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Quantum Magnetoconductance of the Two-Dimensional Electron Gas on a Liquid Helium Surface

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The longitudinal conductivity σ_{xx} of the two-dimensional electron system on a liquid helium surface was measured as function of magnetic field for fields up to 4 Tesla. The temperature was in the range $1.4 < T < 2.0$ K, so that scattering of electrons by vapour atoms is dominant. When the quantum limit is reached, which means that the Landau level separation $\hbar\omega_c$ is larger than the thermal energy k_bT ($\hbar\omega_c/k_bT \lesssim 4$ under the present conditions), a deviation from the classical relation $\sigma_{xx} \sim 1/B^2$ is observed. A discussion is given based on a quantum transport theory.

1. INTRODUCTION

Electrons supported on a liquid helium surface form one of the simplest and most ideal two-dimensional electron systems [1]. It is a classical gas at all practical temperatures, i.e. $E_F \ll k_bT$, with E_F the Fermi energy and k_bT the thermal energy. The interaction with the liquid substrate is very weak. At temperatures above 1 K, it can be neglected and the scattering is then completely caused by collisions between electrons and vapour atoms, which are well understood [2,3].

When a magnetic field of sufficient strength is applied perpendicular to the layer, the inplane motion is confined to Landau orbits and the energy spectrum is completely discrete. Under these conditions, a quantum mechanical description of electron transport is required. Because of its simplicity, electrons on helium form a very suitable system to test quantum magnetotransport theories.

In this paper, measurements of the longitudinal conductivity σ_{xx} are reported at temperatures where vapour atom scattering is dominant. The condition for discrete Landau levels, $\mu B \gg 1$ (μ = mobility in B=0, B = magnetic field) is easily fulfilled for fields of about 4 T and mobilities of the order of 10 m^2/Vs. The magnetic field covers the range $0 \lesssim \hbar\omega_c/k_bT \lesssim 4$ ($\hbar\omega_c$ = Landau level separation, ω_c = cyclotron frequency) so that all electrons eventually occupy the lowest Landau level.

2. EXPERIMENTAL PROCEDURE

The experimental cell, illustrated in Fig. 1(a), is cylindrical symmetric. The electrons are supported on the helium surface, covering an area of $\pi \cdot 8^2$ mm^2, and are confined in the horizontal and vertical directions by means of negative voltages V_p on the upper plate and V_g on the guard ring, typically 10 V and 25 V. The bottom of the cell consists of a central electrode and a concentric ring electrode, separated by a spacing of 0.5 mm, which are kept at dc ground. The distance between upper plate and electrodes is 3 mm. The helium height is typically 1 mm above the electrodes. Magnetic fields up to 4 Tesla can be applied using a superconducting coil. The electrons are deposited on the helium surface by heating a tungsten filament a few times until saturation occurs. The electron density n_0 is then given by $n_0 e = \epsilon_r\epsilon_0 V_p/d$, where d is the height of the helium level, ϵ_r the relative dielectric constant of liquid helium , ϵ_0 the dielectric constant of the vacuum and e the elementary charge.

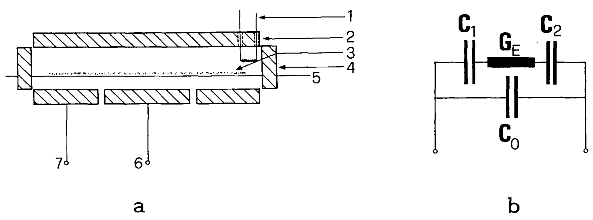

Fig. 1. a) The experimental cell: 1. tungsten filament 2. upper plate 3. electron sheet 4. guard ring 5. liquid helium level 6. center electrode 7. ring electrode.
b) The simplified equivalent circuit of the experimental cell shown in Fig. 1a. C_0 accounts for the direct coupling between the two electrodes, C_1 and C_2 denote the capacitances between the electrodes and the electron sheet and G_E denotes the conductance of the electron sheet above the spacing.

The method of measuring the longitudinal conductivity is similar to the method described by Iye [3]. The response of the electrons to an ac-field is determined by measuring the complex impedance between the two electrodes with a capacitance-conductance bridge operating at frequencies of the order of 10 kHz. The amplitude of the ac driving voltage is usually 200 mV. To interpret the measurements, a simplified equivalent circuit, shown in Fig. 1(b), is used. An elementary circuit analysis gives a relation for the measured conductance G and capacitance C to the conductance of the electrons G_E and $C_E^{-1}=C_1^{-1}+C_2^{-1}$. Since G_E is equal to $\sigma_{xx}(B)/\gamma$, where γ is a geometrical factor, the ratio $\sigma_{xx}(B=0)/\sigma_{xx}(B)$ can be measured as function of magnetic field B. The validity of the simplified circuit was checked by measuring at different bridge angular frequencies which gave the same results for $\sigma_{xx}(B)/\gamma$.

