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1989 J. Phys.: Condens. Matter 1 2743

(http://iopscience.iop.org/0953-8984/1/16/013)

J. Phys.: Condens. Matter **1** (1989) 2743–2746. Printed in the UK

LETTER TO THE EDITOR

Magnetoresistance of 2D electrons on helium at 0.5 K

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Received 1 February 1989

Abstract. Measurements have been made of the resistivity of 2D electrons on liquid helium at $T = 0.5$ K in magnetic fields up to 4 T. Strong quantum magnetoresistance is observed for $\hbar\omega_c/kT \leqslant 10$, where ω_c is the cyclotron frequency, due to the formation of Landau levels.

Electrons above the surface of liquid helium form a two-dimensional (2D) conducting sheet with a very high mobility μ at low temperatures. On bulk helium, electrons are only stable for densities $n < 2 \times 10^{13}\ \mathrm{m}^{-2}$ which corresponds to a Fermi temperature $T_F(n) < 56$ mK. The degenerate region cannot easily be reached experimentally because of the transition to a 2D electron solid below 1 K. Above the melting temperature the electrons behave as a classical 2D electron gas (2DEG). The Drude model for the magnetoresistivity tensor in a magnetic field B gives

$$\rho_{xx} = \rho_0 = 1/ne\mu_0 \qquad \rho_{xy} = B/ne \tag{1}$$

where ρ_0 and μ_0 are the resistivity and mobility in zero field, and it predicts zero magnetoresistance for free electrons. However it has recently been demonstrated that quantum effects are important, particularly for ρ_{xx}, and the Drude model is not valid even in the classical regime for $\mu B > 1$ where Landau levels form. Van der Heijden and co-workers [1–3] measured the quantum magnetoresistance and Hall effect in 2D electrons on helium above 1.4 K while Adams and Paalanen [4] measured the magnetoresistivity of 2D electrons on solid hydrogen. In both cases the theory given in [5] was modified for classical statistics and gave excellent agreement with the experiments for elastic scattering by ^{4}He vapour atoms. We now present measurements of the magnetoresistivity of 2D electrons on liquid helium at 0.5 K, where the mobility is very high and is limited by inelastic scattering by ripplons, in fields up to 4 T so that $\hbar\omega_c/kT \leqslant 10$ where ω_c is the cyclotron frequency.

We used the Sommer–Tanner technique [6] with an array of three rectangular electrodes (overall dimensions 17 mm × 6 mm, see the inset in figure 1) a distance 0.42 mm below the helium surface and the electron sheet. Electrode A was driven with a 31 mV RMS voltage at 10.48 kHz and the AC current I that flowed to electrode D was measured by a lock-in amplifier. The electrons were generated by a glow discharge and the vertical DC holding field E was varied to change the mobility at a fixed temperature. Figure 2 shows the field dependence of both phases of the current, $I(0°)$ and $I(90°)$ for $n = 2.77 \times 10^{12}\ \mathrm{m}^{-2}$ at 0.5 K. At this temperature the mobility μ_0 is very high and the

