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Thermopower of composite fermions

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Measured diffusion thermopower of a low-disorder two-dimensional hole system in the extreme quantum limit is used to probe the thermal properties of the recently proposed particle-flux composite fermions (CF's). The data are consistent with the CF's exhibiting the integral quantum Hall effect away from filling factor $\nu=\frac{1}{2}$. The magnitudes of the thermopower maxima between the fractional quantum Hall states yield an estimate for the CF Landau-level broadening Γ_{CF}, which agrees well with Γ_{CF} deduced from the analysis of the excitation energy gaps for the fractional liquid states.

The striking similarities between the integral and fractional quantum Hall effects[1] (IQHE and FQHE) observed in two-dimensional (2D) systems have recently found an elegant explanation through a gauge transformation that attaches an even number of flux quanta ($2m\Phi$, where m is an integer and $\Phi=h/e$) to each particle.[2,3] The quasiparticles obey Fermi statistics and are termed composite fermions (CF's). They experience an effective magnetic field B^*, which is zero at Landau-level filling factor $\nu=1/(2m)$, even though the applied magnetic field $B=(n_s/\nu)(h/e)$ may be of several tesla (n_s is the particle density). Within this theoretical framework, the FQHE corresponds to the Shubnikov–de Haas effect at low B^* and the IQHE at higher B^* of the CF's. The effective filling factor for the CF's, $\nu^*=|p|$ (p is an integer) relates simply to that of the bare particles as $\nu=p/(2mp+1)$, and their effective mass is different from that of the bare particles at $B=0$, as it depends only on the particle-particle Coulomb interaction.

The results of several recent experiments were found to be remarkably consistent with the predictions of the CF formalism. Among these are the surface acoustic wave measurements by Willett and co-workers,[4] which not only provided the initial motivation for the CF theory of Halperin, Lee, and Read,[3] but also demonstrated the existence of a Fermi surface for the CF's. Equally illuminating are the observations of CF geometrical resonances near $\nu=\frac{1}{2}$ in microstructures,[5,6] and transport measurements[7,8] which have provided information on the CF effective mass and scattering. Missing, however, are detailed and quantitative experimental results on the thermodynamic properties of the CF's.

Most parameters that are directly related to the thermodynamic properties of 2D electronic systems, such as the electronic specific heat, are hardly measurable because of the dominant lattice contribution.[9,10] An exception is the diffusion thermopower, which is experimentally accessible at very low temperature (T) and can render valuable information.[11] For example, the diagonal thermopower of the insulating phase reentrant around $\nu=\frac{1}{3}$ FQH liquid in a dilute 2D hole system (2DHS) was observed to diverge as $T\rightarrow 0$.[12] This observation provided strong evidence that an energy gap, and not a mobility gap, separates the ground state, presumably a pinned Wigner crystal, from its excitations. More recently, thermopower measurements at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ were found to be consistent with the presence of a CF Fermi surface.[13] Here, we report measurements of the low-T thermopower in a very low-disorder 2DHS revealing strong FQH states in the filling range $\frac{1}{3}\leq\nu\leq\frac{2}{3}$. We show that both the temperature and magnetic field dependence of the FQH thermopower data can be explained by treating the FQHE as the IQHE of the CF's. From the data, we also deduce a CF Landau-level broadening Γ_{CF} which compares well with Γ_{CF} obtained from magnetotransport measurements.

The sample, grown by molecular-beam epitaxy on an undoped (311)A substrate, consists of a 200-Å GaAs quantum well surrounded by $Al_{0.3}Ga_{0.7}As$ spacer layers and Si-doped regions. The resulting 2DHS had a density of 1.4×10^{11} cm^{-2}. After thinning the sample and roughening the back surface (to reduce the phonon mean-free path and therefore the phonon-drag contribution to the thermopower), a 6×2-mm^2 sample was glued at one end to the cold finger of a dilution refrigerator and at the other end to a heater, using GE varnish. In addition to electrical contacts, two carbon-paint thermometers were used to measure the T drop along the sample, which was kept below 10% of the mean T. Thermopower was measured by applying a sine-wave current at frequency $f=3$ Hz through the heater and measuring the voltage induced along the sample at frequency $2f$ with a lock-in amplifier.

