# Melting of Interference in the Fractional Quantum Hall Effect: Appearance of Neutral Modes

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We attempted to measure interference of the outer edge mode in the fractional quantum hall regime with an electronic Mach-zehnder interferometer. The visibility of the interferometer wore off as we approached $\nu_B = 1$ and the transmission of the quantum point contacts (QPCs) of the interferometer simultaneously developed a $v = 1/3$ conductance plateau accompanied by shot noise. The appearance of shot noise on this plateau indicates the appearance of nontopological neutral modes resulting from edge reconstruction. We have confirmed the presence of upstream neutral modes measuring upstream noise emanating from the QPC. The lack of interference throughout the lowest Landau level was correlated with a proliferation of neutral modes.

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The discovery of the fractional quantum Hall effects (FQHEs) launched a four-decade-long search for anyonic quasiparticles [1]. Unlike bosons and fermions, these quasiparticles are restricted to exist only in two dimensions. Their exchange statistics [2] are particularly of interest, as they are not expected to follow the ubiquitous Fermi-Dirac or Bose-Einstein statistics. States in the FQHE regime and the edge modes they support are yet to be fully understood. What makes them elusive at times is the presence of different types of neutral modes [3], which are inert to standard electrical measurements. Indeed, neutral modes have recently found a niche in condensed matter physics; they can be topological Abelian [4–7], or the much sought after non-Abelian type [4,8,9]. It is also worth mentioning the nontopological neutral modes that emerge spontaneously due to unexpected edge reconstruction [10].

Interference of anyons is one of the stepping stones needed to establish their exchange statistics. In spite of substantial theoretical work [11–15], an observation of anyonic statistics still remains an experimental challenge. To achieve this purpose, electronic interferometers, be it a Mach-Zehnder interferometer (MZI) [16,17] or a Fabry-Perot interferometer [18–21], have been realized in the quantum Hall effect (QHE) regime. While interference of electrons in the integer QHE is relatively easy to find, reports on observation of interfering quasiparticles [22,23] was not universally substantiated. Our own efforts to observe quasiparticle interference in a MZI, as the bulk filling factor is lowered towards $\nu_B = 1$ and lower, failed [24]. Here, we report finding a direct correlation between the appearance of neutral modes and the disappearance of interference. Specifically, the interference was found to gradually diminish starting from $\nu_B \sim 1.5$ and lower, with an apparent increase of the excitation of the neutral modes (established with a few independent methods). A striking observation was an unexpected appearance of a $\nu_{QPC} = 1/3$ conductance plateau in the QPCs that carried shot noise. This uncharacteristic "noise on plateau" persisted in the range ½ < $\nu_B < 1.5$, resulted due to edge reconstruction that led to an upstream neutral mode. We also show that particlelike states in the lowest Landau level, $\nu_B < 1/2$, are also accompanied by upstream neutral modes—independent of the sharpness of the edge potential in our system. Such energy-carrying modes are expected to dephase the interference.

Three different GaAs-AlGaAs heterostructures, with 2D areal density $n = (0.88–1.00) \times 10^{11}$ cm$^{-2}$ and a 4.2 K dark mobility of $\mu = (4.6–5) \times 10^6$ cm$^2$/V s, were used to fabricate our structures. Devices were patterned on "wet-etched" Hall bar mesas, with alloyed Ni/Ge/Au Ohmic contacts and thin PdAu/Au gates. The electrical conductance and shot noise were measured using a two-stage amplification setup, composed of a cooled (to 4.2 K) homemade voltage preamplifier followed by a commercial RT amplifier (NF-SA 220F5).

We adopted the device design of a MZI that also allows observing neutral modes (Fig. 1). The MZI (lithographic area ∼30 $\mu$m$^2$), preceded by QPC$_0$ [SEM image in Fig. S1(a) in the Supplemental Material [25] ], has two source contacts—labeled $S1$ and $S2$—and three drains $D1$, $D2$, and $D3$. Ground contacts $G$, electrically shorted to the "cold finger" at ∼10 mK, are effective in cooling the electrons. Shot noise, measured in $D1$, is effective in the determination of the electron temperature [27] and the presence of upstream neutral modes [10].

