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Direct observation of a fractional charge

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Since Millikan's famous oil-drop experiments[1], it has been well known that electrical charge is quantized in units of the charge of an electron, *e*. For this reason, the theoretical prediction[2,3] by Laughlin of the existence of fractionally charged 'quasiparticles'—proposed as an explanation for the fractional quantum Hall (FQH) effect—is very counterintuitive. The FQH effect is a phenomenon observed in the conduction properties of a two-dimensional electron gas subjected to a strong perpendicular magnetic field. This effect results from the strong interaction between electrons, brought about by the magnetic field, giving rise to the aforementioned fractionally charged quasiparticles which carry the current. Here we report the direct observation of these counterintuitive entities by using measurements of quantum shot noise. Quantum shot noise results from the discreteness of the current-carrying charges and so is proportional to both the charge of the quasiparticles and the average current. Our measurements of quantum shot noise show unambiguously that current in a two-dimensional electron gas in the FQH regime is carried by fractional charges—*e*/3 in the present case—in agreement with Laughlin's prediction.

The energy spectrum of a two-dimensional electron gas (2DEG) subjected to a strong perpendicular magnetic field, *B*, consists of highly degenerate Landau levels with a degeneracy per unit area $p = B/\phi_0$, with $\phi_0 = h/e$ the flux quantum (*h* being Plank's constant). Whenever the magnetic field is such that an integer number ν (the filling factor) of Landau levels are occupied, that is $\nu = n_s/p$ equals an integer (n_s being the 2DEG areal density), the longitudinal conductivity of the 2DEG vanishes whereas the Hall conductivity equals $\nu e^2/h$ with very high accuracy. This phenomenon is known as the integer quantum Hall (IQH) effect[4]. A similar phenomenon occurs at fractional filling factors, namely when the filling factor equals a rational fraction with an odd denominator *q* and is known as the fractional quantum Hall (FQH) effect[5]. In contrast to the IQH effect, which is well understood in terms of non-interacting electrons, the FQH effect cannot be explained in such terms and is believed to result from interactions between the electrons, brought about by the strong magnetic field.

Laughlin[2,3] had argued that the conduction properties, observed in the FQH effect, could be explained in terms of quasiparticles with a fractional charge, $Q = e/q$. Several experiments attempted to observe the fractional charge directly; the early Aharonov-Bohm measurements[6] were proved to be in principle inadequate to reveal the fractional charge[7,8]. More recently, in an experiment based on resonant tunnelling, Goldman and Su[9] claimed to have measured the fractional charge. However, in a similar experiment, Franklin *et al.*[10] interpreted the results differently. The difficulty in such experiments is that the results do not provide the charge of individual particles unless Coulomb blockade arguments are invoked. Quantum shot noise, on the other hand, probes the temporal behaviour of the current and thus offers a direct way to measure the charge. Indeed, in 1987 Tsui[11] suggested that the quasiparticle's charge could in principle be determined by measuring quantum shot noise in the FQH regime. However, no theory was available until Wen[12] recognized that transport in the FQH regime could be treated within a framework of one-dimensional interacting electrons, propagating along the edge of the two-dimensional plane, making use of the so-called Luttinger liquid model. Based on this model, subsequent theoretical works[13–15] predicted that quantum shot noise, S_i, generated by weak backscattering of the current, at fractional filling factors $\nu = 1/q$ and at zero temperature, should be

