Characterizing Neutral Modes of Fractional States in the Second Landau Level

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Fractionally charged quasiparticles, which obey non-Abelian statistics, were predicted to exist in the $\nu = 8/3$, $\nu = 5/2$, and $\nu = 7/3$ fractional quantum Hall states (in the second Landau level). Here we present measurements of charge and neutral modes in these states. For both $\nu = 7/3$ and $\nu = 8/3$ states, we found a quasiparticle charge $e = 1/3$ and an upstream neutral mode only in $\nu = 8/3$—excluding the possibility of non-Abelian Read-Rezayi states and supporting Laughlin-like states. The absence of an upstream neutral mode in the $\nu = 7/3$ state also proves that edge reconstruction was not present in the $\nu = 7/3$ state, suggesting its absence also in $\nu = 5/2$ state, and thus may provide further support for the non-Abelian anti-Pfaffian nature of the $\nu = 5/2$ state.

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The statistics of quantum particles determines the properties of their many-body wave function under particle exchange. For ubiquitous particles with Abelian statistics, an interchange of two identical particles adds a phase to the original two-particle wave function. Alternatively, for non-Abelian particles [1–3], with a highly degenerate ground state of the system, an interchange of two particles may shift the ground state of the system to an orthogonal (degenerate) ground state. Moreover, as their name suggests, different interchanges do not commute. Prime candidates for non-Abelian behavior are the charged excitations (quasiparticles) in specific fractional quantum Hall states, which have not been proven to exist yet.

The fractional quantum Hall effect is observed in two-dimensional electron gas, subjected to a strong perpendicular magnetic field. It is characterized by quantized plateaus in the Hall resistance, coinciding with zero longitudinal resistance. Three of the incompressible fractional quantum Hall states in the second Landau level, which were predicted to support non-Abelian quasiparticles, are $\nu = 5/2$, $\nu = 8/3$, and its particle-hole conjugate $\nu = 7/3$. Starting with $\nu = 5/2$ state, it could, in principle, be described by a variety of wave functions. While some are Abelian [4–6], others are non-Abelian [7–10]; however, all are expected to support quasiparticles with $e/4$ charge—as was indeed measured recently [11–15]. The recent observation of an upstream neutral mode (with an opposite chirality to that of charge chirality) in the $\nu = 5/2$ fraction [16] tends to support the non-Abelian anti-Pfaffian state [8,9]—although edge reconstruction of a different state (Abelian or non-Abelian states) may also lead to an upstream neutral mode [17]. Note that recent photoluminescence spectroscopy measurements suggested that the $\nu = 5/2$ is spin unpolarized [18], in contradiction to the expected spin polarization in the anti-Pfaffian case, a contradiction which might be explained due to the difference between bulk and edge phenomena [19]. For the two conjugate states $\nu = 7/3$ and $\nu = 8/3$, two main candidate states were proposed: an Abelian, Laughlin-like state (similar in nature to the $\nu = 1/3$ and $\nu = 2/3$ states, respectively [20,21]) and a non-Abelian Read-Rezayi state [22]. Other suggestions include Bonderson-Slingerland hierarchy states over the $\nu = 5/2$ Pfaffian (or anti-Pfaffian state) [23]. Note that although it is natural to assume that the $\nu = 7/3 = 2 + 1/3$ state is a Laughlin-like state, similar to the robust $\nu = 1/3$, numerical calculations [24,25] suggest that it might be described by a hole-conjugate state of the non-Abelian $k = 4$ Read-Rezayi state [22] and thus is expected to support a quasiparticle charge of $e/6$, with a chiral upstream neutral mode only in $\nu = 7/3$ [22]. Alternatively, the Abelian version of $\nu = 7/3$ and the $\nu = 8/3$ states is expected to mimic the $\nu = 1/3$ and $\nu = 2/3$ states, respectively—namely, charge of $e/3$ and no upstream neutral in the $\nu = 7/3$ case and charge $e/3$ or $2e/3$ and an upstream neutral mode in the $\nu = 8/3$ case [21].

