

Observation of the $e/3$ Fractionally Charged Laughlin Quasiparticle

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(Received 30 June 1997)

The existence of fractional charges carrying current is experimentally demonstrated. Using a 2D electron system in a high perpendicular magnetic field we measure the shot noise associated with tunneling in the fractional quantum Hall regime at Landau level filling factor $1/3$. The noise gives a direct determination of the quasiparticle charge, which is found to be $e^* = e/3$ as predicted by Laughlin. The existence of $e/3$ Laughlin quasiparticles is unambiguously confirmed by the shot noise to Johnson-Nyquist noise crossover found for temperature $\Theta = e^*V_{ds}/2k_B$. [S0031-9007(97)04194-X]

PACS numbers: 73.40.Hm, 05.30.Fk, 71.27.+a, 72.70.+m

Can fractional charges carry the current in a conductor? Up to now, there was no evidence of such phenomenon. Usual metals are known to form Fermi liquids with quasiparticles of charge e . Low-dimensional systems are believed to offer a richer spectrum of excitations. Indeed, fractional charges have been predicted for commensurate charge density waves in one-dimensional systems [1], and for two-dimensional electrons systems (2DES) [2] in high perpendicular magnetic field when the fractional quantum Hall effect occurs [3]. In this Letter, we report experimental evidence of charges $e/3$ carrying the current. The observation is done in the fractional quantum Hall (FQH) regime at Landau level filling factor $\nu = 1/3$. 2D electrons in high magnetic field give rise to degenerate Landau levels (LL) with one state per flux quantum $\phi_0 = h/e$ in the plane. For integer LL filling factor $\nu = n_s/n_\phi$, the cyclotron or the enhanced Zeeman gap gives rise to the integer quantum Hall effect [4] IQHE (n_s and $n_\phi = eB/h$ are the electron and quantum flux density) [5]. The simplest elementary excitation is an electron removed from the highest occupied LL, leaving a hole having the size of a flux quantum and a unit charge e . At fractional filling factor $\nu = 1/q$, q odd, a gap $\Delta \approx e^2/\epsilon l_c$ also opens resulting from the interactions [6] [$l_c = (\hbar/eB)^{1/2}$]. This is the FQH effect. Laughlin has proposed [2] that an elementary excitation can be realized by introducing a flux quantum ϕ_0 in the collective wave function. As there is one electron for q flux quanta, the so-called Laughlin quasiparticle has fractional charge $e^* = e/q$. Extensions of the Laughlin approach to higher rational fractions $\nu = p/q$ [7] explain many bulk transport properties, but so far no direct experimental evidence for the bulk Laughlin quasiparticles has been found. The quasiparticles in the bulk have been mostly probed using thermal activation. The prefactor of the activated conductivity has shown a striking [8] relation to the quasiparticle charge but is not fully understood [9]. Comparison of the chemical potential jump at fractional ν obtained from capacitance measurements with the

activation energy may also determine e^* but is not straightforward [10]. An alternative way to determine e^* uses the edge rather than the bulk quasiparticle properties. At the edge, the Landau levels bent by the confining potential cross the Fermi level and form edge channels. The gapless modes at the Fermi energy, the edge states, provide the dominant conduction in low disorder samples [11]. For integer ν the edge channels are chiral Fermi liquids with quasiparticles of charge e . For $\nu = p/q$, fractional edge channels similarly form. They are chiral Luttinger liquids [12,13] with fractionally charged quasiparticles generalizing the bulk Laughlin quasiparticles. Attempts to measure e^* have used the Aharonov-Bohm period of the conductance [14–16]. In a recent beautiful experiment using an antidot at $\nu = 1/3$ [15], the period of the polarization charge on the control back gate was found accurately $e/3 = e^*$. In a similar report, it has been argued that *equilibrium* conductance measurements mostly probe the fractional filling of the ground state [16]. An experiment specifically sensitive to the charge carrying the current was thus needed.

