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Experimental studies of composite fermion conductivity: dependence on carrier density

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Abstract

We present an experimental study of the carrier density dependence of the composite fermion (CF) conductivity σ_{xx}^{CF} at both Landau level filling factors $\nu = \frac{1}{2}$ and $\nu = \frac{3}{2}$ in high-quality front-gated GaAs/Al_{0.33}Ga_{0.67}As heterostructures. Extracting α from the power law $\ln(\sigma_{xx}^{CF}) \propto \ln(n_e)^\alpha$ shows that $\alpha \approx 1$, in qualitative agreement with theoretical predictions based on a random magnetic field approximation in the electron density distribution. © 2002 Elsevier Science B.V. All rights reserved.

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The fractional quantum Hall effect (FQHE) [1] observed in high-quality two-dimensional (2D) electron systems in the low-temperature, high magnetic field regime, arises from strong electron–electron interactions. These interactions cause the 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 then be understood as a manifestation of the integer quantum Hall effect of weakly interacting composite fermions. It has been shown that at a Landau level filling factor $\nu = \frac{1}{2}$, a 2D electron system can be mathematically transformed into a composite fermion system interacting with a Chern–Simons gauge field [4,5]. At $\nu = \frac{1}{2}$, the average of this

Chern–Simons gauge field cancels the external magnetic field B_{ext} so that the effective magnetic field acting on the CFs is zero. Away from $\nu = \frac{1}{2}$, the composite fermions experience a net effective magnetic field $\bar{B} = (1 - 2\nu)B_{\text{ext}}$. To date, a wide variety of experimental results have supported the now well-established composite fermion picture [6–14]. Since each composite fermion is composed of an electron bound to an even number of magnetic flux quanta, the density of a composite fermion system is equal to that of an electron system. Note that the composite fermion conductivity σ_{xx}^{CF} is given by $1/\rho_{xx}(\nu = \frac{1}{2})$.

Existing composite fermion transport measurements have mostly been undertaken on ungated high-quality GaAs/AlGaAs heterostructures [6,9–11]. As a result, an investigation into the carrier density dependence of CF conductivities has not been possible. In this Letter, we show that the exponent α measured from the power law $\ln(\sigma_{xx}^{CF}) \propto \ln(n_e)^\alpha$ is

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Fig. 1. Magnetoresistivity measurements $\rho_{xx}(B)$ at $V_g = 0$ V for Sample A. The inset shows the carrier density as a function of applied front-gate voltage V_g . The linear fit is discussed in the text.

approximately 1 at both $\nu = \frac{1}{2}$ and $\frac{3}{2}$, in qualitative agreement with the theoretical value of $\frac{3}{4}$. We discuss the slight discrepancy between the experimental and theoretical results.

The high-quality HEMTs used in this work were made from ultra-low-disorder GaAs/Al_{0.33}Ga_{0.67}As heterojunctions. Sample A has a carrier density of $9.12 \times 10^{14} \text{ m}^{-2}$ with a mobility μ of $300 \text{ m}^2 \text{ V s}^{-1}$ at $V_g = 0$ without illumination. Sample B has a 2DEG carrier density of $1.4 \times 10^{15} \text{ m}^{-2}$ and a mobility of $200 \text{ m}^2 \text{ V s}^{-1}$ at $V_g = 0$ after brief illumination with a red-light-emitting diode. Measurements were performed in a top-loading ³He cryostat at 0.3 K using standard four-terminal AC phase sensitive techniques. Four samples show similar characteristics and measurements taken from two of these are presented in this paper.

