rm B}T)^r$, a nondegenerate electron gas, and weak magnetic fields $\mu H=\omega\tau\ll1$ ($\omega=eH/mc$ is the cyclotron frequency) we have

$$Q_\perp=-ra_r\frac{k_B}{e}\mu, \qquad (3)$$

$$\Delta\alpha(H)=-rb_r\frac{k_B}{e}(\mu H)^2, \qquad (4)$$

where the coefficients a_r and b_r are simple combinations of gamma functions of r of order unity. Equations (3) and (4) imply that for the scattering of electrons, for instance, on impurity ions ($r=3/2$) and acoustic phonons ($r=-1/2$) the NE effects have opposite signs. The same is true for arbitrary magnetic fields ($\mu H\gtrsim1$) and any degree of degeneracy of the electron system.

In this paper we present the results of measurements of NE effects in HgSe samples containing from 1×10^{18} to 4×10^{20} cm^{-3} iron atoms per cubic centimeter at temperatures ranging from 9 to 40 K. The experimental data are compared with the results of calculations of $Q_\perp(N_{\rm Fe})$ and $\Delta\alpha(N_{\rm Fe})$ done on the assumption that electrons are scattered on a strongly correlated system of Fe^{3+} donors and the alloy potential ΔU, i.e., the difference between the mercury and iron atoms potentials at the lattice sites of HgSe: $\Delta U=U_{\rm Hg^{2+}}-U_{\rm Fe^{2+}}$. Within this model we were able to give a quantitative description of the experimental dependence of electron mobility in HgSe:Fe over a broad range of iron concentrations, from 4.5×10^{18} to 6×10^{20} cm^{-3} (Ref. 1). A theoretical study of NE effects is conducted for a broad range of magnetic field strengths, from weak ($\omega\tau\ll1$) to

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strong ($\omega\tau \gg 1$). One of the main results of these calculations is the conclusion that the sign of the NE effect changes as we go from the region of weak Coulomb correlations between Fe^{3+} ions to that of strong Coulomb correlations (i.e., from low to high densities N_{Fe}). The change of sign is due to the different energy dependences of the electron relaxation time in the regions of weak and strong correlations. As the reader will shortly see, this important theoretical result agrees with the experimental data.

2. RESULTS OF MEASUREMENTS

We measured the transverse and longitudinal NE effects in five HgSe samples alloyed with iron of different content and in a HgSe sample that was intentionally left unalloyed. The temperature range was 9 to 40 K. The iron content N_{Fe} was varied from 1×10^{18} to 4×10^{20} cm^{-3}. The electron number density n and electron mobility μ and the parameter $\omega\tau$ are listed in Table I.

The average sample dimensions were $8\times2\times0.8$ mm^3. The distance between the temperature probes was varied from 2.5 to 3.0 mm. The measured temperature difference was less than 10% of the average sample temperature in the (9–40) K interval.

As Figs. 1 and 2 show, for all samples both $Q_\perp$ and $\Delta\alpha(H)$ increase with temperature, while the dependence of the coefficients on the iron concentration N_{Fe} is nonmonotonic: at $N_{Fe} = 1\times10^{19}$ and 5×10^{19} cm^{-3} the curves have a maximum. Both $Q_\perp$ and $\Delta\alpha(H)$ change their sign at certain values of N_{Fe}, and the temperature at which the NE effects change sign increases as the average sample temperature drops. All measured dependences of $Q_\perp$ and $\Delta\alpha(H)$ on N_{Fe} are nontrivial and require thorough analysis.

3. ELECTRON RELAXATION TIME IN HgSe:Fe WITH ALLOWANCE FOR ALLOY SCATTERING

According to the model suggested in Ref. 1, the Fe^{3+}–Fe^{2+} system of ions can be considered a binary alloy consisting of charged Fe^{3+} centers and Fe^{2+} centers neutral in the lattice. Relaxation of the longitudinal electron momentum is due to the interaction of the electrons with these centers. In the Born approximation the quantity $\tau^{-1}(\varepsilon)$ is quadratic in the interaction of the electrons with scatterers, with the result that both the scattering on correlatively positioned Fe^{3+}–Fe^{3+} ion pairs and the scattering on randomly distributed Fe^{2+}–Fe^{3+} and Fe^{2+}–Fe^{2+} ion pairs contribute to τ^{-1} (Ref. 4). The reciprocal relaxation time can then be represented as follows:

$$\tau^{-1} = \frac{2\pi\hbar k}{m}\int_0^\pi [1-\cos(\theta_{kk'})]\sigma(\theta)\sin\theta d\theta,$$

$$\sigma(\theta) = \left[\frac{m}{2\pi\hbar^2}\right]^2 \sum_{ij=+,0}(N_iN_j)^{1/2}|V^i_{kk'}V^j_{k'k}|S^{ij}_{k'k}. \qquad (5)$$

Here $V(q) = 4\pi e^2\varkappa(q^2 + r_s^{-2})^{-1}$ is the Fourier transform of the Thomas–Fermi scattering potential of the Fe^{3+} ions, with $\varkappa$ the dielectric constant, r_s the screening radius of the potential, and θ the angle between **k** and **k**′.