The following experiment is based on a *nonequilibrium* property, the shot noise, which probes the granularity of the quasiparticles carrying the current. According to Schottky [17], a Poissonian uncorrelated flow of carriers generates current fluctuations. The noise power S_I is directly proportional to the carrier charge. A quasiparticle tunneling through the $\nu = 1/3$ quantum Hall fluid is expected for weak coupling between opposite $1/3$ edge channels. Indeed, the tunneling density of states of quasiparticles diverges at the Fermi energy while that of electron vanishes [12]. The tunneling, or backscattering, current is $I_B = (e^2/3h)V_{ds} - I$. V_{ds} is the voltage difference between ideal contacts connecting the edges, I the total current. At temperature $\Theta = 0$ and for weak coupling $I_B \ll I$, the Schottky formula gives [18–20]:

$$S_I = 2(e/3)I_B. \quad (1)$$

The noise is thus a direct measure of $e^* = e/3$. If

instead electrons were to tunnel the noise power would be $2eI_B$. When the quasiparticle chemical potential difference $(e/3)V_{ds}$ becomes smaller than the temperature a crossover to Johnson-Nyquist noise is expected [18,21] ($I_B \ll I$):

$$S_I = 2 \left[(e/3)I_B \coth\left(\frac{e^*V_{ds}}{2k_B\Theta}\right) - 2k_B\Theta \frac{dI_B}{dV_{ds}} \right] + 4k_B\Theta \frac{dI}{dV_{ds}}. \quad (2)$$

The characteristic voltage is 3 times that expected for electrons. The second part of the right hand side identifies to the Johnson-Nyquist noise at zero bias. Note the differential conductance in the expression. For non-Fermi liquids $I_B(V_{ds})$ is always nonlinear [12]. Expressions for dI/dV_{ds} and S_I for the ideal case of a single tunneling impurity are given in Refs. [12,19,22]. In real samples with smooth edges and where tunneling is induced by the smooth potential of a quantum point contact (QPC) deviations from the calculable ideal case may be expected but the general predicted features remain. We emphasize that the exact edge state dynamics (the way I_B varies with V_{ds}) is less essential here as *in the weak backscattering limit the noise must be given by Eq. (1)*.

In this limit, the shot noise measurements reported here agree with Eq. (1), bringing evidence that $e/3$ charge quanta do carry the current at $\nu = 1/3$. Our observation also confirms the Johnson-Nyquist to shot noise crossover given by Eq. (2). The samples are GaAs/Ga(Al)As heterojunctions with low density $n_s = 0.94 \times 10^{15} \text{ m}^{-2}$ high mobility $100 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ 100 nm deep 2DES. Six wide Ohmic contacts with increased perimeter length provide ideal contacts in the fractional regime. Using electron beam lithography technique metallic gates are evaporated at the center of the wide Hall bar mesa to define 275 nm wide QPC. The QPC locally creates a ($\approx 150\phi_0$) wide $\nu = 1/3$ region upon applying a negative voltage on both gates while keeping a constant filling factor $\nu_L = 2/3$ in the mesa; see Fig. 1(a). The $1/3$ state is signaled by a $e^2/3h$ conductance plateau when sweeping the gate voltage. A quasiparticle tunneling through the $1/3$ state is induced upon applying slightly more negative voltage. The saddle shape QPC potential combines with the weak random potential to give few tunneling paths whose interference leads to conductance oscillations at the end of the $1/3$ plateau. Using the independent control of the gates we can *laterally shift the constriction* to tune the tunnel coupling of a particular conductance peak. Each peak is found to reach a maximum value remarkably equal to $e^2/3h$; see Fig. 1(b). This observation tells us that *tunneling is coherent* and that a $1/3$ FQHE state is still *formed* for this gate voltage range. This is an important check without which the following noise results would have been questionable [23]. Finally, looking at the differential conductance we see that the overall conduction is restored at finite dc bias voltage V_{ds} , in qualitative agree-

