Resistance Fluctuations in Narrow AlGaAs/GaAs Heterostructures: Direct Evidence of Fractional Charge in the Fractional Quantum Hall Effect

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In ∼2-μm-wide Hall bars of a high mobility GaAs/AlGaAs heterostructure resistance fluctuations of quasiperiod $\Delta B \simeq 0.016$ T are observed near the diagonal-resistance minima for Landau-level filling factors $\nu = 1,2,3,4$. This behavior is consistent with resonant reflection through magnetically bound states as a mechanism for the breakdown of dissipationless transport in narrow channels. In the $\nu = \frac{1}{3}$ minimum of the fractional quantum Hall effect we observe similar fluctuation structure, but with a period of $\sim 0.05\ \mathrm{T} \simeq 3\Delta B$, indicative of transport by quasiparticles of fractional charge $e/3$.

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The fractional quantum Hall effect[1] (FQHE) is a manifestation of new ground states of two-dimensional (2D) electrons in strong magnetic fields (B) at special fractional values of the Landau-level filling factor $\nu = p/q$, where p is any integer and q is an odd integer.[2] The ground state is an incompressible electron fluid which can flow with no dissipation. Experimentally, the phenomena are similar to those for the integral quantum Hall effect[3] (IQHE) except that the Hall-resistance plateaus for the state at $\nu = p/q$ are quantized to $R_{xy} = (q/p)h/e^2$. This fractional quantization is understood to be a consequence of the existence of quasiparticles of fractional charge $e^* = e/q$, as predicted by Laughlin's theory.[4] Some independent evidence for e^* has been obtained.[5,6] But until now, evidence afforded by the more direct technique of interference of these fractionally charged carriers has remained unobserved.

Conductance fluctuations due to electron interference in samples of sizes on the order of the phase coherence length, l_Φ, have also seen great interest in recent years. In the weak-B-field limit, the amplitude and the quasiperiod (in B field or Fermi energy) of these fluctuations give a good measure of l_Φ.[7] Alternatively, if l_Φ is known independently, the conductance fluctuations trivially give a measure of the charge of the carriers. Transport in small samples in the strong-B-field limit, however, is less well understood. While large resistance fluctuations in mesostructures have been observed in the IQHE regime,[8] no clear relation between the fluctuations and ν was observed. More recent experimental work[9,10] is beginning to support the notion of edge states and their importance in transport in small samples in the IQHE.[11,12] Jain and Kivelson[13] and Büttiker[14] have proposed that inter-edge-state scattering is the mechanism behind resistance fluctuations in the IQHE. Chang *et al.*[15] have observed nearly periodic resistance fluctuations near the $\nu = 2$ diagonal-resistance minimum due to such scattering through bound states. The use of similar fluctuations in the FQHE to measure the charge of the quasiparticles has also recently been suggested.[16,17]

In this Letter we report the observation of resistance fluctuations immediately near the resistance minima of the IQHE for $\nu = 1$, 2, 3, and 4, and of the FQHE for $\nu = \frac{1}{3}$. While the quasiperiods of the fluctuations for integral ν are all roughly the same, the period for $\nu = \frac{1}{3}$ fluctuations is a factor of ∼3 larger. The data for integer ν agree with Jain and Kivelson's model[13] of resonant tunneling from one edge state to another through magnetically bound states as a mechanism for the breakdown of dissipationless transport. An extension of this model to the FQHE[17] predicts fluctuation behavior similar to that for integral ν, but with the crucial difference that the period of fluctuations for quasiparticles of charge $e^* = e/q$ scales as q. Understood with this model, our data provide direct evidence that the charge of quasiparticles of the $\nu = \frac{1}{3}$ state is $e^* = e/3$.

The experiment was performed on a GaAs/$Al_xGa_{1-x}As$ heterostructure of density $n_{2D} = 1.2 \times 10^{11}$ cm^{-2} and mobility 1.4×10^6 cm^2/Vs at 4.2 K. Two Hall bars connected in series were defined using standard photolithography. One 300-μm-wide Hall bar serves to monitor the sample's 2D density, mobility, and homogeneity during cooldown and illumination with a red

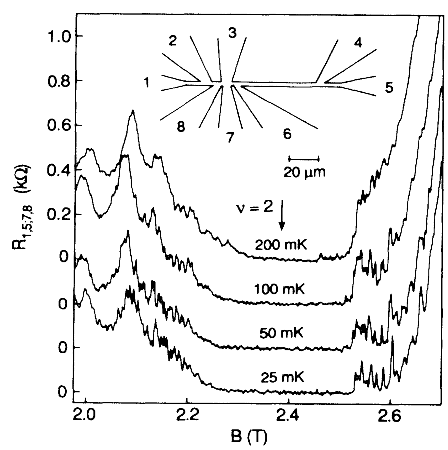

FIG. 1. $R_{1,5;7,8}$ near $\nu = 2$ for four different temperatures. Inset: Sample geometry and probe assignment.