For a binary alloy the product $|V(q)|^2S(q)$ in the formula for the relaxation time must be replaced with the following expression:[4]

$$[N_+/N_{Fe}]|V_+(q)|^2S_{++}(q) + [N_0/N_{Fe}]|V_0(q)|^2S_{00}(q) + 2[(N_+N_0)^{1/2}/N_{Fe}]|V_+(q)V_0(q)|S_{+0}(q).$$

Here the subscripts "+ +," "+ 0," and "00" indicate that the respective quantities are calculated for the Fe^{3+}–Fe^{3+}, Fe^{3+}–Fe^{2+}, and Fe^{2+}–Fe^{2+} interactions, respectively. The interaction of electrons with the neutral Fe^{2+} centers is assumed to be of the contact type because iron is the substitution impurity. Since the spatial distribution of the neutral Fe^{2+} centers is random, the structure factors $S_{00}(q)$ and $S_{+0}(q)$ are equal to unity. To calculate the structure factor

$$S_{++}(q) \approx S(q) = 1 + 4\pi N_{Fe^{3+}}\int_0^\infty [g(r)-1]\frac{r\sin(qr)}{q}dr \qquad (6)$$

one must find the pair correlation function $g(r)$ for the Fe^{3+} ions.

The relaxation times for scattering on nonrandomly distributed Fe^{3+} ions, τ_c, and on the alloy potential, τ_a, can be represesnted as follows:

$$\tau^{-1} = \tau_c^{-1} + \tau_a^{-1}, \qquad (7)$$

where $\tau_c^{-1} = \tau_{++}^{-1}$ and $\tau_a^{-1} = \tau_{+0}^{-1} + \tau_{00}^{-1}$.

In calculating the electron relaxation time one must bear in mind that the conduction band of HgSe is not parabolic. In the two-band approximation the dispersion law for conduction-band electrons is

$$\varepsilon(k) = \frac{\hbar^2k^2}{2m_0} + \frac{\varepsilon_g}{2}\left\{\left[1 + \frac{2\hbar^2k^2}{m_n\varepsilon_g}\right]^{1/2} - 1\right\}, \qquad (8)$$

TABLE I.

Iron content N_{Fe}, 10^{18} cm^{-3}	Electron number density n, 10^{18} cm^{-3}	Electron mobility μ, 10^4 cm^{2}V^{-1}s^{-1}					$\omega\tau$
		H,kOe	9 K	15 K	25 K	40 K	
0	2.4	7.6	2.2	2.2	2.2	2.2	1.7
1	3.0	4.5	2.8	2.8	2.8	2.8	1.3
5	4.8	4.5	4.9	4.8	4.5	4.1	1.8–2.2
10	4.75	3.6	7.8	7.0	6.1	5.0	1.2
50	4.8	3.6	5.5	5.1	4.4	3.7	1.3–2.0
400	6.2	3.6	2.5	2.3	2.2	1.9	0.7–0.9

