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Observation of composite-fermion thermopower at half-filled Landau levels

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Measurements of the diagonal magnetothermopower (S_{xx}) of a high-quality two-dimensional hole system reveal that in the diffusion regime ($T<100$ mK), S_{xx} at filling factors $\nu=\frac{1}{2}$ and $\frac{3}{2}$ depends approximately linearly on temperature and has a much smaller magnitude than expected for noninteracting particles at half-filled Landau levels. We show that both the temperature dependence and the magnitude of S_{xx} at these two fillings can be explained remarkably well based on a recently proposed particle-flux composite-fermion picture.

During the past decade there has been much interest in understanding the fractional quantum Hall (FQH) effect in two-dimensional electron systems (2DES's).[1–3] Recently, theoretical approaches based on composite fermions (CF's), formed by attaching an even number of magnetic flux quanta to each electron, were proposed by Jain[4] and later developed by Halperin, Lee, and Read using the Chern-Simons gauge transformation.[5] In this description, the ground state of the system at the half-filled Landau level is just a filled sea of CF's in an effective zero magnetic field, with a well-defined Fermi surface. The presence of a Fermi surface at Landau-level filling factor $\nu=\frac{1}{2}$ has been established by recent experiments on the surface acoustic wave propagation,[6] the dimensional resonance in antidots arrays,[7] and the observation of magnetic focusing near $\nu=\frac{1}{2}$.[8]

The thermodynamic properties of the 2DES's at a half-filled Landau level are also expected to be similar to those at zero magnetic field if there exits a well-defined CF Fermi surface. For example, if one considers only the contribution from CF excitations, the specific heat (per particle) of a 2DES at $\nu=\frac{1}{2}$ is just $c=\pi^2k_B^2T/3E_{\rm CF}^f$, where k_B is the Boltzmann constant and $E_{\rm CF}^f$ is the Fermi energy of the CF's.[5] Measurements of the specific heat of 2DES's, however, are difficult because the lattice specific heat is dominant.[9,10] On the other hand, the diffusion thermopower, which is a measure of the carrier heat over temperature, or equivalently of the carrier entropy, is experimentally accessible.[11–13] The very low temperatures which are required to probe the diffusion thermopower of 2D systems at GaAs/Al_xGa_{1-x}As heterojunctions, however, have seldom been achieved.[12,13]

In this paper we report measurements of the diagonal thermopower S_{xx} of a high-quality two-dimensional hole system (2DHS) down to $T\approx40$ mK. At low temperatures ($T<100$ mK) where the diffusion thermopower is dominant, S_{xx} at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ varies approximately linearly with temperature. In this temperature range, the magnitude of S_{xx} at $\nu=\frac{1}{2}$ is smaller than at $\nu=\frac{3}{2}$, and both are much smaller than the universal quantized values expected for noninteracting particles. The linear temperature dependence and the magnitude of the measured S_{xx}, on the other hand, are remarkably consistent with the CF picture.

The samples used in these measurements were made from GaAs/$Ga_{1-x}Al_x$As heterojunctions grown by molecular-beam epitaxy on undoped (311)A substrates. The system was modulation doped with Si which is incorporated as an acceptor on the (311)A surface.[14] The 2DHS has a density of $p_s=6.5\times10^{10}/\text{cm}^2$ and mobility of $\mu\approx7\times10^5$ cm^2/V s at low temperatures. An 8×2-mm^2 piece of sample was cut from the wafer and thinned to about 0.1 mm. Ohmic contacts were made to the sample by alloying In:Zn in a hydrogen ambient. One end of the sample was soldered to the cold finger of a dilution refrigerator. A strain gauge was glued to the other end of the sample and was used as a heater to create a temperature gradient. Electrical contacts to the sample were made with thin superconducting wires (NbTi) whose low thermal conductance ensures a negligible heat leak to the surrounding. Two calibrated carbon-paint thermometers on the substrate side of the sample were used to measure the temperature gradient along the sample with an accuracy of about $\pm10\%$. The thermopower was measured by applying a positive square wave current of frequency $f=2$ Hz through the heater and then measuring the voltage induced along the sample with a lock-in amplifier. The thermal time constant of the system was smaller than $1/f$ so that the signal was in phase with the heat excitation. To verify the signal we also applied a sine wave current at $f=1$ Hz to the heater and measured the induced thermopower voltage at $2f$. The data measured via these two methods are in good quantitative agreement.