light-emitting diode; the other, ~2 μm wide (Fig. 1, inset), is the device of experimental interest. (We expect that the conducting width is substantially less, as side-wall depletion lengths of up to 0.8 μm were previously observed.[18]) The center-to-center spacing is 6.5 μm for probe pairs 6,7 and 7,8; 13 μm for 2,3; and 65 μm for 3,4. The diagonal resistance R_{xx} is measured using probe pair 1,5 to supply current and pair 7,8 to measure voltage (using notation $R_{1,5;7,8}$) unless otherwise noted. R_{xy} is always measured as $R_{1,5;3,7}$. The sample was placed in a top-loading dilution refrigerator and cooled and illuminated several times until in a condition of good homogeneity, as determined by the quality of the IQHE and FQHE. (FQHE states $\frac{1}{3}$, $\frac{2}{5}$, $\frac{2}{3}$, $\frac{4}{3}$, and $\frac{5}{3}$ exhibited strong minima in R_{xx} and plateaus in R_{xy}, though only the $\frac{1}{3}$ minimum was nearly zero over a broad B range.) Measurements were performed using an ac lock-in technique at 17 Hz over 25–200 mK. Excitation voltages were typically 0.01–1 μV.

In Fig. 1 we show R_{xx} near the $\nu=2$ minimum for four different temperatures. We note several points: (1) High-frequency fluctuations of period ~0.016 T are apparent on the shoulders of the minimum; (2) further from the minimum, the fluctuations shift to a period of 0.05–0.10 T; and (3) the fluctuations drop to below our resolution for a broad B range in the center of the minimum, where R_{xx} goes to zero. As T is raised, (4) the low-frequency resistance peaks remain relatively unchanged, while the high-frequency peaks diminish rapidly, having almost disappeared at $T=200$ mK; (5) the field range over which the high-frequency fluctuations are present steadily decreases; and (6) as the width of the minimum decreases, new resistance peaks develop, growing out of the $R_{xx}=0$ background, near $B=2.3$ and 2.5 T.

The general behavior described above in points (1)–(6) for $\nu=2$ is also observed near the R_{xx} minima for other integral ν. In Figs. 2(a) and 2(b) we show R_{xx} near the high-field side of $\nu=1$ and 2 at 25 mK. The Fourier power spectrum of the fluctuation region for $\nu=1$ gives a dominant frequency of ~70 T^{-1}, corresponding to a period of ~0.014 T, while for $\nu=2$ the dominant frequency is ~60 T^{-1}, corresponding to a period of ~0.016 T. Because of the limited number of fluctuations and rapidly changing background, this determination has an uncertainty of ±25%. Resistance fluctuations are also observed in the $\nu=3,4$ minima, but so few are present that their Fourier spectra do not show distinct peaks. Nevertheless, the quasiperiod is the same as for $\nu=1$ and 2 within ~30%.

In Fig. 2(c) we show R_{xx} near the high-B side of $\nu=\frac{1}{3}$ at 25 and 100 mK. Again, high-frequency fluctuations are present near the minimum, and no fluctuations are present for a broad B range in the center. The fluctuations closest to the minima become larger at $T=100$ mK, growing out of the background of the R_{xx} minimum. The overall T behavior of the fluctuations is qualitatively similar to that observed for $\nu=2$. Here, however, the period is 0.05 T ± 25%.

After cycling the sample to 300 K and back to 25 mK we measured R_{xx} for several different current and voltage probe combinations. (The n_{2D} decreased by ~10%.) For $R_{1,5;7,8}$ the particular pattern of fluctuations changed, but the periods for each respective minimum remained the same. In Fig. 3 we show the $\nu=\frac{1}{3}$ data for $R_{1,5;7,8}$ after T cycling, at three different current levels. The period is again ~0.05 T. The differences between the curves are due to current heating; when the current is reduced below 0.3 nA, no further changes occur. The behavior of the fluctuations for all ν is again well described by points (1)–(6) above, except