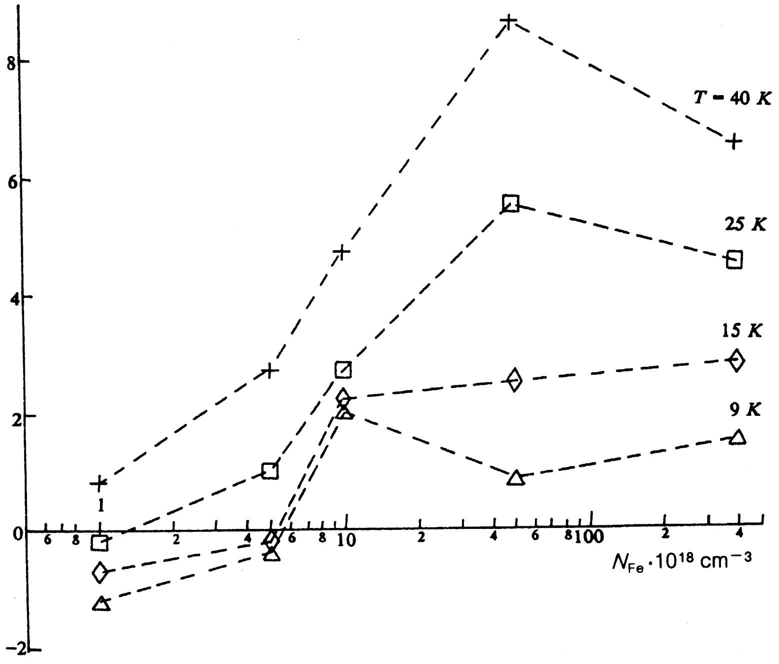

FIG. 1. The transverse NE coefficient $Q_\perp$ for HgSe:Fe as a function of iron content at different temperatures.

where m_n is the effective electron mass at the bottom of the band, $\varepsilon_g = \varepsilon(\Gamma_8) - \varepsilon(\Gamma_6)$, and m_0 is the free electron mass. For HgSe, $\varepsilon_g = 0.22$ eV and $m_n \approx 0.02 m_0$.

Performing the necessary integration in Eq. (5), we find the relaxation time:

$$\tau^{-1} = \frac{4\varepsilon_B(\varepsilon_g + 2\varepsilon_F)}{3\pi\hbar\varepsilon_g} \times \left\{ \frac{\Phi_c(y)}{y^3} + \Lambda \left[2 \left(\frac{N_0}{N_+} \right)^{1/2} \frac{\Phi_{+0}}{y} + \Lambda y_2 \frac{N_0}{N_+} \right] \right\} \qquad (9)$$

Here $y = k_F/k$, ε_B is the Bohr energy, N_+ and N_0 are the concentrations of charged centers Fe^{3+} and neutral centers Fe^{2+}, and

$$\Phi_c(k_F) = 2\int_0^1 \frac{x^3 S(2k_F x)}{(x^2 + b_s^{-2})^2}\,dx,$$
$$\Phi_{+0}(k_F) = 1 - b_s^{-2}\ln(1 + b_s^2), \qquad b_s = 2k_F r_s. \qquad (10)$$

The dimensionless parameter

$$\Lambda = \frac{m a_B k_F^2 U_0}{\pi\hbar^2}$$

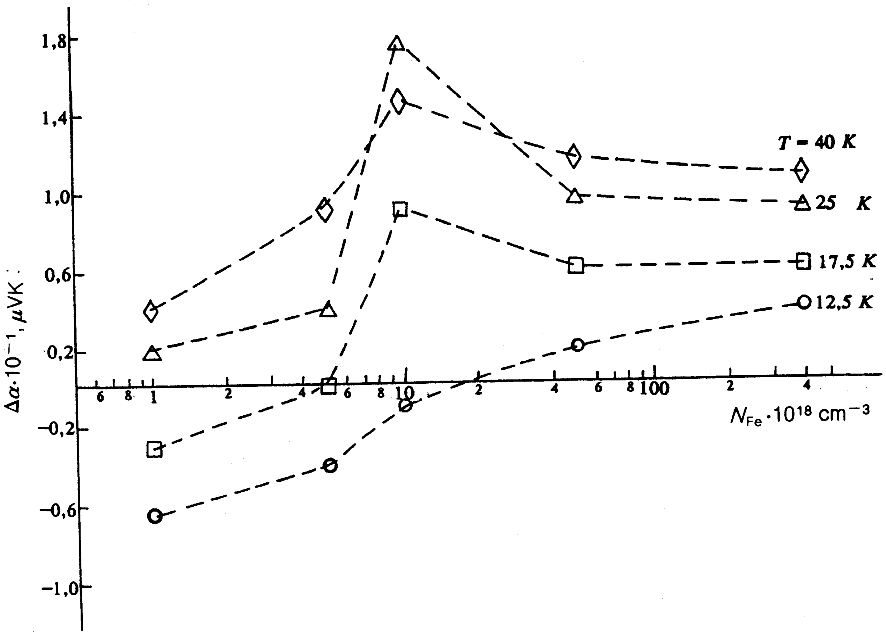

FIG. 2. The longitudinal NE coefficient $\Delta\alpha$ for HgSe:Fe as a function of iron content at different temperatures.

is the ratio of the coupling constants for the interaction of electrons with neutral Fe^{2+} and charged Fe^{3+} centers, a_B is the Bohr radius, and $U_0 = \Omega \Delta U$, where Ω is the unit cell volume and ΔU is the potential on which alloy scattering is realized. According to the estimate done in Ref. 1, $\Lambda \approx 0.1$–0.2 and $\Delta U = (0.32$–$0.35)$ eV.

