Density of states in a magnetic field and electron-electron interactions

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Abstract

We present magnetoconductivity measurements of two-dimensional non-degenerate electrons on liquid helium at 1.22 K. We measured the magnetoconductivity from an extremely low density where e-e interactions are negligible to densities where Coulomb interactions dominate the width of the density of states peaks. We observe a crossover from Drude theory to SCBA as a function of both magnetic field and electron density at finite classical fields.

Key words: density of states; electron-electron interactions; magnetoconductivity

Electrons on helium form one of the simplest and cleanest two-dimensional (2D) electron systems. Aside from the non-degeneracy, it differs from other 2D electron systems in the strength of the electron-electron (e-e) interaction[1,2]. It is an ideal system for the study of properties of interacting electrons since the Coulomb interaction is weakly screened by metallic plates that are separated from the electrons by about 1 mm. In this system, electron-helium atom scattering dominates at temperatures above 0.8 K, while electron-ripplon scattering is important at lower temperatures.

An interesting property of this non-degenerate 2D electron gas is the density of states[3] (DOS) in a magnetic field. The DOS peaks at the Landau levels (LLs) have a width Δ that depends both on the scattering rate[3] and the e-e interaction[1].

In zero magnetic field the density of states is constant: $D_0(E) = m/\pi\hbar^2$. The magnetoconductivity of electrons, $\sigma_{xx}(B)$, is given in the Drude model for $\mu_0 B \ll 1$. Landau levels separate when $\hbar\omega_c/\Delta \sim 1$. The LL width Δ which includes the contributions Δ_a due to collisions with helium atoms and Δ_e due to e-e interactions is given by

$$\Delta^2 = \Delta_a^2 + \Delta_e^2. \quad (1)$$

As LLs separate, the Drude model loses its validity and a crossover to the SCBA regime occurs. In SCBA, the DOS and thus the magnetoconductivity is obtained self consistently in the Born approximation. The broadening Δ_a has been calculated[3] in the SCBA limit for a semi-elliptic DOS and short range scatterers and given by

$$\Delta_a = \frac{\hbar}{\tau_B} = \hbar(\frac{8}{\pi}\frac{\omega_c}{\tau_0})^{1/2}, \quad (2)$$

where $\omega_c = eB/m$ is the cyclotron frequency and τ_B^{-1} is the scattering rate in a magnetic field. For $\Delta_e \to 0$ and $\hbar\omega_c < \Delta_a$, we assume that the broadening Δ_a is determined by the zero field scattering time and is on the order of $\sim \hbar/\tau_0$.

The crossover is delayed by many electron effects[1,4] as seen in Eq. 1. The broadening Δ_e is given by theory[4] as

$$\Delta_e = eE_f\lambda_T; \qquad E_f \approx (\frac{11kTn^{3/2}}{4\pi\bar{\epsilon}\epsilon_0})^{1/2}, \quad (3)$$

where $\bar{\epsilon} = (\epsilon_{He} + 1)/2 = 1.028$, E_f is the fluctuating field[1] an electron feels due to redistribution of other electrons as it moves, and the thermal wavelength λ_T is the characteristic size of an electron in the classical

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limit $\hbar\omega_c < kT$. For our experimental data $\hbar\omega_c < 0.12kT$. The theory predicts that the broadening Δ_e is on the order of the broadening Δ_a for the zero field mobility $\mu_0 = 25\,\mathrm{m}^2/\mathrm{Vs}$ and the density $n \sim 10^{11}\,\mathrm{m}^{-2}$.

We present our magnetoconductivity data which extend to electron densities that are two orders of magnitude smaller than previously reported. We span both the independent-electron regime where the data are qualitatively described by the SCBA, and the strongly-interacting electron regime. At finite fields we observe a crossover from SCBA to Drude theory as a function of electron density.

