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Logarithmic temperature dependence of conductivity at half-integer filling factors: Evidence for interaction between composite fermions

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We have studied the temperature dependence of diagonal conductivity in high-mobility two-dimensional samples at filling factors $\nu=\frac{1}{2}$ and $\frac{3}{2}$ at low temperatures. We observe a logarithmic dependence on temperature, from our lowest temperature of 13 mK up to 400 mK. We attribute the logarithmic correction to the effects of interaction between composite fermions, analogous to the Altshuler-Aronov–type correction for electrons at zero magnetic field.

Recently, an elegant theory of the fractional quantum Hall effect (FQHE), including even-denominator filling factors, came with the theory of composite fermions.[1,2] In this theory, the system of strongly interacting electrons can be mapped onto the system of noninteracting new particles, composite fermions (CF), by attaching an even number $2m$ of vortices to each electron. In the mean-field approximation, the gauge field of vortices partially compensates the external magnetic field B, and CF experience an effective magnetic field $B^{\rm CF}=B-2mn\phi_0$, where n is the concentration of electrons (and CF), ϕ_0 is the flux quantum, and m is an integer. For $m=1$, at filling factor $\nu=\frac{1}{2}$, the external field is fully canceled by the gauge field and $B^{\rm CF}=0$. It has been shown both theoretically[2] and experimentally[3–5] that some properties of a Fermi liquid are preserved for CF, in particular, a reasonably well-defined Fermi surface.

It is well known that at $B=0$, as temperature T is lowered, the diagonal conductivity σ_{xx} of a disordered two-dimensional electron system (2DES) nearly saturates, and only a weak, logarithmic T-dependent correction to σ_{xx} is observed. Both weak localization and electron-electron interaction effects in a disordered 2DES (Refs. 6 and 7) give rise to logarithmic corrections to conductivity at $B=0$. It has been suggested[2] that interactions between CF could lead to a logarithmic correction to conductivity at $\nu=\frac{1}{2}$ also. (Note that weak localization should be suppressed at $\nu=\frac{1}{2}$ because gauge-field fluctuations break time-reversal symmetry for impurity scattering.)

In this paper we report the observation of a logarithmic correction to conductivity of composite fermions at $\nu=\frac{1}{2}$ and $\frac{3}{2}$. This is, to the best of our knowledge, the first observed effect that requires interaction between CF. We find that the coefficient of the logarithmic term is significantly greater than that for electrons at $B\approx 0$; the additional nonuniversal contribution may be attributed[2] to the short-range interaction via gauge-field fluctuations.

We have studied several samples fabricated from high-mobility ($\mu\sim 2\times 10^6$ cm^2/V s) GaAs/Al$_x$Ga$_{1-x}$As heterojunction wafers. The wafers have double Si δ doping; the first layer is separated from the 2DES by a $d_s\approx 120$ nm thick spacer. 2DES's with densities between 0.4 and 1.2×10^{11} cm^{-2} were prepared by illuminating a sample with red light. The temperature was measured with a calibrated ruthenium oxide chip resistor. Measurements were done in a top-loading into mixture dilution refrigerator using a standard lock-in technique at 2.5 Hz and applied current 50 pA rms; no heating effects were observed at this current.

We made samples in a Corbino geometry defined by circular In:Sn Ohmic contacts with the inner radius $0.2\leq r_i\leq 0.6$ mm and the outer radius $r_o=1.5$ mm. In the Corbino geometry, the local conductivity is inversely proportional to the directly measured two-terminal resistance R_{2T}: $\sigma_{xx}=\sharp/R_{2T}$, where $\sharp=(\pi/2)\ln(r_o/r_i)$ is a geometric factor ("the number of squares"). Representative magnetoconductivity data around $\nu=\frac{1}{2}$ and $\frac{3}{2}$ are plotted in Fig. 1. In this paper we concentrate on the temperature dependence of the conductivity at half-integer filling factors. The data were collected either from the B sweeps at several temperatures, or by changing T at a fixed magnetic field. We checked carefully that the sample and the thermometer were in close thermal equilibrium during the measurement: values obtained from both types of measurements differ less than 0.5% for the same (B,T). As shown in Fig. 2, in the experimental temperature range 13 mK$<T<$1.6 K, $\sigma_{xx}(\nu=\frac{1}{2})$ has a weak

