The discovery \cite{1} of a fractional quantum Hall effect (FQHE) at the even-denominator filling fraction $\nu = 5/2$ has sparked a series of experimental \cite{2,3,4,5,6} and theoretical \cite{7,8,9} studies, leading to a prevailing interpretation of the $5/2$ state as comprised of paired fermions condensed into a BCS-like state \cite{10,11,12,13}. Within this picture, excitations of the $5/2$ ground state possess nonabelian statistics \cite{14,15,16} and associated topological properties. The possibility that such a topological state can be accessed in the laboratory has prompted recent theoretical work aimed at experimentally testing the nonabelian character of the $5/2$ state \cite{17,18,19,20,21}, and building topologically protected quantum gates controlled by manipulating the excitations of the $5/2$ state \cite{22,23,24}.

While proposed tests of the statistics of excitations of the $5/2$ state make use of confined ($\sim$ few micron) geometries, previous studies of the $5/2$ state have been conducted in macroscopic (100 $\mu$m - 5 mm) samples. Although experiments using mesoscopic samples with a quantum point contact (QPC) are now routine, the $5/2$ state is exceptionally fragile: only the highest quality GaAs/AlGaAs heterostructures exhibit a $5/2$ state even in bulk samples. Experimental investigation of the statistics of the $5/2$ ground state is crucial, especially since alternative models have been proposed to explain the $5/2$ state in confined geometries \cite{25} and in the bulk \cite{12,26}.

In this paper we study the $5/2$ state in the vicinity of a quantum point contact. Near a QPC, the electron density is not uniform, so the notion of a QPC-filling fraction is not well defined. However, based on transport measurements, it is possible to define an effective filling fraction in the vicinity of the QPC ($\nu_{\text{QPC}}$), as discussed below. Below 30 mK, a plateau-like feature with diagonal resistance (also defined below) near, but above, the bulk quantized value of $0.4 h/e^2$ is evident at $\nu_{\text{QPC}} = 5/2$ in QPCs with 1.2 $\mu$m and 0.8 $\mu$m spacings between the gates. On this plateau, we find a peak in the differential resistance at dc-current bias $I_{dc} = 0$ and a dip around

![Image](image-url)
vanishes when $R_{xy}$ shows a plateau. The diagonal resistance across a QPC, $R_D \sim h/e^2(1/N_{QPC})$, is sensitive only to the number of edge channels traversing the QPC, and hence provides a QPC-analog to the bulk $R_{xy}$. The longitudinal resistance across the QPC, $R_L \sim R_D - R_{xy}$, contains information about both the bulk and the QPC-region, and is not directly analogous to the bulk $R_{xx}$. On bulk IQHE plateaus, the filling fraction is equivalent to the number of edge states, $\nu_{\text{bulk}} = N_{\text{bulk}}$. By analogy, in the QPC, where the filling fraction is not well defined due to nonuniform density, we define an effective filling fraction in the QPC: $\nu_{QPC} \sim h/e^2(1/(R_D))$.

The edge state interpretation for $R_{xy}$, $R_{xx}$, $R_D$, and $R_L$ has been extended to the FQHE [32, 33, 34, 35, 36, 37, 38, 39]. Within this generalized picture, a quantized plateau in $R_{xy} \sim h/e^2(1/\nu_{\text{bulk}})$ corresponds to the quantum Hall state at filling fraction $\nu_{\text{bulk}}$, and a plateau in $R_D \sim h/e^2(1/\nu_{QPC})$ indicates that an incompressible quantum Hall state has formed in the vicinity of the QPC with effective filling fraction $\nu_{QPC}$. We associate deviations from precisely quantized values with tunneling, which we study below as a function of temperature and bias.

To simplify the study of quantum states in the vicinity of the QPC, the perpendicular magnetic field ($B$) and gate voltage of the QPC ($V_g$) are tuned such that $\nu_{\text{bulk}}$ is fixed at an integer quantum Hall effect (iQHE) plateau whenever $\nu_{QPC}$ is at a value of interest. With $R_{xx} \sim 0$ and $R_{xy}$ quantized to an iQHE plateau, features in $R_D$ and $R_L$ measurements can be attributed to the QPC region and not the bulk.

