Scattering of Bunched Fractionally Charged Quasiparticles

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We report the unexpected *bunching* of Laughlin's quasiparticles, induced by an extremely weak backscattering potential at exceptionally low electron temperatures ($T < 10$ mK), deduced from shot noise measurements. Backscattered charges $q = \nu e$, specifically, $q = e/3$, $q = 2e/5$, and $q < 3e/7$, in the respective filling factors, were measured. For the same settings but at a slightly higher electron temperature, the measured backscattered charges were $q = e/3$, $q = e/5$, and $q = e/7$, as expected. Moreover, the backscattered current exhibited distinct temperature dependence that was correlated to the backscattered charge and the filling factor. This observation suggests the existence of "low" and "high" temperature backscattering states, each with its characteristic charge and energy.

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While Laughlin's argument, explaining the fractional quantum Hall effect (FQHE) [1], is useful in predicting the charge of the quasiparticles for fractional filling factors of the type $\nu = 1/(2p + 1)$, the composite fermion (CF) model [2] is helpful in more general filling factors, such as $\nu = n/(2np + 1)$, with p and n integers. The predicted quasiparticle charge is always $e^* = e/(2np + 1)$. For $p = 1, 2$, and 3 and $n = 1$, or alternatively for $\nu = 1/3$, $2/5$, and $3/7$, we expect $q = e/3$, $e/5$, and $e/7$, respectively. Indeed, recent quantum shot noise measurements confirmed these predictions at $\nu = 1/3$ and $2/5$. The shot noise, in turn, resulting from weak backscattering of quasiparticles by a quantum point contact (QPC), was measured at electron temperatures 30–80 mK and led to charges $e/3$ at $\nu = 1/3$ [3] and $e/5$ at $\nu = 2/5$ [4] as expected. Here we report on shot noise measurements in the extreme limits of (a) weak backscattering ($r \sim 2\%$), where backscattering events are so rare, assuring their independence, and (b) extremely low electron temperatures ($T_{\min} \sim 9$ mK). In this regime of a barely perturbed electron system we measured, surprisingly, shot noise corresponding to backscattered charges $q = \nu e$, namely, $q = e/3$, $2e/5$, and $\sim 3e/7$ at $\nu = 1/3$, $2/5$, and $3/7$, respectively. In other words, backscattering in this regime is that of correlated p quasiparticles.

Measurements were conducted in a high mobility low-density two-dimensional electron gas (2DEG), embedded in a GaAs-AlGaAs heterojunction. The magnetic field was set well within the conductance plateaus of the FQHE. For example, the magnetic field at $\nu = 1/3$ was $B \sim 14.26$ T near the center of the $g_Q = e^2/3h$ plateau [Fig. 1(a)]. A QPC-type potential, induced in the 2DEG with two biased metallic gates deposited on the surface of the heterojunction, served as a controlled backscattering potential. A multiple-terminal configuration [Fig. 1(b)] was employed in order to keep the input and output differential conductance constant, $g = g_Q$—independent of the transmission of the QPC [5]. The differential conductance was measured with a 3 Hz ac, 0.5 μV rms, excitation voltage superimposed on a dc bias that was restricted to the linear regime of the QPC. The spectral density of the noise, S, was measured as a function of dc current at a center frequency 1.4 MHz and bandwidth $\sim$30 kHz (determined by a LC resonant circuit; see Refs. [3,4] for more details). A low noise cryogenic preamplifier, in the vicinity of the sample, amplified the voltage fluctuations in terminal A, followed by an amplifier and a spectrum analyzer at ambient temperature, measuring the rms fluctuations at 1.4 MHz. The temperature of the electrons was determined by measuring the equilibrium noise, $S = 4k_BTg$, with k_B the Boltzman constant. Shot noise was determined by subtracting the current independent noise from the total noise signal.

