Electron-electron interaction in bismuth doped with tellurium in a strong magnetic field

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The effect of a strong magnetic field, $\omega_c \tau \gg 1$, on the electron-electron interaction in a disordered metallic system has been observed experimentally. This effect was predicted by Al'tshuler and Aronov[1] {Zh. Eksp. Teor. Fiz. **77**, 2028 (1979) [Sov. Phys. JETP **50**, 968 (1979)]}.

In disordered metallic systems when $kT \ll \hbar/\tau \ll \epsilon_F$ (τ is the momentum-relaxation time, and ϵ_F is the Fermi energy) the interference resulting from the interaction between the conduction electrons and the elastic scattering of these electrons by impurities or lattice defects gives rise to a peculiar temperature dependence of the thermodynamic and kinetic quantities[1]:

$$\frac{\Delta\sigma(T)}{\sigma_0} = 2{,}5\,\frac{2^{1/2}}{6\pi^2}\,\frac{\lambda(kT)^{1/2}}{\nu_0(D_1D_2D_3)^{1/2}\hbar^{3/2}} \equiv \alpha T^{1/2}\ , \qquad (1)$$

where $\Delta\sigma(T) = \sigma(T) - \sigma_0$; $\sigma_0 \equiv \sigma(0)$; D_1, D_2, and D_3 are the principal values of the diffusion-coefficient tensor, ν_0 is the state density at the Fermi level, $\lambda = 1 - (3/2x)\ln(1+x), x = (2p_F/\kappa)^2$, p_F is the Fermi momentum, and κ is the reciprocal screening length.[2,3] A temperature dependence of the conductivity of the form $\Delta\sigma(T) \propto T^{1/2}$ has been observed in many studies[3–9] in the absence of a magnetic field or in a field $\omega_c\tau < 1$ (ω_c is the cyclotron frequency).

The application of a strong magnetic field, $\omega_c\tau \gg 1$, substantially increases the quantity $\Delta\sigma(T)/\sigma_0$ due to a decrease in the diffusion coefficients across the field.[1] Bronevoĭ[10] carried out measurements using a strongly deformed bismuth to study the dependence of $\Delta\sigma(T)/\sigma_0$ on the magnetic field H. He found that $\Delta\sigma(T) \propto T^{1/2}$ in a deformed bismuth and that $\Delta\sigma(T)/\sigma_0$ decreases, instead of increasing, upon the application of a magnetic field, $\omega_c\tau > 1$.

In this letter we report the first experimental observation of the increase of $\Delta\sigma(T)/\sigma_0$ in a strong magnetic field, $\omega_c\tau \gg 1$. In our experiments, we have measured the temperature dependence of the longitudinal magnetoresistance of bismuth doped with tellurium.

1. In the absence of a magnetic field, $\Delta\sigma(T)/\sigma_0$ increases with decreasing relaxation time τ. In a strong magnetic field $\omega_c\tau \gg 1$, in contrast, $\Delta\sigma(T)/\sigma_0$ increases with increasing τ (until $kT < \hbar/\tau$). We have therefore doped bismuth with tellurium to the degree necessary to satisfy the inequality $kT < \hbar/\tau$ at liquid helium temperature, without making it dominant. Since tellurium is a donor in the case of bismuth, the doping increases the electron density and completely fills the valence band. As a result, the carriers of the same sign — the electrons — remain free. The basic measurements were carried out using three single-crystal samples, I, II, and III, in the form of rods ~ 1 cm long with a cross-sectional area of $\sim 10^{-2}$ cm^2. By doping sample III with tin, in addition to tellurium, we were able to reduce τ by a factor of ten, without appreciably increasing the electron density, since tin, in contrast with tellurium, is an acceptor in the case of bismuth. The parameters of the samples are the electron density n, which can be determined by measuring the Hall constant, the resistivity ρ_{00} measured at $H = 0$ and $T = 4.2$ K, the time τ, and the angles between the O axis of the sample and the c_2 and c_3 crystallographic axes, listed in Table I.

The measurements were carried out using a four-point bridge circuit with a 19-Hz, 140-mA alternating current I. The samples were immersed in liquid helium.

2. Figure 1 shows the experimental curves for the longitudinal magnetoresistance **H**||**I** plotted as a function of the magnetic field. The Shubnikov–de Haas temperature-dependent oscillation amplitude turned out to be rather high in our samples. Using expression (see Ref. 11) $\sigma = -\int_0^\infty \sigma(\epsilon)(\partial f_0/\partial\epsilon)d\epsilon$, where $\sigma(\epsilon) \equiv e^2\nu(\epsilon)D(\epsilon)$, $\nu(\epsilon)$ is the state density, $D(\epsilon)$ is the diffusion coefficient of electrons with an energy ϵ, and f_0 is the equilibrium distribution function for an "impure" metal, with $kT \ll \hbar/\tau$, we find

$$\sigma(T) = -\int_0^\infty \sigma(\epsilon)\frac{\partial f_0}{\partial\epsilon}\,d\epsilon = \sigma(\epsilon_F) - \frac{T^2}{\pi}\left(\frac{\partial^2\sigma_0}{\partial\epsilon^2}\right)_{\epsilon_F} \cdot \qquad (2)$$

