Competing $\nu = 5/2$ fractional quantum Hall states in confined geometry

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Some theories predict that the filling factor $5/2$ fractional quantum Hall state can exhibit non-Abelian statistics, which makes it a candidate for fault-tolerant topological quantum computation. Although the non-Abelian Pfaffian state and its particle-hole conjugate, the anti-Pfaffian state, are the most plausible wave functions for the $5/2$ state, there are a number of alternatives with either Abelian or non-Abelian statistics. Recent experiments suggest that the tunneling exponents are more consistent with an Abelian state rather than a non-Abelian state. Here, we present edge-current-tunneling experiments in geometrically confined quantum point contacts, which indicate that Abelian and non-Abelian states compete at filling factor $5/2$. Our results are consistent with a transition from an Abelian state to a non-Abelian state in a single quantum point contact when the confinement is tuned. Our observation suggests that there is an intrinsic non-Abelian $5/2$ ground state but that the appropriate confinement is necessary to maintain it. This observation is important not only for understanding the physics of the $5/2$ state but also for the design of future topological quantum computation devices.

fractional quantum Hall effect | $5/2$ fractional quantum Hall state | edge-current tunneling | quantum point contact | non-Abelian statistics

Among the roughly 100 known fractional quantum Hall (FQH) states, the filling factor $\nu = 5/2$ state is special. It is an even-denominator state with elementary excitations that may have non-Abelian statistics (1–10). If the ground state is non-Abelian, it would be insensitive to environmental decoherence (11) and would therefore be useful for fault-tolerant topological quantum computation. Because of this potential application, much theoretical effort has focused on the $5/2$ state, and a variety of wave functions have been proposed (1–3, 5–7, 12–15). There have also been several experiments on the $5/2$ state, with more of them supporting non-Abelian than Abelian statistics (16, 17). All of the proposed wave functions for the $5/2$ state have an effective charge e^* of the quasiparticles that is a quarter of the elementary charge e , and this effective charge has been confirmed experimentally (18–21). However, the wave function of the $5/2$ state is still under discussion.

The proposed wave functions of the $5/2$ state can be distinguished by the strength of the interaction between quasiparticles, described by a coupling constant g . This coupling constant can be obtained from experiments using weak-tunneling theory (22). The FQH effect emerges in a highly interacting 2D electron gas (2DEG) at high magnetic field and ultralow temperature. The FQH states have gapless conducting edge currents at the boundaries of the 2DEG, in which fractionally charged quasiparticles carry the current. If the counter-propagating edge currents of a FQH state are brought close enough together in a quantum point contact (QPC), back-scattering is induced. In the weak-tunneling regime, the rate of quasiparticle tunneling depends on the small voltage difference between the edges and scales with temperature as a function of e^* and g . The proposed wave functions for $5/2$ state have different values of g , so the determination of g can discriminate among them. The existing tunneling experiments have demonstrated the validity of weak-tunneling theory in the $\nu = 5/2$ FQH state, but one is consistent with the non-Abelian anti-Pfaffian wave

function (23), whereas others indicate the Abelian 331 wave function (24, 25).

We have measured the tunneling conductance between edges of the $5/2$ state in a QPC with adjustable confinement conditions, and we have found signatures of both non-Abelian and Abelian wave functions. The tunneling conductance has been measured as a function of the edge voltage difference and temperature, and by fitting the tunneling conductance to weak-tunneling theory, the strength of the interaction g and the effective charge e^* of the $5/2$ state have been extracted. We find that g depends on the voltage applied to the gates of the QPC.

Results

The separation of the two fingers forming the QPC is 600 nm for the results presented in the main text, but data from additional QPC geometries can be found in Figs. S1 and S2. The width of the QPC finger is 200 nm, similar to that used in the previous works (23, 25). The 2DEG is 210 nm below the QPC and the GaAs/AlGaAs surface, with a density of $2.9 \times 10^{11} \text{ cm}^{-2}$ and a mobility of $2.3 \times 10^7 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. The energy gap of the $5/2$ state is 148 mK calculated from the temperature dependence of the longitudinal resistance R_{xx} , which is thermally activated.

A quantized Hall resistance R_{xy} plateau at filling factor $5/2$ is shown in Fig. 1, with a near-zero R_{xx} , indicating a well-established FQH state. When a negative enough voltage is applied to the gates of the QPC, the edge currents are brought close enough together to induce tunneling. As a result, the Hall resistance across the QPC, the diagonal resistance R_D , increases

Significance

The $5/2$ fractional quantum Hall state has captured the fascination of the scientific and nonscientific community, because of proposals to use it for quantum computation. These proposals have been based on the premise that the quasiparticles in this state have non-Abelian statistics. Experiments supporting both Abelian $5/2$ state and non-Abelian $5/2$ state have been reported, and no consensus has been reached. Using measurements of tunneling between edge states, we suggest that both the Abelian and non-Abelian states can be stable in the same device but under different conditions. Our discovery resolves the inconsistencies between existing experiments. More importantly, the knowledge of the competition between ground states is important for maintaining non-Abelian statistics in application to topological quantum computation.

