Exact Quantization of the Even-Denominator Fractional Quantum Hall State at $\nu = 5/2$ Landau Level Filling Factor

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We report ultralow temperature experiments on the obscure fractional quantum Hall effect at Landau level filling factor $\nu = 5/2$ in a very high-mobility specimen of $\mu = 1.7 \times 10^7$ cm^2/V s. We achieve an electron temperature as low as ~4 mK, where we observe vanishing R_{xx} and, for the first time, a quantized Hall resistance, $R_{xy} = h/(5/2)e^2$ to within 2 ppm. R_{xy} at the neighboring odd-denominator states $\nu = 7/3$ and 8/3 is also quantized. The temperature dependences of the R_{xx} minima at these fractional fillings yield activation energy gaps $\Delta_{5/2} = 0.11$, $\Delta_{7/3} = 0.10$, and $\Delta_{8/3} = 0.055$ K.

Electrons in two-dimensional systems at low temperatures and in the presence of an intense magnetic field condense into a sequence of incompressible quantum fluids with finite energy gaps for quasiparticle excitation, termed collectively the fractional quantum Hall effect (FQHE) [1]. These highly correlated electronic states occur at rational fractional filling $\nu = p/q$ of Landau levels. Their characteristic features in electronic transport experiments are vanishing resistance, R_{xx}, and exact quantization of the concomitant Hall resistance, R_{xy}, to $h/(p/q)e^2$. Over the years, a multitude of FQHE states have been discovered—all q's being odd numbers. The only known exceptions are the states at half filling of the second Landau level $\nu = 5/2$ ($= 2 + 1/2$) and $\nu = 7/2$ ($= 3 + 1/2$) [2–4]. Half filled states in the lowest Landau level show no FQHE, whereas half filled states in still higher Landau levels exhibit yet unresolved anisotropies [5]. Recent experiments in tilted magnetic field even seem to hint at a connection between the $\nu = 9/2$ state and the state at $\nu = 5/2$ [6].

The origin of the $\nu = 5/2$ and $7/2$ states remains mysterious. Observation of odd-denominator FQHE states is intimately connected to the antisymmetry requirement for the electronic wave function. An early, so-called hollow-core model [7] for the FQHE at $\nu = 5/2$ and $7/2$, which takes explicitly into account aspects of the modified single-particle wave functions of the second Landau level, arrived at a trial wave function. However, for a Coulomb Hamiltonian its applicability is problematic [8,9].

With the advent of the composite fermion (CF) model [10] the existence of exclusively odd-denominator FQHE states is traced back to the formation of Landau levels of CFs emanating from even-denominator fillings, such as the sequence $\nu = p/(2p \pm 1)$ from $\nu = 1/2$. Even-denominator fillings themselves represent Fermi-liquid-like states, resulting from the attachment of an even

number of magnetic flux quanta to each electron. The obvious conflict between this theory and experiment at $\nu = 5/2$ is resolved by invoking a CF-pairing mechanism [11–15]. In loose analogy to the formation of Cooper pairs in superconductivity such pairing creates a gapped, BCS-like ground state at $\nu = 5/2$, called a "Pfaffian" state, which displays a FQHE. Indeed, an exact numerical diagonalization calculation by Morf [9] favors the Pfaffian state.

The experimental situation remains poor. Study of the $\nu = 5/2$ state requires ultrahigh mobility specimens and its small energy gap necessitates ultralow temperatures. Previous experiments [2–4] indicated the existence of a local minimum in R_{xx} and a slope change in R_{xy} at $\nu = 5/2$. However, we still lack the observation of the unmitigated, well-developed hallmarks of a FQHE at $\nu = 5/2$, namely, vanishing of the magnetoresistance, R_{xx}, and quantization of the Hall resistance to $R_{xy} = h/(5/2)e^2$.