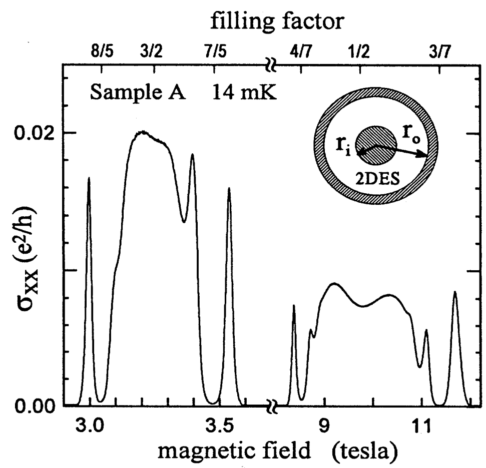

FIG. 1. The electron diagonal magnetoconductivity of sample A near $\nu=\frac{1}{2}$ (right) and $\frac{3}{2}$ (left) at $T=14$ mK; note the break in the horizontal axis. The inset shows the sample layout in the Corbino geometry.

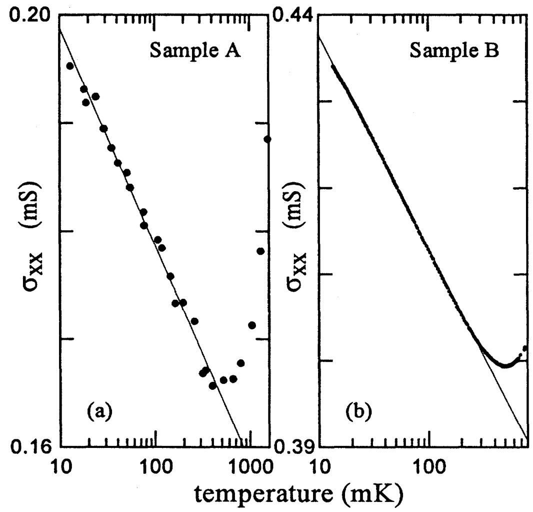

FIG. 2. The temperature dependence of the electron diagonal conductivity at $\nu=\frac{1}{2}$ in samples A and B. The straight lines are the logarithmic fits for the temperature range from 15 to 300 mK.

T dependence with a minimum at $\sim$500 mK. A remarkable result is that σ_{xx} changes logarithmically with T at lower temperatures.

The variation of $\sigma_{xx}(\nu=\frac{1}{2})$ is less than 20% over some two orders of magnitude in T; this indicates a metallic conduction regime. At the same time, the conductivity is about $0.01e^2/h$, that is, well below Mott's minimum metallic conductivity for two dimensions. This apparent contradiction is resolved easily within the theory of composite fermions. Indeed, the theory[2] predicts a metallic state for CF near $\nu=\frac{1}{2}$. At $\nu=\frac{1}{2}$, CF experience zero effective magnetic field, $B^{\rm CF}=0$, and behave similarly to electrons at $B=0$. This has been confirmed experimentally by observations of a Fermi surface of CF in a weak effective magnetic field near $\nu=\frac{1}{2}$.[3–5] The relationship between the transport coefficients of the electron and CF systems was derived in Ref. 2, Appendix B; specifically, the conductivity of composite fermions $\sigma_{xx}^{\rm CF}$ can be calculated from the measured electron conductivity σ_{xx}. Since $\rho_{xx}^{\rm CF}=\rho_{xx}$ and $\rho_{xy}^{\rm CF}(\nu=\frac{1}{2})=0$, at $\nu=\frac{1}{2}$,

$$\sigma_{xx}^{\rm CF}=(1/\rho_{xx}^{\rm CF})=\frac{\sigma_{xx}^2+\sigma_{xy}^2}{\sigma_{xx}}. \tag{1}$$

