Upstream Neutral Modes in the Fractional Quantum Hall Effect Regime: Heat Waves or Coherent Dipoles

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Counterpropagating (upstream) chiral neutral edge modes, which were predicted to be present in hole-conjugate states, were observed recently in a variety of fractional quantum Hall states ($\nu = 2/3$, $\nu = 3/5$, $\nu = 8/3$, and $\nu = 5/2$), by measuring the charge noise that resulted after partitioning the neutral mode by a constriction (denoted, as $N \rightarrow C$). Particularly noticeable was the observation of such modes in the $\nu = 5/2$ fractional state—as it sheds light on the non-Abelian nature of the state's wave function. Yet, the nature of these unique, upstream, chargeless modes and the microscopic process in which they generate shot noise, are not understood. Here, we study the ubiquitous $\nu = 2/3$ state and report of two main observations: First, the nature of the neutral modes was tested by "colliding" two modes, emanating from two opposing sources, in a narrow constriction. The resultant charge noise was consistent with local heating of the partitioned quasiparticles. Second, partitioning of a downstream charge mode by a constriction gave birth to a dual process, namely, the appearance of an upstream neutral mode ($C \rightarrow N$). In other words, splitting "hole conjugated" type quasiparticles will lead to an energy loss and decoherence, with energy carried away by neutral modes.

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Quantum Hall states are characterized by the chiral flow along the edges of a two-dimensional electron gas (2DEG) of one-dimensional-like current modes [1,2]. For some fractional states (such as hole-conjugate states, e.g., $\nu = 2/3$, $\nu = 3/5$, etc.), MacDonald and Johnson [3,4] speculated the existence of counterpropagating ("upstream") charge modes due to "edge reconstruction"; however, such modes were never observed [5]. This motivated Kane *et al*. [6,7] to propose formation of upstream neutral modes, which carry energy without net charge, due to Coulomb interaction and particle exchange between the proposed counterpropagating charge modes. The recent observation of neutral modes by Bid *et al.* [8], via shot noise measurements, accomplished by impinging upstream neutral modes on a partly pinched quantum point contact (QPC) constriction, opened a new field of study. Here, we study in some detail the birth of the modes in the ubiquitous $\nu = 2/3$ state and the mechanism by which they generate shot noise in a constriction.

The $\nu = 2/3$ mode was verified recently to be made of a downstream charge mode with conductance $2e^2/3h$ and an upstream neutral mode carrying only energy [6–8]. When tunneling between two counterpropagating $2/3$ modes takes place (such as in a narrow constriction), the measured tunneling quasiparticles were found to be $e/3$ or $2e/3$ [9], approaching e for a nearly pinched constriction. Moreover, the simultaneous presence of an excited neutral mode in the constriction was found to add charge fluctuations and, at the same time, modify substantially the downstream flowing partitioned quasiparticle charge [8,10]. However, we have yet to understand many of these modes' characteristics, and some of them are studied here. What is the role played by the Ohmic contact in emitting and absorbing these modes? What is the microscopic mechanism that leads to current noise in a narrow constriction? [8,10] Since charged quasiparticles and neutral ones coexist, it is only natural to ask whether a dual behavior, namely, partitioning charged quasiparticles, will excite upstream neutral modes. Moreover, and most importantly, can the neutral modes be described as an ordered stream of neutral quasiparticles with clear quantum numbers and statistics (say dipoles, meaning a spinor), or are they propagating incoherent heat waves?

Measurements were performed on samples fabricated (see the Supplemental Material for details [11]) on a GaAs-AlGaAs heterostructure, embedding, some 130 nm below the surface, a 2DEG with areal carrier density $\sim 9 \times 10^{10}$ cm^{-2} and low temperature (< 1 K) mobility $\sim 10 \times 10^6$ cm^2/V s—both measured in the dark. A schematic representation of the fabricated structure is shown in Figs. 1(a), 1(b), 4(a), and 4(b). It is composed of a mesa 300 μm long and 50 μm wide, with a 10 μm narrow part covered by a split metallic gate, 100 nm wide and opening $\sim$450 nm. Alloying AuGeNi in the usual manner formed Ohmic contacts. Because of the relatively short decay length of the neutral modes (see Ref. [8]), the distance between the "injecting" Ohmic contacts and the detector (e.g., a QPC) was kept relatively short (8 μm). The signal at the voltage probe was first filtered by an *LC* circuit, with a resonance frequency $\sim$850 kHz, amplified by a cooled (to 4.2 K) homemade preamplifier and a room temperature amplifier (NF-220F5), to be finally measured by a spectrum analyzer. Grounded contacts were connected directly to the "cold

