Interaction-Induced Magnetoresistance in a Two-Dimensional Electron Gas

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We study the interaction-induced magnetoresistance of a two-dimensional electron gas subject to a perpendicular magnetic field. While in a diffusive regime (very low temperatures) Altshuler-Aronov corrections [1] lead to a negative magnetoresistance [2], *ballistic magnetotransport* in high magnetic fields has not been investigated yet. This regime, which is directly relevant to experiments on high-mobility systems, is addressed in the present work. Specifically, the ballistic regime corresponds to the range of relatively high temperatures $T \gtrsim \hbar/\tau$, where τ is the *transport* mean free time. Since in high-mobility samples $\hbar/\tau$ can be as small as 50 mK, it is the ballistic regime (rather than the diffusive one) that is realized in a typical experiment.

We develop [3, 4] a general theory of the interaction–induced corrections $\delta\sigma_{\alpha_\beta}$ to the conductivity tensor of 2D electrons valid for arbitrary temperatures, transverse magnetic fields and disorder range. Making use of a "ballistic" generalization of the diffuson diagram technique, we derive a general formula which expresses $\delta\sigma_{\alpha_\beta}$ in terms of propagators of classical motion in the phase space ("ballistic diffusons"). Our formula contains as limiting cases all the previously known results: the diffusive regime in zero [1] and strong [2] magnetic fields and the ballistic regime with white-noise disorder in zero magnetic field [5]. Our formalism allows us to calculate the magnetoresistance in systems with arbitrary type of disorder in the full range of temperatures from the diffusive to the ballistic regimes.

We show that in the ballistic regime the interaction corrections are very sensitive to the type of disorder. In particular, a $T\tau$-contribution to the resistivity in zero magnetic field (derived for the white-noise disorder in [5]) is proportional to the probability of backscattering on disorder and therefore is exponentially suppressed in a smooth random potential. However, the interaction correction reappears in a sufficiently strong magnetic field, $\omega_c \gtrsim T$.

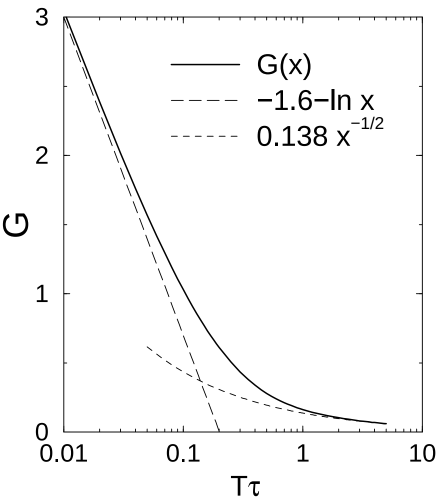
Generally, the magnetoresistivity is determined by return processes (diffusive or cyclotron returns). We find that in the case of a *smooth disorder* characteristic for high-mobility heterostructures the interaction-induced magnetoresistance has the form

$$\frac{\delta\rho_{xx}(B)}{\rho_0} = -\frac{(\omega_c\tau)^2}{\pi k_F l} G(T\tau). \qquad (1)$$

The function $G(x)$ is shown in Fig.1 and has the following asymptotics: $G(x \ll 1) \simeq -\ln x +$ const and $G(x \gg 1) \simeq (c_0/2)x^{-1/2}$ with $c_0 = 3\zeta(3/2)/16\sqrt{\pi} \simeq 0.276$. In other words, the temperature dependence of the quadratic negative magnetoresistance changes from $\ln(T\tau)$ in the diffusive regime $(T\tau/\hbar \ll 1)$ to $(T\tau)^{-1/2}$ in the ballistic one $(T\tau/\hbar \gg 1)$. These results have been confirmed by a very recent experiment [6].

We also discuss the experimentally relevant situation when two types of disorder are present: rare short-range scatterers (residual impurities) and the smooth disorder.

Another realization of the ballistic regime is a high-frequency $(\omega \gg \tau^{-1})$ magnetotransport. At frequencies larger than the cyclotron frequency ω_c the interaction correction to the resistivity shows a sequence of peaks at $\omega = n\omega_c$ related to the cyclotron returns.



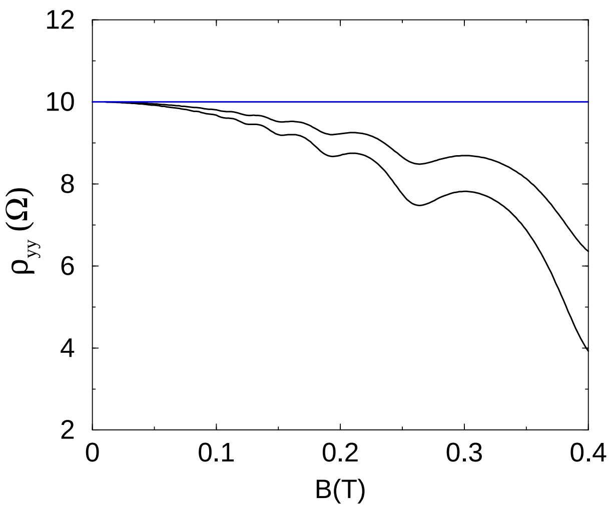


Figure 1: Function $G(T\tau)$ determining the T-dependence of the interaction correction (1).
Figure 2: Development of the interaction-induced magnetoresistivity in the parallel direction in a modulated system with lowering temperature (from top to bottom). The straight line is the quasiclassical result in the absence of interaction.

We further apply the method to nanostructured systems. A quantum correction determined by the interplay of the interaction and disorder-induced scattering is of special interest in the case of a 1D *lateral superlattice*, where the resistivity is anisotropic. We demonstrate that in this case the correction (which has a distinct oscillatory form) shows up in the resistivity in parallel (y) direction, which is unaffected by the modulation within the quasiclassical theory, see Fig.2. This is because the interaction effects mix the two directions,

$$\frac{\delta\rho_{yy}(B)}{\rho_0} = -\frac{(\omega_c\tau)^2}{\pi k_F l}\left(\frac{\rho_o}{\rho_{xx}}\right)^{1/2} G(T\tau). \tag{2}$$

This provides an explanation for puzzling oscillations in the parallel direction (in phase with the commensurability oscillations in the transverse direction) observed recently [7].

References

[1] B.L. Altshuler, A.G. Aronov, in *Electron-Electron Interactions in Disordered Systems*, edited by A.L. Efros and M.Pollak, (Elsevier, Amsterdam, 1985).

[2] A. Houghton, J.R. Senna, and S.C. Ying, Phys. Rev. B **25**, 2196 (1982); S.M. Girvin, M. Jonson, and P.A. Lee, *ibid*, **26**, 1651 (1982).

[3] I.V. Gornyi and A.D. Mirlin, Phys. Rev. Lett. **90**, 076801 (2003).

[4] I.V. Gornyi and A.D. Mirlin, in preparation.

[5] G.Zala, B.N.Narozhny, and I.L.Aleiner, Phys. Rev. B **64**, 214204 (2001)

[6] L. Li, Y.Y. Proskuryakov, A.K. Savchenko, E.H. Linfield, and D.A. Ritchie, Phys. Rev. Lett. **90**, 076802 (2003).

[7] C. Mitzkus, W. Kangler, D. Weiss, W. Wegscheider, and V. Umansky, Physica E **12**, 208 (2002).