Shot-Noise Evidence of Fractional Quasiparticle Creation in a Local Fractional Quantum Hall State

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We experimentally identify fractional quasiparticle creation in a tunneling process through a local fractional quantum Hall (FQH) state. The local FQH state is prepared in a low-density region near a quantum point contact in an integer quantum Hall (IQH) system. Shot-noise measurements reveal a clear transition from elementary-charge tunneling at low bias to fractional-charge tunneling at high bias. The fractional shot noise is proportional to $T_1(1 - T_1)$ over a wide range of T_1, where T_1 is the transmission probability of the IQH edge channel. This binomial distribution indicates that fractional quasiparticles emerge from the IQH state to be transmitted through the local FQH state. The study of this tunneling process enables us to elucidate the dynamics of Laughlin quasiparticles in FQH systems.

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Upon the application of a perpendicular magnetic field (B), a two-dimensional electron system (2DES) forms a fractional quantum Hall (FQH) state at particular rational Landau level filling factors ($\nu = n_e h/eB$, where n_e is the electron density, h is Planck's constant, and e is the elementary charge) [1]. Whereas an electron is an elementary particle with charge e, an elementary excitation in a FQH state called a Laughlin quasiparticle has a fractional charge $e^* = e/m$, where m is an odd number [2–6]. Fractional quasiparticles have been identified in shot-noise measurements [7–12] performed on a quantum point contact (QPC) in the weak-backscattering regime, where the quasiparticles tunnel through the incompressible FQH liquid [Fig. 1(a)].

When two FQH systems are separated by a vacuum state that acts as a high barrier for fractional quasiparticles, the quasiparticles impinging on the barrier must bunch and rebuild an electron to tunnel [Fig. 1(b)] [13–15]. This bunching process has been experimentally identified in the strong-backscattering regime of a QPC [16,17]. In contrast, we can expect the counterpart process, i.e., creation of fractional quasiparticles, if electrons are forced to tunnel through an incompressible FQH state. Experimentally, this tunneling process can be studied with a local FQH (LFQH) state induced by using a QPC in an integer quantum Hall (IQH) system [Fig. 1(c)]. When the transmission probability is varied by a gate voltage, the increased electrostatic potential simultaneously reduces the local electron density at the QPC. This leads to a mismatch between the bulk filling factor ν_B and the local filling factor ν_{QPC}. In previous reports, the FQH nature of such a LFQH state has manifested itself in the power-law behavior of the tunneling current [18–21]. However, the direct identification of the fractional-charge tunneling has not yet been attained. The complete understanding of the creation of fractional quasiparticles, as well as the bunching of quasiparticles, is highly required to reveal the charge dynamics in quantum Hall systems.

In this study, we identify the creation of fractional quasiparticles in the LFQH state using cross-correlation noise measurements [22]. At high field ($\nu_B \cong 1$), fractional charge ($e/3$) tunneling is observed over a wide range of transmission probabilities T_1 of a $\nu_B = 1$ IQH edge channel. As a function of the bias voltage, the transition of the tunneling charge from e to $e/3$ is detected, accompanied by the transition from nonlinear to linear dc transport characteristics. This behavior can be understood from the Tomonaga–Luttinger liquid (TLL) nature of

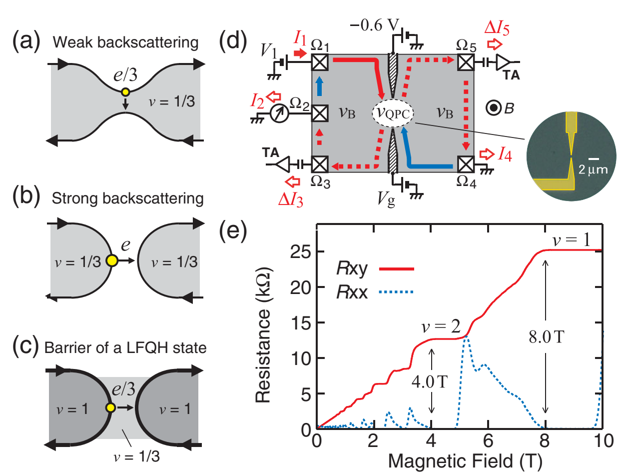

FIG. 1 (color online). (a) Tunneling of $e/3$ quasiparticles in the weak-backscattering regime in a $\nu = 1/3$ FQH state. (b) Electron tunneling in the strong-backscattering regime. (c) $e/3$-charge tunneling through a LFQH state. (d) Schematic of the device and measurement setups. Inset: colored optical micrograph of the split gate. (e) Magnetic field dependence of R_{xx} and R_{xy}.

