Isolated ballistic non-abelian interface channel

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The topological order of a quantum Hall state is mirrored by the gapless edge modes owing to bulk-edge correspondence. The state at the filling of ν = 5/2, predicted to host non-abelian anyons, supports a variety of edge modes (integer, fractional, neutral). To ensure thermal equilibration between the edge modes and thus accurately determine the state’s nature, it is advantageous to isolate the fractional channel (1/2 and neutral modes). In this study, we gapped out the integer modes by interfacing the ν = 5/2 state with integer states ν = 2 and ν = 3 and measured the thermal conductance of the isolated-channel. Our measured half-quantized thermal conductance confirms the non-abelian nature of the ν = 5/2 state and its particle-hole Pfaffian topological order. Such an isolated channel may be more amenable to braiding experiments.

The fractional quantum Hall effect harbors fractionally charged quasiparticles localized in the two-dimensional (2D) bulk, surrounded by gapless chiral edge modes at the periphery (1). Laughlin’s states and their particle-hole conjugated states are abelian (7). In higher Landau levels, exotic non-abelian states are expected. When the bulk hosts a large number of well-separated quasiparticles, the ground state is highly degenerate (2, 3). A proposed state that hosts such exotic quasiparticles is the ν = 5/2 state, which supports gapless edge modes: two integer modes (ν = 2), a fractional mode (ν = 1/2), and neutral Majorana modes (their number and chirality depend on the state’s topological order). To capture the nature of the state, we recently employed thermal conductance (Gth) measurements (4) of the edge modes, which are sensitive to all energy-carrying modes (charged and neutral alike). If all edge modes are fully thermally equilibrated, the measured Gth corresponds to a vital topological invariant that dictates the state’s topological order.

We start by recapping the rationale for measuring the thermal conductance. In the abelian regime, with fully equilibrated downstream (DS) and upstream (US) modes, the thermal conductance is given by

\[ G_{th} = (|n_d - n_u|)k_B T, \]

where \( k_B \) is the thermal conductance, \( k_B \) is the Boltzmann constant, \( h \) is Planck’s constant, \( T \) is temperature, and \( n_d \) and \( n_u \) are the number of downstream (upstream) edge modes. However, in a complete absence of thermal equilibration, one expects \( G_{th} = (|n_d + n_u|)k_B T \). In the non-abelian regime, \( G_{th} \) is a fractional multiple of \( k_B T \), originating from the fractional nature of the chiral central charge (6).

With the assumption of full thermal equilibration among the multiple modes of the ν = 5/2 state, we experimentally found \( K_{th} \) ≅ 2.5\( k_B \) (4), suggesting the particle-hole Pfaffian (PH-Pf) topological order. This result disagrees with numerical calculations (7–22).

In this work, we used a technique introduced in (23) to interface the ν = 5/2 state with the ν = 2 or ν = 3 states. The resulting ν = 1/2 isolated interface channel is composed of neutral mode(s) tied with the ν = 1/2 charge mode. The simpler structure of the isolated channel (without the integer modes) eases considerably the intermode thermal equilibration (4). Our measured upstream noise of the interface channel, done in the thermally unequilibrated regime (23), made it possible to distinguish between the suggested topological orders, however, spontaneous edge reconstruction might add ambiguity. Here, measuring the thermal conductance coefficient of the interface channel in the fully thermally equilibrated regime, and finding \( K_{th} \) ≅ 0.5\( k_B \), we prove the bulk’s non-abelian nature and reaffirm its PH-Pf topological order (4, 23). The isolated 1/2 channel, with its chiral neutral Majorana mode, is an excellent candidate for future interference experiments (i.e., braiding).

Molecular beam epitaxy (MBE)-grown high-quality GaAs-AlGaAs heterostructures, with shallow-DX-center doping (24), allow hysteresis-free gating and feature negligible heat conductance of the bulk (at millikelvin temperatures) (23). This doping method leads to higher disorder than in the conventional short-period superlattice doping technique (4, 24, 25). Our experimental setup containing a “two-arm” structure is shown in Fig. 1A. The inner gates (beige) and the outer ones (violet) tune the

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filling factor of each of the corresponding bulks in the sample. The gates are separated from the sample by a 25-nm-thick HfO2 layer [for more details, see section II of the supplementary text (26)]. Gate voltage in the range $-1.5 \text{ V} < V_g < +0.3 \text{ V}$ allows varying the electron density from pinch-off to $3 \times 10^{11} \text{ cm}^{-2}$ (fig. S1), controlling the filling factor over a wide range. The interface modes between the two bulks split when leaving the floating ohmic contact ($20 \mu\text{m}$ by $2 \mu\text{m}$, shown in red), into the two arms. This contact serves as a heated reservoir. Large ohmic contacts [source (S), drain (D), and ground (G), shown in cyan] are placed at the interfaces; separate contacts, located at the physical edge of the mesa (not shown), probe the filling factor of each of the respective bulks.