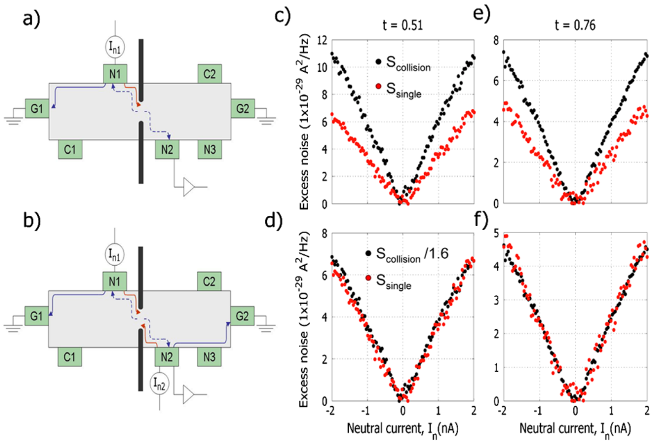

FIG. 1 (color online). Collision measurements—setup and results. Schematics of the measurements setup is presented in (a) and (b). Ohmic contacts in green (medium gray), 2DEG in light gray, and QPC constriction in black. The chiral neutral (charge) mode in red [medium-dark gray] (blue [dark gray]), flowing in opposite directions. Distance from $N1$ and $N2$ to the center of QPC opening 8 μm. Distance from $C1$ and $C2$ to center of QPC opening 150 μm. (a) $N \to C$ setup. Neutral mode injected (upstream) from source $N1$ toward the QPC, where it generates excess noise $S_{\rm single}$, which flows (downstream) towards voltage probe $N2$. (b) Collision setup. Neutral mode injected (upstream) simultaneously from contacts $N1$ and $N2$, flowing toward the QPC, where they generate excess noise $S_{\rm collision}$, which is measured in voltage probe $N2$. (c) and (d) Excess noise generated when a single neutral mode (red, $S_{\rm single}$) or two (black, $S_{\rm collision}$) neutral modes reach the QPC, for two different transmission probabilities t. $S_{\rm single}$ does not depend on the injecting contact ($N1$ or $N2$). (e) and (f) Scaling $S_{\rm collision}$; $S_{\rm collision}/S_{\rm single} = 1.6$.

finger" of a dilution refrigerator at temperature ~10 mK, assuring the electron temperature in this range.

We first address the nature of the neutral mode and the process by which it generates charge noise at the QPC (we denote this process $N \to C$) [8,10]. A modified experiment was designed, where rather than having a single upstream neutral mode impinging at a constriction with a resultant downstream charge noise $S_{\rm single}$, two neutral modes were injected simultaneously, from opposite sides of the constriction, with a resultant charge noise $S_{\rm collision}$ [see schematic in Fig. 1(b)]. If the neutral mode is to be described by a stream of quasiparticles with clear quantum numbers and statistics, which fragment into charge particles at the constriction, the presence of a second neutral mode at the opposite edge of the constriction will alter this process. Since the neutral mode is described by a fermionic field this may lead to $S_{\rm single} > S_{\rm collision}$. On the other hand if the neutral mode is an incoherent heat wave, and the excess noise is generated due to the heat carried to the constriction by the neutral mode, one would expect $S_{\rm collision} > S_{\rm single}$.

The experiment proceeded as follows: First, current was injected from a single contact, and $S_{\rm single}$ for I_{n1} (or $S_{\rm single}$ for I_{n2}) was measured at $N2$. Both configurations led to the same results (within the measurement error). Second, currents were injected from N_1 and N_2 simultaneously, generating $S_{\rm collision}$ at $N2$. The measurements were repeated for different transmission probabilities set by the QPC. Note, that since $N2$ has two roles, injecting and collecting, a large resistor (1 GΩ) was inserted directly on the $N2$ contact; avoiding shorting the noise by the stray capacitance of the wire feeding $N2$.