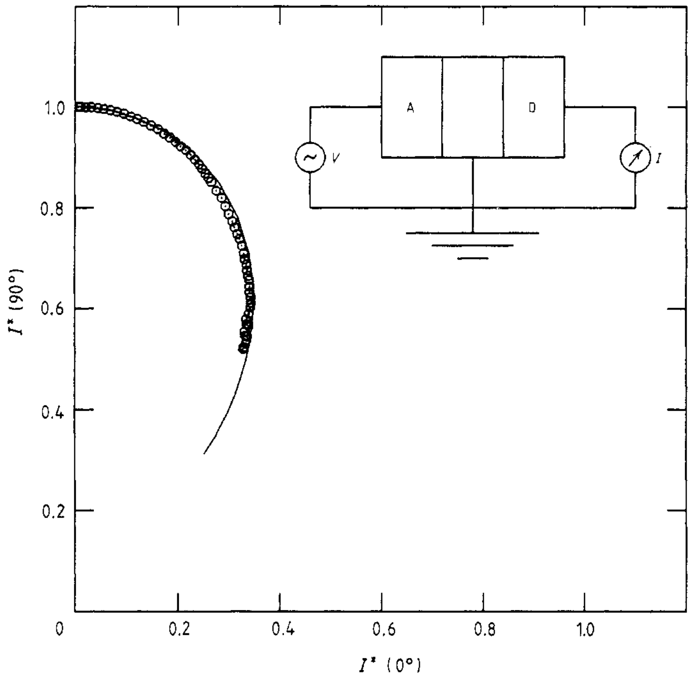

Figure 1. The inset shows the geometrical arrangement of the electrodes used to measure the magnetoresistance of 2D electrons on helium. Electrode A was driven with 31 mV at a frequency of 10.48 kHz. The components $I(0°)$ and $I(90°)$ of the current to electrode D were measured as the perpendicular magnetic field was increased. The locus of the current, normalised to the zero-field value at 0.5 K for $n = 2.77 \times 10^{12}\,\mathrm{m}^{-2}$ is shown on an Argand diagram. The full curve shows the calculated locus as the 2D skin depth, δ_-, is varied.

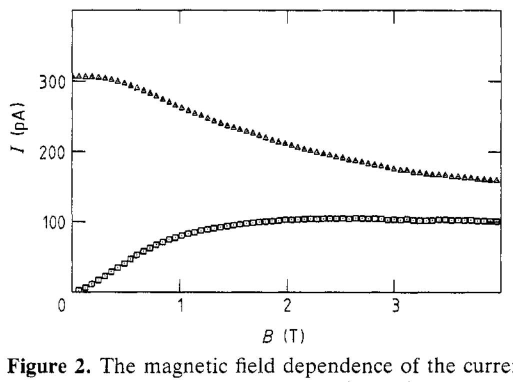

Figure 2. The magnetic field dependence of the currents shown in figure 1. The vertical electric holding field E was $3.27 \times 10^4\,\mathrm{V\,m^{-1}}$. $T = 0.495$ K.

phase of I in zero field (relative to the applied voltage) was set to 90° as a reference. The locus of I^* (the current normalised to the zero-field current) as the field increases is shown on an Argand diagram in figure 1; the magnitude of I decreases, a peak is observed in $I(0°)$ and the high-field phase shift tends towards 45°. The vertical electric holding field E for the data was $3.27 \times 10^4\,\mathrm{V\,m^{-1}}$ as calculated from $E = 0.5\,(\varepsilon E_l + E_v)$ where

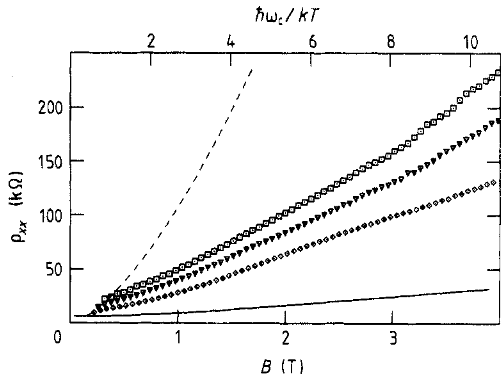

Figure 3. The resistivity ρ_{xx} of 2D electrons on liquid helium at 0.5 K as a function of magnetic field B for values of the holding field E of 2.77×10^4 V m^{-1} (◇), 3.27×10^4 V m^{-1} (▽) and 3.73×10^4 V m^{-1} (□). The upper scale shows the values of $\hbar\omega_c/kT$. The broken curve shows the theoretical magnetoresistance for elastic scattering of the electrons, equation (5). The full curve shows the magnetoresistance expected from the quantisation of the cyclotron radius, equation (6). Both the theoretical lines are calculated for $\rho_0 = 6.1$ kΩ, corresponding to a holding field of 3.27×10^4 V m^{-1}.

E_l and E_v are the electric fields in the helium liquid (dielectric constant ε) and vapour respectively.

We have recently analysed [7] the AC potential distribution on an electron sheet in a magnetic field for our experimental geometry. For a fully screened electron gas the driving voltage V excites a heavily damped perimeter wave that propagates round the edge of the electron sheet with a wavevector $k_\parallel$ parallel to the edge and a wavevector $k_\perp$ perpendicular to the edge, where

$$k_\parallel = (1-j)/\delta_\parallel \qquad k_\perp = (1-j)\delta_\perp . \tag{2}$$