3. RESULTS AND DISCUSSION

The measured ratio $\sigma_{xx}(B=0)/\sigma_{xx}(B)$ is plotted in Fig. 2 for temperatures $1.4 < T < 2.0$ K as a function of magnetic field B. At low B, the classical parabolic behavior is observed [3], since $\sigma_{xx}(B)$ in the single relaxation time ap-

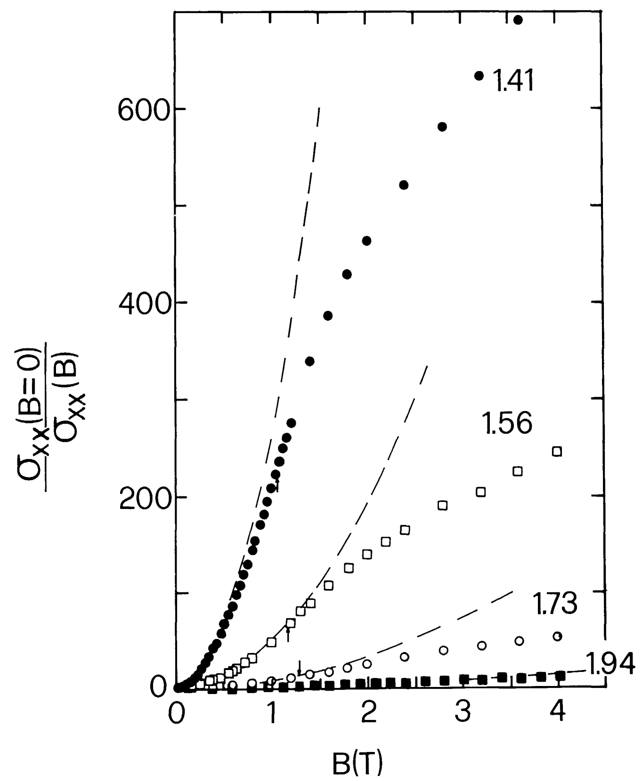

Fig. 2. Measured $\sigma_{xx}(B=0)/\sigma_{xx}(B)$ as a function of B for T varying from 1.41 to 1.94 K. The dashed lines are calculated from eq. (1), fitted to the data at low fields.

proximation is given by [4]

$$\sigma_{xx}(B) = \sigma_{xx}(B=0)/(1 + \mu^2B^2) \qquad (1)$$

Since the relative error in the measured G for B=0 and so in $\sigma_{xx}(B=0)/\gamma$ is large, $\sigma_{xx}(B=0)/\gamma$ and μ are determined by fitting the low field measurements to eq. (1). The values thus obtained for $\mu(T)$ agree with the literature values [3]. When the magnetic field increases a deviation from the parabolic behavior is seen (the dashed curves are the parabolas corresponding to eq. (1)) and the behavior becomes almost linear with B.

Deviation from classical transport theories can be expected when the system enters the quantum limit, i.e. $\hbar\omega_c > k_bT$. The field where $\hbar\omega_c = k_bT$ is indicated with arrows in Fig. 2. The situation can be best understood qualitatively by considering the transport in a diffusion picture [5]. The conductivity can then be written as

$$\sigma_{xx} = \mathcal{D}_e \cdot e^2 \cdot D \qquad (2)$$

where $\mathcal{D}_e$ is the electron density per unit energy, and D the diffusion constant. The latter can be written generally as $D = \ell^2/\tau$, with ℓ and τ the characteristic length and hopping time for the diffusion process. At zero field, ℓ and τ are the mean free path and scattering time respectively. For a non-degenerate electron system and $\hbar\omega_c \ll k_bT$, we have $\mathcal{D}_e \simeq n_0/k_bT$. In a classical strong field, i.e. $\omega_c\tau \equiv \mu B \gg 1$, but $\hbar\omega_c \ll k_bT$, the characteristic lenght ℓ is the classical cyclotron radius $R_c = mv/eB$ with $v = (k_bT/m)^{1/2}$ and m the electron mass. Using these relations, eq. (2) is equivalent to eq. (1), which gives the parabolic magnetoconductance. In the quantum limit, the quantum mechanical cyclotron radius, given by $R_c = (\hbar/eB)^{1/2}$ should be used in eq. (2). Because inter-Landau level scattering is energetically no longer allowed, the scattering time becomes field dependent [5]. The characteristic time for the diffusion process is then given by $\tau(B) = \hbar/\Gamma(B)$, where $\Gamma(B)$ is the Landau level width [5]. As all electrons are in the lowest Landau level, $\mathcal{D}_e \simeq n_0/\Gamma(B)$, for $k_bT \gg \Gamma$. One thus obtains in the quantum limit

$$\sigma_{xx}(B) = \frac{n_0e^2}{m\omega_c} \qquad (3)$$

which gives a linear dependence with B. It should be noted that the change in field dependence of $\sigma_{xx}(B)$ results from the different field dependence of the cyclotron radius in the quantum limit. The Landau level width Γ drops out in the limit $k_bT \gg \Gamma$.

Preliminary calculations of $\sigma_{xx}(B)$ have been performed by integrating over the energy using the theory of Ando and Uemura [5] in the limit of a δ-function scattering potential. This should be a good approximation for electron-vapour atom scattering. A Boltzmann distribution was assumed for the occupation of states within the lowest Landau level ($\Gamma \sim k_bT$ for the experimental conditions). The calculations yielded the approximate linear dependence with B, but the calculated ratio $\sigma_{xx}(B = 0)/\sigma_{xx}(B)$ was about a factor of three smaller than the experimental one in the field- and temperature range of Fig. 2. In contrast to the simple result of eq. (3), the calculations yield a strong temperature dependence resulting from the temperature dependence of the occupation distribution in the Landau level and the strong temperature dependence of the mobility μ. As the theory contains no adjustable parameters, the quantitative discrepancy is unexplained at present.

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