the FQH edge channels. Surprisingly, even when the current is carried by a fully transmitting $\nu_{\mathrm{QPC}} = 1/3$ FQH channel, as manifested in the conductance plateau at $e^2/3h$, shot noise is generated indicating the stochastic tunneling of $e/3$ quasiparticles. The reason is that $e/3$ shot noise is generated by the quasiparticle tunneling between $\nu_B = 1$ IQH channels and not between FQH channels, as demonstrated by the T_1 dependence of the shot noise.

Measurements were performed at 15 mK in a dilution refrigerator on three QPCs fabricated in an $Al_{0.3}Ga_{0.7}As$/GaAs heterostructure containing a 2DES with an electron density $n_e = 2.3 \times 10^{11}$ cm^{-2} and mobility $\mu = 3.3 \times 10^6$ cm^2 V^{-1} s^{-1}. In this Letter, we show a data set obtained for one of these QPCs in a single cooldown unless otherwise noted. The main results presented in this Letter are reproduced in measurements on other QPCs and in different cooldowns. The device has five Ohmic contacts Ω_n ($n = 1$–5) and a split gate with a 200 nm gap. A QPC was formed by applying -0.6 V to one of the split-gate electrodes and varying the other gate voltage V_g. A magnetic field was applied in such a direction that the chirality of the edge channels was clockwise, as shown in Fig. 1(d).

Longitudinal R_{xx} and Hall R_{xy} resistance traces of the 2DES, obtained separately, are shown in Fig. 1(e). The small depression features near 5.4 and 6.8 T indicate the incipient formation of the $\nu_B = 5/3$ and $4/3$ FQH states.

We applied a dc voltage V_1 to Ω_1 to inject current I_1 that is partitioned at the QPC. The reflected (transmitted) current flows to Ω_3 (Ω_5), where only finite frequency (>1 kHz) noise ΔI_3 (ΔI_5) is collected because of the coupling capacitors placed at the input of the transimpedance amplifiers (TAs) [22]. The dc components I_2 and I_4 are collected at Ω_2 and Ω_4 located downstream of Ω_3 and Ω_5, respectively. We measured I_1 and I_2 to evaluate the conductance G of the QPC as $G = I_4/V_1 = (I_1 - I_2)/V_1$. In addition, the differential conductance g was determined as $g = dI_4/dV_1 = dI_1/dV_1 - dI_2/dV_1$ using a standard lock-in technique with a small ac modulation (15 μV) of V_1 at 19 Hz. We define the transmission probability through the narrow constriction using the relation $G = \Sigma_n T_n \times e^2/h$. Here, T_n is the transmission probability of the nth channel. Further details of the measurement setup and analysis are described in Ref. [22].

We verify the LFQH state at high field (8.0 T) in the V_g dependence of g [Fig. 2(a)]. At $V_1 = 0$ μV, g decreases from e^2/h to zero, exhibiting many features, which originate from the formation of LFQH states and the resultant TLL nature of the FQH channels [23]. This observation contrasts with the result at 4.0 T, where g decreases smoothly with no additional features below $g = e^2/h$ [Fig. 2(b)], indicating a smooth variation of the barrier potential. At a finite voltage ($V_1 = 450$ μV)