Our findings, shown in Figs. 1(c) and 1(e), indicate that for all the values of the transmission probability $S_{\rm single} < S_{\rm collision} < 2S_{\rm single}$; moreover, simple scaling of the graphs allow expressing $S_{\rm collision} = \alpha S_{\rm single}$, with $\alpha = 1.6 \pm 0.1$ [Figs. 1(d) and 1(f)]. Both spectra, $S_{\rm single}$ and $S_{\rm collision}$, exhibited the same dependence on the transmission probability, $t(1-t)$, as shown in Fig. 2(a).

The most straightforward explanation for $S_{\rm single}$ ($S_{\rm collision}$) is local heating of the counterpropagating "cold" charge mode(s) by the neutral mode(s), which results in an elevated temperature in the constriction [12,13], thus generating excess charge noise above the Johnson-Nyquist noise in the absence of neutral mode(s) [14,15]. Since, to the best of our knowledge, the consequence of a nonuniform temperature along the sample is not available, we derive a simplified description of such an unorthodox case. The derivation follows Landauer's guidelines [16,17] applied to the configuration in Fig. 2(b). The Fermi-Dirac distributions in contacts $C1$, $C2$, and the ground $G1$, are: $f_1(\mu_1, T_1)$, $f_2(\mu_2, T_2)$, $f_g(\mu_g, T_g)$, respectively, with μ the electrochemical potential and T the temperature. The current distribution injected from a contact is proportional to $f g_Q$, with g_Q the Hall conductance, while its variance is proportional to $f(1-f)g_Q$. Since the voltage fluctuations in $N2$ are with respect to ground $G1$, it is the sum of the variances in these contacts. Since the current distribution arriving at $N2$ is proportional to $F_{N2} = f_1 t^+ f_2(1-t)$, and that leaving $G1$ is proportional to f_g, the measured excess noise at $N2$ is given by:

$$S_{N2} = 2g_Q \int_0^\infty \{F_{N2}(1-F_{N2}) + f_g(1-f_g)\} dE. \quad (1)$$

This expression can be divided into two contributions: $S_{\rm contacts}$—the noise emanating from reservoirs and transmitted (or reflected) by the constriction as t^2 [or $(1-t)^2$], and $S_{\rm QPC}$—the noise that results in the QPC constriction due to partitioning.

$$S_{\rm contacts} = 2g_Q \int_0^\infty [f_1(1-f_1)t^2 + f_2(1-f_2)(1-t)^2 + f_g(1-f_g)] dE$$
$$S_{\rm QPC} = 2g_Q \int_0^\infty \{t(1-t)[f_1(1-f_2) + f_2(1-f_1)]\} dE \quad (2)$$