$\sigma_{xx}^{\rm CF}(\nu=\frac{1}{2})$ is plotted as a function of $\ln T$ for two samples in Fig. 3. Note that $\sigma_{xx}^{\rm CF}$ is much greater than e^2/h, as expected for a metallic regime. Because the T-dependent correction to σ_{xx} is relatively small, the functional dependence of the logarithmic correction is preserved after the transformation from σ_{xx} to $\sigma_{xx}^{\rm CF}$ via Eq. (1), although the sign is changed. In all measured samples, $\sigma_{xx}^{\rm CF}$ shows a logarithmic temperature dependence for a variation of T by at least a factor of 30:

$$\sigma_{xx}^{\rm CF}=\sigma_0^{\rm CF}+\lambda\frac{e^2}{h}\ln\frac{T}{T_0}. \tag{2}$$

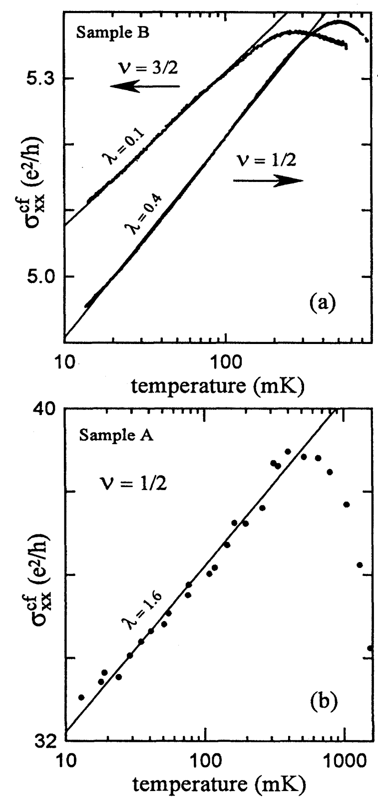

FIG. 3. The temperature dependence of the composite fermion conductivity for the same samples as in Fig. 2. The vertical axes in (a) differ by a factor of 3 for the $\nu=\frac{1}{2}$ and $\frac{3}{2}$ data for sample B. The slope of the fitted straight lines is λ, defined in Eq. (2).

Here T_0 is a characteristic temperature (inverse of the elastic lifetime[7]) and λ is a positive dimensionless coefficient. We find that experimental λ is in the range $0.4\leqslant\lambda\leqslant1.6$ and is sample dependent.

Pursuing the analogy with 2DES at zero field, the logarithmic correction is expected to be of the Altshuler-Aronov type,[6] arising from the interaction effects between CF in the presence of disorder. At $\nu=\frac{1}{2}$, the situation is more complex than at $B=0$ because CF interact additionally with the fluctuations of the gauge field, and λ has not been evaluated theoretically for this case.[2] Nevertheless, we note that the Coulomb exchange contribution of $1/\pi\approx0.32$ to λ is not sufficient to account for the high values observed. For electrons at low B, for comparable GaAs 2DES samples, Paalanen, Tsui, and Hwang[8] obtained $\lambda\approx0.09$ and Choi, Tsui, and Palmateer[9] obtained $\lambda\approx0.17$ (note that CF at $\nu=\frac{1}{2}$ are spin polarized unlike the electrons at $B=0$). CF experience significant large-angle scattering on gauge-field fluctuations, in contrast to the small-angle scattering dominant for electrons at zero field.[2,10] The short-range interaction between CF via gauge-field fluctuations may lead to an additional nonuniversal contribution to λ.

CF can also be formed in the spin-split Landau level. At $\nu=\frac{3}{2}$ the spin-up ($\uparrow$) level is fully occupied by $(\frac{2}{3})n$ electrons and $(\frac{1}{3})n$ electrons occupy the spin-down ($\downarrow$) level to one-half filling. Assuming that both spin-split levels are decoupled, the total conductivity tensor can be written as[11]

$$\sigma = \sigma^{\uparrow} + \sigma^{\downarrow}, \qquad (3)$$

where

$$\sigma^{\uparrow} = \frac{e^2}{h}\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix},$$