Fig. 1 shows the four-terminal longitudinal resistivity $\rho_{xx}(B)$ for sample A at $V_g = 0$ V, showing high-quality fractional states. Plotting the carrier density versus gate voltage in the inset shows there is a good linear fit over the measurement range $-0.3 \text{ V} \leq V_g \leq 0 \text{ V}$ with $n_e = (2.14 \times 10^{15} V_g + 9.12 \times 10^{14}) \text{ m}^{-2}$. The electron system is well described by

Fig. 2. The logarithm of composite fermion conductivity $\ln(\sigma_{xx}^{\text{CF}})$ as a function of the logarithm of carrier density $\ln(n_e)$ at $\nu = \frac{1}{2}$ for Sample A (marked by circles) and Sample B (marked by squares). The slopes of linear fits α for Samples A and B are 1.02 ± 0.06 and 1.03 ± 0.01 , respectively.

a simple parallel plate capacitor model giving an estimated distance $D = 0.32 \text{ } \mu\text{m}$ between the front-gate and the underlying 2DEG. The calculated D is in close agreement with the intended as-grown depth of $0.3 \text{ } \mu\text{m}$. At liquid helium temperatures, the distribution and density of the ionised impurities remain fixed, such that decreasing V_g causes n_e to decrease while the ionised impurity concentration n_i remains constant.

We now present the main experimental finding of our paper. Fig. 2 shows the composite fermion conductivity as a function of the carrier density for both samples at $\nu = \frac{1}{2}$. Calculation of the exponent α from $\ln(\sigma_{xx}^{\text{CF}}) \propto \ln(n_e)^\alpha$ for Sample A and B are 1.02 ± 0.06 and 1.03 ± 0.01 , respectively. Both exponents at $\nu = \frac{1}{2}$ are very close to 1.

A composite fermion can also be formed at $\nu = \frac{3}{2}$. In this case, the spin-up level is filled whereas the spin-down level is half-filled. The composite fermion carrier density at $\nu = \frac{3}{2}$ is one-third of that at $\nu = \frac{1}{2}$ [10]. At $\nu = \frac{3}{2}$, the composite fermion conductivity is therefore $\frac{1}{9}$ of the inverse of the measured ρ_{xx} . Fig. 3 shows the composite fermion conductivity $\ln(\sigma_{xx}^{\text{CF}})$ as a function of the composite fermion carrier density $\ln(n_e/3)$ at $\nu = \frac{3}{2}$ for both samples. Calculation

Fig. 3. The logarithm of composite fermion conductivity $\ln(\sigma_{xx}^{CF})$ as a function of the logarithmic of carrier density $\ln(n_e)$ at $\nu = \frac{3}{2}$ for Sample A (marked by circles) and Sample B (marked by squares). The slopes of linear fits α for Samples A and B are 0.96 ± 0.04 and 1.04 ± 0.01 , respectively.

of the slopes α for both fits gives exponents for Sample A and B as 0.96 ± 0.04 and 1.04 ± 0.01 , respectively. It is evident that the slope of $\ln(\sigma_{xx}^{CF})$ versus $\ln(n_e)$ relation is about 1 both at $\nu = \frac{1}{2}$ and $\frac{3}{2}$. This experimental finding clearly establishes the link between $\nu = \frac{1}{2}$ and $\frac{3}{2}$ —suggesting that the composite fermion conductivity dependence on carrier density in both regimes is the same. It is worth mentioning that at $\nu = \frac{3}{2}$ the electrons occupied in the spin-up level are unable to screen the disorder within the system [10], in contrast to the case at $\nu = \frac{1}{2}$ in which all electrons are occupied in the lowest Landau level. Thus, our results are somewhat unexpected given that the effective disorder within the system at $\nu = \frac{1}{2}$ is different from that at $\nu = \frac{3}{2}$.

Various analogies between the $B = 0$ and $\nu = \frac{1}{2}$ such as on geometric resonances [8] and magnetic focussing [12] have been reported in the literature. It is interesting to see the relation between the conductivity versus carrier density at zero magnetic field and at $\nu = \frac{1}{2}$ in our system. The measured exponents α for Samples A and B are 1.82 ± 0.02 and 1.74 ± 0.01 , respectively, in contrast to the case of $\alpha \approx 1$ at $\nu = \frac{1}{2}$. Since $\mu \propto n_e^{0.82 \pm 0.02}$ and $\mu \propto n_e^{0.74 \pm 0.01}$ for Samples

A and B, we know that back-ground impurity scattering is the dominant mechanism in our system at zero magnetic field.