Current $I_S$ injected from S toward the floating contact, carrying power $P_S = \frac{1}{2} I_S^2 R_S$, dissipates a power $\Delta P = \frac{1}{2} I_S^2 R_S$ in the contact ($R_S$ is the resistance of the interface channel). Figure 1B provides a schematic representation of the heat balance in the floating contact at the interface. The heat leaving the contact is composed of a phononic contribution $\Delta P_{\text{ph}} = \beta (T_m^2 - T_0^2)$ and an electronic contribution $\Delta P_e = 0.5 K (T_m^2 - T_0^2)$, where $T_m$ is the temperature of the floating contact and $T_0$ is the base temperature, with $\Delta P = \Delta P_{\text{ph}} + \Delta P_e$ at equilibrium. For our small reservoir, the phononic contribution is negligible at temperatures $T_m < 20 \text{ mK}$. The temperature $T_m$ is determined by measuring the thermal conductance $K$ is determined from the slope, via $D_P = \frac{1}{2} K (T_m^2 - T_0^2)$ and indicated in the figure. (D) Dissipated power as a function of temperature in the range $T_m < 30 \text{ mK}$. Here, phonon contribution is included via $D_P = \frac{1}{2} K (T_m^2 - T_0^2) + \beta (T_m^2 - T_0^2)$, with electron–phonon coupling constant $\beta \approx 5 \times 10^9 \text{ W K}^{-5}$; the extracted values of $K$ are indicated in the figure.

FIG. 3. Interface resistance and thermal conductance of states in the second Landau level. (A) Two terminal interface-mode resistance of $7/3$-2 and -3, $5/2$-2 and -3, and $8/3$-2 and -3. Accurate quantized plateaus indicate full charge equilibration at the interface. The peaks and dips are attributed to reentrant effects (30). (B) Determination of the thermal conductance for $T_m < 18 \text{ mK}$, as was done in Fig. 2. The slope for $7/3$-2 is close to unity, as expected for the 1/3 interface mode. The slope for $7/3$-3 is $0.37 k_0$, not zero, owing to the well-known lack of equilibration of the resultant 2/3 mode (27). (C) Similar data as in (B), at different interfacing conditions with $v = 8/3$. 
Fig. 4. Thermal conductance of the 5/2-n interfaces. (A to H) Plots of the interface modes of the interfaced PH-Pf and the A-Pf orders with different integers and the expected thermal conductance in each case.

Fully equilibrated value in light blue and unequilibrated value in red. The double-line arrow indicates an integer mode, the single-line arrow indicates the 1/2 charge mode, and the dashed-line arrow indicates the Majorana mode. Clockwise chirality is indicated by the circled arrow. (I to L) Plots of the dissipated power as a function of the squared temperature with linear fits as in Figs. 2 and 3, for all four 5/2 interfaces. The extracted thermal conductance values, in particular for 5/2-3, unambiguously exclude the A-Pf topological order [see (G) and (H)] and agrees (with small estimated errors) with the PH-Pf topological order.

Interfacing the fillings $v = 7/3$, 5/2, and 8/3 with $v = 2$ and $v = 3$ leads to the source resistance shown in Fig. 3A. Well-quantized resistance plateaus indicate full charge equilibration at the interface. We start with the $v = 7/3$ and $v = 8/3$ abelian states. Interfacing these two states with $v = 2$ results in an effective mode filling of $v = 1/3$ for 7/3-2 and $v = 2/3$ for 8/3-2 (the latter is accompanied by an upstream neutral mode). The chirality at the interface is reversed when these states are interfaced with $v = 3$; with $v = 2/3$ charge channel for 7/3-3 and $v = 1/3$ mode for 8/3-3. The measured two-terminal interface thermal conductance for each of these four cases is shown in Fig. 3, B and C. The results agree with good accuracy with the theoretical expectations (4).