Figure 1(c) shows typical differential conductance curves of a QPC at bulk filling $\nu = 1/3$. Measurements were conducted at the lowest electron temperatures $T \sim 9$ mK for different backscattering potential strengths (controlled by the QPC gates voltage V_g). Even a relatively weak backscattering potential, with high voltage transmission $t = g/g_Q \sim 0.7$ ($r \sim 0.3$), leads to rather strong backscattering near zero applied voltage. Moreover, both the voltage and temperature dependence of the differential conductance were positive, qualitatively agreeing with the prediction of the chiral Luttinger liquid (CLL) model [6–9]. However, when the QPC potential was tuned even weaker, this dependence reversed sign [see Figs. 1(c) and 1(d)], namely, the differential conductance is enhanced rather than suppressed both at low temperature and low bias. Similar behavior was observed for $\nu = 2/5$ [presented in Fig. 2(a)] and for $\nu = 3/7$. We concentrate now on the limiting case, namely, the extremely weak backscattering regime, with the temperature dependence of the backscattered current for $r \sim 0.03$ shown in Fig. 1(d). A distinct positive slope over a decade of the current is seen in the $\log(I_B)$ vs $\log(T)$ characteristic, with I_B the backscattered current.

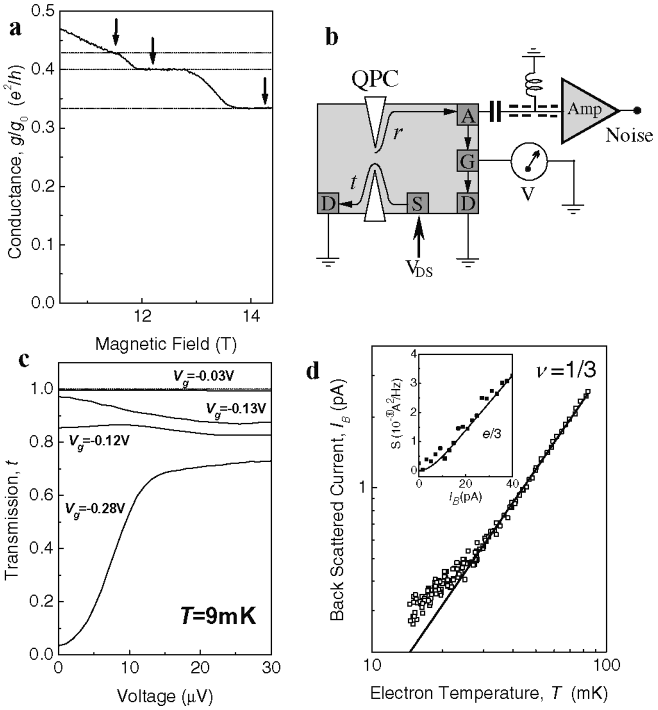

FIG. 1. (a) Quantum Hall conductance as a function of magnetic field. Filling factors were established by the pointed out magnetic fields. Similar results were obtained at different magnetic fields around the middle of the conductance plateau. (b) The measurement setup of shot noise and differential conductance. The noise generated by the QPC passed through a resonant circuit tuned to 1.4 HMz and amplified by a cryogenic amplifier. This small capacitance at A allowed only the high frequency component through. The multiple-terminal geometry kept the conductance seen from S and A constant. (c) Typical dependence of the transmission coefficient on bias voltage for different QPC gate voltage, at $\nu = 1/3$. When the QPC is very weakly pinched off ($V_g = -0.03$ V), the transmission has a very weak negative dependence on the applied bias, opposite of a CLL. (d) The backscattered current as a function of electron temperature with ac 10 μV rms is applied. The curve can be fitted with a single slope. Inset: The shot noise generated by a very weakly pinched off QPC ($t \sim 0.97$) at a filling factor $\nu = 1/3$ and electron temperature of 9 mK. Noise is classical and quasiparticle charge is $e/3$.