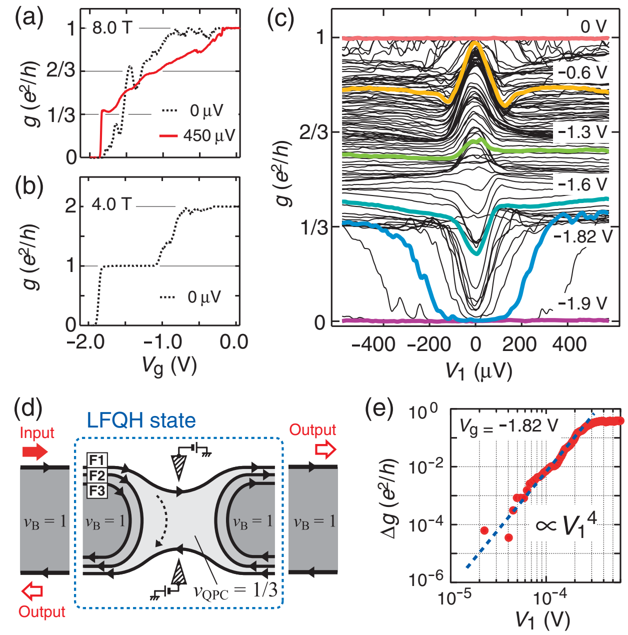

FIG. 2 (color online). (a) V_g dependence of g at $B = 8.0$ T, $V_1 = 0$, and 450 μV. (b) V_g dependence of g at 4.0 T and $V_1 = 0$ μV. (c) V_1 dependence of g measured at 8.0 T in 20 mV steps for V_g from 0 to -2.0 V. Colored thick lines indicate some of the typical traces. (d) Schematic of the edge states near the QPC. Fi ($i = 1$, 2, and 3) labels three FQH channels. (e) Log-log plot of $\Delta g(V_1) = g(V_1) - g(0)$ for the data at $V_g = -1.82$ V.

where TLL-induced nonlinear behavior disappears, a plateaulike structure is observed at $g \cong e^2/3h$, implying the formation of a $\nu_{\mathrm{QPC}} \cong 1/3$ LFQH state (for more details, see the Supplemental Material [24]).

FQH channels are known to form even in an IQH system because of the gradual electron-density decrease at the edge of the 2DES [28]. These FQH channels copropagate to form an IQH channel along the periphery of the bulk IQH region, and at a QPC they can be separated [Fig. 2(d)] [23,29]. Figure 2(c) shows the V_1 dependence of g for different V_g. The $g \cong e^2/3h$ plateau appears as accumulated traces at $|V_1| > 200$ μV, indicating the complete transmission of the outermost $\nu_{\mathrm{QPC}} = 1/3$ channels [F1 in Fig. 2(d)]. In the low-bias region, the nonlinear behavior of g reflects the suppressed transmission of fractional quasiparticles [arrowed dotted line in Fig. 2(d)] induced by the TLL nature of the FQH channels. Note that at $V_g = -1.82$ V, $\Delta g = g(V_1) - g(0)$ shows a clear power-law dependence ($\Delta g \propto {V_1}^{\alpha}$) with exponent $\alpha = (2/\nu_{\mathrm{QPC}}) - 2 = 4$ [Fig. 2(e)], in agreement with the TLL theory for $\nu_{\mathrm{QPC}} = 1/3$ [18–21]. These characteristics are a clear indication of the LFQH states.

We evaluated the noise generated at the QPC by measuring the cross correlation $S_{35} = \langle \Delta I_3 \Delta I_5 \rangle$. In the present setup, S_{35} should equal the shot noise ${S_{35}}^{\mathrm{shot}}$, which is theoretically given as follows [7,22]:

$$S_{35}^{\rm shot} = -2e^* I_1 F\left[\coth\left(\frac{e^* V_1}{2k_B T_e}\right) - \frac{2k_B T_e}{e^* V_1}\right]. \quad (1)$$

In Eq. (1), $F = [\Sigma_n T_n(1 - T_n)]/N$ is the shot-noise reduction factor, k_B is the Boltzmann constant, and T_e is the electron temperature. N is the number of channels involved. For a $\nu_B \cong 2$ IQH system, for example, we have $F = [\Sigma_\sigma T_\sigma(1 - T_\sigma)]/2$, where $\sigma(= \uparrow {\rm or} \downarrow)$ denotes the spin direction.