Figure 1 shows the B dependence of the diagonal thermopower, S_{xx}, at different temperatures. The data exhibit strong S_{xx} oscillations characteristic of the IQHE and FQHE.[12–17] The developing high-order FQH states up to $\nu=\frac{4}{9}$ and $\frac{5}{9}$ attest to the very high quality of the sample. The magnitude of S_{xx} at all ν decreases with decreasing T although its T variation depends on ν. At the integral and fractional ν where the IQHE and FQHE are observed, S_{xx} minima decrease exponentially with decreasing T. At the fillings where S_{xx} exhibits maxima, on the other hand, S_{xx} has a power-law dependence on T. As we will discuss in more details later in the paper, at these filings, we can dis-

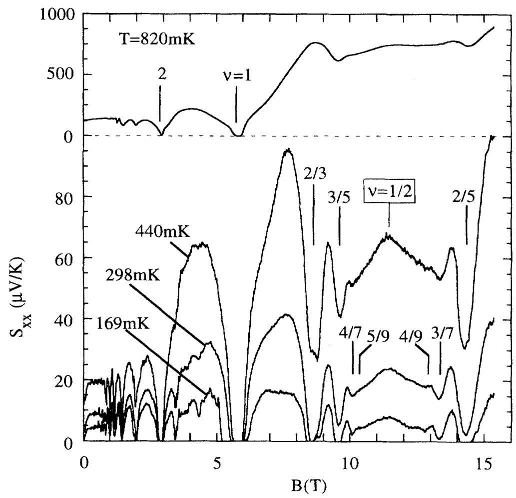

FIG. 1. Thermopower vs magnetic field for a 2DHS with density of 1.4×10^{11} cm^{-2}.

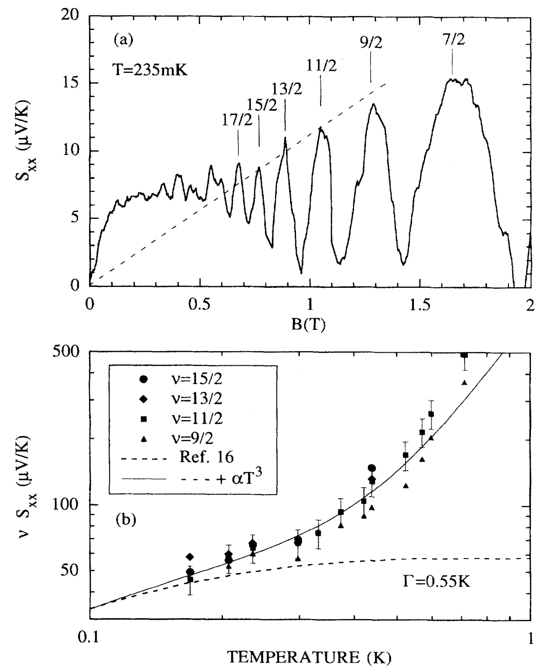

FIG. 2. (a) Low-B S_{xx} at $T=235$ mK. The dashed line is a guide to the eye. (b) The product νS_{xx} is plotted vs T at the indicated ν. The solid curve is a fit to the data and has a diffusion component which is shown by the dashed curve.

tinguish between a low-T regime where the magnitude of S_{xx} maxima varies approximately linearly with T, and a high-T regime where S_{xx} shows a faster ($\approx T^3$) variation. The linear T dependence of S_{xx} is a signature of a thermopower dominated by the diffusion mechanism, while phonon drag, with a faster T dependence, becomes predominant at higher T.[12–17] Even though the relative importance of the two contributions may depend on B, we can situate the transition between the low-T to the high-T regimes around 0.3 K. Here we mainly focus on the diffusion S_{xx} observed at very low T.