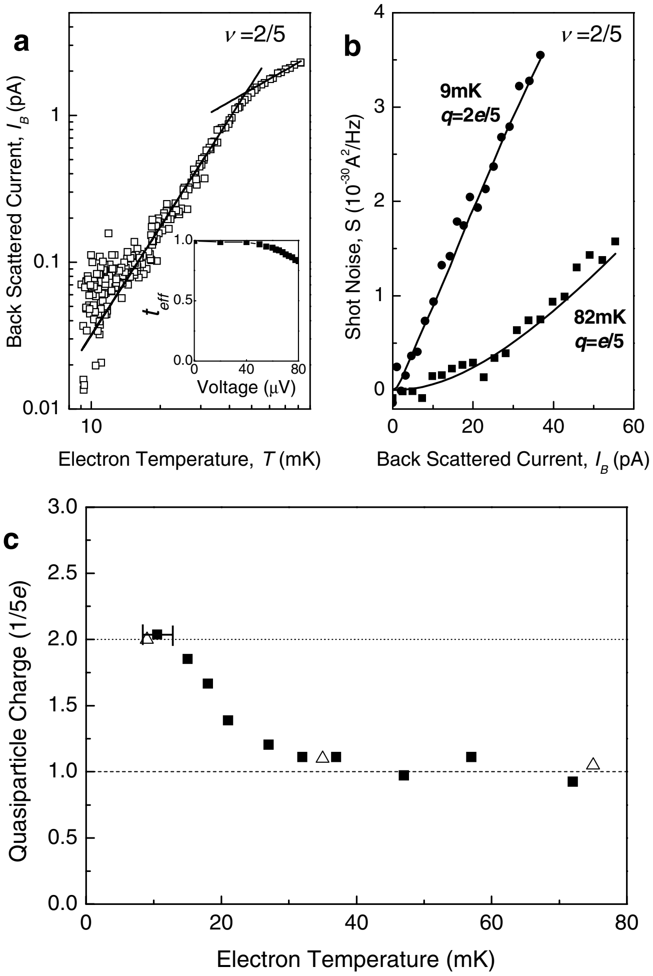

FIG. 2. (a) Backscattered current as a function of the electron temperature at a filling factor $\nu = 2/5$. Two distinct slopes are observed with a transition temperature of about 45 mK. Inset: The effective transmission as a function of bias voltage showing enhancement rather than suppression of conductance at zero bias. (b) Shot noise at two different temperatures. The backscattered quasiparticle charge is $2e/5$ at 9 mK and $e/5$ at 82 mK. The QPC was set to reflect some 2% of the impinging current at the two temperatures. (c) The temperature dependence of the scattered charge when QPC was set to reflect some 2% of the impinging current. The measurements are done on two samples and the data points are presented as squares and hollow triangles for each sample. The lowest electron temperature was hovering around 8–13 mK depending on cooldown.

We turn now to shot noise measurements. At zero magnetic field and at high integer filling factors the noise was found to be Poissionian with charge e. However, the low temperature quantum shot noise of partitioned quasiparticles in the CLL regime was predicted [6,7] and later found [8,9] to be highly nonclassical (non-Poissonian). This is expected since backscattering of quasiparticles is correlated and energy dependent. On the other hand, when backscattering events are very rare and the temperature is finite, it is expected that scattering events are stochastic with a resultant classical-like shot noise [10]. Indeed, the measured spectral density of the shot noise, S, shown in the inset of Fig. 1(d), is classical-like. The solid line is the expected shot noise due to stochastic scattering of independent particles at $T = 9$ mK and charge $q = e/3$ [11]. It depends on V, q, t, and T via $S = 4k_BTg + 2qI_Bt\Theta(T, V)$, with $\Theta(T, V) = \coth[qV/(2k_BT)] - 2k_BT/(qV)$, $I_B = Vg_Q(1 - t)$, and $g_Q = \nu e^2/h$. Here, for $qV \gg k_BT$, $\Theta(T, V) \sim 1$ and the dependence of S on I_B is linear, and for $qV \ll k_BT$ the Johnson-Nyquist thermal noise dominates. Note that at $T \sim 0$ and $t \rightarrow 1$, as in our case, $S \simeq 2qI_B$. The excellent agreement between experiment and prediction proves that scattering events of $e/3$ quasiparticles are independent down to the lowest temperatures provided that the backscattering potential is extremely weak.

