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The magnetoconductance of the 2d system of electrons on liquid helium in the extreme quantum limit

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Abstract

The magnetoconductivity σ_{xx} of the nondegenerate two-dimensional system of electrons on a liquid helium surface has been measured for magnetic fields up to 22 T in the temperature range 0.4 K < T < 2 K. At strong fields, deviations from the classical parabolic behavior are observed. In this case, we compare our measured magnetoconductivity with a quantum transport theory of scattering within broadened Landau levels.

One of the cleanest two-dimensional electron systems is formed by depositing electrons on the surface of liquid helium. The surface electrons may interact with vapor atoms (dominant for temperatures $T > 1\text{K}$) and with thermal vibrations of the helium surface (= ripplons, dominant for $T < 1\text{K}$). As a consequence of the low electron density $n_e = 10^7 - 10^8\text{cm}^{-2}$, the Fermi energy $E_F \ll k_B T$ for all practical temperatures. So we deal with a nondegenerate two-dimensional electron gas (2DEG). In a strong magnetic field perpendicular to the surface, the energy spectrum splits up into discrete Landau levels and a quantum mechanical treatment is required to explain the transport properties.

To explore the magnetoconductance of the electrons on liquid ^{4}He, measurements were performed in the temperature range $0.4K < T < 2K$ in magnetic fields up to 22 T. The measurements were done using the Sommer-Tanner technique [1] in an experimental cell with a Corbino geometry [2]. We measured the complex impedance presented by the Corbino geometry with a capacitance-conductance bridge in conjunction with a dual-phase lock-in amplifier. From this the conductance of the 2DEG was determined using a simplified equivalent circuit analysis [2]. Electrons were deposited on the helium surface by pulse-heating of a tungsten filament. The electron density n_e was calculated from the vertical holding field.

Radial gradients of the magnetic field lead to a deformation of the surface of the diamagnetic ^{4}He [3]. Minimizing the sum of gravitational and magnetic energy we calculated the shape of the surface. The deformation causes a redistribution of the electrons, i.e. $n_e = n_e(r, B)$ (r: distance from the center). Since $\sigma_{xx} \propto n_e$ we can correct the measurements for this effect.

For $T > 1\text{K}$ in low magnetic fields our conductance measurements show the classical Drude behavior. When the system enters the quantum limit, i.e. $\hbar\omega_c > k_B T$ (ω_c: cyclotron frequency) the curves show a reduced field dependence. For δ-like impurities, theoretical calculations based on intra Landau level scattering within impurity-broadened Landau levels get a semi-elliptic density of states (DOS) in a self-consistent Born approximation [4] or a gaussian DOS (for higher order calculations [5] or a cumulant expansion [6]). For a gaussian DOS and using Boltzmann statistics, $\sigma_{xx}(B)$ can be calculated analytically:

$$\sigma_{xx}(B) = \frac{\sqrt{\pi}}{4}\frac{\Gamma}{k_B T}\exp\left(-\left(\frac{\Gamma}{4k_B T}\right)^2\right)\coth\left(\frac{\hbar\omega_c}{2k_B T}\right)\frac{n_e e}{B} \qquad \text{where } \Gamma = \frac{\hbar e}{m}\sqrt{\frac{2B}{\pi\mu_H}}$$

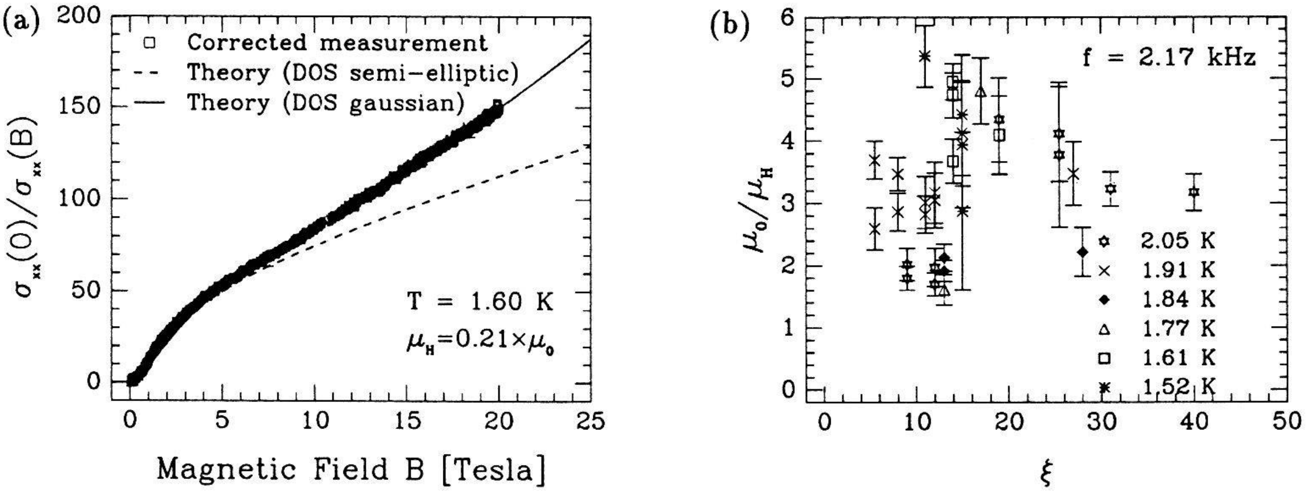

Figure 1: a) Inverse magnetoconductance of electrons on He, theory DOS semi-elliptic see [2,3], $n_e = 5.6 \times 10^7 cm^{-2}$. b) Inverse fitparameter μ_H normalized to μ_0 calculated from [7].

where Γ is the half-width of the Landau level, μ_H is the mobility in high fields and μ_0 is the zero field mobility. The theory predicts $\mu_H = \mu_0$. To fit our high field data (for $B > 10\,\mathrm{T}$), we use μ_H as a fitparameter. To get rid of a geometrical factor and also to be independent of the electron density n_e, we plot the ratio $\sigma_{xx}(0)/\sigma_{xx}(B)$ where $\sigma_{xx}(0) = n_e e \mu_0$ was calculated with values for μ_0 according to [7]. Our data are normalized to the value of the theoretical curve for gaussian DOS at 10 T. Our high field data are in good qualitative agreement with the theoretical calculations for gaussian DOS. We get $\mu_H < \mu_0$ (Fig.1b)) which is equal to $\Gamma_{exp} > \Gamma_{theo}$ in agreement with [2]. Electrons on liquid helium can be characterized by the dimensionless parameter $\xi = \frac{\langle E_{pot}\rangle}{\langle E_{kin}\rangle} = \frac{\sqrt{\pi n_e} e^2}{k_B T}$. For $\xi < 1$ we deal with an electrongas, for $1 < \xi < 130$ the motion of the electrons are strongly correlated and are fluidlike and for $\xi > 130$ the electrons form a Wigner lattice. The theories are valid for $\xi < 1$ whereas our experiments were done for $5 < \xi < 40$. A possible explanation for the differences between the theory and our experimental results is that the electron-electron interaction might reduce the mobility μ.

For $T < 1\mathrm{K}$ the measurements of $1/\sigma_{xx}(B)$ as a function of B show a steep increase at low fields then they saturate and for high fields they are almost independent of B.

In conclusion, we have measured the high-field magnetoconductance of electrons on liquid helium. Our data can be fitted by theoretical calculations which assume a gaussian DOS. The experimental linewidth Γ_{exp} resulting from this fit is larger than the value predicted by the theory.

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