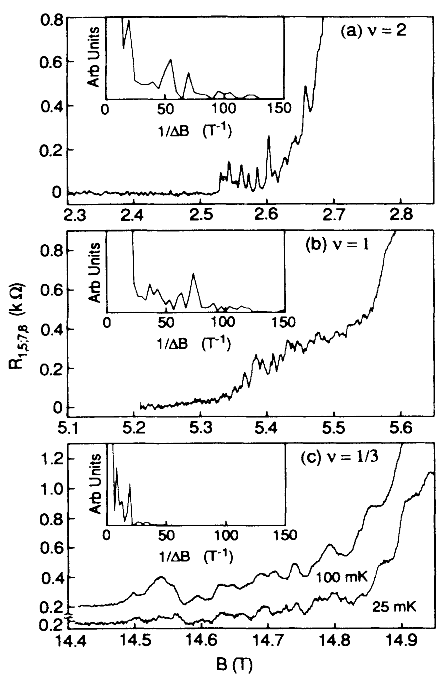

FIG. 2. $R_{1,5;7,8}$ near the high-B sides of R_{xx} minima for (a) $\nu=2$ at 25 mK, (b) $\nu=1$ at 25 mK, and (c) $\nu=\frac{1}{3}$ at 25 and 100 mK, all plotted with the same field scale. Insets: Fourier power spectra of the fluctuation regions for each ν.

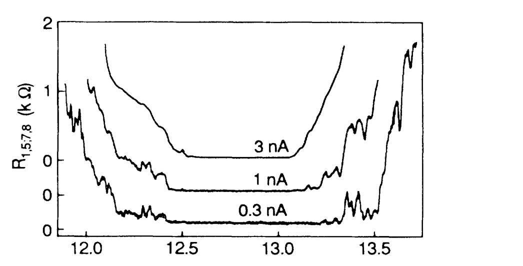

FIG. 3. $R_{1,5;7,8}$ near $\nu=\frac{1}{3}$ at 25 mK for three different currents. Changes are due to current heating.

for the factor of ~3 difference in period for $\nu=\frac{1}{3}$. For other probe combinations the resistance fluctuations near R_{xx} minima are similar to those in $R_{1,5;7,8}$: Those near $\nu=1$, 2, 3, and 4 have a period of 0.016 T ± 30%, while those near $\nu=\frac{1}{3}$ have a period of 0.05 T ± 30%. Thus for four different pairs of voltage probes, irrespective of the choice of current leads, and irrespective of T cycling for the one pair measured over two T cycles, *the period of high-frequency fluctuations in the integral does not depend on B or ν, while for ν = ⅓ we find an approximate tripling of the period.* These data are summarized in Fig. 4.

The typical amplitudes of the fluctuations are ~25 Ω near $\nu=3,4$; ~100–200 Ω near $\nu=2$; ~50 Ω near $\nu=1$; and ~100–200 Ω near $\nu=\frac{1}{3}$. Only on one T cycling were fluctuations observed above our resolution near the plateaus in R_{xy} and then only for the low-B sides of $\nu=1$, 2, and $\frac{2}{3}$. For $\nu=1,2$ the amplitude is ~100 Ω and the period is ~0.017 T, while for $\nu=\frac{2}{3}$ the amplitude is ~500 Ω and the period is ~0.045 T, a factor of ~3 larger.

Our data in the IQHE regime are in agreement with the resonant tunneling model of resistance fluctuations of Jain and Kivelson[13] and Büttiker.[14] In the high-B-field limit, when the characteristic length of potential fluctuations in the 2D system is much larger than the magnetic length, the electron state can be treated semiclassically. The guiding centers of the 2D electrons, in the absence of scattering, move along the equipotential contours. In a sufficiently narrow sample, the current is the difference between the edge currents along the two edges of the sample, and R_{xx} is given by a Landauer-type formula $R_{xx}=[R/(1-R)]h/e^2$, where R is the probability that an electron will be scattered from one edge to the opposite edge. R is vanishingly small except when electrons can resonantly tunnel via a magnetically bound state encircling a defect potential in the Landau level (see Fig. 4, inset). Such bound states are only allowed when they meet the Bohr-Sommerfeld quantization criterion that an integral number of flux quanta $\Phi_0=h/e$ penetrate their area. Tunneling occurs when the energy of a bound state coincides with the chemical potential μ_c of the sample edge. Thus R, and hence R_{xx}, will exhibit sharp peaks as a function of μ_c. In the experiment, the bound-state energy is varied by sweeping B and peaks are observed in R_{xx}. The separation ΔB of such peaks is found by solving[19]

$$\frac{h}{e}=\Delta B\,\frac{d(B\pi r^2)}{dB}=\Delta B\left[\pi r^2+2\pi rB\left(\frac{\partial r}{\partial \nu}\right)_{\mu_c}\frac{d\nu}{dB}\right],$$

where r is the radius of the (assumed circular) bound state. Assuming that μ_c is constant,

$$(\partial r/\partial \nu)_{\mu_c}=\hbar\omega_c/eE_r=\hbar B/m^*E_r(\mu_c),$$

where $\hbar\omega_c$ is the Landau-level energy spacing and $E_r(\mu_c)$ is the radial electric field at the bound state. We then have

$$\Delta B=\frac{h}{e}\left(\pi r^2+\frac{rh^2 n_{2\mathrm{D}}}{m^*eE_r(\mu_c)}\right)^{-1}. \tag{1}$$

Hence ΔB will be the same for all integral-filling-factor R_{xx} minima. Davies and Nixon[20] have recently calculated the effect of the random placement of impurities in the doped layer of a heterojunction. They find potential fluctuations with a length scale of a few tenths of a micron, and local electric fields of a few times 10^5 V/m. Using a value $E_r=10^5$ V/m and $\Delta B\simeq 0.016$ T in Eq. (1), we obtain $r\simeq 0.4$ μm and an energy spacing at $B=2.4$ T of $hE_r/k_B 2\pi rB\simeq 800$ mK, of the same order as the ~200 mK at which the fluctuations near $\nu=2$ decrease appreciably.