Our measurements were performed on two similar samples, with a two-dimensional electron gas embedded in a 30 nm wide AlGaAs-GaAs-AlGaAs quantum well, doped on both sides, with an areal electron density 2.9×10^{11} cm^{-2} and a low temperature mobility 29×10^6 cm^2/V s (both measured in the dark; see Umansky *et al.* [26]). Hall measurement at 10 mK [Fig. 1(a)] shows five significant fractional states, $\nu = 11/5, 7/3, 5/2, 8/3$, and $14/5$ (with $R_{xx} \sim 0$ for $\nu = 7/3$, $5/2$, and $8/3$), measured on the ungated part of a Hall-bar-type sample [width 50 μm and total length 380 μm; Fig. 1(b)]. A single quantum point contact (QPC) constriction was formed by a negatively biased split gate on top of a narrower part of the mesa (width 5 μm), with a distance of 40 μm between the closest Ohmic contact and the QPC. Three types of measurements were performed: (a) downstream noise measurements, in which current was driven through $C1$ or $C2$ and partitioned by the QPC constriction—leading to shot noise in M; (b) upstream noise measurements, in which an upstream neutral mode emanates from N [in Fig. 1(b)]—impinging on the QPC constriction, it is expected to generate shot noise [16] that is monitored at contact M (the *downstream* current is collected $G1$); (c) when an upstream neutral mode was found, its influence on charge partitioning in the QPC constriction (due to a simultaneously injected current from another contact) was measured.

For the analysis of the excess noise (the added noise when current was injected), we apply the "single particle" model—used successfully before [11,13,27–32]—to determine particles' charge e, $e/3$, $e/5$, $e/7$, $e/4$, and $2e/3$ ($e/3$) at filling factors $\nu =$ integer, $1/3$, $2/5$, $3/7$, $5/2$, and $2/3$, respectively. The model is based on the assumption that quasiparticles are stochastically partitioned by a QPC constriction and, thus, obey a binomial distribution with a variance proportional to the quasiparticle charge. Other models, based on backscattering of a chiral Luttinger liquid, were found to be inconsistent with the conductance and the excess noise produced in the QPC constriction (see [13] for more details). When multiple edge channels coexist (such as in the second Landau level), partitioning the ith channel, flowing along the boundary between filling factors ν_i and ν_{i-1}, leads to a low frequency spectral density of current fluctuations at finite temperature T [33,34]:

$$S^i(V_{\rm sd})_T = 2e^* V_{\rm sd}\Delta g_i t_{\nu_i-\nu_{i-1}}(1 - t_{\nu_i-\nu_{i-1}}) \times \left[\coth\left(\frac{e^*V_{\rm sd}}{2k_BT}\right) - \frac{2k_BT}{e^*V_{\rm sd}}\right] + 4k_BTg, \quad (1)$$

where e^* is the partitioned quasiparticle charge, $V_{\rm sd}$ is the applied dc excitation voltage, $\Delta g_i = g_i - g_{i-1}$, with $g_j = \nu_j e^2/h$, and $t_{\nu_i-\nu_{i-1}} = \frac{g-g_{i-1}}{\Delta g_i}$ is the transmission probability of the ith channel, with g the two-terminal (Hall) conductance. In our samples, for bulk filling factors $\nu_i = 7/3, 5/2$, and $8/3$, the next lower lying state traversing freely the QPC constriction was $\nu_{i-1} = 2$ [11]. Since the tunneling charge can be the fundamental (bulk) quasiparticle charge or its integer multiple (due to *bunching*) [21,35,36], its measurement sets an upper limit on its fundamental value [13]. This upper limit was obtained either when the differential transmission of the QPC constriction was energy independent [13], at an elevated electron temperature [13], or in the simultaneous presence of a neutral mode in the QPC constriction [16].