As shown in Fig. 1, the MZI is composed of QPC$_L$ and QPC$_R$, serving as beam splitters, and two drains, $D1$ and $D2$ ($D2$ grounded). The width of the split gates that form

 

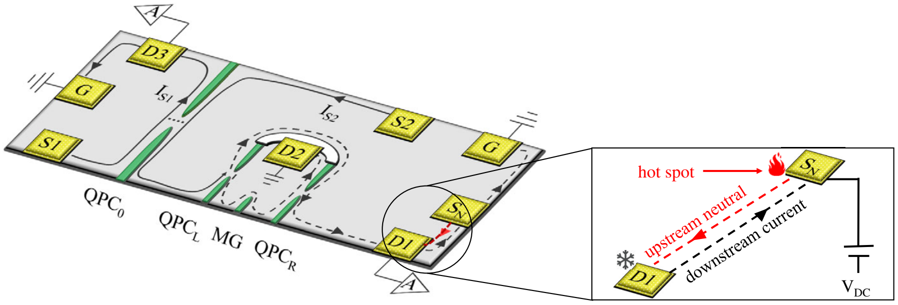


FIG. 1. Device schematic. Schematic of the structure. The outer periphery is defined by an etched mesa. The MZI is defined by two QPCs, labeled as $\text{QPC}_L$ and $\text{QPC}_R$, with the upper path separated by an etched mesa (a white arc). The modulation gate, affecting the area of the MZI, is labeled as MG. The path of the interfering edge channel along the mesa is shown in black broken lines with arrows defining the chirality. Shot-noise measurements were performed using $\text{QPC}_0$, whereas for conductance measurements all the QPCs were used. $\text{QPC}_0$ can also be used to switch between $I_{S1}$ and $I_{S2}$ as the impinging edge channels on the MZI.

the QPCs are ~40 nm wide [Fig. S1(b)]. The modulation gate (MG) is used to vary the threaded Aharonov-Bohm (AB) flux in the MZI. An added source contact $S_N$, placed 7 $\mu$m downstream from the preamplifier, is used to excite an upstream neutral mode (by the "hot spot" [28]).

The profile of the chiral edge modes is customarily accessed by scanning its transmission through the QPC. A conductance plateau indicates full transmission (and full reflection) of certain edge modes. Since no partitioning of particles then takes place, the transmitted current is expected to be noiseless [27]. However, as described below, we found an exceptional behavior in a range of bulk states, ½ $< \nu_B <$ 1.5. A clear QPC conductance plateau in filling $\nu_{\text{QPC}} = 1/3$ was observed—carrying downstream shot noise (Fig. 2 and Fig. S2 in the Supplemental Material [25]). This type of "noise-carrying plateau" was identified to result from an excitation of upstream neutral modes in the QPC (referred to as the "noisy plateau" hereafter) [29].

We dwell initially on the correlation we found between the strength of the visibility of the AB interference and the