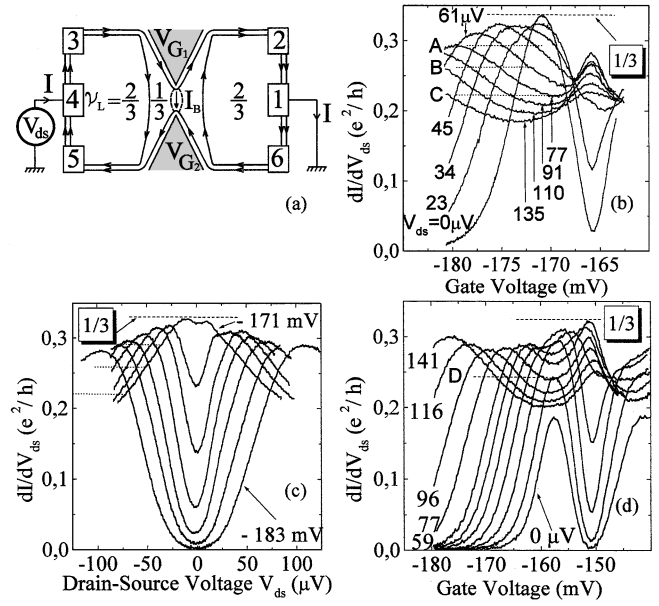


FIG. 1. (a) Schematic picture of the Hall sample. (b) Differential conductance versus gate voltage for different bias V_{ds} for a tuned resonance at $\nu = 1/3$. (c) dI/dV_{ds} versus V_{ds} for different gate voltages (2 mV steps) describing the left wing of the tuned resonance. (d) Untuned resonance: dI/dV_{ds} versus gate voltage for different V_{ds} (10 μV steps from 0 to 59 μV). All data are taken at 25 mK.

ment with chiral Luttinger models. Figure 1(c) shows the dI/dV_{ds} characteristics for a series of gate voltages describing the left wing of the resonance of Fig. 1(b).

The global features, similarly observed in many samples, are consistent with a singular density of state, being a decreasing function of the energy with respect to the Fermi surface as expected for quasiparticle tunneling [12]. We are thus in the good regime to detect $e/3$ charges; a detailed analysis of the nonlinear transport will be given elsewhere. For the following noise measurements we only need to know I_B and keep $I_B \ll I$.

Noise measurements use the correlation method described in [24,25] for the observation of the Pauli suppression of fermion shot noise, but here the sample is voltage biased; see Fig. 1(a). The voltages $V_{5,6}$ and $V_{3,2}$ are separately measured by two ultra low noise amplifiers and a spectrum analyzer calculates the cross-correlation spectrum. This technique removes from the detected signal the uncorrelated amplifiers voltage noise and the noise of the leads and contacts. The cross-correlation spectrum $S_{V_{5,6}V_{3,2}}$ contains the physical shot noise contribution S_I plus some white noise sources of the circuit $S_{V_{4,1}}$, S_{I_3} , and S_{I_6} : $S_{V_{5,6}V_{3,2}} = R_H^2 S_I + (1 - R_H dI/dV_{ds})^2 [S_{V_{4,1}} + R_H^2 (S_{I_3} + S_{I_6})]$, where $R_H = 3h/2e^2$ is the quantized Hall resistance of the mesa. The circuit noise sources require one to keep dI/dV_{ds} constant to reliably extract S_I . This is done with a 0.2% accuracy for each series of noise measurements. The amplifier gains known to 0.5% allows for accurate determination of S_I .

Finally, Johnson-Nyquist noise measurements for different temperatures at fixed conductance *in the fractional regime* provide an *absolute* calibration as in [24].

The results of a series of current noise power measurements versus backscattering current I_B at $\Theta = 25$ mK is shown in Fig. 2. The noise measured in the 4–8 KHz frequency range is white. The background noise $\approx 5.32 \times 10^{-28}$ A²/Hz is due to the circuit noise. The error bars represent the statistical accuracy expected for 1500 s acquisition time. I_B can be varied by changing either the dc bias V_{ds} or the tunnel coupling with gate voltage. In order to keep $dI/dV_{ds} = G_{diff}$ constant and follow the path A shown in Figs. 1(b) and 1(c) both the bias (40 to 78 μ V) and the gate voltage (-170.5 to -178.5 mV) are varied. The backscattering current is obtained within 5% accuracy by measuring the dc voltage $V_B = V_{3,2}$ or $V_{5,6}$ across the QPC, using $I_B = (2V_B - V_{ds})e^2/3h$. The “reflexion coefficient” $R = I_B 3h/e^2 V_{ds}$ is kept small for weak backscattering. It increases with I_B from 4% to 35%. The linear variation of the noise with I_B tells us that we do observe shot noise associated with backscattering. We can compare the rate of noise variation with that given by Eq. (1) (dashed line). *The agreement with the prediction of Laughlin quasiparticle tunneling is excellent.* Electron tunneling would have given a very different result (dotted line). Electron shot noise is found for similar conductance $G = 0.32e^2/h$ at a lower field in the integer quantum Hall regime ($\nu_L = 4$ in the leads), inset

