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Physica B 312–313 (2002) 557–558

PHYSICA B

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Many-electron conductivity of a non-degenerate 2D electron liquid in strong magnetic fields

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Abstract

We study the frequency-dependent conductivity of a nondegenerate two-dimensional electron system (2DES) in a quantizing magnetic field in the presence of weak short-range disorder. The 2DES is correlated, forming a liquid, which makes it necessary to account for electron–electron interaction (EEI) nonperturbatively. In strong magnetic fields, the low-frequency conductivity can be expressed perturbatively in disorder, in terms of the time-dependent density–density correlator of the liquid. For short-range disorder the relevant time scale t_c is much shorter than the characteristic hydrodynamical cut-off time. As a result, the expression is dominated by short-time correlators of the liquid, which allows us to obtain an explicit expression for the frequency-dependent conductivity. The results directly apply for the strong-field magnetoconductivity of electrons on helium surface. © 2002 Elsevier Science B.V. All rights reserved.

PACS: 73.23.–b; 73.50.–h; 73.40.Hm

Keywords: Two-dimensional plasma; Transport; Disorder

Understanding transport in strongly correlated systems is one of the most challenging problems in physics of low-dimensional systems. Especially difficult for analysis are the systems which do not support any long-lived quasiparticle-like excitations. The intuition gained in weak coupling calculations is no longer useful for such systems, and one often has to invent new approaches.

In this work, we report results on dissipative frequency-dependent conductivity in one such situation, a nondegenerate two-dimensional electron system (2DES) with weak short-range disorder and quantizing magnetic field. We consider the regime where electrons form a strongly correlated magnetized classical liquid. Specifically, we assume that the electron filling fraction at the lowest Landau level is very small, $n^2 \ll 1$, where the magnetic length $l \equiv (\hbar/m\omega_c)^{1/2}$ and n is the electron density. At the same time, the characteristic Coulomb

energy $e^2(\pi n)^{1/2}$ is assumed to be large compared to the electron kinetic energy E_{kin} given by the temperature $k_B T$ in this nondegenerate case. Electrons form a liquid if the ratio $\Gamma \equiv e^2(\pi n)^{1/2}/k_B T$ does not exceed the critical value $\Gamma_w \approx 130$ [1].

A physical realization of this system is provided by electrons floating on helium surface [1]. The most common parameter range is such that the characteristic force on an electron from the random potential is weaker than the force from other electrons. In this regime, the low-frequency ($\omega \ll \omega_c$) conductivity of the system can be calculated perturbatively in disorder. For delta-correlated disorder, the corresponding expression is proportional to the Fourier-transformed single-site density–density correlator of the liquid. The characteristic decay time of such a correlator, $t_c = l(B/c) \langle E_f^{-1} \rangle \sim (\hbar/el)(n^{3/2}k_B T)^{-1/2}$, can be interpreted as the time it takes for a magnetized electron wavepacket of size l to drift past a point (the impurity location) driven by the electric field $E_f(t)$ from other electrons. Since all hydrodynamical modes evolve over much longer time, the field E_f can be considered static over

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the time $\sim t_e$, which significantly simplifies the calculation. The instantaneous distribution of this field is Gaussian, except for far tails, and $\langle E_f^2 \rangle = F(\Gamma)n^{3/2}k_B T$, with $F(\Gamma)$ varying only slightly, from 8.9 to 10.5, in the whole range $\Gamma \gtrsim 20$ [2]. Ignoring the deviations of the distribution of \mathbf{E}_f from Gaussian, in the range $\omega \ll k_B T/\hbar \ll \omega_c$ we obtained:

$$\sigma_{xx}(\omega) = \frac{\pi n e^2 \gamma^2 l^2 \tau_e}{16 k_B T} (1 + \omega \tau_e) \exp(-\omega \tau_e). \quad (1)$$

Here $\tau_e \equiv (2/\pi)^{1/2} t_e$ and $\hbar \gamma$ ($\gamma t_e \ll 1$) is the width of the single-particle disordered Landau level; for delta-correlated Gaussian potential with r.m.s. amplitude V_0 , $\hbar \gamma = (2/\pi)^{1/2} V_0/l$.

