





Synthesizing $2h/e^2$ resistance plateau at the first Landau level confined in a quantum point contact

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A comprehensive understanding of quantum Hall edge transmission, especially a hole-conjugate of a Laughlin state such as a $2/3$ state, is critical for advancing fundamental quantum Hall physics and enhancing the design of quantum Hall edge interferometry. In this study, we show a robust intermediate $2h/e^2$ resistance quantization in a quantum point contact (QPC) when the bulk is set at the fractional filling $2/3$ quantum Hall state. Our results suggest the occurrence of two equilibration processes. First, the co-propagating $1/3$ edges moving along a soft QPC arm confining potential fully equilibrate and act as a single $2/3$ edge mode. Second, the $2/3$ edge mode is further equilibrated with an integer 1 edge mode formed in the QPC. The complete mixing between them results in a diagonal resistance value quantized at $2h/e^2$. Similar processes occur for a bulk filling $5/3$, leading to an intermediate $(2/3)h/e^2$ resistance quantization. This finding highlights the importance of understanding the equilibration mechanisms that occur between different edge modes, offering insights into the processes of edge equilibration.

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When a two-dimensional electron gas (2DEG) is placed in a strong magnetic field at low temperature, its Hall resistance can be quantized into $(1/\nu)h/e^2$ (or $\nu e^2/h$ in conductance). Fractional Quantum Hall Effects occur when the filling factor ν takes a fractional number. They exhibit several remarkable properties, such as fractional charge excitations¹, fractional or anyonic statistics², and chiral Luttinger edge modes³. The nature of Luttinger liquid is manifested in the power-law behavior of the tunneling conductance, which has been experimentally verified^{4,5}. While the original Laughlin states, $1/(2m+1)$ with m being an integer, carry a single chiral edge mode as described by Wen^{6,7}, other fractional states derived from the Laughlin states, such as in the Haldane-Halperin hierarchy^{8,9}, can be reconstructed and may carry multiple propagating edge modes¹⁰. A prominent example is the $\nu = 2/3$ fractional state, the hole-conjugate of Laughlin $\nu = 1/3$ state, where several edge models have been contested to date^{10–13}.

The reconstructed edge states for the fractional $2/3$ depend on the profile of the edge confining potential. For a sharp confining potential, such as the edge of a Hall bar, MacDonald has proposed that the $2/3$ edge is reconstructed into two distinct counter-propagating states: a downstream integer 1 edge state and an upstream fractional $-1/3$ edge state¹⁰. An ideal Büttiker two-terminal conductance for the MacDonald edge picture should result in $(4/3)e^2/h$ quantized conductance¹⁴; however, $(2/3)e^2/h$ is usually observed. A theory proposed by Kane-Fisher-Polchinski suggests that the two-terminal conductance quantization can yield $(2/3)e^2/h$ due to the formation of a single downstream $2/3$ charge mode and an upstream neutral mode in the presence of

disorders and interactions between the edges¹¹. This edge model has been verified through a recent experiment by Cohen et al.¹⁵. Conversely, for a soft confining potential, Meir has proposed that two co-propagating downstream fractional $1/3$ edge channels are more favorable to form¹². Indeed, in a quantum point contact (QPC) with a soft confining potential, an intermediate quantized conductance $(1/3)e^2/h$ is observed^{16,17}, consistent with the Meir edge picture.

Fu et al.¹⁸ reported a $G_{\text{QPC}} = (3/2)e^2/h$ plateau when the bulk filling is set to $\nu_{\text{bulk}} = 5/3$ in an ultra-high mobility constriction; and Hayafuchi et al.¹⁹ reported a similar plateau in a conventional QPC with a center gate. Yan et al.²⁰ conducted an extended experiment over a wider bulk filling factor and provided an interpretation by assuming an important role of an elevated density in the constricted region. However, there is no experimental proof of this assumption in this intermediate half-conductance state, and the possible more fundamental state of $G_{\text{QPC}} = (1/2)e^2/h$ and $\nu_{\text{bulk}} = 2/3$, which may be created by removing the outer integer 1 edge channel from $G_{\text{QPC}} = (3/2)e^2/h$ and $\nu_{\text{bulk}} = 5/3$.