To check the experimental setup, in addition to the thermopower measurements, we also measured the thermal conductivity of the sample as a function of temperature. In the range $40<T<300$ mK concerned in this paper, the thermal

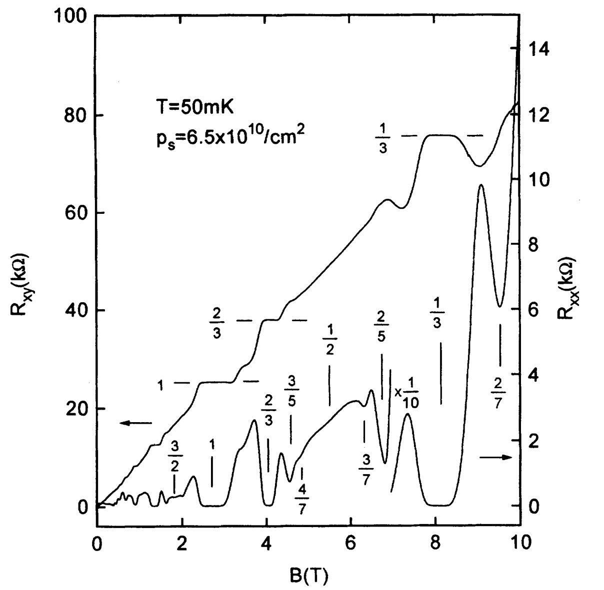

FIG. 1. Diagonal (R_{xx}) and Hall (R_{xy}) resistances vs applied magnetic field. Filling factors are marked with vertical lines.

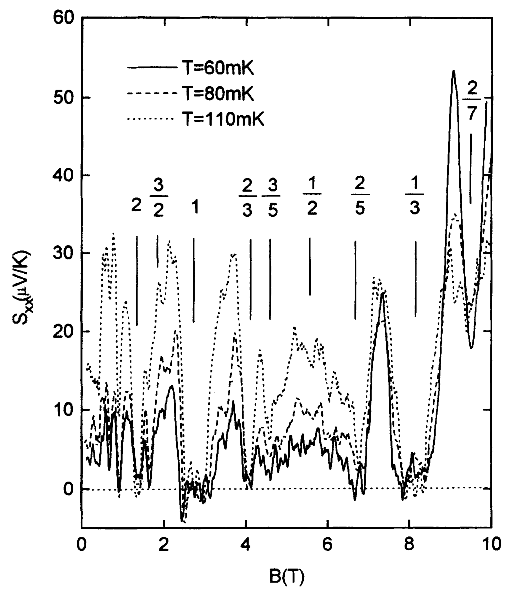

FIG. 2. Diagonal thermopower S_{xx} as a function of magnetic field at three temperatures.

conductivity was found to have approximately a T^3 dependence, as expected in the limit of phonon boundary scattering.

Figure 1 shows the diagonal (R_{xx}) and Hall (R_{xy}) resistances of the 2DHS as a function of applied magnetic field B at $T=50$ mK. The data were measured in the isothermal condition (heater off). The high quality of the 2DHS is evident by the set of FQH states at $\nu=j/(2j\pm1)$ (j is a positive integer) which, in the CF picture, are just the integer quantum Hall (IQH) states of CF's in an effective magnetic field measured from $\nu=\frac{1}{2}$; these include the strong $\frac{1}{3}$ and $\frac{2}{3}$ states and the high-order $\frac{2}{5}$, $\frac{3}{5}$, $\frac{4}{7}$, and $\frac{3}{7}$ states. The FQH states descending from $\nu=\frac{3}{2}$ (i.e., $\nu=\frac{5}{3}$ and $\frac{4}{3}$) are also discernible, albeit weak in this 2DHS partly because of the large hole mass which results in substantial Landau-level mixing.[14] The two large R_{xx} peaks around $\nu=\frac{1}{3}$ diverge as $T\rightarrow0$; these insulating phases reentrant around $\nu=\frac{1}{3}$ and $\frac{2}{7}$ FQH liquids, have been associated with the localization of the 2DHS into a pinned Wigner solid.[14]