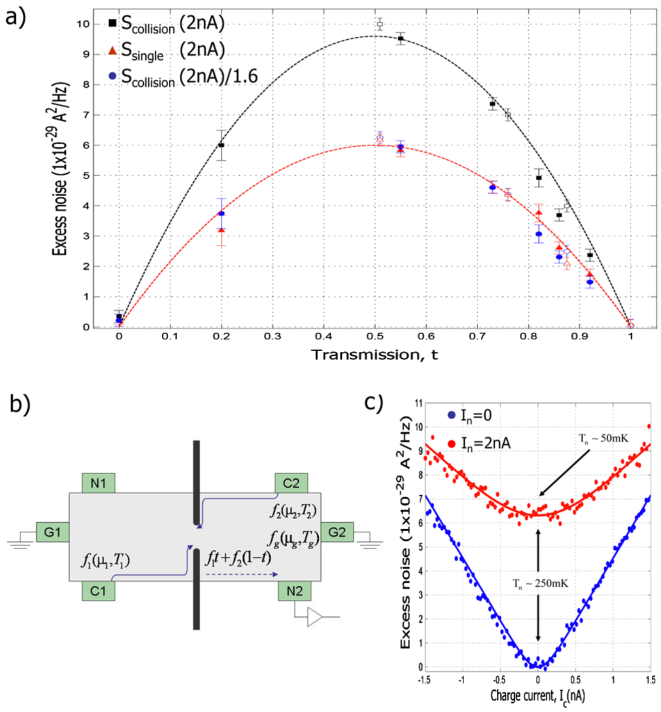

FIG. 2 (color online). Collision experiment—results and model. (a) Dependence of excess noise at injection current 2 nA on transmission probability t of the QPC—one (red triangles) or two (black squares) upstream neutral mode(s) reach the QPC. The noise follows the $t(1-t)$ trend (represented by a dashed line), with $S_{\text{collision}}/S_{\text{single}} = 1.6$ for all t. Empty/full shapes represent measurements performed on different samples. (b) Schematics of the model calculation in the text. The charge mode propagates from $C1$ or $C2$ toward the voltage probe and partitioned by the QPC. The measured noise signal is made of the emitted noise from the contacts and the noise generated at the QPC. (c) Noise generated by partitioning the charge mode. Without an excited neutral mode (blue [dark gray]), the noise agrees with the tunneling of $2e/3$ quasiparticles at low temperature. When a constant neutral mode is introduced to the opposite edge (red [medium gray], $I_n = 2$ nA), it elevates its temperature to T_n, and a reduction in the tunneling quasiparticles charge (to $e/3$) is observed. A temperature increase to $T_n \sim 50$ mK is estimated from the dependence of the noise near $I_c = 0$. In contrast, the increase in background noise leads to $T_n \sim 250$ mK.

In thermal equilibrium, with no voltage applied, $T_1 = T_2 = T_g$ and $\mu_1 = \mu_2$:

$$S_{\text{contacts}} = 4k_B T g_Q (t^2 - t + 1)$$
$$S_{\text{QPC}} = 4k_B T g_Q\, t(1-t). \qquad (3)$$

With the total noise $S = S_{\text{contacts}} + S_{\text{QPC}}$ measured in $N2$ is, as expected, $S_{\text{thermal}} = 4k_b T g_Q$ (independent of t). The excess noise, induced by increasing the electrochemical potential of the injected edge is:

$$S_{\text{excess}} = 2\Delta\mu g_Q t(1-t)\left[\coth\left(\frac{\Delta\mu}{2k_B T}\right) + \frac{2k_B T}{\Delta\mu}\right]. \qquad (4)$$

When the temperature is not the same in all contacts, their contribution to the noise is:

$$S_{\text{contacts}} = 2g_Q k_B[T_1 t^2 + T_2(1-t)^2 + T_g], \qquad (5)$$

however, that of the single constriction (S_{QPC}) can be solved only numerically.

We apply now this model to local heating in the constriction. According to this model the neutral mode increases the temperature of the current carrying channel. For simplicity we assume each neutral mode will heat only one side of the constriction from T_g to T_n, while all other contacts ($C1$, $C2$) remain at T_g, since they are located far enough (> 100 μm) from $N1$ and $N2$, and the neutral mode decays before reaching them. As a result excess noise is generated only at the QPC. Such energy exchange may be the reason for the decay of the neutral mode as it propagates upstream. The numerical solution for $T_n \gg T_g$ results in a modified Johnson-Nyquist noise,

$$S_{\text{QPC-single}} \simeq 2.75 k_b T_n g_Q t(1-t). \qquad (6)$$

Evidently, when the two sides of the constriction are heated to T_n in the "collision" type experiment, the Johnson-Nyquist noise is,

$$S_{\text{QPC-collision}} = 4k_B T_n g_Q t(1-t), \qquad (7)$$

agreeing with the main experimental observations for $N \rightarrow C$ as follows: (1) the temperature T_n grows linearly with the injected current, in agreement with the Wiedemann-Franz law (see Ref. [12]), hence also the observed noise ($T_n \gg T_g$), reaching $T_n \sim 250$ mK for $I_n = 2$ nA; (2) observed $S_{\text{QPC-collision}} = \alpha S_{\text{QPC-single}}$, with $\alpha = 1.6 \pm 0.1$, while estimated $\alpha = 1.45$; and (3) measured noise follows the predicted $t(1-t)$ dependence.

While the agreement with measurements is encouraging, the temperature estimate it provides ($T_n \sim 250$ mK) stands in contrast with measurements where a charge mode I_{c1} was injected from $C1$, and a neutral mode emanated from $N1$ (driven by current I_{n1}); with the two modes arriving at two opposite edges of the constriction. While the "charge side" of the constriction is at T_g the "neutral side" is at T_n. For a constant I_{n1}, our model predicts the two contributions to the excess noise are: an increased thermal noise for all I_{c1} with $T \rightarrow T_n/1.45$, and shot noise due to the partitioned I_{c1} obeying Eq. (4) with $T \rightarrow T_n/1.45$. The measured excess noise at $I_{c1} = 0$ and $I_{n1} = 2$ nA suggests $T_n \sim 250$ mK (as above) while the dependence of the excess noise on I_{c1} (the "rounding" near $I_{C1} = 0$, [18]) leads to $T_n \sim 50$ mK accompanied by an unpredicted reduction of the tunnelling charge in the constriction [see Fig. 2(c)] (see also Ref. [8]). While the reason for this discrepancy is not clear, recalling that a similar reduction from $2e/3$ to $e/3$

takes place with increasing the temperature to ~100 mK [9] may support the higher temperature estimate.