First, we show S_{35} measured at 4.0 T, where the dc transport shows no signature of a LFQH state. The QPC was set at $g = e^2/3h$ ($V_g = -1.86$ V), where partitioning occurs only in the outer up-spin channel ($T_\uparrow = 1/3$ and $T_\downarrow = 0$). The measured S_{35} is plotted in the inset of Fig. 3(b). With increasing $|V_1|$, S_{35} decreases from zero owing to the generation of shot noise. The data agree well with the ${S_{35}}^{\rm shot}$ calculated using Eq. (1) with $e^* = e$ and $T_e = 82$ mK. This result indicates that at 4.0 T, the QPC works as an ideal beam splitter for incident (up-spin) electrons.

At 8.0 T, we observed markedly different behavior reflecting the formation of a LFQH state. Figures 3(a) and 3(b) show g and S_{35}, respectively, as a function of V_1. At this gate voltage ($V_g = -1.30$ V), g remains almost constant over the entire V_1 range. S_{35} decreases with increasing $|V_1|$ in a similar manner as that at 4.0 T; however, the data are better fitted by Eq. (1) with $e^* = e/3$ rather than $e^* = e$. Note that we consider F in Eq. (1) as $F = T_1(1 - T_1)$.

At gate voltages where g exhibits a power-law V_1 dependence, a transition of the tunneling charge from e to $e/3$ was observed. Figures 3(c) and 3(d) show g and S_{35}, respectively, measured at $V_g = -1.6$, -1.7, and -1.8 V. The behavior of S_{35} at low bias is well described by Eq. (1) with $e^* = e$, whereas S_{35} departs from the curve at high bias, exhibiting a much weaker V_1 dependence that is again in accordance with $e^* = e/3$. Here again, we consider $F = T_1(1 - T_1)$. Notably, for each V_g, the transition between $e* = e$ and $e/3$ occurs at the same V_1 as the onset of the power-law suppression of g. This transition is observed not only at these V_g values but also over a wide range of V_g (see the Supplemental Material [24]); the shot noise of $e/3$ quasiparticles is generally measured in the linear conductance regime at high bias, while $e^* = e$ is obtained in the nonlinear conductance regime at low bias.

We here note that the $e* = e$ shot noise in the nonlinear regime is understood from the TLL nature of the FQH channels, which enhances the backscattering of $e/3$ quasiparticles; namely, it suppresses the $e/3$-charge transport through the QPC [see Fig. 2(d)]. In this case, current through the QPC is carried by electron tunneling, which leads to the generation of $e^* = e$ shot noise [30–32]. This explanation is confirmed in the temperature dependence of g and S_{35} (Fig. 4). At high temperatures, where the TLL-induced nonlinear behavior of g disappears, the $e^* = e$ shot

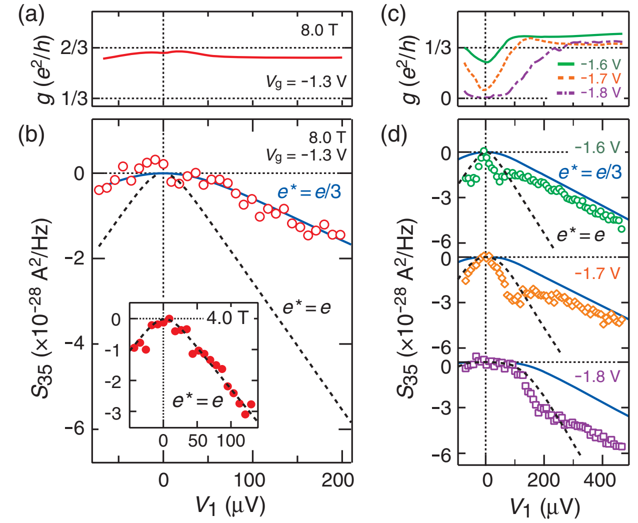

FIG. 3 (color online). (a),(b) V_1 dependence of (a) g and (b) S_{35} measured at $B = 8.0$ T and $V_g = -1.30$ V. Solid blue and dotted black lines in (b) are ${S_{35}}^{\rm shot}$ calculated with $e^* = e/3$ and $e^* = e$, respectively. Inset in (b) shows S_{35} measured at $B = 4.0$ T and $V_g = -1.86$ V, plotted with the trace of ${S_{35}}^{\rm shot}$ with $e^* = e$. (c) V_1 dependence of g measured at $V_g = -1.6$, -1.7, and -1.8 V at 8.0 T. (d) S_{35} measured at these values of V_g.

noise at low bias is suppressed and S_{35} follows ${S_{35}}^{\rm shot}$ with $e^* = e/3$ over the entire V_1 range (for more details, see the Supplemental Material [24]).