As in Ref. 1, we calculate the structure factor $S(q)$ for the range of strong Coulomb correlations in the Percus–Yevick approximation.[5] This approximation is justified by the fact that the results of calculations of the thermodynamic and kinetic characteristics of such strongly correlated systems as liquid metals and alloys are in good agreement with those of Monte Carlo calculations. Since the structure and properties of liquids are basically determined by the rapidly varying repulsive part of the ion–ion interaction potential,[4] the potential can be farily accurately approximated by the solid-medium potential. This suggests that such an approach can also be fruitful in describing the system of charged donors in HgSe:Fe whose spatial correlation is ensured precisely by Coulomb repulsion. In the hard-sphere model the integral equation for the pair correlation function can be solved exactly,[5] and the structure factor $S(q)$ can be expressed in terms of the Fourier transform of the direct correlation function $c(q)$ as follows:

$$S(q) = [1 - N_+ c(q)]^{-1}. \tag{11}$$

Here

$$c(q) = \frac{4d^3}{u^3}\left\{\left[\beta + 2\gamma + 4\delta - \frac{24}{u^2}\right]\sin u + \left[\frac{2}{u}(\gamma + 6\delta) - (\beta + \gamma + \delta) - \frac{24}{u^3}\right]\cos u + \frac{24\delta}{u^3} - \frac{2\gamma}{u}\right\},$$

$$\beta = \frac{(1 + 2\eta)^2}{(1 - \eta)^4}, \quad \gamma = \frac{6\eta(1 + 0{,}5\eta)}{(1 - \eta)^4}, \quad \delta = 0{,}5\beta\eta, \quad u = qd,$$

and $\eta = \pi d^3 N_+/6$ is the packing factor, which determines the degree of correlation in the location of solid spheres of diameter d. The inequality $\eta \ll 1$ corresponds to a weakly correlated gas, and as $\eta \to 0$ the collection of scattering centers becomes completely disordered $[S(q) = 1]$. For a strongly correlated liquid, $\eta \to \eta_L \approx 0.45$. Obviously, the spatial correlations in the system of Fe^{3+} ions are the stronger the higher the concentration of the neutral Fe^{2+} centers, that is, the greater the number of vacant locations for the redistribution of electrons in the Fe^{3+}–Fe^{2+} system with mixed valence. The redistribution of electrons occurs, obviously, according to the requirement that the free energy of the system be minimal. When this happens, short-range order sets in in the system of charged donors Fe^{3+}.

The equation determining the packing factor $\eta(N_{Fe})$ and valid for the case of strong correlations in the system of Fe^{3+} ions can be written as[1]

$$\eta(N_{Fe}) = \eta_L \left[1 - \exp\left(\frac{\eta N_{Fe}}{\eta_L N_+}\right)\right]. \tag{12}$$

Combining Eqs. (9), (11), and (12) makes it possible to calculate the dependence of the relaxation time τ on the energy ε in the vicinity of the Fermi level. The calculated functions $\tau(\varepsilon)$ for systems with different degrees of correlation are depicted in Fig. 3. Curve *1* corresponds to weak spatial correlations, and curve *2* to strong correlations. Our calculations have shown that the energy dependence of the relaxation time undergoes a qualitative charge as the degree of correlation in the system of Fe^{3+} ions increases: for $N_{Fe} < 8 \times 10^{18}$ cm^{-3} the derivative $\partial\tau/\partial\varepsilon$ is positive and for $N_{FE} > (8$–$9) \times 10^{18}$ cm^{-3} it is negative. Clearly, such behavior of $\tau(\varepsilon)$ in the vicinity of the Fermi energy ε_F must strongly influence the dependence of the thermomagnetic coefficients on the iron content.

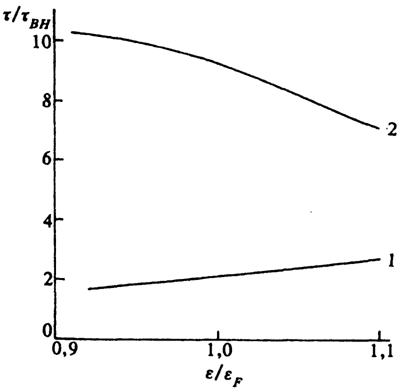

FIG. 3. The energy dependence of the relaxation time for weak and strong correlations. Curve *1* corresponds to $N_{Fe} = 3 \times 10^{18}$ cm^{-3}, curve *2* to $N_{Fe} = 8 \times 10^{18}$ cm^{-3}, and τ_{BH} is the Brooks–Herring relaxation time at $N_{Fe} = 4.5 \times 10^{18}$ cm^{-3}.

