Experimental evidence of a metal-insulator transition in a half-filled Landau level

C.–T. Liang, J. E. F. Frost, M. Y. Simmons, D. A. Ritchie, and M. Pepper

Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, United Kingdom

Abstract

We have measured the low-temperature transport properties of a high-mobility front-gated GaAs/Al$_{0.33}$Ga$_{0.67}$As heterostructure. By changing the applied gate voltage, we can vary the amount of disorder within the system. At a Landau level filling factor $\nu = 1/2$, where the system can be described by the composite fermion picture, we observe a crossover from metallic to insulating behaviour as the disorder is increased. Experimental results and theoretical prediction are compared.

Key words: A. heterojunctions, semiconductor. D. electron transport, fractional quantum Hall effect, phase transitions.
The fractional quantum Hall effect (FQHE) [1] arises from strong electron-electron interactions, causing the two-dimensional (2D) electrons to condense into a fractional quantum Hall liquid [2]. In the elegant composite fermion (CF) picture, where each electron is bound to an even number of magnetic flux quanta [3], the FQHE can be understood as a manifestation of the integer quantum Hall effect of weakly interacting composite fermions. It has been shown [4,5] that at Landau level filling factor $\nu = 1/2$, a 2D electron gas (2DEG) can be mathematically transformed into a CF system interacting with a Chern–Simons gauge field. A wide variety of recent experimental results [6–10] have demonstrated that at $\nu = 1/2$ the effective magnetic field acting on the composite fermions is zero.

It is well known that both weak localisation and electron-electron interaction theories [11] produce a logarithmic dependence of conductivity with temperature observed [12] in weakly disordered 2D electron systems at zero magnetic field. Rokhinson, Su, and Goldman [13] ascribe the logarithmic temperature $T$ dependence of conductivity at $\nu = 1/2$ to CF–CF interactions, analogous to electron-electron interactions at zero magnetic field. Recent theoretical work [14] has shown that in the case of short–range interactions, the correction term to the classical composite fermion conductivity due to CF–CF interactions is given by

$$\delta \sigma_{xx}^{CF} = \left( \frac{e^2}{2\pi \hbar} \ln(k_F\ell) \right) \ln(T\tau_{tr}),$$

where $k_F$ is the CF wave vector, $\tau_{tr}$ and $\ell$ are the elastic scattering time and elastic mean free path for composite fermions, respectively. Note that weak localisation is suppressed at $\nu = 1/2$ since the Chern–Simons gauge field fluctuations break time reversal symmetry for impurity scattering [5,13].
Recently there has been much interest in the global phase diagram in the quantum Hall effect [15,16]. With the same theoretical approach [15], Kalmyer and Zhang [4] have investigated 2D electron systems at $\nu = 1/2$ with various amount of disorder. They predict that for sufficiently weak disorder, the system is metallic at $\nu = 1/2$, characterised by positive magnetoresistance (PMR) centred around $\nu = 1/2$. When disorder increases, the system enters an insulating phase where negative magnetoresistance (NMR) around $\nu = 1/2$ is observed. In this communication, we shall show that our experimental results on the temperature dependence of CF conductivities as a function of disorder are consistent with their prediction of a metal-insulator transition. However, we cannot test the prediction of a crossover from PMR to NMR due to large background magnetoresistance around $\nu = 1/2$ as the disorder becomes stronger.

We have studied gated Hall bars made from a high-mobility GaAs/Al$_{0.33}$Ga$_{0.67}$As heterostructure, with the magnetic field $B$ directed perpendicular to the interface. At gate voltage $V_g = 0$, the carrier concentration of the 2DEG is $\approx 1.0 \times 10^{15}$ m$^{-2}$ with a mobility of 300 m$^2$/Vs without illumination. Experiments were performed in a $^3$He cryostat at 0.3 K using standard four-terminal ac phase-sensitive techniques. By changing $V_g$, we can vary the carrier density and hence effectively the disorder in our system. Three samples showed similar characteristics, and measurements taken from one of these are presented in this paper.

Figure 1 shows the four-terminal longitudinal $\rho_{xx}$ and transverse $\rho_{xy}$ magnetoresistance for $V_g=0$. The minima in $\rho_{xx}$ coincide with the quantum Hall plateaux, indicating that the carrier density $n_s$ in our wafer is uniform. There
is a good fit $n_s = (2.136 \times 10^{15}V_g + 9.124 \times 10^{14})m^{-2}$ over the measurement range $-0.38 \leq V_g \leq 0$ V. Thus $n_s(V_g)$ in our system can be described by a simple capacitor plate model with a distance $0.322 \mu m$ between the surface Schottky gate and the underlying 2DEG, in close agreement with the intended as–grown depth of $0.3 \mu m$.

Figure 2 shows the magnetoresistance measurements at various $V_g$. At $V_g = 0$, PMR around $\nu = 1/2$ is observed. As $V_g$ is made more negative and hence the amount of disorder within the system is increased, $\rho_{xx}$ at $\nu = 1/2$ increases, and PMR centred around $\nu = 1/2$ gradually diminishes as indicated by arrows. At $V_g \leq -0.22$ V, PMR around $\nu = 1/2$ is no longer observable and $\rho_{xx}(B)$ increases with magnetic field, as shown in Fig. 2 and the inset. The linear rising background $\rho_{xx}$ [17] may mask the magnetoresistance around $\nu = 1/2$, excluding the possibility of testing the theoretical prediction of a PMR/NMR crossover [4]. For $V_g = -0.34$ and $-0.38$ V, the magnetoresistance minima at $\nu = 1/3$, the most pronounced fractional quantum Hall state, are observed at around 2.7 T and 1.6 T, respectively, demonstrating that the composite fermion picture is valid in this case. For $V_g = -0.412$ V and $-0.413$ V, the minimum at $\nu = 1/3$ is no longer observable. This is consistent within the picture of the global phase diagram [4,15]. As the amount of disorder in the system is sufficiently strong, the $\nu = 1/2$ state enters an insulating phase and the fractional quantum Hall state $\nu = 1/3$ is no longer observable, as shown in the inset to Fig. 3 (a).