The parameters $\delta_\parallel$ and $\delta_\perp$ are the 2D skin depths parallel and perpendicular to the current flow in the electron sheet and are given by

$$\delta_\parallel = (2/\omega C'\rho_{xx})^{1/2} \qquad \delta_\perp = (\rho_{xx}/\rho_{xy})\delta_\parallel \tag{3}$$

where C' is the capacitance per unit area between the electrons and the electrodes. For the Drude model, $\delta_\parallel$ would be field independent while $\delta_\perp = \delta_\parallel/\mu B$. We have calculated the theoretical response function of our cell for arbitrary values of $\delta_\parallel$ and $\delta_\perp$. For high mobilities $\delta_\parallel$ is much longer than the dimensions of the electron sheet. The current I to electrode D then depends only on $\delta_\perp$ and follows a distinctive locus on the Argand diagram, as shown in figure 1. Our experimental results lie close to this theoretical line. Hence we can obtain values of $\delta_\perp$ versus B from our data. Previous measurements and theoretical calculations [3, 8] have shown that $\rho_{xy} = B/ne$ is a good approximation for a classical 2DEG in a magnetic field, with only small corrections due to the Landau levels. The quantum effects primarily alter ρ_{xx} by changing the density of states and the scattering rate. We therefore assume that $\rho_{xy} = B/ne$ where n is determined from the DC electrode potentials during charging. Hence we can calculate

$$\rho_{xx} = (\omega C'/2n^2e^2)B^2\delta_\perp^2 \tag{4}$$

from our measurements, as shown in figure 3, which demonstrates the strong magnetoresistance. Results are given for three values of the holding field, $E = 2.77, 3.27$ and 3.73×10^4 V m^{-1} respectively. The zero-field resistivity ρ_0 can be found by extrapolation and gives $\mu_0 = 470, 370$ and 310 m^2 V^{-1} s^{-1} for the three holding fields. The holding field decreases the mobility by increasing the electron–ripplon interaction [8]. The values of μ_0 are slightly higher than those found experimentally in [9]. The change in μ_0 with E is in good agreement with the theoretical predictions. As expected, the values of $\mu_0 B$ in our experiments are very large and $\mu_0 B = 1$ occurs at very low fields, typically 2.7 mT.

The magnetoresistance is due to quantum effects as the Landau levels form, which change the electron diffusion length and the scattering time. An expression for ρ_{xx} for elastic scattering has been given in [3]. This predicts a very strong magnetoresistance, starting at $B \simeq 1/\mu$ given by

$$\rho_{xx} = 0.34(\hbar\omega_c/kT)(\mu_0 B)^{1/2}\rho_0 \tag{5}$$

in the high-field limit. This is shown as a broken curve in figure 3 for $\rho_0 = 6.1\ \mathrm{k\Omega}$, corresponding to the data for $E = 3.27 \times 10^4\ \mathrm{V\,m^{-1}}$. However, the predominant scattering mechanism at 0.5 K is electron–ripplon scattering which is inelastic. Some insight can be gained from the Einstein relation for conductivity

$$\sigma_{xx} = (ne^2/kT)(L^2/\tau_B) \tag{6}$$

where $\overline{L}$ is the $\overline{\text{diffusion}}$ length and τ_B is a field-dependent scattering time. We put $L^2 = \overline{R_N^2}/2 = (\overline{N + 0.5})\,h/2eB$ where R_N is the cycloltron radius of the Nth Landau level and the average is taken over the thermally excited levels. For $\rho_{xy} \gg \rho_{xx}$ we then find

$$\rho_{xx} = \tfrac{1}{2}(\hbar\omega_c/kT)[(1+y)/(1-y)](\tau_0/\tau_B)\rho_0 \tag{7}$$

where $y = \exp(-\hbar\omega_c/kT)$ is a Boltzmann factor and τ_0 is the scattering time in zero magnetic field. This expression is plotted as a full curve in figure 3 for $\rho_0 = 6.1\ \mathrm{k\Omega}$ assuming $\tau_0 = \tau_B$. The ratio of the experimental and theoretical plots shows the enhanced scattering due to change in the density of states and hence τ_B is less than τ_0. The field dependence of this enhanced scattering is a function of $\hbar\omega_c/kT$ as all the data in figure 3 lie on a common curve when plotted as ρ_{xx}/ρ_0 versus $\hbar\omega_c/kT$.

In conclusion, we have measured a strong magnetoresistance for 2D electrons on liquid helium at 0.5 K. This is due to quantum effects and the formation of Landau levels. Further theoretical work is required to elucidate these effects for inelastic electron–ripplon scattering.

We would like to thank Professor E R Dobbs for his support, A K Betts, F Greenough, J Noad, D Smith and J D Taylor for technical assistance, and the SERC (UK) for a Research Grant and a Research Studentship (for AOS).

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