Nakamura et al.¹⁷ reported an interesting observation of an intermediate half-conductance plateau $G_{\text{QPC}} = (1/2)e^2/h$ in a particular dc-biased non-linear conductance region by utilizing a specially designed GaAs/AlGaAs heterostructures. They explain the intermediate half-conductance plateau as being due to the full reflection of the inner counter-propagating $-1/3$ edge mode, which may be induced by a sharp QPC confining potential where the MacDonald edge picture is favorable to form.

Here, we employ a conventional QPC possessing a soft confining potential, where the Meir edge picture is more favorable, and directly controls the filling factor in the constricted region. Under these conditions, we found a clear intermediate $G_{\text{QPC}} = (1/2)e^2/h$ plateau without dc bias and experimentally demonstrated the essential role of elevated density in the constricted region. We propose a model to explain our observations based on an inter-edge mixing between the two propagating $1/3$ and integer 1 edge modes formed at the edge of the QPC.

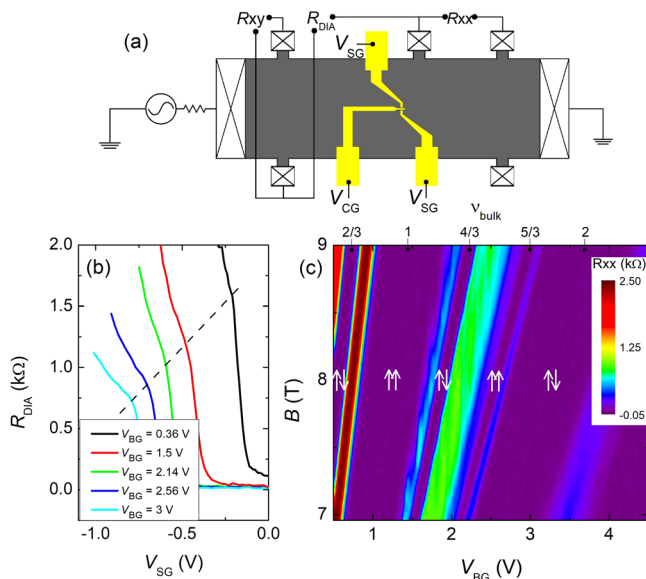


Fig. 1 Device and basic transport properties. **a** Schematic of device and measurement setup. A pair of split gates defines a quantum point contact (QPC). An additional center gate in between the split gates is used to control the density inside the quantum point contact. The length of the split gates is 500 nm, with the gap between them being 500 nm. The width of the center gate is 300 nm. **b** Zero-field diagonal resistance R_{DIA} as a function of split gate bias voltage V_{SG} measured at five different back gate bias voltage V_{BG} values and center gate bias voltage $V_{\text{CG}} = 0$ V. The dashed line corresponds to the threshold voltage to deplete electron density underneath the split gates. The split gates are equally biased throughout the measurements. **c** 2D map of bulk longitudinal resistance R_{xx} measured as a function of back gate bias voltage V_{BG} and magnetic field B . Several notable bulk-filling factors ν_{bulk} and the corresponding spin-states are indicated.

Results and discussion

Basic transport properties. The device and measurement setup are schematically depicted in Fig. 1a (refer to Methods for detailed information on device fabrication and measurements). The QPC is defined by applying a negative bias voltage to a pair of split gates (V_{SG}). Additional center metal gate (V_{CG}) put in between the split gates is used to control the QPC electron density¹⁹, as well as the QPC confinement potential^{21–23}. Figure 1b displays the basic operation of our QPC at zero magnetic fields under various 2DEG densities controlled by the back gate voltage (V_{BG}). The threshold voltage, at which the electron density underneath the split gates is completely depleted, scales linearly with V_{BG} (indicated by the dashed line in Fig. 1b). This is consistent with that of a parallel plate capacitor model²⁴. By applying a more negative bias to V_{SG} , we can observe a series of quantized conductance steps, similar to the previous report in ref. 19. Further details of basic transport properties are given in supplementary note 1.