The actual potential in our sample is expected to have many noncircular potential hills and valleys. Because $E_r(\mu_c)$ will vary dramatically with B, the resistance fluctuations will deviate from strict periodicity. Different potential hills may be active for different ν. Yet, because the tunneling probability is exponentially dependent on the distance between the edge states and the bound states, at any given integer ν one such bound state whose diameter is close to the width of the channel should dominate.

The half-width Γ of the resistance peaks in this model is expected to be strongly dependent on their position relative to the center of the R_{xx} minima.[13] Peaks near the center will be extremely sharp, while peaks farther from the center will be much broader. Any particular peak will begin to broaden and decrease in strength once kT

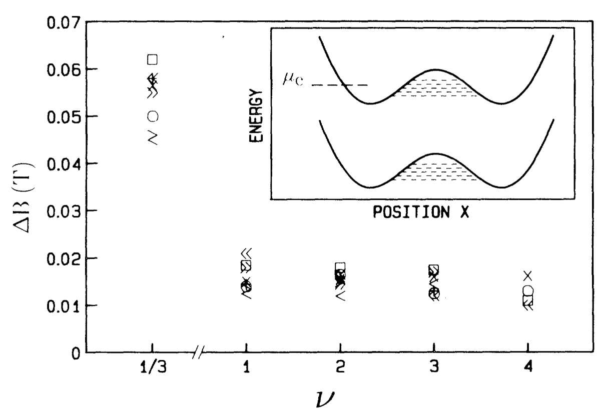

FIG. 4. Data on quasiperiods of resistance fluctuations on the high-B sides of R_{xx} minima for $\nu=1$, 2, 3, 4, and $\frac{1}{3}$: from first T cycle, $R_{1,5;7,8}$ (○); and from the second T cycle, $R_{1,5;7,8}$ (□), $R_{2,5;7,8}$ (≫), $R_{1,5;6,7}$ (×), $R_{2,5;6,7}$ (+) $R_{1,5;3,4}$ (>), $R_{2,5;3,4}$ (<), and $R_{1,5;2,3}$ (≪). Uncertainties are all ~25%. Points for $\nu=\frac{1}{3}$, 1, and 2 represent Fourier power spectra; $\nu=3$ and 4 are estimates by eye. Inset: Landau levels in a narrow sample with a potential hill. Dashed lines show magnetically bound states.

becomes comparable with its Γ. Thus there will be temperatures for which all peaks near the center of the minima are destroyed, while peaks far from the center are still undiminished, qualitatively consistent with the behavior of our sample.

In the FQHE case, the ground state can carry current with no dissipation and, consequently, R_{xx} must result from transport of the fractionally charged quasiparticles. To date, no theory exists on transport of the quasiparticles. However, if the length scale of the potential fluctuations is much longer than the spatial extent of the quasiparticle (roughly the magnetic length), and it is assumed that the quasiparticle density is sufficiently dilute, one can, following Kivelson and Pokrovsky, regard the quasiparticles as independent point particles of charge $e^* = e/q$. The argument made by Jain and Kivelson for electrons in the IQHE can also be made for quasiparticles in the FQHE, with only the substitution of e^* for e. The results remain the same, except that the flux quantum in the Bohr-Sommerfeld quantization condition is $\Phi_0^* = h/e^*$. Thus for $\nu = \frac{1}{3}$ we expect the period of the resistance fluctuations to be 3 times that seen for $\nu = 1$, 2, 3, and 4.

In summary, we have observed resistance fluctuations in an AlGaAs/GaAs mesostructure. The period remains roughly the same for integer ν, and corresponds to a magnetically bound state of a diameter commensurate with the width of the channel, in good agreement with Jain and Kivelson's model of the breakdown of dissipationless transport in the IQHE due to tunneling through bound states. Fluctuations of similar character are also observed near $\nu = \frac{1}{3}$, but with a period 3 times larger, in agreement with an extension of the model to the FQHE. Together, the data provide direct evidence for a quasiparticle charge of $e^* = e/3$ in the $\nu = \frac{1}{3}$ FQHE.

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