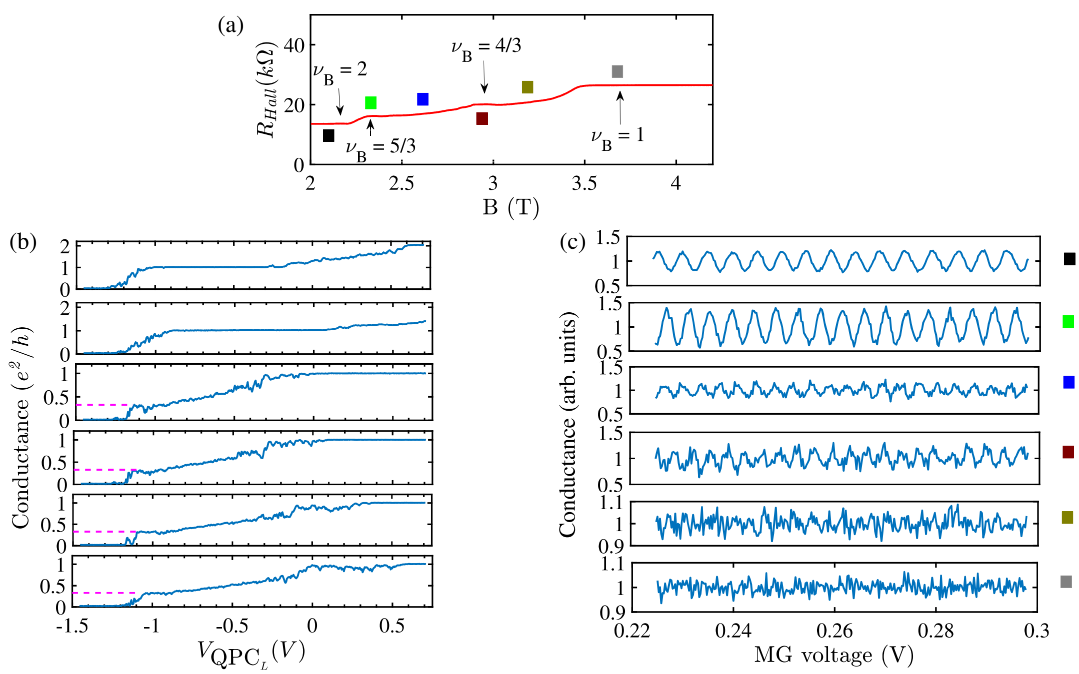


FIG. 2. Correlation between the appearance of a $\nu = 1/3$ noisy plateau and the diminishing interference in the MZI. (a) A "two-probe" quantum Hall resistance as a function of magnetic field in bulk filling $\nu_B = 2$ to $\nu_B = 1$. Filling factors corresponding to observed plateaus are noted with arrows showing the plateaus. The colored squares show the places where the experiments for (b) and (c) were performed. (b) Plots show the conductance vs gate voltage applied to $\text{QPC}_L$ at different bulk states. The dotted magenta lines are a guide to the eye of the $\nu = 1/3$ conductance plateau in the QPC. (c) Plots show the corresponding interference signal of the outermost edge mode as a function of MG voltage in the MZI. Note the diminishing visibility of interference once $1/3$ plateau in the QPC appears. The interference quenches once the plateau is fully grown at $\nu_B = 1$.

apparent excitation of neutral modes (in the range $1 \leq \nu_B < 2$). The noisy plateau will be one of our "canaries in a coal mine," indicating an excitation of an upstream neutral mode. The noise on this plateau was characterized by a Fano factor $F$ in the expression of the spectral density of the current fluctuations $S_i$ (at zero temperature): $S_i = 2FeIt(1\text{-}t)$, where $I$ is the impinging current, $t$ is the transmission coefficient of the QPC, and $e$ is the electron charge [27,30].

We start by monitoring the transmission of $\mathrm{QPC}_L$ as the bulk filling is lowered from $\nu_B = 2$. Simultaneously, the AB interference of the outermost $v = 1$ edge mode is monitored in the MZI. Strong AB oscillations were observed as the bulk filling approached $\nu_B \sim 5/3$ [top two panels in Fig. 2(c)]. The oscillation's visibility gradually diminished with lowering further the filling factor, concomitantly with an appearance of $v = 1/3$ noisy plateau (see also Fig. S2 [25]). As shown in Figs. 3 and 4, the Fano factor was equal to the quantized bulk fillings ($\nu_B = 1, 2/3, 3/5, 4/7$) [30,31].

In a different, complementary, and more direct measurement, an upstream neutral mode was found to be excited in a partly pinched QPC at $\nu_B = 1$. This was done by measuring the upstream noise in a contact placed 7 $\mu$m upstream from the QPC along a gated mesa [Figs. S3(a) and S3(b)] [10].

We attribute the onset of upstream neutral modes at bulk fillings $1 < \nu_B < 1.5$ to a spontaneous reconstruction of the edge potential leading to two downstream chiral edge modes: an inner $v = 2/3$ and an outer $v = 1/3$. This is similar to the reconstruction of the edge at $\nu_B = 2/3$, which led to two copropagating $v = 1/3$ chiral modes (accompanied by two upstream neutral modes) [29]. Here, say, in $\nu_B = 1$, the reconstructed $v = 2/3$ and $v = 1/3$ modes [Fig. S4(a)], split at the QPC to two modes that equilibrate downstream with the released energy exciting an upstream neutral mode [Fig. S4(b)]. Moving upstream, the neural modes fragment at the QPC to electron-hole pairs, giving rise to downstream shot noise [Fig. S3(b)].

It is important to stress here that the appearance of neutral modes at $\nu_B = 1$ is not topological, and they are relatively short lived. The thermal conductance of any bulk filling must obey a universal value, being for $\nu_B = 1$ a single quanta of thermal conductance (without topologically added modes) [32,33]. As the bulk filling is lowered further, entering the "hole-conjugate regime," the presence of counterpropagating modes (usually, more than a single neutral mode) becomes a topological must [7,32,33]. Indeed, the $v = 1/3$ noisy plateau (Fig. 3) remained prominent (accompanied by more noisy plateaus) up to bulk filling $\nu_B = 1/2$. Figure 4 shows such plateaus and the corresponding shot noise on the $v = 1/3$ plateau as the filling is being lowered. The Fano factor (not shown in all plateaus) in every noisy plateau was found to be that of the corresponding bulk filling ($F = 2/3$, $3/5$, and $4/7$, respectively). As the bulk filling approached $\nu_B = 1/2$, the $v = 1/3$ noisy plateau shrinks and disappears. In bulk fillings lower than $\nu_B = 1/2$, i.e., in the particlelike regime ($\nu_B = 4/9$, $3/7$, $2/5$), all the QPC conductance plateaus correspond to the integer number of composite fermion modes and do not carry any downstream shot noise, as expected. However, upstream neutral edge modes are prevalent in all these particle states. Being nontopological, they were found to survive only in short upstream propagating distances (~10–20 $\mu$m propagation length, and in Ref. [10]).