Figure 1c displays a 2D map of bulk longitudinal resistance R_{xx} as a function of V_{BG} and magnetic field B . We can attribute the spin polarization for each quantum Hall state observed in Fig. 1c, in particular for the fractional $2/3$ and $5/3$ states. The spin for the fractional $2/3$ state, within the magnetic field window shown in Fig. 1c, is unpolarized as we do not observe a spin transition to spin-polarized. We expect the spin transition to occur at a higher magnetic field for a narrow quantum well owing to the large Coulomb interaction^{25,26} (spin transition measured in a wider

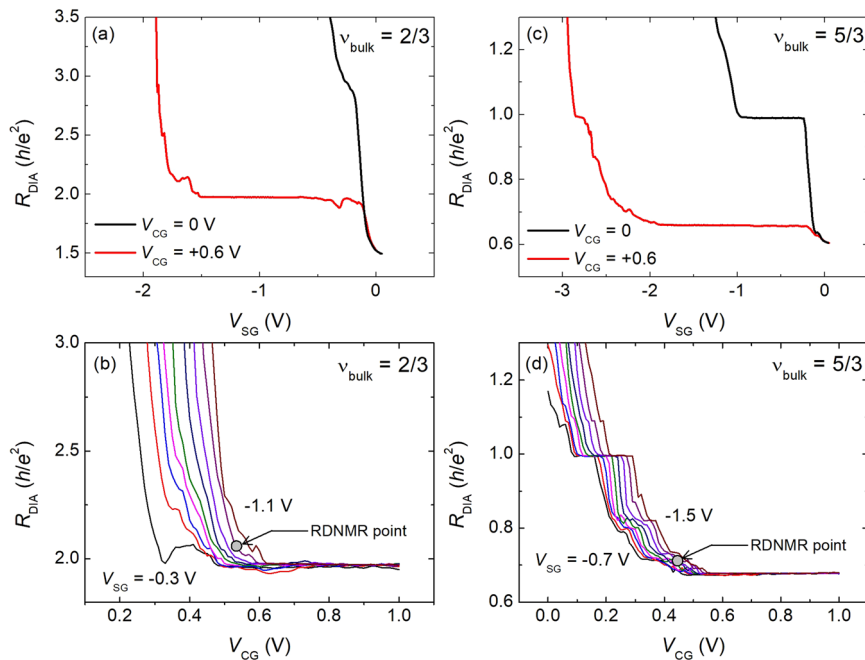


Fig. 2 Observation of $2h/e^2$ and $(2/3)h/e^2$ resistance plateaus from edge mixing in the quantum point contact. **a** Diagonal resistance R_{DIA} measured as a function of split gate bias voltage V_{SG} with the bulk filling factor set to $\nu_{\text{bulk}} = 2/3$. An extended intermediate resistance plateau at $2h/e^2$ is observed for $V_{\text{CG}} = +0.6$ V. **b** Diagonal resistance R_{DIA} is now measured as a function of center gate bias voltage V_{CG} at several split gate bias voltage V_{SG} values at an interval of 0.1 V. **c, d** Similar to the case in **a, b**, but the bulk filling factor is set to $\nu_{\text{bulk}} = 5/3$. All the data are measured at 100 mK and 7 T. RDNMR point displayed in **b** and **d** describes a point where resistively-detected nuclear magnetic resonance (RDNMR) measurements are carried out.

quantum well is given in Supplementary Note V). On the other hand, the spin of the fractional $5/3$ ($=2-1/3$) state is established both theoretically²⁷ and experimentally measured by Resistively-Detected NMR (RDNMR)²⁸ to be always fully polarized, similar to the fully polarized $\nu = 1/3$ Laughlin state¹.