Typical traces of S_{xx} as a function of B are shown in Fig. 2. A positive S_{xx} is observed, consistent with hole conduction. Despite the presence of noise (primarily because of the small signal), several features of the data are very clear. At integer fillings, S_{xx} vanishes as $T\rightarrow0$. This vanishing of S_{xx} is characteristic of the IQH effect and can be associated with the vanishing of the entropy of the filled Landau levels.[15] By analogy, one also expects the incompressible FQH liquid to have zero entropy and therefore vanishing thermopower as observed, although no calculations are available. In the insulating phases reentrant around $\nu=\frac{1}{3}$ and $\frac{2}{7}$, S_{xx} diverges as $T\rightarrow0$, reflecting the presence of an energy gap for these insulating states as discussed elsewhere.[13] Of central interest in this paper, however, is the behavior of S_{xx} at $\nu=\frac{1}{2}$ and $\frac{3}{2}$. Denoting the value of S_{xx} at filling factor ν by $S_{xx}(\nu)$, we note that $S_{xx}(\frac{1}{2})<S_{xx}(\frac{3}{2})$ even though $R_{xx}(\frac{1}{2})$ is larger than $R_{xx}(\frac{3}{2})$ by nearly an order of magnitude. The measured $S_{xx}(\frac{1}{2})$ and $S_{xx}(\frac{3}{2})$ are plotted as a function of temperature in Fig. 3. For comparison, the temperature dependence of S_{xx} at $B\approx0$ is also shown in the figure.[16] At all three fillings, S_{xx} follows a similar temperature dependence: $S_{xx}\sim T^3$ for $T>100$ mK and $\sim T$ for $T<100$ mK.

We first discuss the temperature dependence of S_{xx} at zero field. At low temperatures, primarily two mechanisms, the diffusion and the phonon drag, are expected to contribute to the thermopower. The diffusion thermopower S_d for a 2D system can be calculated using the Mott formula:

$$S_d=\frac{\pi^2}{3}\frac{k_B^2T}{q\sigma}\left.\frac{\partial\sigma}{\partial E}\right|_{Ef}, \tag{1}$$

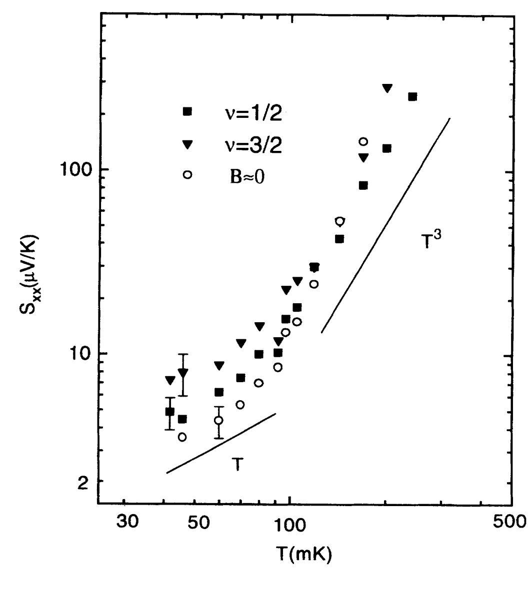

FIG. 3. Temperature dependence of S_{xx} at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ and at $B\approx0$. Typical error bars for the low temperature S_{xx} are indicated.