We first briefly review the theoretically predicted behavior of diffusion S_{xx} for a noninteracting 2D system in the IQH regime.[15–17] In its simplest description, the diffusion S_{xx} is given by the entropy per particle divided by the particle charge q. Since carriers in a full Landau level (LL) have zero entropy, S_{xx} is expected to vanish at integer ν for $k_BT\ll\hbar\omega_c$ and $\Gamma\ll\hbar\omega_c$, where $\hbar\omega_c$ and Γ are the LL separation and broadening, respectively. Such vanishing has been widely reported[12–14] and is also seen in the data of Fig. 1. On the other hand, the entropy per particle is maximum for a half-filled LL, and theory predicts that when $\Gamma\ll k_BT\ll\hbar\omega_c$, S_{xx} at such fillings has a "universal" value:[15–17]

$$S_{xx}=\frac{k_B}{q}\frac{\ln 2}{\nu}\approx\frac{60}{\nu}\quad(\mu\text{V/K}),\tag{1}$$

which only depends on ν and is independent of the effective mass, density, or disorder. In the case of GaAs heterostructures and in the low-T range where diffusion thermopower is dominant, Γ is usually larger than k_BT, and S_{xx} at half-filled LL is reduced by a factor g with respect to the universal value given by relation (1).[15,16] According to Zawadski and Lassnig,[16] g depends only on k_BT/Γ, implying that, for fixed T and Γ, S_{xx} maxima at half-filled LL's should increase linearly with ν^{-1} or B, and that Γ can be obtained from the magnitude of S_{xx}.[18] We emphasize, however, that the model of Ref. 16 is approximate and incomplete, as it is based only on entropy arguments and does not take the effect of scattering on the magnitude of S_{xx} maxima fully into account.[17] We use it here to analyze our data primarily because its simplicity allows us to compare the IQH and FQH data; we caution that our deduced values for Γ should be considered only semiquantitatively correct.

Figure 2 summarizes S_{xx} data at low and intermediate B: (a) shows S_{xx} vs B at $T=235$ mK while in (b) we show a plot of the measured νS_{xx} product vs T at several half-filled LL's for $\frac{9}{2}\leq\nu\leq\frac{15}{2}$. The data are consistent with the expected behavior discussed in the preceding paragraph. First, at a given half-filled LL, the T variation of S_{xx} changes from a $\approx T^3$ dependence at high T to a weaker dependence at low T. This T dependence can in fact be fitted [solid curve in Fig. 2(b)] to a sum of two terms: a T^3 term to account for the phonon-drag contribution and a term according to Ref. 16 (dashed curve) to account for the diffusion contribution. The two fitting parameters are the coefficient of the T^3 term and Γ for the diffusion term. Second, the deduced $\Gamma=0.55$ K is in good agreement with $\Gamma\approx0.7$ K obtained from the onset of the magnetoresistance oscillations in the same sample (assuming $\Gamma/\hbar\omega_c\approx1$ for the onset and an effective mass for the bare 2D holes ≈0.38 times the free-electron mass). Third, for $\frac{9}{2}\leq\nu\leq\frac{15}{2}$, S_{xx} maxima at the lowest T increases approximately linearly with B, i.e., at a fixed T the νS_{xx} product is observed to be a constant within our experimental accuracy of $\pm15\%$.