Emergence of $2h/e^2$ and $(2/3)h/e^2$ resistance plateaus from edge mixing in QPC. Figure 2a displays the transport through the QPC at two V_{CG} bias values with the bulk fractional filling set to $\nu_{\text{bulk}} = 2/3$. At $V_{\text{CG}} = 0$ V where the density in the middle of the QPC would presumably be equal to or slightly smaller than the bulk density, we observe a weak intermediate plateau at $R_{\text{DIA}} = 3h/e^2$ centered around $V_{\text{SG}} = -0.24$ V. This observation is consistent with the Meir edge picture. However when the center gate is biased with a positive voltage $V_{\text{CG}} = +0.6$ V, we expect the density in the middle of the QPC to be higher than the bulk. In this case, as the V_{SG} is swept toward a negative voltage and passes the threshold voltage, the diagonal resistance gets quantized to within 2% of $R_{\text{DIA}} = 2h/e^2$. The plateau extends over a wide range of V_{SG} before the channel finally pinches off with no other intermediate plateaus observed in between. This exceptionally long extended plateau suggests the existence of a stable edge channel formed inside the QPC. The plateau persists over a wide gate voltage and temperature range of up to approximately 300 mK (see Supplementary Note II and III for temperature and magnetic field dependence). No intermediate $3h/e^2$ resistance plateau is observed, as in the usual case. It is presumed that a non-linear confining potential created by the center gate destabilizes the formation of $\nu = 1/3$ state in our QPC²⁹. No finite dc bias is required to stabilize the $2h/e^2$ plateau, as in ref. ¹⁷, suggesting that the inter-edge back-scattering in the QPC is highly suppressed.

We then examine the influence of applying positive center gate bias V_{CG} on transport properties. Applying positive V_{CG} increases the electron density in the QPC. V_{CG} is swept at several fix V_{SG}

bias voltages from -0.3 down to -1.1 V with an interval of 0.1 V as displayed in Fig. 2b. To deplete the electron underneath the split gate, a threshold voltage of -0.21 V is required (see the black curve for $V_{\text{BG}} = 0.36$ V in Fig. 1b) for the QPC to always be defined. A pronounced dip in the R_{DIA} at $V_{\text{SG}} = -0.3$ V before reaching the plateau, shown in Fig. 2b, is indicative of interaction between an edge channel running outside the QPC and a classical skipping orbit formed inside the QPC^{30,31}. The dip disappears when a more negative bias voltage is applied to V_{SG} because the effective channel length increases. All curves merge toward $2h/e^2$ with the increase in V_{CG} . This observation complements the result shown in Fig. 2a, and more importantly, it gives us a solid idea that the density inside the QPC is higher when the $2h/e^2$ quantization occurs.

We perform similar measurements for a bulk filling factor $5/3$ at a magnetic field of 7 T, as displayed in Fig. 2c. The filling factor $5/3$ is supposed to have an edge structure similar to that of the filling factor $2/3$, but with an additional outer integer 1 edge mode. Accordingly, for $V_{\text{CG}} = +0.6$ V, we observe an intermediate long plateau at $(2/3)h/e^2$ followed by a short intermediate h/e^2 plateau before the channel pinches off, in line with our previous finding using a wider GaAs quantum well and shorter QPC geometry size¹⁹ and Ref. ^{18,20}. No intermediate resistance plateau $(2/3)h/e^2$ is observed for $V_{\text{CG}} = 0$ V, in agreement with our previous study¹⁹. Sweeping V_{CG} at a fix V_{SG} , as shown in Fig. 2d, yields quantitatively similar results where all curves merge with the $(2/3)h/e^2$ plateau but with the h/e^2 plateau being more well-developed. In addition, we observe a plateau-like structure at approximately $(0.8)h/e^2$ and $(0.7)h/e^2$ between $(2/3)h/e^2$ and h/e^2 plateaus, which are absent in Fig. 2b. Development of another resistance plateau from different fractional and integer quantum Hall states is given in the Supplementary Note IV.

The mechanism of edge mixing in QPC. Next, we discuss the model to explain $2h/e^2$ and $(2/3)h/e^2$ resistance quantization. We