The $v = 5/2$ state may host different topological orders, with each having a different mode structure and a different thermal conductance (29). Here, we consider two competing candidates: particle-hole Pfaffian (PH-Pf) and anti-Pfaffian (A-Pf). For a discussion of other possible orders, see section VI of the supplementary text (26). Both orders support counterpropagating modes at the bare edge of the sample, namely, the 5/2-0 configuration (Fig. 4, A and B). Here, $v = 0$ reflects the outside vacuum. Aside from two downstream integer charge modes and a $v = 1/2$ charge mode, the PH-Pf order supports an upstream Majorana mode, whereas the A-Pf order supports three upstream Majorana modes (two Majorana modes form a single bosonic neutral mode). For PH-Pf, this leads to a thermal conductance of $2.5\kappa_0 T$ for all thermally equilibrated modes and $3.5\kappa_0 T$ for thermally unequilibrated modes; for A-Pf, the values are $1.5\kappa_0 T$ for thermally equilibrated and $4.5\kappa_0 T$ for thermally unequilibrated. Thus, with counterpropagating modes, an accurate determination of the topological order on the basis of thermal conductance requires a full thermal equilibration between all modes.

Figure 4, A to F, presents different configurations: 5/2-0, 5/2-1, and 5/2-2. As shown in the figures, the expected thermal conductance of the two competing orders may overlap when considering the range from a full thermal equilibration to no equilibration. However, interfacing 5/2-3 clearly distinguishes between the topological orders (Fig. 4, G and H). In an A-Pf order, the interface channel supports two co-propagating modes, which leave the hot reservoir at the same temperature, $T_m$ (hence, equilibrated), leading to a thermal conductance of $1.5\kappa_0 T$. By contrast, the PH-Pf order supports an interface channel with counterpropagating charge and Majorana mode, leading to thermal conductance in the range $0.5\kappa_0 T$ to $1.5\kappa_0 T$.

In Fig. 4, I to L, we present the measurement results of $\Delta R$ versus $T_m^2$ for the four 5/2 interfaces: 5/2-0, 5/2-1, 5/2-2, and 5/2-3. The

low-frequency Johnson-Nyquist (J-N) noise at the drain contact D, which is placed ~160 µm away along the downstream direction, in one of the two arms [see section III of the supplementary text (26)]. The noise is filtered by a resonant circuit (resonant frequency: 630 kHz; bandwidth: 10 to 30 kHz) and amplified by a low-noise cold voltage preamplifier (placed on the 4.2 K plate) followed by a room-temperature amplifier.

In general, our experimental strategy is to tune the inner regions to the “tested” state $v_{in}$ (e.g., 5/2) and the outer regions to an integer state $v_{out}$ (e.g., 0, 1, 2, 3), leading to an interface filling $v_{int} = v_{in} - v_{out}$ (the nomenclature “$v_{in} - v_{out}$” is used in all figures). Note that the chirality of the interface charge mode reverses when the interfacing condition changes from $v_{in} > v_{out}$ to $v_{in} < v_{out}$. Owing to a single amplifier located downstream, the magnetic field was reversed between the latter two cases [see section III of the supplementary text (26)].

We start with measurements of the interface modes formed in the configurations 3-2, 3-1, and 3-0. The two-terminal S-D resistance, $R_{SD}$, exhibits quantized plateaus as a function of the gate voltage, $h/e^2$, $h/2e^2$, and $h/3e^2$, with the expected thermal conductances $k_0 T$, $2k_0 T$, and $3k_0 T$, respectively (27, 28). In these chiral configurations, the downstream modes are thermally equilibrated right from the start at the reservoir temperature $T_m$. The latter is determined by the measured J-N noise, $S_{th}$, at the drain [Fig. 2, A and B, and section V of the supplementary text (26)]. We analyzed the data in two ways: (i) by fitting the linear electronic contribution, $\Delta R$ versus $T_m^2$ for $T_m < 18$ mK, finding the thermal conductance of the interface $K \cong k_0 T$, $2k_0 T$, and $3k_0 T$, for the three configurations, respectively (Fig. 2C); and (ii) by fitting the data for $T_m < 30$ mK (Fig. 2D), which reflects the electronic and phononic contributions. Using $\beta = 5 \times 10^{-8}$ W K$^{-5}$, a similar quantization of the thermal conductance is found (4).
measured thermal conductances are (2.55 ± 0.07)κ₀T, (1.53 ± 0.04)κ₀T, (0.55 ± 0.02)κ₀T, and (0.53 ± 0.02)κ₀T, respectively. These results, especially for the decisive 5/2–3 interface, rule out the A-Pf order and support the PH-Pf order (Fig. 4, A to H). Notably, the observed 1/2-quanta thermal conductance of the isolated 1/2-channel at the 5/2–3 interface establishes the non-abelian nature of the bulk.