The expression for $\sigma_{xx}(0)$ has a form of the single-electron conductivity in a magnetic field, with the scattering rate $\tau^{-1} = \gamma^2 t_e$ which is quadratic in the disorder potential but also depends on EEI through the time t_e . The identical result for the static conductivity was obtained earlier [3] using different approaches; the corresponding magnetic-field, density, and temperature dependences are in excellent agreement with experiment [1,4].

Unexpectedly, the frequency dependence of conductivity (1) is very different from the standard Drude form. The conductivity $\sigma_{xx}(\omega)$ reaches a maximum at $\omega = 0$, and the characteristic width of the peak is given not by the rate of disorder scattering $\tau^{-1} = \gamma^2 t_e$, but solely by the inverse many-electron time t_e^{-1} . The extent of the tail can be understood by noticing that the conductivity is formed by processes in which the energy $\hbar \omega$ of the absorbed photon goes to the many-electron system, namely the absorbing electron is shifted by the distance $\delta r = \hbar \omega / e E_f$ along the electric field \mathbf{E}_f . The associated momentum $\hbar / \delta r$ is provided by short-range scatterers. Since the size of the electron wave packet is l , the probability of transferring momentum bigger than \hbar/l is exponentially small. Therefore, the conductivity decays for $\omega \gtrsim e E_f l / \hbar$, or $\omega t_e \gtrsim 1$. For much larger ω , the necessary displacement δr becomes so large that multiple scattering is always advantageous, and decay of $\sigma_{xx}(\omega)$ slows down to $|\ln \sigma_{xx}(\omega)| \propto (\omega t_e)^{2/3} / [\ln(\omega/\gamma)]^{1/3}$ [5].

In contrast to the static conductivity which increases with the magnetic field for quantizing fields, $\sigma_{xx}(0) \propto B^{1/2}$, the magnetic-field dependence of the many-electron microwave conductivity $\sigma_{xx}(\omega)$ is non-monotonic, see Fig. 1. The position of the maximum is

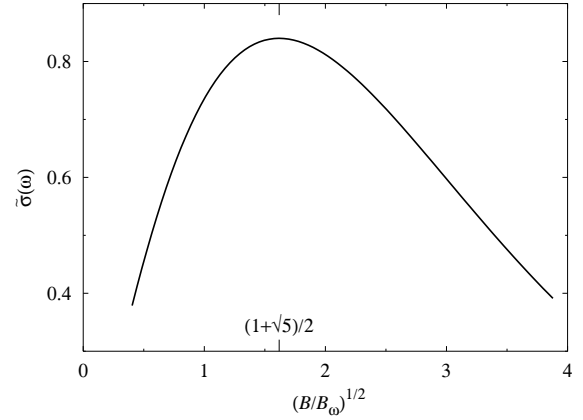


Fig. 1. The dependence of the reduced microwave conductivity $\tilde{\sigma}(\omega) \equiv (n e^2 V_0^2 / 8 \hbar^2 \omega k_B T)^{-1} \sigma_{xx}(\omega)$ on the magnetic field. The characteristic magnetic field scale B_ω corresponds to $\omega \tau_e(B_\omega) = 1$, which gives, for a given magnetic field, $B_\omega = B / [\omega \tau_e(B)]^2$ (since $\tau_e(B) \propto B^{1/2}$).

given by the expression $(\omega \tau_e)_{\max} = (1 + \sqrt{5})/2$, or, equivalently, $B_{\max} \propto \omega^{-2}$. The maximum results from the competition between the increase of the scattering rate with increasing magnetic field B and the decrease of the probability to absorb a photon for $\omega t_e > 1$ associated with the increase of t_e with B .

Work at MSU was supported in part by the NSF through Grant No. PHY-0071059.

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