In this Letter, we present ultralow temperature data on the even-denominator FQHE state $\nu = 5/2$ and its vicinity. For the first time, we observe a wide Hall plateau, precisely quantized to $R_{xy} = h/(5/2)e^2$ to an accuracy better than 2×10^{-6}. Concomitantly, the longitudinal resistance assumes vanishing values $R_{xx} = 1.7 \pm 1.7\Omega$ at a bath temperature, $T_b = 8$ mK. True activation energy measurements, performed between 8 and 50 mK, yield an energy gap of $\Delta_{5/2} = 0.11$ K. The energy gaps of neighboring FQHE states at $\nu = 7/3$ and $\nu = 8/3$ are $\Delta_{7/3} = 0.10$ K and $\Delta_{8/3} = 0.055$ K, respectively.

We used a standard 4 mm $\times$ 4 mm geometry for our samples with eight indium contacts diffused symmetrically around the perimeter. An electron density of 2.3×10^{11} cm^{-2} was established by illuminating the sample at 4.2 K. The sample mobility is $\mu = 1.7 \times 10^7$ cm^2/V s at ~1 K and below. Cooling the electron system to ultralow temperatures is a formidable task, since the electron-phonon coupling between the two-dimensional

electron system (2DES) and its host lattice decreases precipitously with decreasing temperature [4,16]. In fact, at very low temperatures cooling of the electrons proceeds largely via the electrical contacts. Electrons diffuse to the contacts, where they cool in the highly disordered region formed by the "dirty" alloy of GaAs and indium. Therefore, cooling of the contacts is of paramount importance in low-temperature transport experiments and our cooling system was designed to cool specifically the contact areas of the 2DES specimen. Eight sintered silver heat exchangers each having an estimated surface area of ~0.5 m^2 and formed around a 10 mil silver wire were soldered directly to the indium contacts of the sample using indium as a solder. They provide electrical contact and simultaneously function as large area cooling surfaces. The back side of the sample was glued with gallium to yet another large surface area heat exchanger for efficient cooling of the lattice of the specimen. The inset of Fig. 1 shows a sketch of this arrangement. Sample and heat exchangers were immersed into a cell made from polycarbonate and filled with liquid ^{3}He. The liquid is cooled by the PrNi$_5$ nuclear demagnetization stage of a dilution refrigerator via annealed silver rods that enter the ^{3}He cell. This brings the system's base temperature to 0.5 mK, well below the 8 mK of the dilution unit.

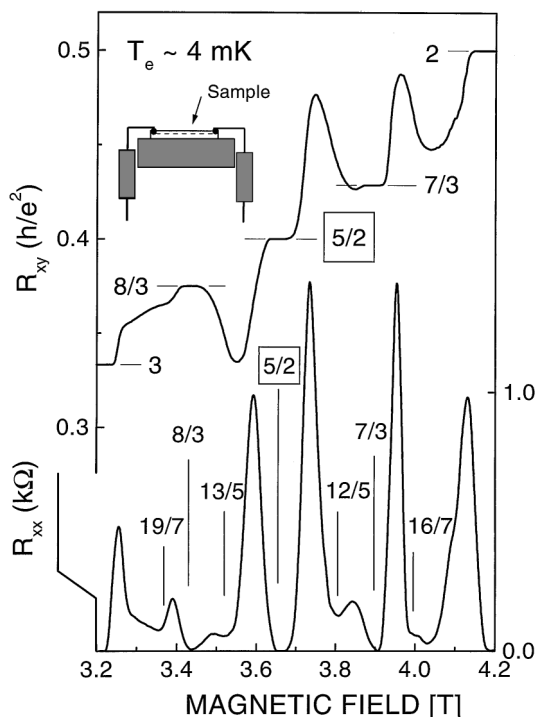A cerium magnesium nitrate thermometer, a ^{3}He melting curve thermometer, and/or a Pt NMR thermometer are mounted in the low-field region, at the top of the nuclear stage. The accuracy of the thermometry is estimated to be better than 0.05 mK. All measurements were performed in an ultraquiet environment, shielded from electromagnetic noise. *RC* filters with cutoff frequencies of 10 kHz were employed to reduce rf heating. The data were collected using a PAR-124A analog lock-in with an excitation current of 1 nA at typically 5 Hz. At this current level electron heating was undetectable for a temperature greater than 8 mK. This was deduced from a series of heating experiments, in which R_{xx} was measured at different currents from 0.5 to 100 nA at $T_b = 8.0$ mK. The resistance of the strongly T-dependent R_{xx} peak at 3.75 T in Fig. 1 was used as an internal thermometer for the electron temperature, T_e, assuming $T_e = T_b$ at higher T_b and in the limit of low current. The T_e vs I data fit the expected T^5 relationship [4,16], $\ln(I^2) = \text{const} + \ln(T_e^5 - T_b^5)$, where I is in nA, T in mK, and const $= -7.5$. At $T_b = 8.0$ mK and 1 nA current it yields $T_e = 8.05$ mK, sufficiently close to T_b for the difference to be negligible.