The data of Fig. 2(a) at the lowest T reveal that the approximately linear dependence of S_{xx} maxima on B (dashed line) is observed only from $\nu=\frac{9}{2}$ up to $\nu=\frac{15}{2}$. At higher ν, $\Gamma/\hbar\omega_c$ becomes comparable to unity and S_{xx} maxima devi-

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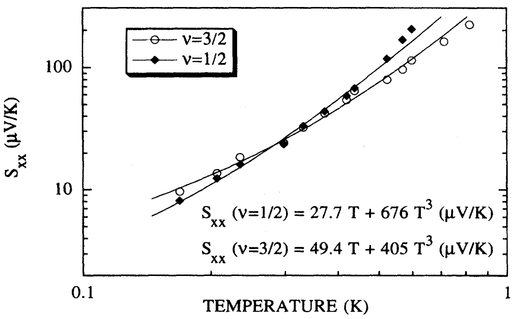

FIG. 3. Temperature dependence of S_{xx} at $\nu=\frac{1}{2}$ and $\frac{3}{2}$. The curves are fits to the data and correspond to the indicated relations.

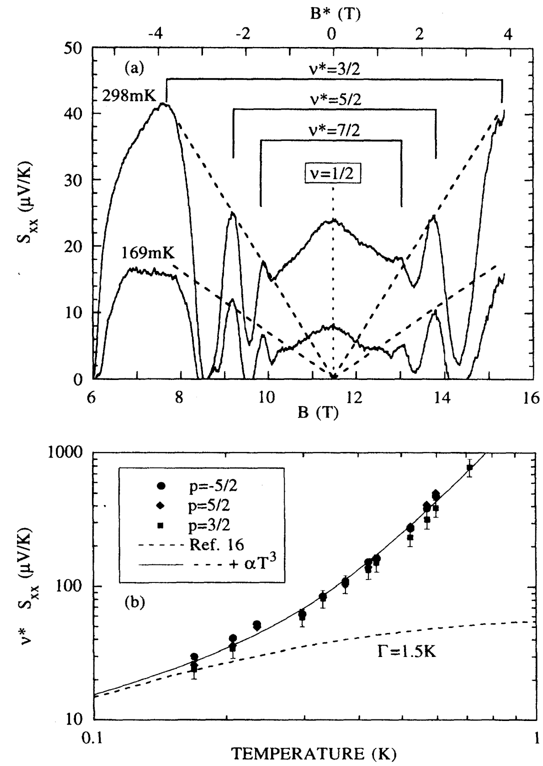

FIG. 4. (a) S_{xx} vs B and $B^*=B-B_{\nu=\frac{1}{2}}$ at $T=298$ mK (top) and 169 mK (bottom). The positions of some effective filling factors ν^* are indicated. Dashed lines are symmetric with respect to $B^*=0$ and emphasize the linear dependence of S_{xx} maxima with $|B^*|$. (b) The product $\nu^* S_{xx}$ vs T at the indicated values of p. The solid curve is a fit to the data with its diffusion component shown as a dashed curve.

ate from the linear B dependence.[16,18] For $\nu \leq 4$, the maxima are significantly smaller than expected from the intermediate-B linear dependence and FQH features appear in S_{xx} and in the magnetoresistance data. Here the system enters a new regime where the simple noninteracting picture is no longer valid. In the remainder of the paper we show that the magnitude and T dependence of S_{xx} at small-ν half-filled LL's ($\nu=\frac{1}{2}$ and $\frac{3}{2}$), and at maxima between the FQH states observed in the range $\frac{1}{3}<\nu<\frac{2}{3}$, find a simple and natural explanation within the hole-flux composite particle picture.

The magnitude of S_{xx} maxima at half-filled LL's $\nu=\frac{1}{2}$ and $\frac{3}{2}$ and its dependence on T were the subject of a recent paper.[13] It was shown that at these fillings and in the low-T diffusion regime, the measured S_{xx} varies approximately linearly with T. As shown in Fig. 3, the T dependence of S_{xx} at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ for the present sample can also be fitted to a sum of linear and cubic terms, representing the diffusion and phonon-drag contributions, respectively. The approximately linear T dependence of the diffusion S_{xx} at these fillings can be interpreted to be consistent with the CF picture as it is similar to what is observed in a 2D metal. More importantly, as emphasized in Ref. 13, the ratio of the measured diffusion terms at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ is 0.6 ± 0.1, in agreement with the ratio $1/\sqrt{3}=0.58$ one may expect for CF's.[13] Note that this ratio is very different from the ratio of 3 expected from relation (1) or the data of Fig. 2(b) for noninteracting particles.