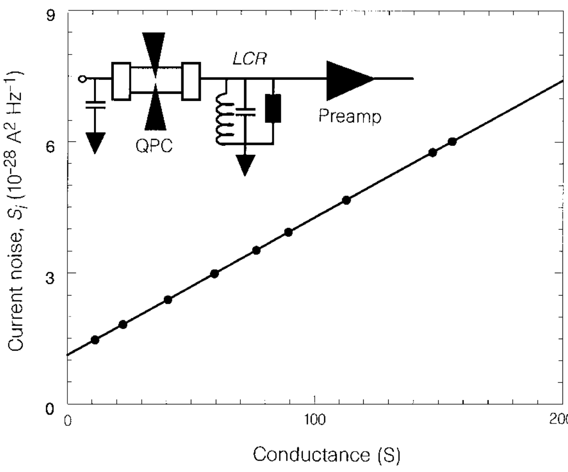

Figure 1 The total current noise inferred to the input of the preamplifier as a function of the input conductance at equilibrium (circles). The measured noise is a sum of thermal noise, $4K_BTG$ (leading to a straight line) and the constant noise of the amplifier. This measurement allows the determination of both the temperature of the 2DEG as 57 mK and the amplifier's current noise as $S_i(G = 0) = 1.1 \times 10^{-28}$ A^2 H_3^{-1}. Inset, the QPC embedded in the two-dimensional electron gas is shown to be connected to an *LCR* circuit at the input of a cryogenic preamplifier.

proportional to the quasiparticle's charge $Q = e/q$ and to the backscattered current I_B:

$$S_i = 2QI_B \tag{1}$$

To realize such a measurement we utilized a quantum point contact (QPC)—a constriction in the plane of a 2DEG—that partly reflects the current. The high-quality 2DEG, embedded in a GaAs–AlGaAs heterostructure, ~100 nm beneath the surface, has a carrier density, n_s, of $10^{11}\,\text{cm}^{-2}$ and a mobility, μ, of $4.2 \times 10^6\,\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$ at 1.5 K in the dark. The QPC is formed by two metallic gates evaporated on the surface of the structure, separated by an opening of ~300 nm that is a few Fermi wavelengths wide (see inset to Fig. 1). By applying negative voltage to the gates with respect to the 2DEG, thus imposing a local repulsive potential in the plane of the 2DEG, one can controllably reflect the incoming current. The sample was inserted into a dilution refrigerator with a base temperature of ~50 mK. Noise measurements were made by employing an extremely low-noise home-made preamplifier, placed in a 4.2 K reservoir. The preamplifier was manufactured from GaAs transistors, grown in our molecular beam epitaxy system. The preamplifier has a voltage noise as low as $2.5 \times 10^{-19}\,\text{V}^2\,\text{Hz}^{-1}$ and a current noise of $1.1 \times 10^{-28}\,\text{A}^2\,\text{Hz}^{-1}$ at 4 MHz.

Current fluctuations, generated in the QPC, were fed into an inductance–capacitance–resistance (*LCR*) resonant circuit, with most of the capacitance contributed by the coaxial cable which connects the sample at 50 mK to the preamplifier at 4.2 K. Outside the cryostat the amplified signal was fed into an additional amplifier and from there to a spectrum analyser which measured the current fluctuations within a band of ~100 kHz about a central frequency of ~4 MHz. As the absolute magnitude of the noise signal is of utmost importance, a careful calibration of the total gain from the QPC to the spectrum analyser was done by utilizing a calibrated current noise source. This allows the translation of the spectrum analyser output into a spectral density of current fluctuations (current noise). Although our amplifier has excellent characteristics it still introduces current fluctuations into the circuit. This unwanted current noise must be subtracted from the total measured noise to extract the noise associated solely with the QPC. By measuring the total current noise while varying the conductance, G, of the unbiased sample (see Fig. 1), we deduce both the electron temperature, $T = (\delta S_i/\delta G)/4k_B$ (where k_B is the Boltzmann constant), and the contribution of our amplifier to the total noise (extracted from the extrapolated total noise to zero conductance). Note that the temperature we find, 57 mK, is very close to that of the sample holder.

As the temperature, T, and the applied voltage, V, across the QPC during our measurement are both finite, the results must be compared with a more elaborate theory than that leading to equation (1). Such general calculations were indeed performed numerically[16]. An analytical general expression for the zero-frequency spectral density of the current fluctuations is available for a non-interacting single one-dimensional channel and is given by[17–19]:

$$S_i = 2g_0t(1-t)\left[QV\coth\left(\frac{QV}{2k_BT}\right) - 2k_BT\right] + 4k_BTg_0t \tag{2}$$

where the transmission of the QPC, t, is given by the ratio between the conductance, G, and the quantum conductance, $g_0 = e^2/h$. This dependence was verified experimentally[20,21] in the absence of a magnetic field where electron–electron interactions are believed to be non-crucial, with $Q = e$. The same expression, with $Q = e/3$ and $g_0 = e^2/3h$, also does not deviate significantly from the numerical calculations[16] in the limit of weak backscattering of quasiparticles in the FQH regime at $\nu = \frac{1}{3}$ and in addition reduces to equation (1) in the zero-temperature limit ($Vg_0t(1-t) = I_Bt \approx I_B$). Comparing our data with equation (2) will thus suffice to deduce the quasiparticles' charge.