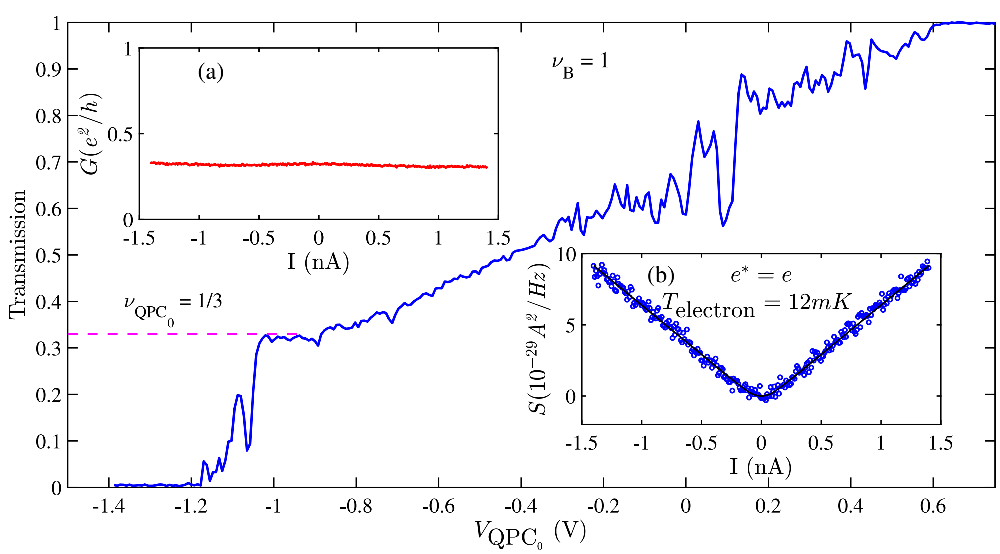


FIG. 3. Differential conductance and shot noise at $\nu_{\mathrm{QPC}} = 1/3$ at bulk filling $\nu_B = 1$. The peripheral axes are defined for transmission through $\mathrm{QPC}_0$ as a function of gate voltage. A plateau at $t = 1/3$ (dotted magenta line) shows the formation of $e^2/3h$ conductance plateau in the QPC. (a) The nonlinear differential conductance of $\mathrm{QPC}_0$ as a function of dc bias applied to the source at $t = 1/3$. (b) Shot noise at the $t = 1/3$ plateau. Black solid line shows the fitting curve to the shot-noise data. Partitioned quasiparticles charge (here, the Fano factor) and temperature as obtained by the fitting curve is provided as inset text.