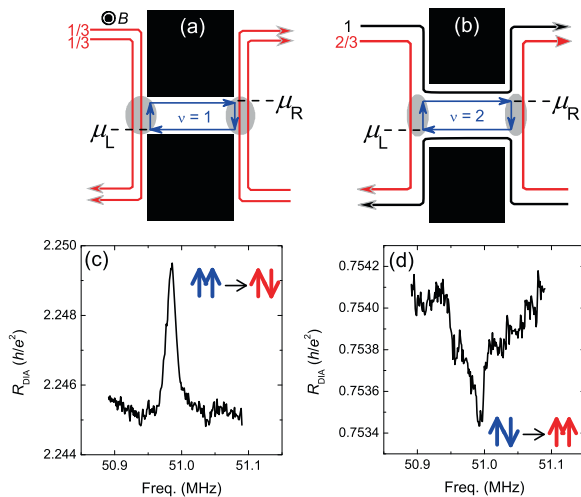


Fig. 3 Edge mixing model and resistively-detected nuclear magnetic resonance spectra in the quantum point contact. Schematic of edge structure when the inner edge $2/3$ mixes with an integer **a** 1 or **b** 2 in the quantum point contact, leading to the resistance quantization at $2h/e^2$ and $(2/3)h/e^2$, respectively. The gray circle regions indicate the equilibration. μ_L and μ_R denote the chemical potential at which the edges are fully equilibrated. **c, d** Resistively-Detected Nuclear Magnetic Resonance spectra recorded in the quantum point contact at the bulk filling $2/3$ and $5/3$ with increasing frequency at a radio frequency power of -30 dBm. The inset shows the spin-flip scattering inducing nuclear spin polarization. The Resistively-Detected Nuclear Magnetic Resonance spectra are carried out near the $2h/e^2$ and $(2/3)h/e^2$, respectively.

consider the co-propagating $1/3$ fractional edges running along the soft edge potential equilibrating with the integer 1 edge at the entrance and exit of the point contact, as indicated by the gray circle in Fig. 3a. The fully equilibrated point, where the chemical potential becomes the same, can be modeled as an Ohmic contact²⁰ and we label them as μ_L and μ_R . Considering the equilibration length for $\nu = 2/3$ at 6.5 T is $\sim 8 \mu\text{m}$ ³² and the QPC arm is much longer than $8 \mu\text{m}$, it is reasonable to assume that the co-propagating $1/3$ edge modes are in the incoherent regime (fully equilibrated)³³ before entering the QPC and mixing with the integer 1 edge mode. We can presume the co-propagating $1/3$ edge mode as a single $2/3$ edge mode when it mixes with the integer 1 edge mode. Considering these two equilibration processes, we can express the formula similar to that derived by Yan et al. in ref.²⁰

$$R_{\text{DIA}} = \frac{h}{e^2} \left/ \left(\frac{\nu_{\text{bulk}} - i}{2 - (\nu_{\text{bulk}} - i)} + i \right) \right. \quad (1)$$

Plugging $\nu_{\text{bulk}} = 2/3$ and $i = 0$ yields $2h/e^2$ resistance quantization, in agreement with the observed value. We get $(2/3)h/e^2$ value for the bulk filling factor $5/3$ with $i = 1$ since we have an additional outer integer 1 edge mode as indicated in Fig. 3b. It is important to note that the actual path where the inter-mode edge mixing happens may not follow a straight line, as drawn in the schematic. The actual path may follow a more complex route owing to the geometry of the center gate.

We can infer the edge spin polarization by using spin-flip scattering-induced dynamic nuclear polarization (DNP) and RDNMR³⁴. DNP requires a momentum-conserving spin flip-flop process between two edges with different spin polarities. In other words, no DNP occurs and hence no RDNMR signal arises if the edges have similar spin polarities. The spin flip-flop processes operate equivalently in integer (governed by electrons) and fractional (governed by CF quasi-particles) quantum Hall

states, as reported by Kou et al. for QPCs³⁵. The polarity of nuclear spin polarization is determined by the direction of the spin-flip process³⁶, which can modify the diagonal resistance of the QPCs.