The ν = 5/2 state has been attracting widespread attention owing to growing expectations of realizing non-abelian anyons in condensed matter systems. Here, we exploit the interfacing method introduced in (23), which allows measuring the thermal conductance of an emergent interface channel at the interface between two adjacent quantum Hall states (ν = 5/2 and integers ν = 2 and ν = 3). The advantage of the interfacing method lies in the simplification of equilibration among the remaining modes, providing a direct determination of the non-abelian nature of the bulk, along with a clear distinction between competing orders of the ν = 5/2 state. The isolated 1/2-channel is amenable to interference experiments, which could test its robustness against decoherence mechanisms [see section IX of the supplementary text (26)].

REFERENCES AND NOTES
1. M. Heiblum, D. E. Feldman, Int. J. Mod. Phys. A 35, 2030009 (2020).
2. X. G. Wen, Phys. Rev. Lett. 66, 802–805 (1991).
3. J. B. Pendry, J. Phys. Math. Gen. 16, 2161–2171 (1983).
4. M. Banerjee et al., Nature 559, 205–210 (2018).
5. C. L. Kane, M. P. A. Fisher, Phys. Rev. B Condens. Matter 55, 15632–15837 (1997).
6. A. Gromov, G. Y. Cho, Y. You, A. G. Abanov, E. Fradkin, Phys. Rev. Lett. 114, 066805 (2015).
7. R. H. Morf, Phys. Rev. Lett. 80, 1505–1508 (1998).
8. M. Storni, R. H. Morf, S. Das Sarma, Phys. Rev. Lett. 104, 076803 (2010).
9. G. Moore, N. Read, Nucl. Phys. B 360, 362–396 (1991).
10. M. Levin, B. I. Halperin, B. Rosenow, Phys. Rev. Lett. 99, 236806 (2007).
11. S. S. Lee, S. Ryu, C. Nayak, M. P. Fisher, Phys. Rev. Lett. 99, 236807 (2007).
12. M. P. Zaletel, R. S. K. Mong, F. Pollmann, E. H. Rezayi, Phys. Rev. B Condens. Matter Mater. Phys. 91, 045115 (2015).
13. E. H. Rezayi, Phys. Rev. Lett. 119, 026801 (2017).
14. P. T. Zucker, D. E. Feldman, Phys. Rev. Lett. 117, 096802 (2016).
15. D. F. Mross, Y. Oreg, A. Stern, G. Margalit, M. Heiblum, Phys. Rev. Lett. 121, 026801 (2018).
16. C. Wang, A. Vishwanath, B. I. Halperin, Phys. Rev. B 98, 045112 (2018).
17. I. C. Fulga, Y. Oreg, A. D. Mirlin, A. Stern, D. F. Mross, Phys. Rev. Lett. 125, 236802 (2020).
18. B. Lian, J. Wang, Phys. Rev. B 97, 165124 (2018).
19. S. H. Simon, Phys. Rev. B 97, 121406 (2018).
20. D. E. Feldman, Phys. Rev. B 98, 164701 (2018).
21. S. H. Simon, B. Rosenow, Phys. Rev. Lett. 124, 126801 (2020).
22. K. K. W. Ma, D. E. Feldman, Phys. Rev. Lett. 125, 016801 (2020).
23. B. Dutta et al., Science 375, 193–197 (2022).
24. V. Umansky, M. Heiblum, in Molecular Beam Epitaxy: From Research to Mass Production, M. Henini, Ed. (Elsevier Science BV, 2013), pp. 121–137.
25. K. A. Villegas Rosales et al., Phys. Rev. Lett. 127, 056801 (2021).
26. See supplementary materials.
27. M. Banerjee et al., Nature 545, 75–79 (2017).
28. S. Jozouin et al., Science 342, 601–604 (2013).
29. K. K. W. Ma, D. E. Feldman, Phys. Rev. B 100, 035302 (2019).
30. M. O. Goerbig, P. Lederer, C. Morais Smith, Phys. Rev. B Condens. Matter 68, 241302 (2003).
31. B. Dutta, V. Umansky, M. Banerjee, M. Heiblum, Isolated ballistic non-abelian interface channel, Zenodo (2022); https://doi.org/10.5281/zenodo.6559780.

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