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showed monotonic behavior between the energy gap and the density (38). Lastly, the electrostatic potential caused by the gates will certainly not be constant over the width of the confined region, and its shape may influence the relative stability of the two states.

In summary, our results support that the non-Abelian state is the proper description of the 5/2 state under weak confinement. More importantly, the indication of that two different states compete in confined geometries enriches the understanding of the 5/2 FQH state, as well as resolves some apparent inconsistencies between existing measurements using various techniques. Knowing how to stabilize the non-Abelian state will be important for interferometer experiments to directly test the quasiparticle statistics and in applications to topological quantum computation.

Methods

Fabrication and Transport Measurement. A Hall bar with a width of 150 μm was shaped by wet etching of 240:8:1 $\text{H}_2\text{O}:\text{H}_2\text{O}_2:\text{H}_2\text{SO}_4$ solution for 120 s after coating with photoresist AZ1500 and photolithography. Ohmic contacts were made of Pt/Au/Ge alloy deposited by e-beam evaporation and annealed at 550 $^\circ\text{C}$ for 100 s. QPCs were formed by two Cr/Au top gates deposited by e-beam evaporation after lithography. Applying a negative voltage to the gates depleted the electrons underneath at $V_{\text{QPC}} \sim -1.3$ V, and more negative voltage brought the opposite edges closer, before the QPC was completely pinched-off. QPCs were annealed at -1.6 , -1.8 , and -2.5 V (400, 600, and 800 nm, respectively) near 4 K.

The transport experiments were carried out in a dilution refrigerator (MNK126-450; Leiden Cryogenics BV) with a base refrigerator temperature below 6 mK. The main thermometry was calibrated against a noise thermometer and checked by a cerium magnesium nitrate susceptibility thermometer. The lowest electron temperature for this study was 18 mK determined by measuring the temperature dependence of the longitudinal resistance R_{xx} at an appropriate FQH state. Above 20 mK, the electron temperature was equal to the refrigerator temperature confirmed by the temperature dependence of FQH states' R_{xx} . The measurements were performed by using standard lock-in techniques, with an alternating current excitation of 1 nA at 6.47 Hz.

Data Analysis. The effective charge e^* and the strength of the interaction g can be extracted from the following equations (22, 23):

$$g_T(T, I_{\text{DC}}) = AT^{(2g-2)} F\left(g, \frac{e^* I_{\text{DC}} R_{XY}}{k_B T}\right)$$

$$F(g, x) = B\left(g + i\frac{x}{2\pi}, g - i\frac{x}{2\pi}\right) \left\{ \pi \cosh\left(\frac{x}{2}\right) - 2 \sinh\left(\frac{x}{2}\right) \text{Im}\left[\Psi\left(g + i\frac{x}{2\pi}\right)\right] \right\},$$

where $g_T = (R_D - R_{XY})/(R_{XY}^2)$, $B(x, y)$ represents the Euler beta function, and $\Psi(x)$ is the digamma function. Because there is only a scale factor and an offset difference between R_D and g_T , we directly fitted R_D to obtain e^* and g . The line shape of the tunneling conductance as a function of bias current is sufficiently complex in this equation that g and e^* are well determined at any temperature and gate voltage if weak-tunneling theory applies. By fixing e^* and g , we fit R_D versus I_{DC} at different temperatures simultaneously to verify the agreement between the 5/2 state's theories and our data in Fig. 2B. Except where noted, the three parameters in this equation, A , e^* , and g are allowed to vary to get the best least-squares fit. Because g_T is calculated from the diagonal resistance and there is a small hysteresis in I_{DC} , two more free parameters are added to offset the resistance and the bias current, but these are substantially independent of temperature. The reliability of the fitting is checked by the normalized fitting error, defined as the fit residual divided by the experimental noise 2×10^{-4} h/e 2 .

g can be calculated from a proposed wave function and is a discrete number. In an ideal experiment, we would find one of the g values predicted by theory. In real measurements, there may be deviations from the theoretical values resulting from the influence of device geometry (26). Nonetheless, because the total number of known 5/2 wave functions is limited, we can exclude some candidate wave functions. In this work, g is very close to 1/2 at $V_{\text{QPC}} = -1.50$ V and very close to 3/8 at $V_{\text{QPC}} = -1.65$ V. Among the theoretically predicted states, there are only two with $g = 1/2$, which are non-Abelian, and only one with $g = 3/8$, which is Abelian.

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