We now study the regime of extremely weak backscattering at $p = 2$, namely, electron filling factor $\nu = 2/5$. The magnetic field was tuned to $B = 12.2$ T within the $g_Q = (2/5)e^2/h$ plateau [see Fig. 1(a)] and the QPC to $r \sim 0.02$. Note that the general features seen in Fig. 1(c) at $\nu = 1/3$ are also found at $\nu = 2/5$. We measured the temperature dependence of the backscattered current, as shown in Fig. 2(a), and find this time two distinct slopes in $\log(I_B)$ vs $\log(T)$ with a crossover at $T \sim 45$ mK. We then measured the shot noise at different electron temperatures and found it, again, to be classical-like in all temperatures [see in Fig. 2(b) two extreme examples]. When determining the charge in a most general filling factor one has to rely on the CF model. According to that model the reflected current, carrying the noise, is that of CFs in the 2nd Landau level (LL), namely $p = 2$, with the $e/3$ quasiparticles (in the 1st LL) being fully transmitted without contributing to the shot noise [4]. Hence, one can define an effective transmission coefficient of 2nd LL CFs, $t_{\mathrm{eff}} = (tg_{2/5} - g_{1/3})/(g_{2/5} - g_{1/3}) = 6t - 5$, which is smaller than the bare transmission t. However, when t is very close to unity, $t_{\mathrm{eff}} \sim t$ and the determination of q is not sensitive to the exact value of t. The two solid lines in Fig. 2(b), agreeing with the data, are the calculated shot noise according to the expression above with charges $q = 2e/5$ at $T \sim 9$ mK and $q = e/5$ at $T \sim 82$ mK (with electron temperatures determined independently). While the scattered charge at *high* temperature $q = e/5$ had been verified before [4], the scattered charge at *low* temperature $q = \nu e = 2e/5$ was unexpected. Note that while the lowest electron temperature was hovering around 8–13 mK for different cooldowns, the quasiparticle charge was consistently measured to be $q = 2e/5$. Measurements were repeated on two different MBE grown samples with slightly different carrier densities, and each sample was thermally recycled a few times; always leading to the same quasiparticle charge $2e/5$ at the lowest temperature range. Figure 2(c) shows the charge evolution as the temperature is being increased in the range 9 mK $< T <$ 50 mK. Most of the change takes place over a 20 mK range. In comparison, temperature dependence measurements were conducted in a separately patterned Hall bar. While the $\nu = 2/5$ conductance plateau remained unaffected at this temperature range and the longitudinal resistance R_{xx} increased with temperature, the dependence was quite different from that of I_B from the QPC.

Does such unexpected *bunching* take place also in higher CF filling factors $p = 3$, namely, at $\nu = 3/7$? Because of the relatively weak magnetic field at the $\nu = 3/7$ ($B = 11.5$ T) the many-body energy gap required to establish the $g_Q = (3/7)e^2/h$ plateau is rather small. Consequently, the plateau is barely established even at the lowest temperature [see Fig. 2(a)], and there is a finite backscattered current through the bulk (some 0.5%) and the minimum longitudinal resistance $R_{xx} > 0$. Inducing a very weak QPC potential in the 2DEG increased the backscattered current and produced a measurable shot noise, as seen in Fig. 3. Using the effective transmission (that is more sensitive here to the bare t) the fitted charge at the lowest temperature was extremely sensitive to minute variations in the electron temperature and seems to hover in the range (2–2.5)$e/7$. Warming the electrons to $T \geq 27$ mK lowered significantly the shot noise and established firmly a quasiparticle charge of $e/7$. This is the first measurement of such a small fractional charge. The higher scattered charge at the lowest temperature indicates again bunching of $e/7$ quasiparticles—very much like the behavior at $\nu = 2/5$; however, it seems that an even lower temperature than our lowest temperature ($T < 9$ mK) is needed to establish bunching of three $e/7$ quasiparticles to a charge $q = 3e/7$ as well as to achieve a perfect FQH plateau.