We begin the discussion for fractional shot noise in the linear conductance regime at $\nu_{\rm QPC} \cong 1/3$. The formation of FQH channels was confirmed by the $e^2/3h$ plateau in the dc measurements. On the other hand, shot-noise measurements indicated $e/3$ quasiparticles. These two experiments may appear contradictory because the $g \cong e^2/3h$ plateau suggests the absence of stochastic processes in the FQH channels [Fig. 5(a)], whereas the observed shot noise indicates that the stochastic tunneling of fractional quasiparticles must be occurring [Fig. 5(b)]. The key observation

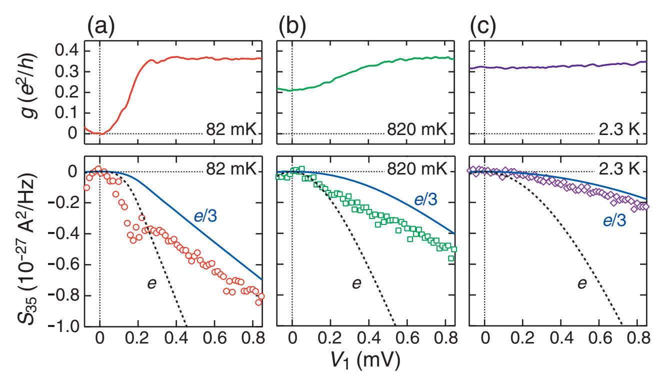

FIG. 4 (color online). V_1 dependence of g (upper panels) and S_{35} (lower panels) measured at $B = 8.8$ T and (a) $T_e = 82$ mK, (b) 820 mK, and (c) 2.3 K. These data were taken from the same sample in a different cooldown, with -0.7 and -1.6 V applied to the split-gate electrodes to form a QPC with $T_1 \cong 1/3$.

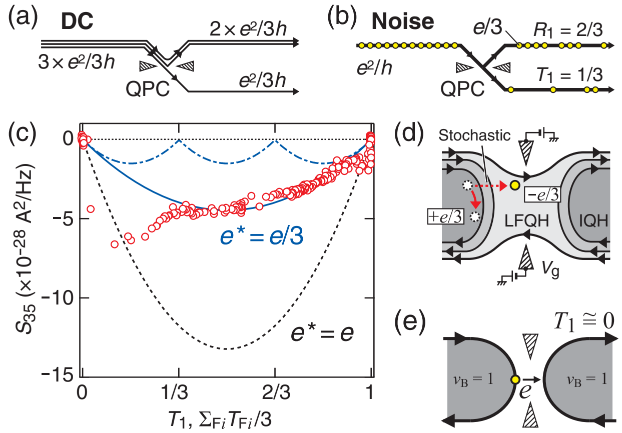

FIG. 5 (color online). (a) Simple schematic of the FQH channels at $V_{\rm QPC} \cong 1/3$ expected from the dc transport characteristics. (b) Simple schematic of partitioning $e/3$ quasiparticles expected from the shot noise. (c) T_1 dependence of S_{35} measured at $V_1 = 450\ \mu$V and 8.0 T. Solid blue and dotted black lines show $S_{35}{}^{\rm shot}$ calculated with $e^* = e/3$ and e, respectively, considering $F = T_1(1 - T_1)$. Blue dash-dotted line is $S_{35}{}^{\rm shot}$ with $e^* = e/3$ considering $F = [\sum_{\rm F\it i} T_{\rm F\it i}(1 - T_{\rm F\it i})]/3$. (d) Model schematic of the tunneling process. Fractional charges are stochastically generated at the boundary of IQH and LFQH regions, and deterministically fed to the partitioned channels. (e) Electron tunneling between the IQH channels at $T_1 \cong 0$.

to solve this question is that the shot noise is proportional to $F = T_1(1 - T_1)$. This is demonstrated by plotting S_{35} measured at different V_g as a function of T_1 [Fig. 5(c)]. Here, we plotted the data acquired at $V_1 = 450\ \mu$V to focus on the behavior at high bias.