No theoretical predictions are yet available for the thermodynamic properties of CF's *away* from exactly half-filled LL's. Here we analyze our S_{xx} data assuming that CF's obey the entropy argument valid for bare holes in the IQH regime, and then check the consistency of this assumption with data available from other experiments. The FQH data between $\nu=1$ and $\frac{1}{3}$ are shown in more detail in Fig. 4. Denoting the effective magnetic field that the CF's experience by B^* and their effective fillings by ν^* (see the opening paragraph), we make the following observations in Fig. 4(a), where the low-T S_{xx} is plotted vs B and B^*: (1) S_{xx} is symmetric with respect to $B^*=0$; (2) the field positions of the S_{xx} maxima match half-odd-integer ν^*; (3) the magnitude of S_{xx} maxima increases linearly with $|B^*|$ (dashed lines). We note that the behavior of the thermopower of CF's as a function of B^* is qualitatively similar to that of bare holes as a function of B, which was discussed in the first part of the paper. Moreover, the symmetry of S_{xx} with respect to B^* is particularly noteworthy, as it suggests that the CF's have similar thermodynamic properties on both sides of $\nu=\frac{1}{2}$.

Next, we discuss the T dependence of S_{xx} in the FQH regime around $\nu=\frac{1}{2}$. Figure 4(b) presents the product $\nu^* S_{xx}$ vs T for various values of p, where $\nu^*=|p|$ and p takes the sign of B^*.[19] The similarity of this plot to the one shown in Fig. 2(b) for the IQHE is clear. In particular, the T dependence of S_{xx} can be fitted in a similar fashion using a T^3 phonon-drag term and a diffusion term based on the noninteracting theory of Ref. 16 (dashed curve). From the fitted curve we obtain a CF LL-broadening $\Gamma_{CF}\approx 1.5$ K. This value is in agreement with $\Gamma_{CF}\approx 1.4$ K deduced in magnetotransport measurements on a similar 2DHS sample from the analysis of the excitation energy gaps for the FQH states.[8] Also consistent with magnetotransport measurements[7,8] is our conclusion that $\Gamma_{CF}=1.5$ K is of the order of $\Gamma=0.55$ K deduced from the low-B S_{xx} data for the bare particles in the same sample.

Finally, we wish to note the qualitative difference between diffusion thermopower, which is related to the thermodynamic properties of the quasiparticles, and the phonon-drag thermopower, which is governed by the particle-phonon interaction. The high-T data in Fig. 1 show a similar trend to those reported by Zeitler *et al.*,[20] who attributed the plateaulike behavior of S_{xx} for $1>\nu>\frac{1}{3}$ to the semiclassical behavior of CF's when k_BT becomes of the order of the activation energy of the FQH liquid states.

In summary, we have measured S_{xx} of a low-order 2DHS at very low temperatures and high magnetic fields, and find that the data support the CF formalism. The T and B dependences of the diffusion S_{xx} in the FQH regime $\frac{1}{3}\leq\nu\leq\frac{2}{3}$ are consistent with the prediction that CF's exhibit IQHE away from filling factor $\nu=\frac{1}{2}$. The values of Γ deduced from S_{xx} for both bare holes and CF's agree with the magnetotransport data.

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[19] The data for $p=-\frac{3}{2}$ are not included in Fig. 4(b) because at low T a FQH state develops at $\nu=\frac{4}{5}$ between $p=-1$ and $p=-2$, thus lowering S_{xx} maximum at $p=-\frac{3}{2}$. The data at $p=\pm\frac{7}{2}$ are not included since $\Gamma_{\rm CF}/\hbar\omega_c^*\approx0.9$ is too large at these p.

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