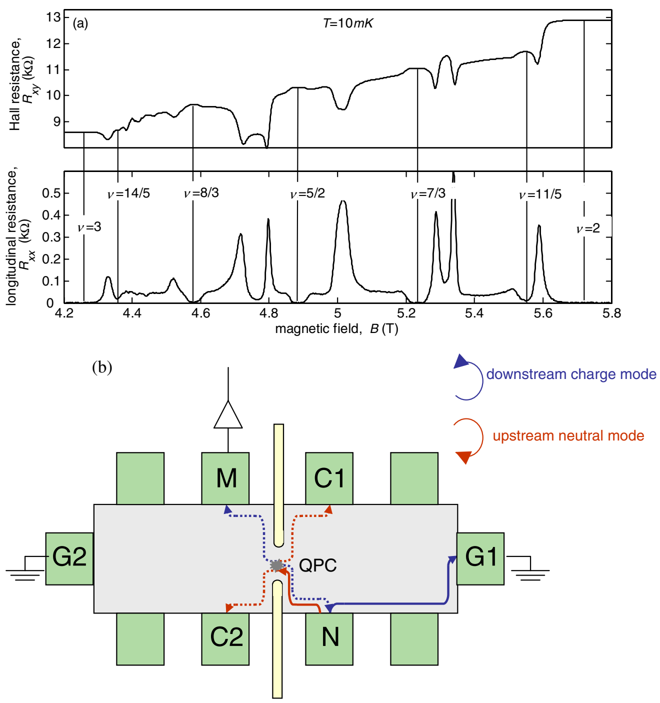

FIG. 1 (color online). Hall effect data. (a) Fully developed fractional quantum Hall states are observed in $\nu = 7/3$, $5/2$, and $8/3$ states. (b) Schematic description of the gated Hall bar. The chiral charge mode flows counterclockwise. Current driven into "charge sources" $C1$ and $C2$ flows towards the QPC; it is being partitioned and thus generating shot noise proportional to the tunneling charge, which is measured in probe M. The upstream neutral mode, if present, flows clockwise, presented by the red and blue trajectories that emerge from the "neutral source" N. The charge current (blue) flows into the ground $G1$. The upstream neutral mode (red) flows towards the QPC and generates charge mode fluctuations (dashed blue), which can be measured in M.

We start with measurements performed at $\nu = 8/3$. Injecting current through N and finding excess noise, with no average current, in M provides a direct proof for the existence of an upstream neutral chiral mode [16]. Noise detected in M can be attributed to the fact that an arrival of the neutral mode at the QPC constriction induces tunneling of charged quasiparticles or, equivalently, viewing the neutral mode as a stream of "dipoles," which are being fragmented by the constriction, thus forming oppositely propagating particle-hole pairs. Alternatively, the heat transported by the upstream neutral mode may "heat up" one side of the constriction, thus leading to an added noise [37].

The excess noise in M, as a function of the current flowing in the relevant "upper 2/3 channel" $I_N^{8/3-2}$ in N, is shown in Fig. 2(a) for three different transmission probabilities $t_{8/3-2}$ of the QPC constriction [measured by driving a small ac signal (2 μV rms at 910 kHz) into $C1$ and measuring the transmitted signal at M]. The excess noise for $I_N^{8/3-2} = 1.25$ nA is plotted for a few values of the average transmission probability in Fig. 2(b). It roughly follows $t_{8/3-2}(1 - t_{8/3-2})$, dropping to zero at $t_{8/3-2} = 0$. This indicates that the two lower integer edge modes do not participate in the process of tunneling. Moreover, and easier to measure, the effect of the upstream neutral mode on the transmission of the QPC constriction (measured for current injected from $C1$) was found to be significant only for rather low transmission probabilities [see Fig. 2(c)].

Observing an upstream neutral mode at $\nu = 8/3$ is not consistent with a non-Abelian $k = 4$ Read-Rezayi state [20]. Moreover, for a nearly energy-independent $t_{8/3-2}$, with current injected from $C1$, the partitioned charge was