4. DEPENDENCE OF THERMOMAGNETIC COEFFICIENTS ON IRON CONTENT

The transverse NE effect coefficient $Q_\perp$ is expressed in terms of the kinetic coefficients σ_{ik} and β_{ik} for arbitrary magnetic fields as follows:[6]

$$Q_\perp = \frac{(\sigma_{11}\beta_{12} - \sigma_{12}\beta_{11})}{H(\sigma_{11}^2 + \sigma_{12}^2)}, \tag{13}$$

where

$$\sigma_{11} = ne^2 \left\langle \frac{\tau}{m} \frac{1}{1 + (\omega\tau)^2} \right\rangle, \quad \sigma_{12} = ne^2 \left\langle \frac{\tau}{m} \frac{\omega\tau}{1 + (\omega\tau)^2} \right\rangle,$$

$$\beta_{11} = -\frac{ne}{T} \left\langle \frac{\tau}{m} \frac{1}{1 + (\omega\tau)^2} \right\rangle, \quad \beta_{12} = -\frac{ne}{T} \left\langle \frac{\tau}{m} \frac{\omega\tau(\varepsilon - \varepsilon_F)}{1 + (\omega\tau)^2} \right\rangle,$$

$$\langle A \rangle = \frac{1}{3\pi^2 n} \int_0^\infty \left(\frac{\partial f}{\partial \varepsilon}\right) k^3 A(\varepsilon) d\varepsilon,$$

where f and n are the distribution function and the electron number density in the conduction band.

The thermopower in a magnetic field, $\alpha(H)$, is related to the kinetic coefficients σ_{ik} and β_{ik} by the formula

$$\alpha(H) = \frac{(\sigma_{11}\beta_{11} + \sigma_{12}\beta_{12})}{(\sigma_{11}^2 + \sigma_{12}^2)}, \tag{14}$$

and the thermopower in the absence of a field is

$$\alpha(0) = \frac{\beta_{11}(0)}{\sigma_{11}(0)}. \tag{15}$$

To calculate the quantities $Q_\perp$, $\alpha(H)$, and $\alpha(0)$ measured in the experiments we must evaluate the kinetic coefficients σ_{ik} and β_{ik}. For a degenerate electron gas, in which we are currently interested (under the experimental conditions $\varepsilon_F \gg k_B T$), calculations yield

$$Q_\perp = -\frac{\pi^2}{3e}\frac{k_B^2 T}{H\varepsilon_F}\frac{\omega\tau}{1+(\omega\tau)^2} D, \tag{16}$$

$$\Delta\alpha(H) = -\frac{\pi^2}{3e}\frac{k_B^2 T}{\varepsilon_F}\frac{(\omega\tau)^2}{1+(\omega\tau)^2} D, \tag{17}$$

$$\begin{gathered}\alpha(0) = -\frac{\pi^2}{3e}\frac{k_B T}{\varepsilon_F}\left(\frac{3}{2}+D\right), \\ D = \varepsilon_F\left\{\frac{\partial}{\partial\varepsilon}\ln\tau(\varepsilon) - \frac{\partial}{\partial\varepsilon}\ln m(\varepsilon)\right\}\Big|_{\varepsilon=\varepsilon_F},\end{gathered} \tag{18}$$

where

$$Q_\perp \propto \tau D, \qquad \Delta\alpha \propto \tau^2 H^2 D.$$

Equations (16)–(18) make it possible to analyze the dependence of the NE coefficients on the magnetic field and on the iron content of the sample. For instance, in weak magnetic fields ($\omega\tau < 1$), we have $Q_\perp \propto \tau D$ and $\Delta\alpha \propto \tau^2 H^2 D$, while for $\omega\tau \gg 1$ we have $Q_\perp \propto \tau^{-1} H^{-2} D$ and $\Delta\alpha \propto D$. Obviously, the nonmonotonic dependence of the relaxation time τ on the iron content $N_{\rm Fe}$ caused by the competition of correlation and alloy scattering must lead, respectively, to nonmonotonic variation of $Q_\perp$ and $\Delta\alpha$ with $N_{\rm Fe}$.