In this expression the coefficient of T^2 oscillates, changing its sign as a function of H. To determine the magnitude of the contribution to the temperature dependence of the

TABLE I.

	n, 10^{18} cm^{-3}	ρ_{00}, 10^{-5} $\Omega\cdot$cm	τ, 10^{-13} s	$\angle c_2, O$	$\angle c_3, O$	α_σ, 10^{-3}K$^{-1/2}$	α_T, 10^{-3}K$^{-1/2}$
I	0.9	2.7	13	$\approx 30°$	$\approx 60°$	2,9	8,6
II	1.05	3.3	11	75°	51°	3.2	14
III	2.4	16	1.0	60°	36°	0.5	0.4

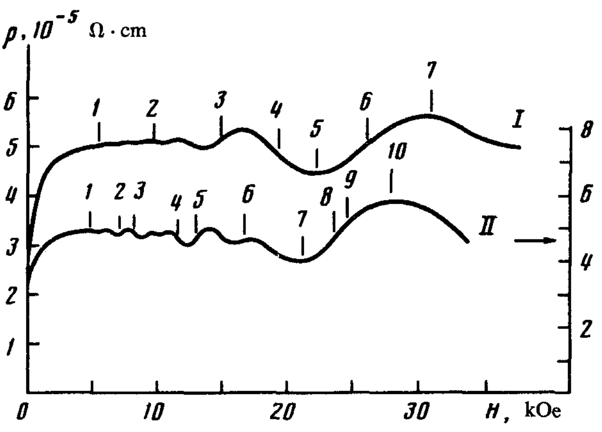

FIG. 1. Dependence of the longitudinal magnetoresistance ρ on the magnetic field H. The scale on the left is for sample I and the scale on the right is for sample II. $T = 4.2$ K. The fields in which the temperature dependences were measured are given.

term $\Delta\sigma_{\rm osc} = -(T^2/\pi)\times(\partial^2\sigma/\partial\epsilon^2)_{\epsilon_F}$, we have measured the temperature dependences of the resistance ρ in one of the minima (minimum labeled 5 in Fig. 1 for sample I and minimum labeled 7 for sample II) and in the maximum adjacent to this minimum (maximum labeled 7 in Fig. 1 for sample I and maximum labeled 10 for sample II). These temperature dependences for sample II are shown in Fig. 2 (curve 7 and 10). In the temperature interval 2.6–4.2 K, $\partial\rho/\partial T$ has different signs, consistent with Eq. (2). Below 2.6 K, we have $(\partial\rho/\partial T) < 0$ both in maximum and in the minimum, indicating that the electron-electron interaction is the dominant contribution to the temperature dependence. To reduce the contribution of $\Delta\sigma_{\rm osc}$, we have carried out the basic measurements of $\rho(T)$ in magnetic fields in which $\partial^2\rho/\partial H^2 \approx 0$ (see Fig. 1).

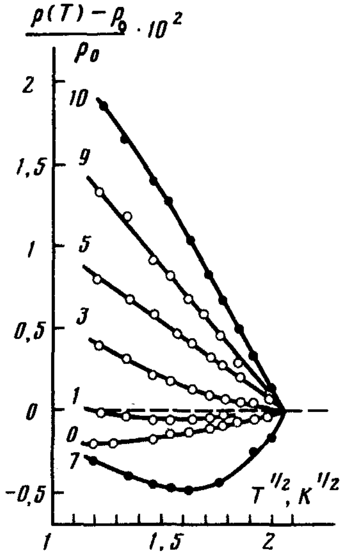

FIG. 2. Temperature dependences of the resistance in various magnetic fields. Sample II, $\rho_0 \equiv \rho$ (4.2 K). The numbers on the curves correspond to the numbers in Fig. 1. 0 — $H = 0$; 1 — $H = 4.9$ kOe; 3 — 8.2 kOe; 5 — 13 kOe; 7 — 21.3 kOe; 9 — 24.7 kOe; 10 — 28 kOe.