Figure 1 shows the Hall resistance R_{xy} and the longitudinal resistance R_{xx} between Landau level filling factors $\nu = 3$ and $\nu = 2$ at $T_b = 2$ mK. Using the above equation for an excitation current of 1 nA, the deduced electron temperature, T_e, is ~4 mK. Ultimately it is unclear, whether the T^5 law continues to hold. However, if anything, we would expect $T_e \sim 4$ mK to be a conservative estimate, since electron cooling via the well heat-sunk contacts should lower T_e below the limit set by lattice cooling. Strong minima emerge in R_{xx} in the vicinity of filling factors $\nu = 5/2$, $\nu = 7/3$, and $\nu = 8/3$. Satellite features can be made out that are probably associated with filling factors $\nu = 19/7$, 13/5, 12/5, and 16/7. If this identification is correct, apart from the $\nu = 5/2$ state, the successive development of FQHE states is not unlike the one observed in the lowest Landau level. However, as long as such minima do not show concomitant Hall plateaus, one cannot be certain as to their quantum numbers. Strikingly different from the R_{xx} pattern around $\nu = 1/2$ is not only the existence of the central $\nu = 5/2$ state, but also the emergence of very strong maxima flanking this minimum.

The primary minima at $\nu = 5/2$, $\nu = 7/3$, and $\nu = 8/3$ show well developed Hall plateaus. In particular, the $5/2$ plateau is extensive, allowing its value to be measured to high precision. This was performed with a current of 20 nA, which raises T_e to ~15 mK, but increases the signal to noise, while keeping the plateau intact. The lock-in operated at 23 Hz and its output was averaged for 20 min. The neighboring integral quantum Hall effect (IQHE) plateaus at $\nu = 2$ and $\nu = 3$ were used as standard resistors to which the value at $\nu = 5/2$ was compared. In the center of the plateau, as determined by the midpoint between the sharply rising flanks on either side, R_{xy} was found to be quantized to $h/(5/2)e^2$ to better than 2×10^{-6} over a range of at least 0.01 T, equivalent

FIG. 1. Hall resistance R_{xy} and longitudinal resistance R_{xx} at an electron temperature $T_e \approx 4.0$ mK. Vertical lines mark the Landau level filling factors. The inset shows a schematic of the sample with attached sintered silver heat exchangers (gray) to cool the 2DES.

to the central 20% of the plateau. It unambiguously establishes the state at $\nu = 5/2$ as a true FQHE state. The plateau values around filling factor $\nu = 7/3$ and $\nu = 8/3$ were derived in a similar fashion. They are quantized to their respective R_{xy} values to better than 3.5×10^{-4}.

An unusual set of features of the Hall trace is pronounced maxima and minima between plateaus. Ultimately we do not know their origin. The simplest interpretation is a mixing of R_{xx} into R_{xy}. Indeed, two of the peaks in R_{xy} ($B \sim 3.8$ and $B \sim 4.0$ T) become dips on field reversal, although of smaller amplitude than the peaks. The minimum in R_{xy} at $B \sim 3.5$ T does not invert on field reversal but remains a dip of similar strengths. In any case, these pronounced features in R_{xy} do not line up with the strong maxima in R_{xx}, but seem to be shifted farther away from the central $\nu = 5/2$ state. It is also remarkable that R_{xy} of these maxima and minima approaches the Hall resistance of the IQHE at $\nu = 2$ and $\nu = 3$, respectively. The situation is somewhat reminiscent of data taken in the regime of the anisotropic phase around $\nu = 9/2$ and $11/2$ [5], but it is premature to invoke similar mechanisms.