Summarizing our results, one should recall the following: (a) the 2DEG is rather pure with mobility 2×10^6 cm^2 V^{-1} s^{-1}; hence, scattering is dominated by the

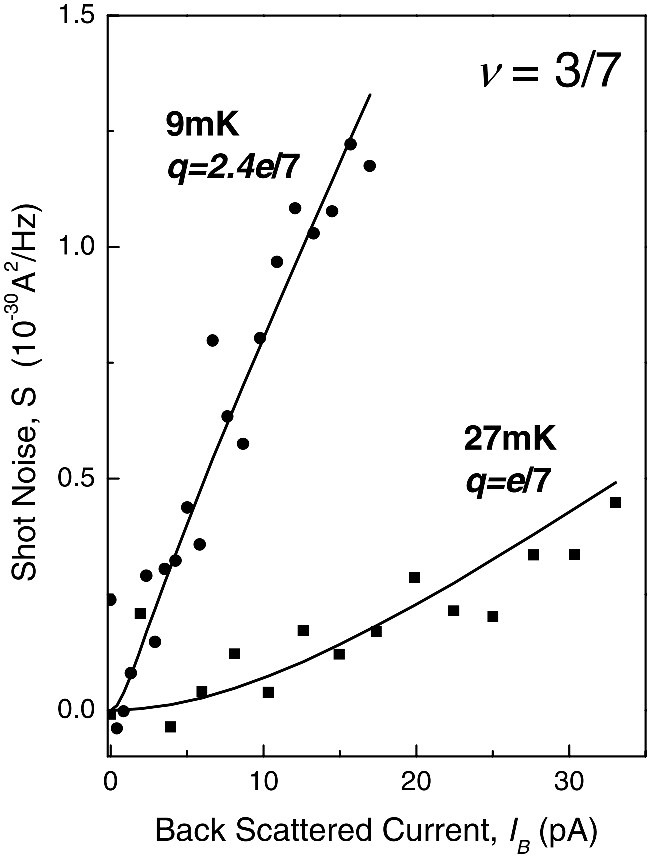

FIG. 3. Shot noise at a filling factor $\nu = 3/7$ at two different temperatures. The backscattered quasiparticle charge is found to be around (2–2.5)$e/7$ at 9 mK and $e/7$ at 27 mK. The QPC was set to reflect some 2% of the impinging current at the two temperatures.

weak potential of the QPC; (b) the electron temperature is very low ($T \sim 9$ mK, $k_BT \sim 0.8$ μeV), minimizing thermal noise and alleviating any ambiguity in analyzing the data; (c) the QPC is very open, leading to very rare backscattering events; (d) shot noise is classical-like with linear dependence of noise on the current, suggesting independent scattering of quasiparticles with a specific charge; (e) pinching the QPC ever so slightly more renders both the dc current and shot noise to be highly nonlinear functions of voltage, suggesting correlated scattering of quasiparticles with charge dependent on bias. These results confirm that in a barely perturbed 2DEG and $T \sim 0$, a very weakly bound scattering state is formed, with transport dominated by independent scattering events of p bunched quasiparticles with charge $q = \nu e$. In the CF model, rare backscattering events of simultaneous p quasiparticles, one from each LL, are taking place.

Relying on the CLL model, Kane and Fisher predicted such a possibility of bunching due to backscattering via a point scatterer [12]. However, their expression for the backscattered current, $I_B \propto v^2 T^{-|\alpha|}$, with v an energy independent backscattering amplitude and α a coefficient dependent on the scattered charge, suggests a decrease of the backscattered current with temperature, contradicting our data. Note though that since our QPC is almost fully open, its potential is expected to be rather smooth and shallow with energy dependent backscattering amplitude, $v = v(T, V)$. This dependence might dominate the behavior of the backscattered current leading to our result. Still, we stress that our observations were reproducible among samples with different QPCs and different cooling cycles; hence, we believe that it is not sensitive to the details of the QPC potential.

It should be noted that our observed bunching at low temperatures is quite different from the already observed bunching by strong backscattering potentials (at $\nu = 1/3$, bunching of quasiparticles leads to *electron* scattering) [5,8,13]. In the latter case the FQHE state does not exist in the barrier region, hence preventing the existence of elementary quasiparticles, *forcing* the quasiparticles to bunch to an electron. Here, however, the FQHE state is hardly perturbed in the barrier region, still allowing the existence of elementary quasiparticles. Hence, the *spontaneous* bunching of quasiparticles is possibly related to their fractional statistics, namely, their partly bosonic nature, encouraging them to bunch upon scattering.

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