3. The temperature curves $\rho(T)$ measured in various magnetic fields are shown in Fig. 2. In the absence of a magnetic field (curve 0 in Fig. 2), we have $\partial \rho/\partial T > 0$ and the temperature dependence of the resistance is determined by the inelastic scattering of electrons. At $H = 0$ the contribution from the electron-electron interaction is small. This contribution can be determined from Eq. (1) if we take into account that $(D_1 D_2 D_3)^{1/2} \approx (e^2 \nu_0 \rho_{00})^{-3/2}$. At $T = 4.2$ K, for example, we have $\Delta\sigma(T)/\sigma_0 \approx 10^{-5}$ for sample II. The application of a strong magnetic field, $\omega_c \tau \gg 1$, does not change the shape of the monotonic part of the temperature curve of the resistance in a pure or slightly doped bismuth ($\hbar/\tau \ll kT$). In samples I–III in a magnetic field $\partial \rho/\partial T$ begins to decrease and then changes its sign (see curves 3, 5, and 9 in Fig. 2). In a strong field the experimental points conform well to the straight lines corresponding to the functional dependence $\Delta\sigma(T)/\sigma_0 = \alpha T^{1/2}$ [see curves 5 and 9 in Fig. 2;

$$\frac{\Delta\sigma(T)}{\sigma_0} \approx -\frac{\rho(T)-\rho_0}{\rho_0} + \frac{\rho(0)-\rho_0}{\rho_0}, \text{ and } \rho_0 \equiv \rho\,(4{,}2)\ ].$$

4. Figure 3 is a plot of the coefficient α of $T^{1/2}$ as a function of the magnetic field [according to (1), $\alpha = 2T^{1/2}(1/\rho)(\partial\rho/\partial T)$]. It follows from Eq. (1) that when the longitudinal magnetoresistance is independent of the magnetic field, the field dependence of α and $(1/\rho)(\partial\rho/\partial T)$ is determined by the conductivity across the field $\sigma_\perp(H)$: $(1/\rho)(\partial\rho/\partial H) \propto \sigma_\perp$. To determine the field dependence of $\sigma_\perp$, we measured the transverse magnetoresistance ρ_{xx} and the Hall resistance ρ_{xy} of the samples in a magnetic field perpendicular to the axis of the sample. These measurements show that $\rho_{xy} \propto H$ in a strong field and that the monotonic part of $\rho_{xx} \propto A + BH$, $\rho_{xy} \gg \rho_{xx}$. The inverse conductivity $\sigma_\perp^{-1} \propto (H^2/A + BH)$. [A divergence from the $\sigma_\perp \propto H^{-2}$ law in metals and semimetals in a strong magnetic field has been observed in several studies (see Ref. 10, for example), but this divergence has so far not been explained satisfactorily.] In the case of samples I–III in fields $H > 5$ kOe, we have $BH > A$, so that $\sigma_\perp^{-1}$ and hence $(1/\rho)(\partial\rho/\partial T)$ should be approximately proportional to H, consistent with the experimental dependence of $(1/\rho)(\partial\rho/\partial T)$ on H, shown in Fig. 3.

5. The measured values of $\sigma_\perp$ can be used to estimate the coefficients of $T^{1/2}$ in Eq. (1). The values of α_σ obtained in this manner are given in Table I, along with the

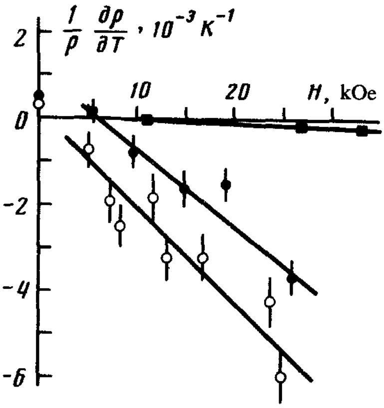

FIG. 3. Dependence of the monotonic part of the thermal resistance $(1/\rho)(\partial\rho/\partial T)$ on the magnetic field at $T = 1.75$ K, ● — sample I; ○ — sample II; ■ — sample III.

values of α_T found from the experimental temperature dependences. Since the value of α_σ was estimated ignoring the multivalley effects and the strong anisotropy of the electron spectrum of bismuth, and since the transverse and longitudinal conductivities measured for different directions of the magnetic field were used to estimate this value, we can assume that the agreement is completely satisfactory. The measurements of sample III have confirmed that in a strong magnetic field, $\omega_c \tau \gg 1$, the quantity $\Delta\sigma(T)/\sigma_0$ decreases with decreasing τ, in contrast with the case in which there is no magnetic field.

The experimental results: the dependence of $\Delta\sigma(T)/\sigma_0$ on the temperature, on the magnetic field, and on the relaxation time τ confirm the conclusions of the theory,[1] although the dependence of the transverse conductivity $\sigma_\perp$ on the magnetic field is not clear.

We note in conclusion that in the ultraquantum limit, when all electrons are situated in a single Landau level, a formal substitution of the diffusion coefficients and of the state density found in Ref. 12 into expression (1) yields $\Delta\sigma(T)/\sigma_0 \sim 1$ for $kT \sim \hbar/\tau$ in the case of scattering by point defects and $\Delta\sigma(T)/\sigma_0 \gg 1$ in the case of scattering by a screened Coulomb potential. A theoretical study of the electron-electron interaction in these cases would therefore be useful.

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