Having established the existence of correctly quantized FQHE states at $\nu = 5/2$, as well as at $\nu = 7/3$ and $8/3$, we turn to the measurement of their energy gaps. Figure 2 gives an overview over the temperature dependence of R_{xx} between $\nu = 2$ and $\nu = 3$ at four different temperatures. These data were recorded during a separate cooldown than the data of Fig. 1. Comparison of both provides some measure for their reproducibility. The predominant fractions at $\nu = 7/3$, $5/2$, and $8/3$ reproduce very well, whereas the secondary features, assigned in Fig. 1 to $\nu = 19/7$, $13/5$, $12/5$, and $16/7$ are considerably weaker than there. Accordingly, only the gaps of the primary fractions are accessible. However, the approach of vanishing R_{xx} in these three cases enables us to perform true activation energy measurements on all these states.

Figure 3 shows on a semilog graph the value of R_{xx} at the position of the $\nu = 7/3$, $5/2$, and $8/3$ minima as a function of inverse temperature for $8 < (T_e = T_b) < 50$ mK. The characteristic S shape of such data is observed [17]. The high-temperature (low $1/T$) roll-off is a result of the temperature approaching the energy gap. The low-temperature (high $1/T$) saturation is also a standard feature of such data. Its origin has never unambiguously been identified, but is most likely associated with a transition to hopping conduction. The $\nu = 5/2$ data show an anomalous feature at low temperature. The kink at $T \sim 15$ mK has been observed in all three activation measurements that we performed during a half year span, while the sample had been kept below 4.2 K. We do not know its origin. In any case, for all three fractions there exists a central region of data points that follow an exponential dependence for almost 1 order of magnitude. We use a straight line approximation to this region to determine the activation
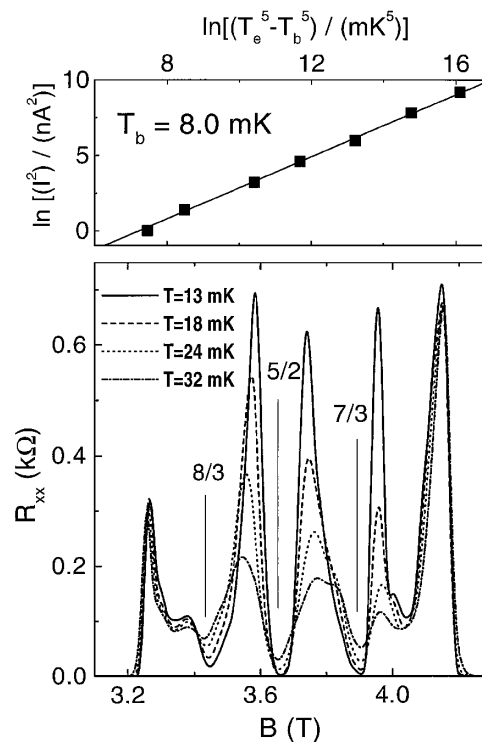

FIG. 2. Lower panel: The temperature evolution of R_{xx} between $\nu = 2$ and $\nu = 3$. Upper panel: $\ln(I^2)$ vs $\ln(T_e^5 - T_b^5)$. I is current in nA. T_e is electron temperature and T_b is bath temperature, in mK.

energy of each fraction and deduce an energy gap Δ_ν from $R_{xx}(T) = \text{const} \times \exp(-\Delta_\nu/2kT)$. Their values are included in Fig. 3.