If we allow for scattering on acoustic phonons in the expression for $\tau(\varepsilon)$, Eq. (5), according to Ref. 3, we arrive at the following expressions for $D(\varepsilon_{\rm F})$ and $\tau(\varepsilon_{\rm F})$:

$$D = \frac{(\varepsilon_g + 2\varepsilon_F)}{2(\varepsilon_g + \varepsilon_F)}\left\{\frac{K_c + K_a - K_{ph}}{K_b + K_{ph}}\right\} - \frac{4\varepsilon_F}{(\varepsilon_g + \varepsilon_F)}, \tag{19}$$

$$\tau = \frac{3\pi\hbar\varepsilon_g}{4\varepsilon_{Bn}(\varepsilon_g + 2\varepsilon_F)}\frac{1}{K_b + K_{ph}}, \tag{20}$$

where

$$\begin{gathered}K_a = \Lambda\left[2\left(\frac{N_0}{N_+}\right)^{1/2}\left[\Phi_{+0}(y) - \frac{\partial\Phi_{+0}}{\partial y}\Big|_{y=1}\right] - \frac{N_0}{2N_+}\Lambda\right], \\ K_b = \Phi_c + \Lambda\left[2\left(\frac{N_0}{N_+}\right)^{1/2}\Phi_{+0} + \frac{\Lambda N_0}{2N_+}\right], \\ K_c = 3\Phi_c - \frac{\partial\Phi_c}{\partial y}\Big|_{y=1}, \qquad K_{ph} = A\frac{k_F T}{K_{F0}T_0}, \\ A = \frac{3\varepsilon_1^2 m_n k_B T_0 k_{F0}}{4\hbar^2\varepsilon_{Bn}\rho s^2}, \qquad \varepsilon_{Bn} = \frac{m_n e^4}{2\hbar^2\varkappa^2}.\end{gathered} \tag{21}$$

Here ε_1 is the electron–phonon coupling constant, ρ is the density, s is the speed of sound in HgSe, and T_0 and $k_{F0} = (3\pi^2 n_0)^{1/3}$ are the values of the temperature and wave vector of electrons on the Fermi surface at which $Q_\perp = 0$ or $\Delta\alpha = 0$.

For $N_{\rm FE} < 4.5\times10^{18}$ cm^{-3} the contribution of alloy scattering is negligible and the system of Fe^{3+} ions is completely disordered $[S(q) = 1]$. In this case we can drop the term describing alloy scattering in (20) and perform the following substitution:

$$\begin{gathered}\Phi_c(k_F) \to \Phi_{BH} = \ln(1+b_s^2) - \frac{b_s^2}{1+b_s^2}, \\ \tau_c \to \tau_{BH} = \frac{3\pi\hbar}{4\varepsilon_B\Phi_{BH}(k_F)},\end{gathered} \tag{22}$$

where $\Phi_{\rm BH}$ and $\tau_{\rm BH}$ are quantities corresponding to scattering on a random system of charged impurities according to the Brooks–Herring theory. From the condition $Q_\perp(n_0, T_0) = 0$ or $\Delta\alpha(n_0, T_0) = 0$ we find an expression for the parameter A valid in the low iron-content range ($N_{\rm Fe} < 4.5\times10^{18}$ cm^{-3}):

$$A = \frac{\left\{\left[3 + \frac{4\varepsilon_{F0}}{\varepsilon_g} + 4\left(\frac{\varepsilon_{F0}}{\varepsilon_g}\right)^2\right]\Phi_{BH}(k_{F0}) - \left(1 + \frac{2\varepsilon_{F0}}{\varepsilon_g}\right)^2 \frac{\partial\Phi_{BH}}{\partial y}\Big|_{y_0=1}\right\}}{1 + \frac{12\varepsilon_{F0}}{\varepsilon_g} + 12\left(\frac{\varepsilon_{F0}}{\varepsilon_g}\right)^2}. \tag{23}$$

Now let us estimate the magnitude of the electron–phonon coupling constant. Estimates reveal $A \approx 0.25$ at $T_0 \approx 28$ K and $n_0 = N_+ = 3.1\times10^{18}$ cm^{-3}, which corresponds to a coupling constant $|\varepsilon_1| \approx 7$ eV.