where σ is the conductivity and q is the carrier charge. If σ can be expressed in terms of an energy-dependent relaxation time $\tau(E)\propto E^p$ where p is a constant, Eq. (1) becomes

$$S_d=\frac{\pi^2}{3}(p+1)\frac{k_B^2T}{qE^f}. \qquad (2)$$

Calculations suggest that p for a 2DES at GaAs/Al$_x$Ga$_{1-x}$As heterojunctions is only weakly dependent on electron density and has a value of ≈ 1 when the scattering from remote and background ionized impurities and from the surface roughness is taken into account.[17] Equation (2) implies that the diffusion thermopower depends linearly on temperature with a slope $a=(\pi^2/3)(p+1)k_B^2/qE^f$. On the other hand, the phonon drag thermopower ($S_{\rm ph}$), which is proportional to the phonon specific heat, has roughly a T^3 dependence at low temperatures.[18] This yields $S_{\rm ph}=bT^3$, where the constant b can vary from sample to sample, depending on sample quality and processing techniques. The total thermopower is given by the sum of these two contributions: $S=S_d+S_{\rm ph}=aT+bT^3$.

The phonon drag effect often dominates thermopower measurements at high temperatures.[11–13,19,20] At sufficiently low temperatures, however, the diffusion thermopower becomes dominant and can be measured. In fact, Ruf *et al.* measured the diffusion thermopower of a high-mobility 2DES and found that their data can be well fitted by Eq. (2) with $p\approx 1$.[12] In our 2DHS, S_{xx} at $B\approx 0$ follows approximately a T^3 dependence for $T>100$ mK, characteristic of $S_{\rm ph}$. As T is reduced below 100 mK, S_d starts to become dominant, exhibiting a nearly linear temperature dependence from which we obtain $a=80$ μV/K^2. From this value and using $p=1$, we estimate the carrier effective mass of the 2DHS to be $0.3m_0$ (m_0 is the free electron mass), which is in good agreement with the weighted hole effective mass deduced from the cyclotron resonance and magnetotransport experiments.[21]

We now turn to a discussion of the thermopower in a quantizing magnetic field. S_d was calculated as a function of field in the IQH regime for $k_BT\ll\hbar\omega_c$, where $\hbar\omega_c$ is the cyclotron energy.[15,22,23] The calculations show that S_d vanishes for the IQH states, and reaches maximum values at half-filled Landau levels except for the lowest Landau level in which S_d diverges as $\nu\rightarrow 0$. In the limit of zero impurity scattering, S_{xx} at half-filled Landau levels has the universal quantized values:

$$S_{xx}=\frac{k_B}{q}\frac{\ln 2}{\nu}\approx\pm\frac{60}{\nu}\ (\mu\text{V/K}), \qquad (3)$$

where "+" is for holes and "−" is for electrons. Clearly Eq. (3), which is based on a single-particle model, cannot account for our data in the FQH effect regime. For example, the diffusion thermopower $S_{xx}(\frac{1}{2})$ is found to be temperature dependent; its value (~ 10 μV/K at $T=100$ mK) is much less than the universal quantized value predicted by Eq. (3) (~ 120 μV/K); and $S_{xx}(\frac{1}{2})\approx 0.7S_{xx}(\frac{3}{2})$ while Eq. (3) predicts $S_{xx}(\frac{1}{2})=3S_{xx}(\frac{3}{2})$. When the impurity scattering is taken into account, $S_{xx}(\frac{1}{2})$ may be reduced significantly from the quantized value if $k_BT/\Gamma\ll 1$, where Γ is the Landau-level broadening.[15,22] However, $\Gamma(\frac{1}{2})$ has to be about four times larger than $\Gamma(\frac{3}{2})$ to account for $S_{xx}(\frac{1}{2})\approx 0.7S_{xx}(\frac{3}{2})$. Although in principle this is possible, we believe it is unlikely: e.g., specific-heat measurements on 2DES's, which were performed for $\nu>1$, have indicated that Γ has nearly the same value at half-integer fillings.[10] Moreover, there is no obvious reason why S_{xx} should vary linearly with temperature when $k_BT<\Gamma$. We conclude that the impurity scattering is unlikely to account for our experimental data. Instead, we believe that electron-electron interactions are dominant and should be considered.