and $\sigma^{\downarrow}$ is similar to σ_{xx} for $\nu=\frac{1}{2}$. Thus, $\sigma_{xx}^{\rm CF}$ for $\nu=\frac{3}{2}$ can be calculated by substituting $\sigma_{xx}^{\downarrow}$ instead of σ_{xx} into Eq. (1). The resulting $\sigma_{xx}^{\rm CF}(\nu=\frac{3}{2})$ is approximately $(\frac{1}{3})\sigma_{xx}^{\rm CF}(\nu=\frac{1}{2})$ because the density of CF is reduced three times at $\nu=\frac{3}{2}$, compared to $\nu=\frac{1}{2}$. Experimentally, a factor of 3 difference between σ_{xx} (or $\sigma_{xx}^{\rm CF}$) at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ is observed in the full experimental temperature range. In Fig. 3(a), the left and right axes (for $\nu=\frac{3}{2}$ and $\frac{1}{2}$, respectively) differ by a factor of 3 to emphasize this fact.

At $\nu=\frac{3}{2}$, $\sigma_{xx}^{\rm CF}$ also has a logarithmic temperature dependence at low T [Fig. 3(a)], although the experimental range of temperatures is limited to 13–180 mK. The similarity of the T dependencies of $\sigma_{xx}^{\rm CF}$ at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ suggests that the underlying physics is the same and originates from the interactions between CF in the spin-split Landau level. The coefficient λ, obtained from a fit of the data with Eq. (2), is about four times smaller than at $\nu=\frac{1}{2}$. It can be expected that the screening length at $\nu=\frac{3}{2}$ is smaller compared to $\nu=\frac{1}{2}$ ($\frac{2}{3}$ of electrons are in fully filled spin-split level and therefore cannot screen disorder potential). However, since no explicit theoretical treatment of the logarithmic correction to the conductivity of CF exists at present, it is not clear what can affect λ in this regime.

One of the observable consequences of the electron interaction effects at $B\approx 0$ is a temperature-dependent parabolic negative (for $\lambda>0$) magnetoresistance.[12] At $\nu\approx\frac{1}{2}$, the CF resistivity $\rho_{xx}^{\rm CF}=\rho_{xx}\approx\sigma_{xx}\rho_{xy}^2$ follows the same B dependence as σ_{xx} (see Fig. 1). Thus, in contrast to the $B\approx 0$ case, in the vicinity of $\nu=\frac{1}{2}$ magnetoresistance is positive, despite the fact that the measured $\lambda>0$. Presumably, the different sign of the magnetoresistance at $B\approx 0$ and $\nu\approx\frac{1}{2}$ originates from the difference in leading scattering mechanisms in two regimes. Electrons at $B\approx 0$ predominantly scatter on fluctuations of electron density δn that are a reflection of a random distribution of remote donors. These fluctuations should be of the order of 1% of the total electron concentration n. At $\nu\approx\frac{1}{2}$, the fluctuations of the electron density produce fluctuations of the effective magnetic field $B^{\rm CF}$ for CF: $\delta B^{\rm CF}/B(\frac{1}{2})=\delta n/n$. For a typical magnetic field $B(\frac{1}{2})\sim 10$ T and $\delta n/n\sim 1\%$, fluctuations of $B^{\rm CF}$ can be as big as 0.1 T. Thus, the dominant scattering mechanism for CF is on fluctuations of the effective magnetic field that may account for high experimental resistance,[2] large-angle scattering,[13] and, perhaps, the positive magnetoresistance at $\nu\approx\frac{1}{2}$. To support this conjecture we would like to note that a spatially nonuniform static magnetic field leads to a positive magnetoresistance at $B\approx 0$.[14]

Previous experiments, focused on the study of the FQHE states or the existence of the Fermi surface for CF around $\nu=\frac{1}{2}$, are sufficiently well described by theories of noninteracting CF.[1] We have found that a simple picture of noninteracting CF is not fully adequate, and that the CF interaction effects should be taken into account in a more comprehensive description of the FQHE regime. This finding further deepens the similarity between 2DES at $B\approx 0$ and at $\nu\approx\frac{1}{2}$.

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