The interplay between charge and neutral modes raises the obvious question whether partitioning of a charge mode results also in energy transfer to an excited upstream neutral mode ($C \rightarrow N$). In principle, in order to perform this experiment one would need two constrictions; the first to test the $C \rightarrow N$ process and the second to detect the presence of the neutral mode via the $N \rightarrow C$ process. However, unexpectedly, and contrary to the previous experiments [8], we found that noise is generated at our Ohmic contacts (with no net current) when they absorb an upstream neutral mode at $\nu = 2/3$, $\nu = 3/5$, $\nu = 5/2$, $\nu = 5/3$, and $\nu = 8/3$ (in different samples) as shown in Fig. 3. No noise was observed when the same measurements were performed at filling factors which lack an upstream neutral edge mode (at $\nu = 1$, $\nu = 2$, $\nu = 3$, $\nu = 1/3$, $\nu = 2/5$, $\nu = 4/3$, $\nu = 7/3$). This effect may be related to the unique location of the heat dissipation we impose at the "front side" of the Ohmic contact. Usually, a "hot spot" is generated at the "back side" of a charged contact [19], when a difference in electrochemical potentials leads to dissipation with temperature increase. Here, an upstream neutral mode arrives at the "front side" of an unbiased contact, and thus heats up the injected downstream charge mode (from the unbiased contact). The distribution $f(\mu = 0, T_g)$ changes to $f(\mu = 0, T_n)$, resulting in excess noise $2k_B g_Q(T_n - T_g)$. For the current configuration, where the injecting and detecting contacts are 25 μm apart, the measured noise suggests

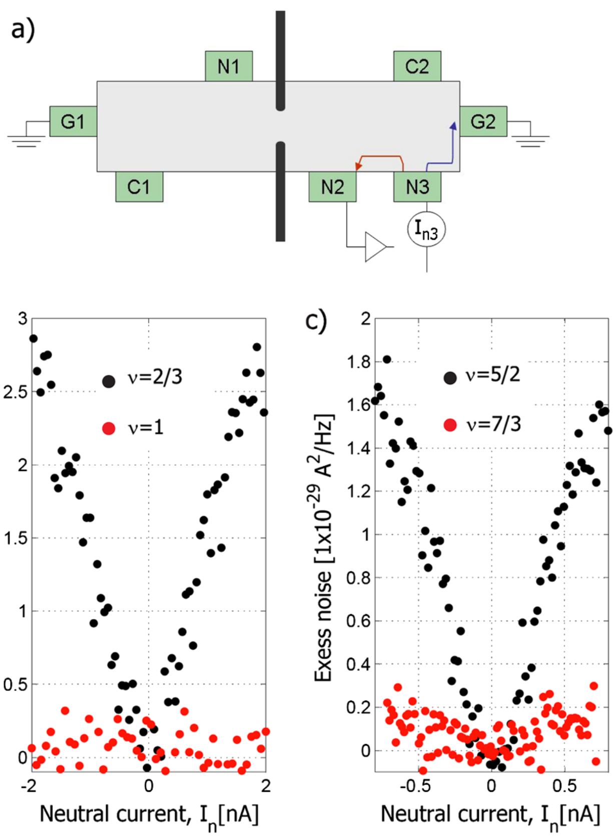

FIG. 3 (color online). Detection of the neutral mode by an Ohmic contact. (a) Schematics of the measurement setup. Injecting current from contact $N3$, gives birth to a neutral mode flowing upstream, reaching the voltage probe $N2$ (25 μm away), where it generates excess noise. (b) Noise at voltage probe $N2$ as a function of injected current at $N3$ for $\nu = 2/3$ (black). No noise is observed at $\nu = 1$ (red). (c) Similar results at the first excited Landau level, measured on a different sample. Noise signal is observed at $\nu = 5/2$ but not at $\nu = 7/3$.