Quantum shot noise measurements as a function of the current through a partly pinched QPC were performed first in the absence of a magnetic field. The results, after calibration and subtraction of amplifier noise, are shown in Fig. 2. The transmission of the lower-lying quasi-one-dimensional channel in the QPC is simply deduced from the measured conductance normalized by $2e^2/h$ (the factor 2 accounts for spin degeneracy). Our data fit almost perfectly the expected noise of equation (2) using the measured electron temperature without any fitting parameters.

The magnetic field was then swept from zero to 14 tesla. The two-terminal conductance exhibits Hall plateaux, expected in the IQH and in the FQH regimes ($\nu = \frac{2}{5}, \frac{3}{5}, \frac{2}{3}$ and $\frac{1}{3}$ are clearly visible with a plateau width of ~1 tesla around $\nu = \frac{1}{3}$). At $\nu = \frac{1}{3}$ and full

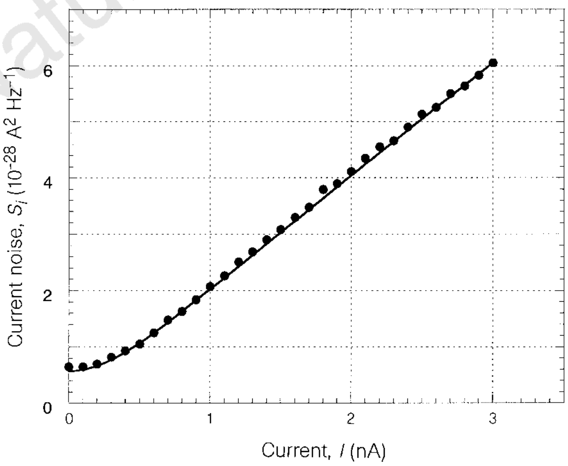

Figure 2 Quantum shot noise as a function of direct current, I, through the QPC without an applied magnetic field (circles). The solid line is equation (2) with the temperature (57 mK) deduced from Fig. 1. The transmission, t, is 0.37.

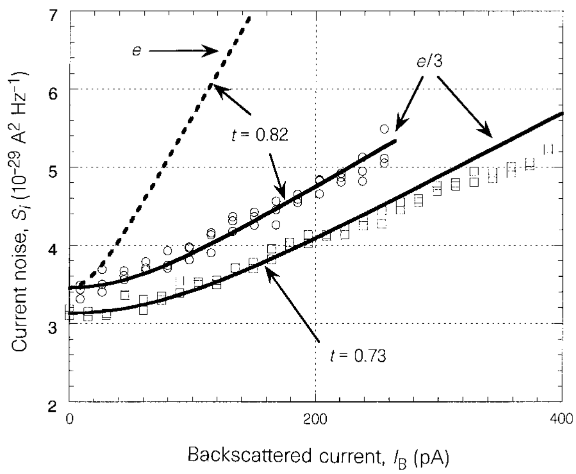

Figure 3 Quantum shot noise as a function of the backscattered current, I_B, in the FQH regime at $\nu = \frac{1}{3}$ for two different transmission coefficients through the QPC (circles and squares). The solid lines correspond to equation (2) with a charge $Q = e/3$ and the appropriate t. For comparison the expected behaviour of the noise for $Q = e$ and $t = 0.82$ is shown by the broken line.