Existing measurements [6–10] were mostly performed in the regime where PMR around $\nu = 1/2$ is clearly observed. We choose to concentrate on the regime where PMR around $\nu = 1/2$ disappears and we have also studied the
dependence of CF conductivity in this limit. Note that composite fermion conductivity \( \sigma_{xx}^{CF} \) is given by \( 1/\rho_{xx} \) [5,6]. Figure 3 (a) shows the composite fermion conductivity for \( V_g = -0.34 \) V at various temperatures. There is a good logarithmic fit \( \sigma_{xx}^{CF} = (3.663 \times \ln T + 124.363) \mu S \) for \( 0.3 \) K \( \leq T \leq 0.65 \) K. As shown in Fig. 3 (b), there is also a good fit \( \sigma_{xx}^{CF} = (6.909 \times \ln T + 69.457) \mu S \) for \( 0.3 \) K \( \leq T \leq 0.55 \) K at \( V_g = -0.38 \) V, where the disorder within the system is further increased. We observe that \( \sigma_{xx}^{CF} \) shows a deviation from a logarithmic temperature dependence at high temperatures, similar to those reported in previous work [9,13]. This effect might be due to CF-phonon scattering [18]. Using equation (1), we estimate the prefactor in \( \ln T \) term to be 7 for \( V_g = -0.38 \) V, in excellent agreement with the experimental results. However, for \( V_g = -0.34 \) V, the estimated prefactor is 11.4, somewhat larger than the value 3.663 obtained from the experimental data. It is important to note that the theory predicts the prefactor in \( \ln T \) increases as \( k_F \ell \) increases, i.e., when the disorder becomes weaker. However, our experimental results show the opposite behaviour. The discrepancy is not understood at present.

Previous experimental results have shown that \( \sigma_{xx}^{CF}(\nu = 1/2) \) exhibits a weak [6,8] or logarithmic [9,13] temperature dependence, demonstrating the existence of a composite fermion metallic phase. Figure 4 shows \( \sigma_{xx}^{CF}(T) \) for \( V_g = -0.412 \) V and \( -0.413 \) V. The experimental data follows 2D Variable Range Hopping (VRH) \( \sigma_{xx}^{CF} \approx \exp[-(T_0/T)^{1/3}] \), with a fit yielding characteristic temperatures \( T_0 \) of 24 K and 25 K for \( V_g = -0.412 \) V and \( -0.413 \) V, respectively. The exponential temperature dependence of \( \sigma_{xx}^{CF} \) provides, to the best of our knowledge, the first experimental evidence of an insulating phase for CFs at \( \nu = 1/2 \). The data shown in Fig. 3 and 4 suggests that a transition from metallic (~\( \ln T \) dependence) to insulating (~\( \exp[-(1/T)^{1/3}] \) dependence)
behaviour occurs as the amount of disorder is increased. To map out the proposed phase diagram [4,5,15], further detailed measurements on a large number of samples with varying degree of disorder and different carrier densities need to be performed.

In conclusion, we have studied a 2D composite fermion system with various amounts of disorder. At $\nu = 1/2$, a crossover from metallic to insulating behaviour is observed in the temperature dependence of the CF conductivity, in agreement with theory. However, the rapidly rising background magnetoresistance around $\nu = 1/2$ precludes the observation of a crossover from positive to negative magnetoresistance with increasing disorder.

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Figure Captions

Figure 1. Longitudinal $\rho_{xx}$ and transverse $\rho_{xy}$ magnetoresistance measurements for $V_g = 0$ V.

Figure 2. Magnetoresistance measurements $\rho_{xx}(B)$ for various $V_g$. From left to right: $V_g = -0.3$ V to $-0.08$ V in 0.02 V steps, $V_g = -0.04$ V, and $V_g = 0$ V, respectively. The inset shows $\rho_{xx}(B)$ for $V_g = -0.34$ V, $-0.38$ V, $-0.412$ V and $-0.413$ V, respectively. The positions of $\nu = 1/2$ are indicated by arrows.

Figure 3. (a) $\sigma_{xx}^{CF}(T)$ at $\nu = 1/2$ for $V_g = -0.34$ V. (b) $\sigma_{xx}^{CF}(T)$ at $\nu = 1/2$ for $V_g = -0.38$ V. The straight line fits are discussed in the text. The inset shows a schematic global phase diagram illustrating that in a highly disordered system, as the magnetic field is increased, at $\nu = 1/2$ the systems can enter an insulating (I) phase rather than a metallic (M) phase and the fractional quantum Hall state $\nu = 1/3$ may be no longer observable as shown by the dotted line.

Figure 4. $\sigma_{xx}^{CF}(T)$ at $\nu = 1/2$ for $V_g = -0.412$ V (marked by circles) and for $V_g = -0.413$ V (marked by squares). The linear fits are discussed in the text.
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