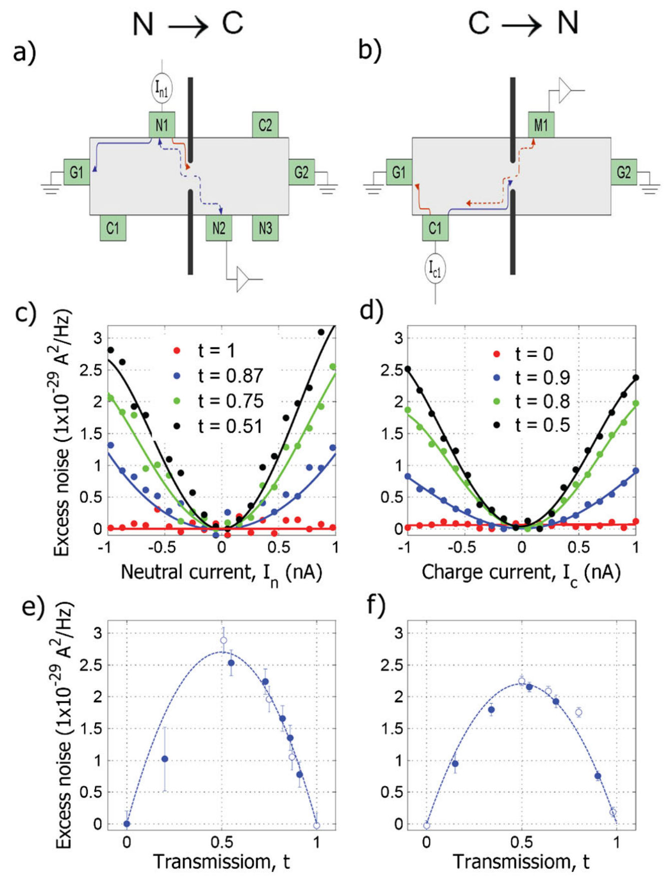

FIG. 4 (color online). $N \rightarrow C$ and $C \rightarrow N$ processes. (a) and (b) Schematics of the measurement setup for $N \rightarrow C$ and $C \rightarrow N$, respectively. In the $C \rightarrow N$ process, current (blue [dark gray]) is injected from source $C1$, flowing downstream and reaching the QPC, where it is partitioned. The neutral mode (red [medium gray]), generated at the QPC, flows upstream and reaches the voltage probe $M1$ (8 μm apart). The distance from the center of the QPC to $C1$ is 150 μm. (c) and (d) Noise measured at the voltage probe as a function of the injected current for different transmission probabilities t of the QPC. Noise in the $N \rightarrow C$ process is presented in (c), and noise in the $C \rightarrow N$ process is presented in (d). Data points are connected by a guide to the eye. (e) and (f) Noise measured at the voltage probe for different transmission probabilities t for 1 nA injection current. In the two plots the data follows the $t(1 - t)$ trend—given by a dashed line. Empty and full circles represent data points from different samples.

$T_n \sim 40$ mK—not an unreasonable temperature. It is presently unclear why this effect was not observed in the previous samples [8]. As we study this effect, we can only speculate now that it crucially depends on details in the interface between the contact and the 2DEG.

An injected downstream current I_{c1} was partitioned by a constriction with a resultant upstream neutral mode, which was detected at $M1$ [$C \rightarrow N$ process, see Fig. 4(b)]. Like in the $N \rightarrow C$ process, the noise increased with the source current with a dependence $t(1 - t)$ [Figs. 4(d) and 4(f)]. Being the ubiquitous dependence of shot noise on t due to stochastic partitioning, it suggests that the neutral mode is an outcome of the stochastic tunneling process of charged quasiparticles in the constriction. The observation of the $C \rightarrow N$ process opens up another way to identify the ground state wave function of the $\nu = 5/2$ state—the current best candidate for a non-Abelian state [20]. It might be important to note that such excitation of neutral modes may render the partitioning of charged quasiparticles inelastic, leading to incoherent scattering by the constriction, limiting its use as an elastic beam splitter in finite bias interference experiments [21,22].

Here, we explore in some depth some of the very basic properties of the upstream neutral modes in the 2/3 fractional state. We focused mainly on the mechanism of their detection and the interplay between the charge and neutral modes in a constriction. Our results suggest that neutral modes are likely to excite charge modes, in the narrow constriction, by heating them up. We observed a dual process, in which, partitioned charged quasiparticles transfer energy to upstream neutral modes. This observation brings to light an important question: Can partitioned charged quasiparticles, in a "hole-conjugate" fractional state, split, and thus partition, elastically, as needed in interference experiments?

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