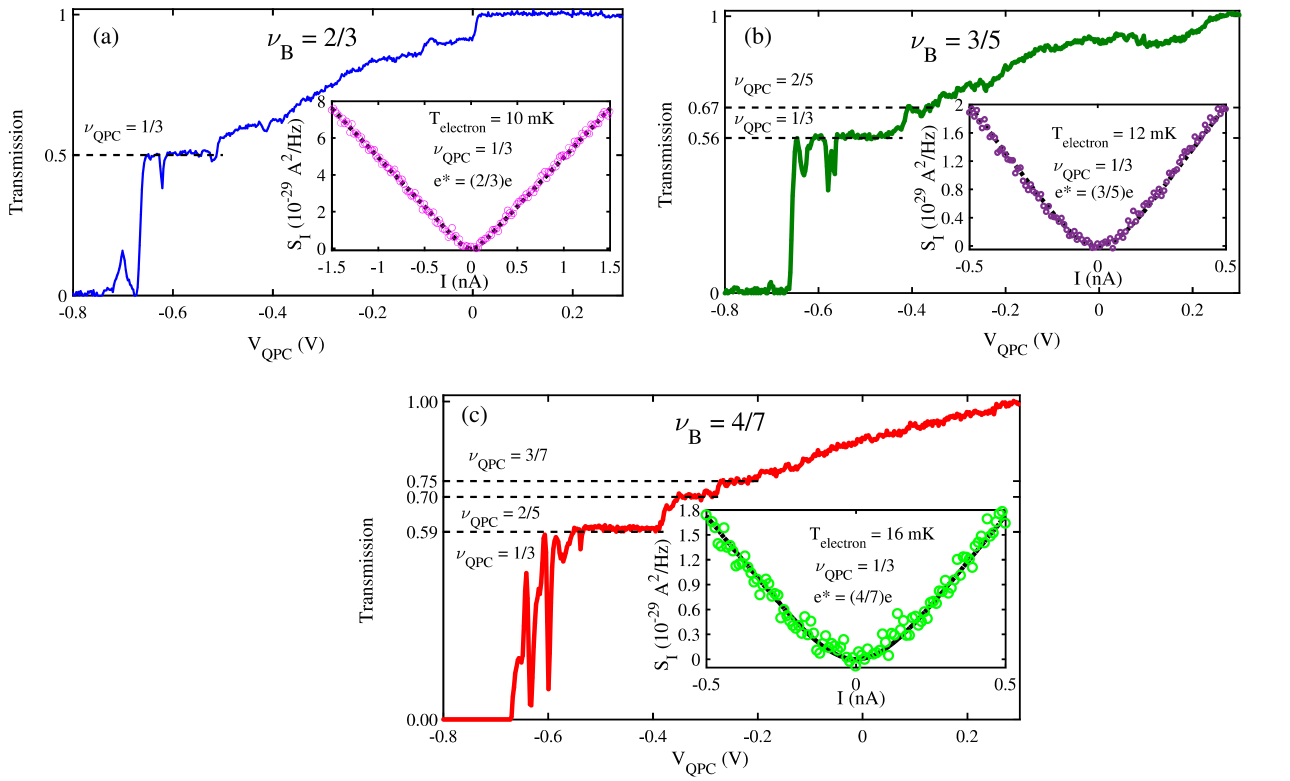


FIG. 4. Differential conductance and shot-noise in the hole-conjugate states $\nu_B = \frac{2}{3}, \frac{3}{5}, \frac{4}{7}$. The transmissions through $QPC_0$ as a function of applied voltage on the split gates, showing conductance plateaus for three different filling factors ($\nu_B = 2/3$–$v = 1/3$ plateau; $\nu_B = 3/5$–$v = 1/3$ and $2/5$ plateaus; $\nu_B = 4/7$–$v = 1/3$, $2/5$, and $3/7$ plateaus). (Insets) Excess noise measured on the $v = 1/3$ plateau in each filling factor. Fitted lines through the noise data gives the Fano factors corresponding to each bulk filling.

The source marked as $S_N$ (Fig. 1, inset) was dc biased in order to excite upstream neutral modes that emerge from the hot spot at the upstream side of $S_N$ [4,24], with excess noise measured in $D1$ (Fig. S5) [10]. The measured noise in the particlelike states was much more feeble than the noise measured under similar conditions at $\nu_B = 2/3$, and it vanished at ~90 mK. No upstream noise could be measured at the lowest temperature when the propagating distance was increased to 30 $\mu$m.

Attempts to quench these nontopological upstream modes by sharpening the edge-potential profile by positively biasing a side gate on the etched mesa failed [Figs. S6(a) and S6(b)].

With the onset of edge reconstruction at bulk filling $\nu_B \sim 1.5$, the observed interference in a MZI was found to decay, to fully quench at $\nu_B = 1$. The interference did not recover throughout the fractional regime, $\nu_B < 1$. This was correlated with the appearance of neutral modes, be it topological or resulting from edge reconstruction [34–36]. The exact cause of edge reconstruction in the lowest Landau level, i.e., $\nu_B < 2$, leading to proliferation of upstream neutral modes, is not clear, but is assumed to result from the softness of the edge potential in the GaAs system. Artificial construction of chiral fractional modes away from the physical edge of the 2DEG may lead to a more controlled local potential and thus quench nontopological neutral modes.

Proliferations of unprecedented nontopological neutral energy-carrying chiral edge modes, causing the disappearance of coherence, have been identified. Two methods were employed: (1) via detecting a downstream shot noise on a $v = 1/3$ conductance plateau in a quantum point contact at bulk filling factors $2 < v \leq 1$ and (2) via observing an upstream noise emanating from the back side of a source contact. In all bulk fillings $v < 1$, upstream neutral modes persisted, either being topological in the hole-conjugate states or emergent (nontopological) in the particlelike states, with no signature of coherent interference.

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