The energy gap $\Delta_{5/2} = 0.11$ K is very close to the value deduced earlier [3] and the energy gaps of the two $p/3$ states are $\Delta_{7/3} = 0.10$ and $\Delta_{8/3} = 0.055$ K. This implies $\Delta_{7/3} \approx \Delta_{5/2}$ and $\Delta_{8/3} \approx \Delta_{5/2}/2$. At first glance such a relationship between gaps in the second Landau level is very satisfying, since it closely reproduces the relationship between the calculated energy gaps [9], assuming the $5/2$ state to be of the Pfaffian type. However, with $\Delta_{5/2}^{\text{theo}} \approx 0.02 e^2/\varepsilon\lambda_0 \approx 1.9$ K at 3.67 T, the absolute values in theory and in experiment differ by more than an order of magnitude. This is a common observation for small energy gaps in the FQHE regime. It is most likely attributable to residual disorder in the specimen, which leads to a smearing out of the energy gap. For FQHE states around $\nu = 1/2$ an approximately B-independent gap reduction has been deduced from activation energy measurements on the primary $\nu = p/(2p \pm 1)$ FQHE sequence and was rationalized as a broadening of the associated CF Landau level [18]. Even for such very high-mobility samples the value of the gap reduction is ~ 2 K. This value also agrees with scattering rates determined at $\nu = 1/2$. We must assume that a similar gap reduction mechanism is at work in the second Landau level and that its magnitude is not unlike the magnitude around
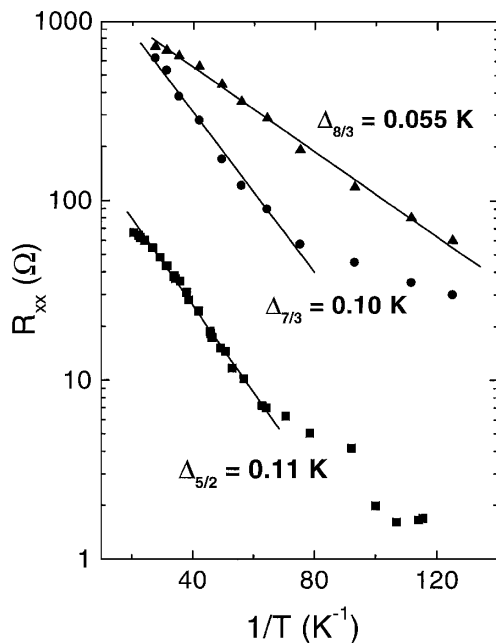
FIG. 3.   Activation energy plots for R_{xx} at the $\nu = 5/2$, 7/3, and 8/3 minima for $8.0 < T_b < 50.0$ mK. The data for $\nu = 7/3$ and $\nu = 8/3$ are multiplied by 10 for clarity. Activation energy gaps, Δ_ν, are determined from the slope of the extended linear regions.

$\nu = 1/2$. Accepting such a rationale, we are led to conclude that, in fact, $\Delta_{5/2} \approx \Delta_{7/3} \approx \Delta_{8/3}$ and all three gaps are on the order of ~ 2 K. This brings the value of experiment in the range of theory, but the result is at variance with the theoretically derived ratios between the gaps [9]. The above line of thought has a more general implication. Accepting in general a gap reduction of ~ 2 K for FQHE gaps due to remnant disorder even in the highest-mobility samples, one would have to conclude that presently measurements of activation energies much less than ~ 2 K establish only the existence of true gaps of ~ 2 K. Comparison between measured activation energies of different fraction becomes less meaningful, although it should remain an acceptable indicator for whether a specific gap increases or decreases in response to a perturbation.

In summary, we have conducted ultralow temperature experiments on the FQHE states in the second Landau level, at $\nu = 5/2$ and its vicinity. The longitudinal resistance assumes vanishingly low values at this ominous even-denominator filling factor, and the concomitant Hall plateau is quantized to $h/(5/2)e^2$ to an accuracy better than 2×10^{-6}. Neighboring minima at $\nu = 7/3$ and $\nu = 8/3$ also show vanishing resistance and Hall quantization to their respective quantum number. Activation energy measurements on all three fractions yield $\Delta_{5/2} = 0.11$, $\Delta_{7/3} = 0.10$, and $\Delta_{8/3} = 0.055$ K, yet we conjecture that the underlying energy gaps for all three FQHE states are very similar and of magnitude $\Delta \sim 2$ K.

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