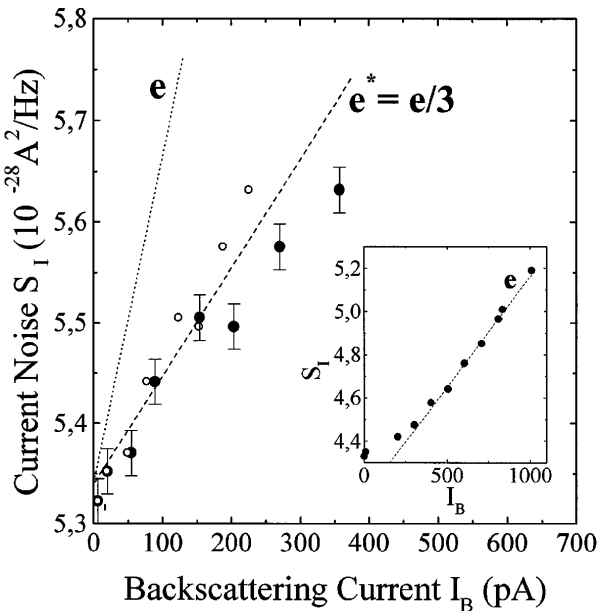


FIG. 2. Tunneling noise at $\nu = 1/3$ ($\nu_L = 2/3$) when following path A and plotted versus $I_B = (e^2/3h)V_{ds} - I$ (filled circles) and $I_B(1 - R)$ (open circles). The slopes for $e/3$ quasiparticles (dashed line) and electrons (dotted line) are shown. $\Theta = 25$ mK. Inset: data in same units showing electron tunneling for similar $G = 0.32e^2/h$ but in the IQHE regime ($\nu_L = 4$). The expected slope for electrons $2eI_B(1 - R)$ [$R = 0.68$, $I_B = (e^2/h)V_{ds} - I$] is shown. $\Theta = 42$ mK.

of Fig. 2. The data agree with the electron theory for a lowest Landau level transmission 0.32 [26].

How is this remarkable result robust against parameter changes? Figure 3(a) shows the current noise versus I_B for two different G_{diff} (path B and C). The noise also compares well with that expected for $e/3$ charges except for the points at high bias where the backscattering is no longer weak and less noise is found. A good agreement is also found for a different tunneling regime obtained by detuning a resonance [Fig. 1(d), path D: $V_{ds} = 78$ to 175 μ V and gate voltage -161 to -177 mV]. The result is also robust against temperature change as shown by the series E corresponding to the tunneling conditions of Fig. 1(b) but at $\Theta = 150$ mK. Finally, room temperature thermal cycling changes the resonance shape but not the noise results.

How to take into account the deviations for large R ? As long as electron tunneling does not start to compete with quasiparticle tunneling, we may expect a decrease of noise when R increases. Indeed, the tunneling events are no longer Poissonian as the exclusion statistics and the interactions correlate the quasiparticles. If they were fermions a noise reduction $(1 - R)$ would occur [24,26,27]. It is not legitimate [21], but nevertheless tempting to plot the noise data as a function of $I_B(1 - R)$ (open circles of Figs. 2 and 3). Within experimental accuracy, the simple $(1 - R)$ reduction factor accounts well for the data but slightly overestimates e^* . The least squares linear fit gives $e^* = 0.38$, 0.36, 0.35, and 0.36 for A, B, C, and D.