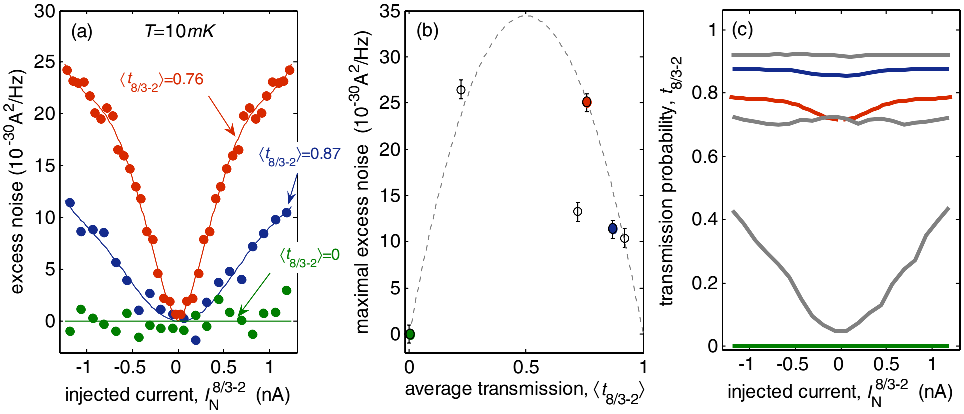

FIG. 2 (color online). Excess noise and conductance in $\nu = 8/3$ due to the arrival of a neutral mode at the QPC at $T = 10$ mK. (a) Excess noise as a function of the current in the upper 2/3 channel, $I_N^{8/3-2}$, injected from N (charge current flows into $G1$ and the upstream neutral mode arrives at the QPC), for three different transmission probabilities of the QPC (obtained in three different gate voltages on the QPC). Excess noise proves the existence of an upstream neutral mode. (b) Excess noise at $I_{8/3-2} = 1.25$ nA as a function of the transmission probability of the QPC. The dashed line is proportional to $t_{8/3-2}\,(1 - t_{8/3-2})$. (c) Differential transmission probability (measured by current in $C1$ and measurement at M) as a function of the current $I_N^{8/3-2}$ at N. Strong dependence of the transmission probability is observed at lower transmissions.

determined to be $e/3$ [blue curves for transmission and noise in Figs. 3(a) and 3(b)]—again inconsistent with the predicted $e/6$ for the non-Abelian state. How will the partitioned quasiparticle charge be affected by the presence of a neutral mode? With $I_N = 5$ nA, the transmission and excess noise were measured versus the current injected at $C1$, as shown by the red curves in Figs. 3(a) and 3(b), respectively. The striking effect is the increased temperature of the partitioned quasiparticles to 25 mK [using Eq. (1)], while the quasiparticle charge remained $e/3$. At somewhat lower and energy-dependent transmission [Fig. 3(c)], with an apparent partitioned charge *bunching* ($\sim 0.55e$ [13]), the added upstream neutral mode affected the temperature, the transmission, and the partitioned charge. The transmission turned to be energy independent (*linear*), the charge returned to nearly $e/3$, and the temperature of the partitioned quasiparticles increased to $T = 25$ mK, using Eq. (1). Note that Eq. (1) is valid for an equal temperature T on both sides of the QPC; hence, the hidden assumption in the above analysis is that the neutral mode heats up the entire QPC. In the case that the neutral mode heats up only one side of the QPC, while the other remains at the base temperature of $T_0 = 10$ mK, a modification to Eq. (1) is required, which results in an elevated temperature of the partitioned quasiparticles to $T = 35$ mK.

Partitioning charge in the $\nu = 7/3$ state led to excess noise with a corresponding $e/3$ charge [13] for nearly energy-independent transmission. This is in contradiction to the prediction of $e/6$ for an hole-conjugate state of the $k = 4$ Read-Rezayi state [22]. As seen in Fig. 4, an upstream neutral mode is absent—strengthening our conclusion that the $\nu = 7/3$ state is a Laughlin-like state. Moreover, an edge reconstruction, which may have led to an upstream neutral mode, is not likely to take place.