In Fig 1., we show the normalized inverse magnetoconductivity $\sigma_{xx}(0)/\sigma_{xx}(B)$ as a function of B^2 for six electron densities. We observe a crossover from the Drude magnetoconductivity (B^2 dependence) to the SCBA magnetoconductivity ($B^{3/2}$ dependence) as the electron density is reduced for $\hbar\omega_c/\Delta > 1$. The dashed line is the Drude theory.

In order to obtain a quantitative result for the crossover field, we fit our normalized inverse-magnetoconductivity with a function $1 + F(\mu_0, B, B_c)$ with

$$F(\mu_0, B, B_c) = [1 - C](\mu_0 B)^2 + C\frac{3\pi^{3/2}}{8\sqrt{2}}(\mu_0 B)^{3/2}. \quad (4)$$

Here μ_0 and B_c are the free parameters, and $C = C(B, B_c)$ is a crossover function. We find an excellent fit to the low-density data by choosing $C(B, B_c) = \tanh^{1/2}(\frac{B}{4B_c})$. This function is 0.5 at $B = B_c$. The function F starts in the Drude regime at $B = 0$ and goes into SCBA at a magnetic field characterized by the crossover field B_c. The SCBA theory obtained from Eq. 4 for $B \gg B_c$ is valid[5] in classical fields. In our fits shown by solid lines in Fig. 1, we allow μ_0 and B_c to be free parameters. The values of B_c obtained from the fits give an approximate width $\Delta^\star$ of the LLs for each electron density. We obtain the values of $\Delta^\star$ by setting $\Delta^\star = \hbar e B_c/m$ and plot them in Fig. 2. In the figure we plot, for comparison, the theoretical expression for the width Δ given in Eq. 1 as a solid line for $\Delta_a = 15$ mK and $\Delta_e = 11eE_f\lambda_T$. We find that the values of $\Delta^\star$ give the correct functional dependence on the electron density, but differ from theory in the value of Δ_e by a factor of 11.

In conclusion, we measured the magnetoconductivity of non-degenerate electrons in the very low-density limit. The data show the effect of e-e interactions clearly. Electron-electron interactions have a significant effect on the magnetoconductivity causing a delay in the transition from Drude to SCBA regime as a function of a magnetic field. When the many electron effects are negligible, the transition is observed in classical fields. We also studied the effect of e-e interactions on the LL width. Our results agree with theory qualitatively but differ by a numerical factor.

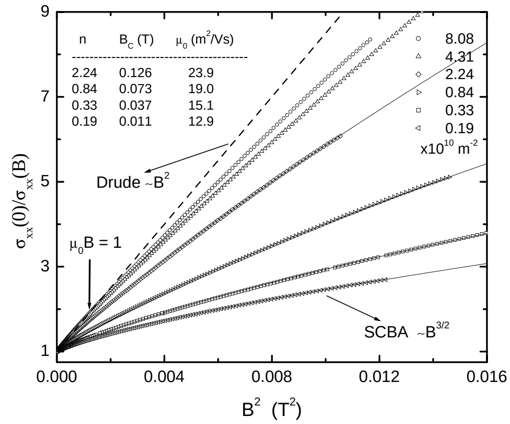

Fig. 1. Normalized inverse-magnetoconductivity vs. B^2. The values of the fitting parameters B_c and μ_0 for the fits to Eq. 4 are given in the inset.

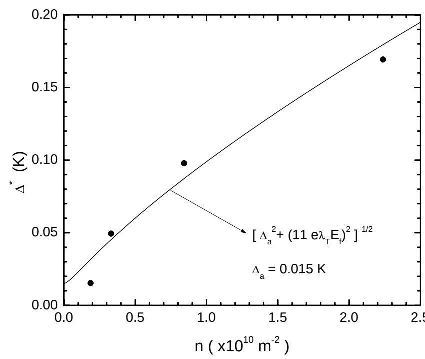

Fig. 2. The values of $\Delta^\star$ as a function of electron density. The solid line is described in the text.

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