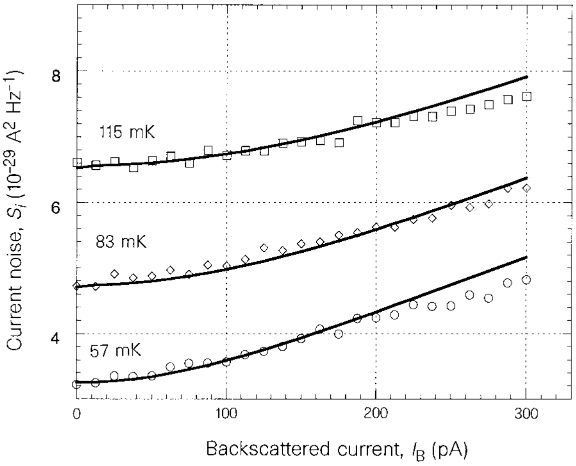

Figure 4 Quantum shot noise as a function of backscattered current, I_B, in the FQH regime at $\nu = \frac{1}{3}$, for three different temperatures and a constant transmission coefficient, $t = 0.8$, through the QPC.

transmission (zero gate voltage) no excess noise above the thermal noise is observed on driving a current through the sample, thus ruling out noise related to overheating. The noise measured on partly reflecting the current is drastically suppressed compared with the noise measured in the absence of a magnetic field as shown in Fig. 3.

Our data fit very well the expected noise of a current carried by quasiparticles of charge $Q = e/3$. The backscattered current is calculated using the transmission, t, deduced from the ratio of the conductance to $g_0 = e^2/3h$. The slope of the noise versus backscattered current curve increases with applied voltage approaching the expected slope of $2te/3$ at voltages larger than $2k_BT/Q$ as expected. For comparison, the expected noise for $Q = e$ and the same g_0 is also shown.

The noise tends to saturate at even larger backscattered currents (note the deviation of the data points from the solid line). This additional noise suppression is accompanied by an onset of nonlinearity in the I–V characteristics (not shown). The nonlinearity in the FQH regime may result from the interaction among the electrons, from an energy dependence of the bare transmission coefficient and from a finite excitation gap (a gap[11], $\Delta \approx 250\ \mu$eV, is expected at $\sim$13 T). These three sources are practically indistinguishable. Nonlinearity complicates the otherwise straightforward interpretation of our results and we thus choose to show data in a smaller voltage range and for moderate reflection coefficients where the I–V is linear.

To investigate further the behaviour of quantum shot noise in the FQH regime, we measured the noise against backscattered current for three different temperatures and a fixed transmission through the QPC (shown in Fig. 4). The data fit the curves expected from equation (2) with $Q = e/3$. Note that equation (2) with a charge $Q = e/3$ suggests not only that the amplitude of the noise is proportional to Q but also that shot noise is observed above the thermal noise at a characteristic voltage $V = 6k_BT/e$, threefold larger than the value for non-interacting electrons. This is because the potential energy of the quasiparticles is $eV/3$. The agreement between the data and the detailed shape of equation (2) at small backscattered currents thus gives an additional indication for the existence of a smaller charge $e/3$.

Our noise measurements show unambiguously that the current in the FQH regime, at filling factor $\frac{1}{3}$, is carried by quasiparticles with charge $e/3$. In contrast to conductance measurements, which measure an averaged charge over quantum states or over time, our quantum shot noise measurement is sensitive to the charge itself. The 'magic' of an apparent smaller charge due to electron–electron interactions is a beautiful manifestation of the strength of the theoretical methods[2,3] used to predict such counterintuitive behaviour.

During the writing of this manuscript we became aware of similar work[22] in which the authors measured the same charge at a filling factor $\frac{2}{3}$ in the bulk and $\frac{1}{3}$ near the constriction also using shot noise measurements. □

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Application of scanning SQUID petrology to high-pressure materials science

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High-pressure synthesis is increasingly being used in the search for new materials. This is particularly the case for superconductors[1], but the synthesis products are difficult to analyse because they are small in size ($\sim$50 mg) and often consist of a mixture of unknown phases exhibiting a low superconducting volume fraction. X-ray or electron diffraction cannot identify a superconductor unambiguously if it is a minority constituent. Here we report a methodology—'scanning SQUID petrology'—that