The final check to confirm our observation of $e/3$ Laughlin quasiparticles is the crossover from Johnson-Nyquist to shot noise at $e^*V_{ds}/2 = k_B\Theta$. Figure 4 shows measurements at $\Theta = 134$ mK and low bias. Here, the bias voltage V_{ds} varies from 13 to 140 μ V and $G_{diff} = 0.26e^2/h$. The nearly linear noise variation at high bias, consistent with Eq. (1), saturates at low bias. The arrow, indicating when $e^*V_{ds} = 2k_B\Theta$, is well in the crossover region. Comparison with Eq. (2) (solid curves) shows

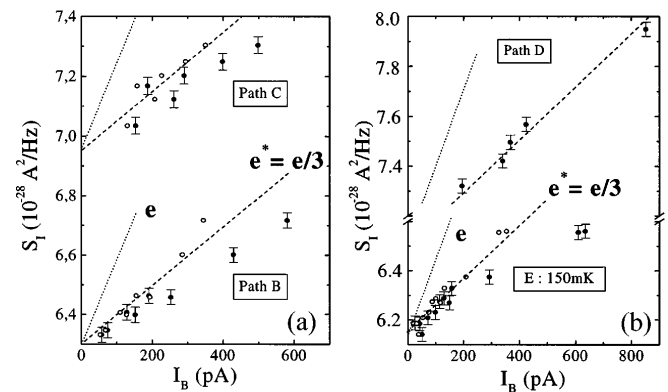


FIG. 3. Filled circles: Shot noise measured at 25 mK versus I_B corresponding to the paths B, C, and D of Fig. 1, and to a series of measurements (E) at 150 mK. Open circles: same data versus $I_B(1 - R)$.

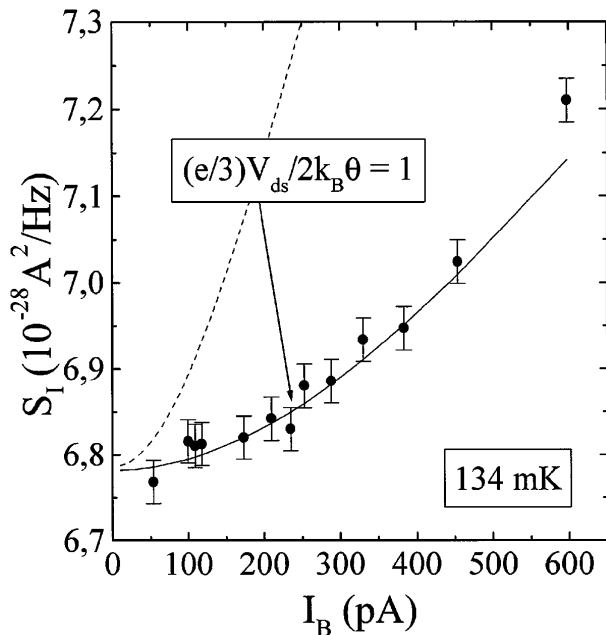


FIG. 4. Crossover from Johnson-Nyquist to shot noise. The arrow indicates the data for which $e^*V_{ds} = 2k_B\Theta$. A comparison with Eq. (2) (solid curve) and a similar expression for electrons (dotted curve) is shown.

a remarkable agreement [the experimental variation of $V_{ds}(I_B)$ is used]. The dashed curve describing the thermal crossover for charge e does not fit the data.

In conclusion, using shot noise, we have brought evidence of $e/3$ Laughlin quasiparticles carrying the current through the $1/3$ FQH state. The result is robust against various tunneling and temperature conditions and the Johnson-Nyquist to shot noise crossover confirms the nature of the quasiparticles. At larger backscattering a noise reduction factor similar to that expected for fermions accounts for the observation but slightly overestimates the noise. After submission of this work, we became aware of a similar observation by another group [28].

We warmly thank A. Kumar for participating at the early stage of the experiment and P. Jacques for his precious technical contribution. Useful discussions with Th. Martin, H. Saleur, I. Safi, M. Büttiker, C. de C. Chamon, M. H. Devoret, and V. Pasquier are acknowledged.

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