Our data can find a natural and satisfactory explanation in the CF picture. First, if S_{xx} at a half-filled Landau level is due to the CF's, its temperature dependence should be similar to that at zero field, in analogy to the specific heat of CF's as mentioned earlier. This is consistent with the diffusion thermopower ($T<100$ mK) data of Fig. 3. Second, the ratio of the diffusion thermopower at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ should be consistent with the Fermi energy of CF's: $E_{\rm CF}^f=\hbar^2k_{\rm CF}^2/2m_{\rm CF}$, where $k_{\rm CF}$ and $m_{\rm CF}$ are the Fermi wave vector and the effective mass of CF's, respectively. $m_{\rm CF}$, which is determined by electron-electron interactions, should roughly scale with l_B^{-1}, where $l_B=(\hbar/eB)^{1/2}$ is the magnetic length.[5] Since a filled Landau level does not contribute to conduction, we have $k_{\rm CF}^2(\frac{1}{2})=3k_{\rm CF}^2(\frac{3}{2})$ and

$$\frac{S(\frac{1}{2})}{S(\frac{3}{2})}=\frac{k_{\rm CF}^2(\frac{3}{2})}{k_{\rm CF}^2(\frac{1}{2})}\frac{m_{\rm CF}(\frac{1}{2})}{m_{\rm CF}(\frac{3}{2})}=\frac{1}{3}\sqrt{3/1}\cong 0.58.$$

This ratio is close to the value measured in the experiment (≈ 0.7). Finally, $m_{\rm CF}$ can be estimated from the magnitude of the thermopower. Assuming $p\approx 1$ is valid for CF's, we obtain $m_{\rm CF}(\frac{1}{2})\approx 0.7m_0$ for $B=5.6$ T with an accuracy of about $\pm 20\%$. As we discuss in the next paragraph, this is a reasonable value for $m_{\rm CF}$.

Recent magnetotransport experiments in 2DES's have yielded values for $m_{\rm CF}$ from the analysis of the excitation gaps or the amplitudes of the resistance oscillations for the FQH states around $\nu=\frac{1}{2}$.[24] Similar measurements on a 2DHS of density $p_s=1.6\times 10^{11}$/cm^2 yield $m_{\rm CF}\approx 1.4m_0$ at $B\approx 13$ T,[25] which implies $m_{\rm CF}\approx 0.9m_0$ at $B=5.6$ T when the magnetic-field dependence of $m_{\rm CF}$ ($\propto B^{1/2}$) is taken into account. This value is in fair agreement with our thermopower measurement, suggesting that $p\approx 1$ is a good approximation for the CF's at $\nu=\frac{1}{2}$. From the magnetotransport measurements on 2DES's,[24] $m_{\rm CF}(\frac{1}{2})\approx 0.5m_0$ for $B=5.6$ T can be inferred. This is also reasonable: $m_{\rm CF}$ for the 2D electron and hole systems should not differ by as much as their band effective masses ($0.067m_0$ for 2DES's and $0.3m_0$ for 2DHS's) since, due to the large band mass of holes and the ensuing Landau-level mixing, the CF mass enhancement relative to the band mass for 2D holes should be less than for 2D electrons.[5]

In conclusion, the temperature dependence of the diagonal thermopower S_{xx} of a high-quality 2DHS indicates that S_{xx} at $\nu=\frac{1}{2},\frac{3}{2}$ and at $B\approx 0$ is dominated by the diffusion thermopower for $T<100$ mK, and by the phonon drag effect for $T>100$ mK. Both the approximately linear temperature dependence and the magnitude of the low-temperature diffusion thermopower at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ can be explained in terms of the CF picture.[26] We estimate $m_{\mathrm{CF}}(\frac{1}{2})\approx 0.7m_0$ for $B=5.6$ T.

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[26] In a lower density 2DHS with $p_s=4\times 10^{10}/\mathrm{cm}^2$, $S_{xx}(\frac{1}{2})$ at $T=100$ mK is about 20 μV/K, a factor of 2 larger than $S_{xx}(\frac{1}{2})$ for the present sample, and shows a weaker than linear decrease with decreasing T. Both the larger value of S_{xx} and the weak temperature dependence in the more dilute 2DHS may be a result of substantial Landau-level mixing and the strong insulating phase near $\nu=\frac{1}{3}$ which extends to larger filling factors (see Ref. 13 for further details).