The results of calculating the coefficients $Q_\perp(N_{\rm Fe})$ and $\Delta\alpha(N_{\rm Fe})$ are depicted in Figs. 4 and 5. It can be seen that in magnetic fields ranging from 1 to 5 kOe the point at which both $Q_\perp$ and $\Delta\alpha$ change sign is practically fixed, that is, does not move along the horizontal axis. Calculations also show that the curves for $Q_\perp$ and $\Delta\alpha$ for different values of the alloy scattering parameter separate only when $N_{\rm Fe} > 1\times10^{19}$ cm^{-3}. Here we give the experimentally established values of the coefficients $Q_\perp$ and $\Delta\alpha$ at $T = 15$ K and $H = 3.6$ kOe; the dashed curves depict the results of calculations. Good agreement between the results of calculations and the experimental data suggests that the thoery correctly allows for the basic mechanisms of electron scattering.

As the diagrams show, the NE coefficients are positive in the iron-content range $N_{\rm Fe} \geqslant 6\times10^{18}$ cm^{-3} and for $T > 10$ K, where the scattering of electrons on the correlated system of charged donors Fe^{3+} dominates (Ref. 1). Obviously, the scattering on correlatively positioned Fe^{3+} ions manifests itself more the lower the temperature, i.e., the greater the order realized in the system of Fe^{3+} ions. However, as the experimental data imply (Figs. 1 and 2), the NE coefficients are small at fairly low temperatures $T < 10$ K and for $N_{\rm Fe} \geqslant 6\times10^{18}$ cm^{-3}. Analysis of the temperature dependence of the thermomagnetic coefficients shows that at such temperatures drag effects begin to come into play. These, as Figs. 1 and 2 exhibit, considerably decrease $Q_\perp$ $[Q_\perp(15\ {\rm K}) \sim Q_\perp(9\ {\rm K})]$ and $\Delta\alpha$ $(\Delta\alpha < 0)$. In a future paper we hope to elaborate on this aspect and analyze the behavior of thermomagnetic coefficients at high temperatures.

Our analysis shows that the change of sign in the NE coefficients for electrons with a parabolic dispersion law occurs only in the region of strong Coulomb correlations

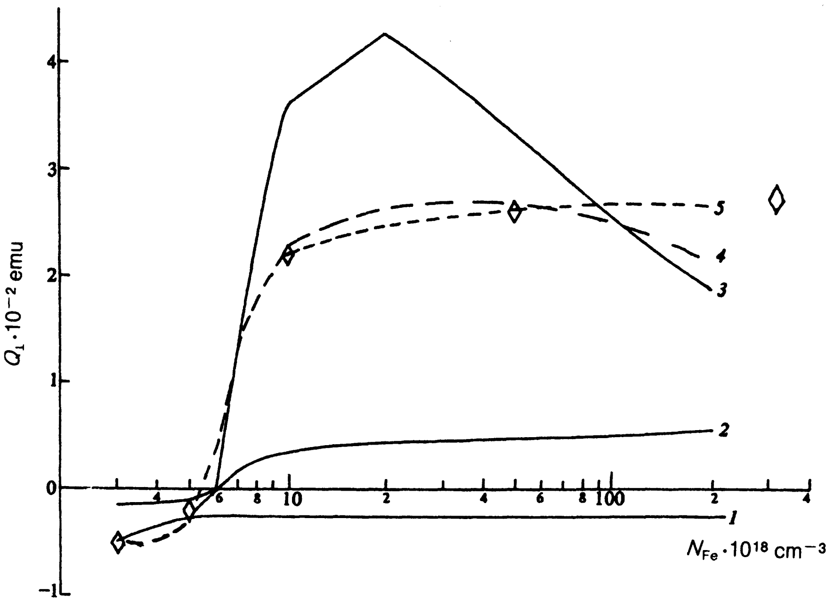

FIG. 4. $Q_\perp$ vs N_{Fe} for different magnetic field strengths. The ◊ represent the experimental data, and the curves represent the results of calculations. Curve *1* corresponds to scattering on randomly distributed charged centers at $T = 5$ K, and curves *2* to *5* to calculations with allowance for scattering on a correlated system of charged donors: curve *2* to $H = 5$ kOe at $T = 5$ K and $\Delta U = 0.32$ eV with $\omega\tau > 1$, curve *3* to $H = 1$ kOe at $T = 5$ K and $\Delta U = 0.32$ eV with $\omega\tau < 1$, curve *4* to $H = 3.6$ kOe at $T = 15$ K and $\Delta U = 0.35$ eV, and curve *5* to $H = 3.6$ kOe at $T = 15$ K and $\Delta U = 0.32$ eV.