Since the filling factor $2/3$ at a magnetic field of 7 T is a spin-unpolarized state as noted in Fig. 1c and the filling factor 1 is a spin-polarized state, we expect the spin-flip process to occur in the QPC with the direction indicated in the inset of Fig. 3c. The flip polarizes the nuclei in the direction parallel to the external magnetic field. RDNMR measurements are carried out near the plateau at a point shown in Fig. 2c, d. We sweep the rf frequency around ^{75}As nuclei, as displayed in Fig. 3c and observe a peak in the diagonal resistance at a frequency of 50.986 MHz. On the other hand, when we tune the bulk to the filling factor $5/3$ and the QPC to the filling factor less than 2, we expect a reversal in the RDNMR signal. This is because the filling factor 2 is a spin-unpolarized state while the filling factor $5/3$ is a spin-polarized state. Indeed, we observe a reversal in the RDNMR spectrum as displayed in Fig. 3d with a resonance frequency occurring at 50.993 MHz. Although the fractional $2/3$ and the inner fractional $5/3$ are expected to have the same edge mode, our RDNMR measurements revealed that they have different spin structures. In addition, pump-and-probe RDNMR measurements suggest a gradual change in electron density inside the QPC even in the plateau region (see Supplementary Note VI). This suggests an important role of the integer edge channel formed in the QPC.

In summary, we synthesized $2h/e^2$ and $(2/3)h/e^2$ resistance quantization in the QPC within 2% deviation. We proposed a model to explain the observed quantization based on edges mixing between the co-propagating $1/3$ edges and integer 1 edge formed inside the QPC. We confirmed the spin polarization of these edges through current-induced DNP and RDNMR measurements, which is consistent with the proposed model to explain the $2h/e^2$ and $(2/3)h/e^2$ quantization. Our findings shed light on the importance of edge channel equilibration processes in driving anomalous resistance quantization. Understanding the interactions of edges in a QPC is crucial for improving the design of quantum Hall interferometry and fractional quantum Hall-based quantum circuitry.

Methods

Device fabrication. Our measurements were conducted using an 18-nm-wide GaAs/AlGaAs quantum well, with the 2DEG located 185 nm beneath the surface. The wafer was processed into a 100 μm Hall bar using standard photolithography and wet etching techniques, with etching extending ~ 200 nm below the surface. Ohmic contact pads were created by sequentially evaporating Ni(5 nm)/AuGe(250 nm)/Ni(25 nm) metals in vacuum. The metals were then rapidly annealed at 390 $^\circ\text{C}$ for 1 min in a hydrogen gas flow chamber. Fine surface gates, patterned by using electron beam lithography, were composed of Ti(5 nm)/Au(25 nm) metals, evaporated in sequence using electron beam in a vacuum. These fine surface metal gates were then connected with a thicker Ti(50 nm)/Au(200 nm) metal pad to facilitate wire bonding. The device was affixed to a 16-pin dual-in-line chip carrier using silver glue. Aluminum wires were employed to establish connections between the device and the chip carrier, enabling electronic transport measurements.

Electronic transport measurements. The device was mounted in a sample puck and bottom-loaded into a dry dilution fridge (Oxford Triton-200), achieving a base temperature of 20 mK. The fridge was equipped with a superconducting magnet capable of producing magnetic fields up to 12 T. For electronic measurements, a source-drain AC current of 1 nA was introduced into the

device via a function generator (NF WF1984). All resistive tensor components (R_{xx} , R_{xy} , and R_{DIA}) were measured by a standard lock-in amplifier technique (NF LI5660). The lock-in amplifiers were externally locked at a frequency of 17.3 Hz. Each gate was independently biased by a multi-channel source meter unit (Keysight E5270B) with the compliance set at 100 nA.

RDNMR measurements. Prior to RDNMR detection by scanning the rf wave around the Larmor frequency of ^{75}As nuclei, we dynamically polarized the nuclear spins in the point contact. This polarization was achieved by applying an ac excitation current of 5 nA for 1000 s. A custom-made, three-turn coil, wrapped around the device, was employed to administer an in-plane rf magnetic field. The rf power, applied at the top of the cryostat, was maintained at a low -30 dBm throughout the sequences. The rf wave was scanned at a rate of 100 Hz/s, ensuring the nuclear spin remained in equilibrium with the electron spin.

Data availability

All relevant data presented in the Manuscript are available from the corresponding author upon reasonable request.

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Author contributions

M.H.F. and Y.H. conceived the experiments. M.H.F. fabricated devices and conducted measurements with the help of K.N. and K.H. N.S. supported the theoretical parts. M.H.F. wrote the manuscript along with the feedback from all co-authors. The project was supervised by Y.H.

Competing interests

The authors declare no competing interests.

Additional information

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