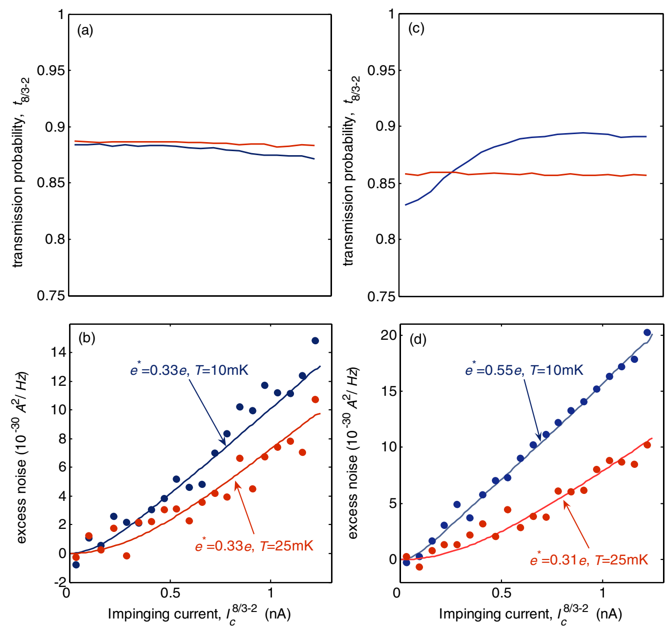

FIG. 3 (color online). Transmission probability and shot noise in $\nu = 8/3$ as a function of the impinging current (injected from $C1$), with (red) and without (blue) an additional upstream neutral mode (injected from N). Measured shot noise is in dots; solid lines are the expected shot noise for specific charges and temperatures, as indicated. (a),(b) For a transmission probability independent of the impinging current, charge equals $e/3$ with and without the additional neutral current. (c),(d) For a transmission probability dependent on the impinging current, the presence of a neutral mode linearizes the transport as well as lowers the charge to almost $e/3$. In both cases the addition of the neutral mode raises the temperature to 25 mK.

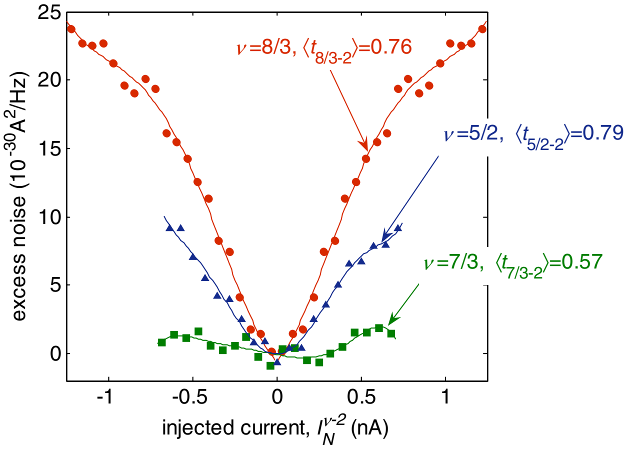

FIG. 4 (color online). Comparison between the excess noise, as a function of the injected current from contact N, in $\nu = 7/3$, 5/2, and 8/3. Excess noise in $\nu = 8/3$ and 5/2 states proves the existence of an upstream neutral mode, oppositely to the case of $\nu = 7/3$. Excess noise in the $\nu = 8/3$ state was measured only for the positive injected current range and was mirror imaged.

We compare the excess noise for $\nu = 7/3$, $\nu = 5/2$, and $\nu = 8/3$ states due to fragmentation of the neutral mode as a function of $I_N^{\nu-2}$ (one can also plot this comparison as a function of V_N) in Fig. 4. The fact that the excess noise for $\nu = 5/2$ is smaller than for $\nu = 8/3$ for similar transmission probabilities might indicate either that the carried energy by the mode is smaller or, alternatively, the decay length for the $\nu = 5/2$ (as it traverses from N to the QPC constriction) is shorter [16].

We studied the most pronounced fractional states in the second Landau level via shot noise measurements, determining the charge of the quasiparticles and the existence of an upstream neutral mode. In the $\nu = 8/3$ and $\nu = 7/3$ states, we find a fundamental charge of $e/3$ for both, with an upstream neutral mode existing only in $\nu = 8/3$. This strongly suggests that $\nu = 7/3$ and 8/3 are the ubiquitous Laughlin-type states, although a Bonderson-Slingerland hierarchy state cannot be ruled out for $\nu = 8/3$ (in the $\nu = 7/3$ our data contradict such an hierarchy state). Similar conclusions were obtained from measurements of the energy gap [38], in which the simple model of noninteracting composite fermions explained the magnitude of gaps in $\nu = 7/3$ and 8/3—but not in other states suspected of being of a more exotic origin. Hence, with its upstream neutral mode and charge of $e/4$, the $\nu = 5/2$ state is the most likely candidate for a non-Abelian state, with an anti-Pfaffian wave function [8,9,16].