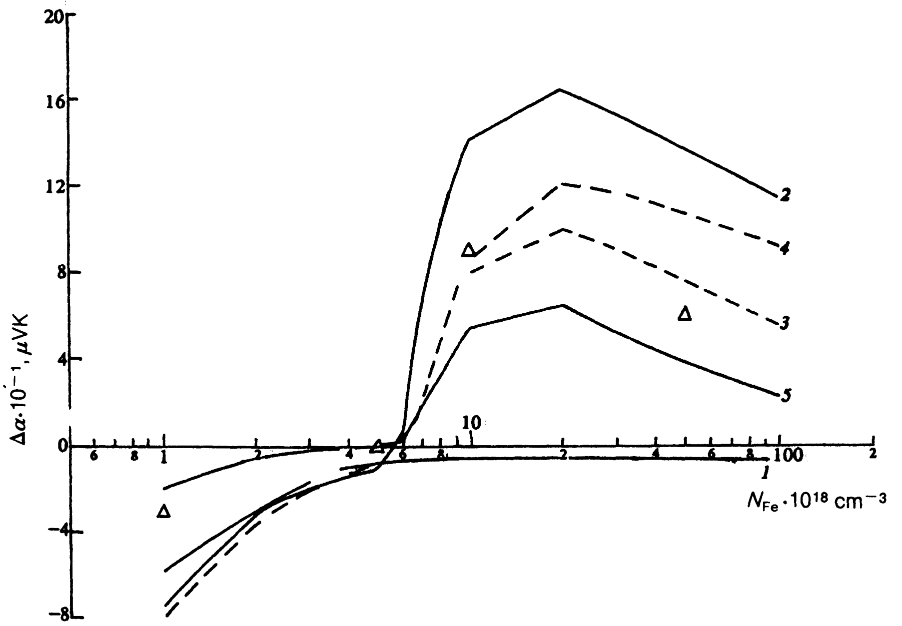

FIG. 5. $\Delta\alpha$ vs N_{Fe} for different magnetic field strengths. The Δ represent the experimental data, and the curves represent the results of calculations. Curve *1* corresponds to scattering on randomly distributed charged centers at $T = 10$ K, and curves *2* to *5* to calculations with allowance for scattering on a correlated system of charged donors: curve *2* to $H = 1$ kOe at $T = 10$ K and $\Delta U = 0.32$ eV with $\omega\tau < 1$, curve *3* to $H = 3.6$ kOe at $T = 17$ K and $\Delta U = 0.35$ eV, curve *4* to $H = 3.6$ kOe at $T = 17$ K and $\Delta U = 0.32$ eV, and curve *5* to $H = 5$ kOe at $T = 10$ K and $\Delta U = 0.32$ eV with $\omega\tau > 1$.

$[N_{Fe} \sim (8\text{–}9) \times 10^{18}$ cm$^{-3}]$. Allowance for the fact that the conduction band is not parabolic shows that the change of sign in $Q_\perp$ and $\Delta\alpha(H)$ occurs at $N_{Fe} \approx (5\text{–}6) \times 10^{18}$ cm^{-3}. As the temperature is raised to $\sim(25\text{–}40)$ K, the positive contribution to $Q_\perp$ and $\Delta\alpha$ due to phonon scattering increases. In the $N_{Fe} = (2\text{–}4) \times 10^{18}$ cm^{-3} range, where Coulomb correlations are weak, the observed change of sign in the NE coefficients at $T \sim (25\text{–}40)$ K is caused by an increase of the phonon contribution in the electron scattering. As Eqs. (19) and (20) imply, the increase in this contribution is related to the growth in the electron number density as the iron content in HgSe:Fe rises.

5. CONCLUSION

We have interpreted the unusual experimentally observed dependence of the transverse and longitudinal NE effects on the iron content in HgSe:Fe crystals at low temperatures. The nonmonotonic curves representing this dependence, $Q_\perp(N_{Fe})$ and $\Delta\alpha(N_{Fe})$, support the conclusion drawn in Ref. 1 that the main mechanisms for electron scattering in HgSe:Fe at low temperatures and fairly high iron concentrations are the scattering on the correlated system of Fe^{3+} ions and alloy scattering. The observed change of sign in the NE effects with increasing iron content serves as convincing proof of the transition from the range of weak Coulomb correlations to that of strong Coulomb correlations in the system of charged donors.

At high iron concentrations, when the system of Fe^{3+} ions is a strongly correlated Coulomb liquid, the behavior of the NE effects $Q_\perp(N_{Fe})$ and $\Delta\alpha(N_{Fe})$ differs qualitatively from that at low iron concentrations N_{Fe}, where Coulomb correlations between Fe^{3+} ions are negligible.

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