We now compare our experimental data with theoretical results. Recently Mirlin, et al. [15] investigated CF transport in a long-ranged random magnetic field. In their approach, the disorder in the system is assumed to be created by remote ionised impurities distributed with a sheet density n_i . The inhomogeneous electron density distribution leads to the fluctuations of the Chern–Simons gauge field. This gives rise to the fluctuations in the effective magnetic field $B(r) = (1 - 2\nu(r))B_{\text{ext}}$, where $\nu(r)$ is the local filling factor. For non-interacting CFs in a random magnetic field (RMF) Mirlin and co-workers [15] consider that there are two limits: the weak RMF and the strong RMF regimes. In the weak RMF regime, they show that the composite fermion conductivity at zero $\vec{B}$ is given by $\sigma_{xx} = (k_F d / \beta^2)$, where $k_F = \sqrt{4\pi n_e}$, $\beta = \sqrt{(n_i / 2n_e)}$ and d is the correlation radius, respectively. However Mirlin and co-workers note that it is difficult to reach the weak RMF regime in experiments since the CF mean free path l is rather short ($\approx 1 \mu\text{m}$) so that the theoretical assumption $l \gg d$ does not hold. In the strong RMF-regime they show that $\sigma_{xx}^{CF} \approx (k_F d / \sqrt{\beta}) = (\sqrt{4\pi n_e} d / (n_i / 2n_e)^{1/4})$ (Eq. (5) in Ref. [15]), for $\beta \gg 1$. With the assumption that n_i is constant for various n_e i.e. where changing the gate voltage can vary the electron density but the ionised impurity distribution remains constant, gives

$$\ln(\sigma_{xx}^{CF}) \approx \frac{3}{4} \ln(n_e) + A, \quad (1)$$

where A is constant. This allows us to determine the effect of varying the random magnetic field within the system.

Following the model of Mirlin and co-workers [15], we assume that at zero gate voltage $V_g = 0$, $n_i = n_e$ and that n_e decreases with decreasing V_g while n_i remains constant. In this case from the determined carrier density, we calculate β to be between 0.71 and 2.6 for Sample A and between 0.71 and 1.15 for Sample B over the whole measurement range. Thus, our samples are better described by the strong RMF regime in the theoretical model of Mirlin and co-workers [15]. From Eq. (1), we know that the theoretical exponent α in $\ln(\sigma_{xx}^{CF}) \propto \ln(n_e)^\alpha$ is predicted to be $\frac{3}{4}$, in qualitative agreement with our experimental result $\alpha \approx 1$ at both $\nu = \frac{1}{2}$ and $\frac{3}{2}$.

Finally, we propose a possible reason for the discrepancy between our experimental data and the theoretical results. The result in the work of Mirlin and co-workers is an asymptotic formula for $\beta \gg 1$. A theoretical study [16] shows that the region from $0.2 \leq \beta \leq 10$ is a crossover region between $\beta \gg 1$ and $1 \gg \beta$. Since we have $0.71 \leq \beta \leq 2.6$ in our system, then one would expect deviations from the asymptotic behavior for $\beta \gg 1$. It is believed that the screening length at $\nu = \frac{3}{2}$ is shorter than that at $\nu = \frac{1}{2}$ since $\frac{2}{3}$ of electrons are in a fully-filled spin-split Landau level and cannot screen the disorder potential. Thus, the fact the exponent α is the *same* for both $\nu = \frac{1}{2}$ and $\frac{3}{2}$ is somewhat unexpected.

In conclusion, we have measured the composite fermion conductivity dependence on carrier density. The measured exponents α from the relation $\ln(\sigma_{xx}^{CF}) \propto \ln(n_e)^\alpha$ at $\nu = \frac{1}{2}$ and $\frac{3}{2}$ are found to be *both* ≈ 1 , in qualitative agreement with the theoretical predicted value $\frac{3}{4}$. This experimental finding suggests the link between the case between $\nu = \frac{3}{2}$ and $\frac{1}{2}$ despite different amount of effective disorder in these two cases. It is believed that the difference between the experimental exponent α and theoretical value is that our system is in the cross-over region between strong and weak random magnetic field regimes.

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