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[1] C. Nayak *et al.*, Rev. Mod. Phys. **80**, 1083 (2008).
[2] A. Stern, Ann. Phys. (N.Y.) **323**, 204 (2008).
[3] A. Stern, Nature (London) **464**, 187 (2010).
[4] B. I. Halperin, Helv. Phys. Acta **56**, 75 (1983).
[5] B. I. Halperin, P. A. Lee, and N. Read, Phys. Rev. B **47**, 7312 (1993).
[6] X. G. Wen and Q. Niu, Phys. Rev. B **41**, 9377 (1990).
[7] G. Moore and N. Read, Nucl. Phys. **B360**, 362 (1991).
[8] S. S. Lee *et al.*, Phys. Rev. Lett. **99**, 236807 (2007).
[9] M. Levin, B. I. Halperin, and B. Rosenow, Phys. Rev. Lett. **99**, 236806 (2007).
[10] X. G. Wen, Phys. Rev. Lett. **66**, 802 (1991).
[11] M. Dolev *et al.*, Nature (London) **452**, 829 (2008).
[12] I. P. Radu *et al.*, Science **320**, 899 (2008).
[13] M. Dolev *et al.*, Phys. Rev. B **81**, 161303 (2010).
[14] J. E. Willett, L. N. Pfeiffer, and K. W. West, Proc. Natl. Acad. Sci. U.S.A. **106**, 8853 (2009).
[15] V. Venkatachalam *et al.*, Nature (London) **469**, 185 (2011).
[16] A. Bid *et al.*, Nature (London) **466**, 585 (2010).
[17] C. D. Chamon and X. G. Wen, Phys. Rev. B **49**, 8227 (1994).
[18] M. Stern *et al.*, Phys. Rev. Lett. **105**, 096801 (2010).
[19] M. Stern and I. Bar-Joseph (private communication).
[20] R. B. Laughlin, Phys. Rev. Lett. **50**, 1395 (1983).
[21] C. L. Kane and M. P. A. Fisher, Phys. Rev. B **51**, 13 449 (1995).
[22] N. Read and E. Rezayi, Phys. Rev. B **59**, 8084 (1999).
[23] P. Bonderson and J. K. Slingerland, Phys. Rev. B **78**, 125323 (2008).
[24] B. A. Friedman and G. C. Levine, Int. J. Mod. Phys. B **24**, 4707 (2010).
[25] A. Wojs, Phys. Rev. B **63**, 125312 (2001).
[26] V. Umansky *et al.*, J. Cryst. Growth **311**, 1658 (2009).
[27] R. dePicciotto *et al.*, Nature (London) **389**, 162 (1997).
[28] M. Reznikov *et al.*, Nature (London) **399**, 238 (1999).
[29] Y. C. Chung, M. Heiblum, and V. Umansky, Phys. Rev. Lett. **91**, 216804 (2003).
[30] A. Bid *et al.*, Phys. Rev. Lett. **103**, 236802 (2009).
[31] L. Saminadayar *et al.*, Phys. Rev. Lett. **79**, 2526 (1997).
[32] C. L. Kane and M. P. A. Fisher, Phys. Rev. Lett. **72**, 724 (1994).
[33] G. B. Lesovik, JETP Lett. **49**, 592 (1989).
[34] T. Martin and R. Landauer, Phys. Rev. B **45**, 1742 (1992).
[35] D. Ferraro *et al.*, Phys. Rev. Lett. **101**, 166805 (2008).
[36] D. Ferraro *et al.*, Phys. Rev. B **82**, 085323 (2010).
[37] S. Takei and B. Rosenow, arXiv:1012.0315.
[38] A. Kumar *et al.*, Phys. Rev. Lett. **105**, 246808 (2010).