In Fig. 5(c), S_{35} agrees well with Eq. (1) calculated for $e/3$ charge. What is important to note is that its variation with V_g is governed by the binomial distribution $-T_1(1 - T_1)$ over a wide T_1 range (from 1/3 to 0.9) (blue solid line). To make this point clearer, we plot the expected behavior if the shot-noise generation is governed by the transmission probability of each fractional channel (blue dash-dotted line), which is given by considering $F = [\Sigma_{{\rm F}i} T_{{\rm F}i}(1 - T_{{\rm F}i})]/3$, where F$i$ ($i = 1$, 2, and 3) labels the three FQH channels. If $T_{{\rm F}i}$ varies individually in succession from 1 to 0, S_{35} oscillates as a function of the total transmission probability $\Sigma_{{\rm F}i} T_{{\rm F}i}/3 (= T_1)$, as it is expected for partitioning of the three copropagating IQH channels [7]. Obviously, the experimental result differs from the calculation with this assumption. The shot noise governed by the binomial distribution of T_1 (and not $T_{{\rm F}i}$) indicates that stochastic tunneling occurs in the IQH channels [Fig. 5(b)] and not in the FQH channels. This demonstrates that fractional quasiparticles emerge from the IQH system at the LFQH state. This process arises from the fact that the bulk and constricted regions have different filling factors and thus possess distinct eigenstates.

When T_1 is close to 0 or 1, S_{35} approaches $S_{35}{}^{\rm shot}$ for $e^* = e$ [Fig. 5(c)]. This is because, when a large negative V_g is applied to achieve $T_1 \cong 0$, an opaque barrier is established between the two IQH channels, which forbids the transmission of $e/3$ quasiparticles [Fig. 5(e)]. Similarly, at $T_1 \cong 1$, an incompressible IQH state ($\nu_{\rm QPC} \cong 1$) forms between the transmitting IQH channels, inhibiting the reflection of $e/3$ quasiparticles. Thus, at $T_1 \cong 0$ or 1, the tunneling current is carried in units of e.

Let us consider the details of the $e/3$-charge tunneling. If the LFQH state acts as a tunnel barrier, the width of the barrier and hence T_1 should vary as functions of V_g. However, we observed a $g \cong e^2/3h$ plateau, which indicates that T_1 is not affected by changes in V_g. Although the full mechanism is not yet clear, the following scenario is possible. Near the QPC, the IQH channel splits into three FQH channels, being accompanied by the one-by-one fractional quasiparticle tunneling from the biased IQH region to the LFQH state. This tunneling creates $-e/3$ and $+e/3$ charges, which are composed of the deformation of the LFQH edges [18]. Each of them is deterministically transmitted or backscattered at the QPC [Fig. 5(d)], and therefore T_1 does not depend on the width of the LFQH state. Away from the QPC, the three FQH channels again merge into $\nu_B = 1$ IQH channels, and the fractional excitations propagate as edge-magnetoplasmon pulses with $e/3$ charge [33,34]. In this model, shot noise is generated because of the stochastic tunneling at the boundary of IQH and FQH regions. We expect that further investigations will validate this scenario and completely explain the mechanism.

In summary, we experimentally identified fractional-charge tunneling through a LFQH state in a $\nu_B = 1$ IQH system. In the dc transport measurements, the formation of the LFQH state was confirmed in the $g \cong e^2/3h$ plateau, as well as the power-law behavior of the tunneling current. The shot-noise measurements demonstrated $e/3$-charge tunneling through the LFQH state. The binominal distribution factor $-T_1(1 - T_1)$ indicated that fractional quasiparticles emerge from the IQH system. This quasiparticle creation is regarded as the counterpart of the bunching of quasiparticles, which has been observed in the strong backscattering regime of a QPC in FQH systems.

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