Previously, QPCs have been used to selectively transmit integer [40, 41] and fractional edge channels [36, 42], and to study inter-edge tunneling between fractional edge channels, including in the regime where the bulk is intentionally set to an iQHE plateau [28, 43]. Comparisons with these results are discussed below. QPCs have also been employed in studies of noise [44, 45] and (along with etched trenches) interference of quasiparticles [46] in the FQHE regime. In all of these studies $\nu < 2$, where the FQHE gaps are typically much larger than those with $\nu > 2$.

The sample is a GaAs/AlGaAs heterostructure grown in the [001] direction with electron gas layer 200 nm below the surface, with Si $\delta$-doping layers 100 nm and 300 nm below the surface. A 150 nm-wide Hall bar is patterned using photolithography and a H2O:H2SO4:H2O2 (240:8:1) wet-etch, followed by thermally evaporated Cr/Au (5 nm/15 nm) top-gates patterned using electron-beam lithography (see Fig. 1). The gates form QPCs with lithographic separation between gates of 0.5, 0.8 and 1.2 μm. Depleting the electron gas beneath only one side of a QPC has no effect on transport measurements. Gate voltages were restricted to the range -1.9 V (depletion) to -3 V and were allowed to stabilize for several hours at each setpoint before measuring; beyond -3 V the conductance was typically hysteretic as a function of gate
FIG. 3: Typical magnetoresistance curves measured concurrently in the QPC and the bulk at low magnetic field (a and b) and high magnetic field (c and d). Quantized resistance values are indicated in units of $h/e^2$. The colored stripes indicate field ranges where one quantum Hall state exists in the bulk while a different quantum Hall state exists in the bulk. All data is for $T \sim 8$ mK.

Voltage. Measurements are performed in a dilution refrigerator with base temperature 6 mK using standard four-wire lock-in techniques, with an ac current-bias excitation ($I_{ac}$) ranging from 0.2 nA to 0.86 nA, and a dc current-bias ranging from 0 to 20 nA. The differential resistances ($dV/dI_{ac}$) are measured in four places, as shown in Fig. 1. All quoted temperatures are measured using a RuO$_2$ resistor mounted on the mixing chamber. The bulk mobility of the device measured at base temperature is 2000 m$^2$/Vs and the electron density is $2.6 \times 10^{13}$ m$^{-2}$.

Bulk $R_{xx}$ and $R_{xy}$ measurements for the filling fraction range $\nu_{bulk} = 3$ to 2, measured in the vicinity of the 1.2 $\mu$m QPC before the gates are energized, are shown in Fig. 2. $R_{xx}$ and $R_{xy}$ are also measured in a region of the Hall-bar without gates, and found to be virtually indistinguishable, showing that the surface gates do not significantly affect the 2DEG. $R_{xx}$ and $R_{xy}$ in an ungated region show no changes caused by energizing gates.

As temperature is increased, $R_{xy}$ near $\nu_{bulk} = 5/2$ evolves from a well-defined plateau at $R_{xy} = 0.4 \pm 0.0002 h/e^2$ to a line consistent with the classical Hall effect for a material with this density. There is a stationary point in the middle of the plateau where $R_{xy}$ is very close to $0.4 h/e^2$, consistent with scaling seen in other quantum Hall transitions. Activation energies $\Delta$ for the three fractional states $\nu_{bulk} = 5/2$, 21/3 and 22/3 are extracted from the linear portion of the data in a plot of $\ln(R_{xx})$ vs $1/T$ (using the minimum $R_{xx}$ for each IQHE state, and $R_{xx} \propto e^{-\Delta(2T)}$), giving $\Delta_{21/3} \sim 60$ mK, $\Delta_{22/3} \sim 130$ mK and $\Delta_{23/3} \sim 110$ mK, consistent with previous measured values.

We now focus on measurements with one QPC formed, as shown in Fig. 1. Low-field $R_D$ and $R_L$ data from the 1.2 $\mu$m QPC along with concurrently measured $R_{xx}$ and $R_{xy}$ show regions where one IQHE state forms in the bulk with a lower IQHE state in the QPC (see Fig. 3a and Fig. 3b). Figure 3a also shows the appearance of a plateau-like feature in the QPC between $\nu_{QPC} = 5$ and $\nu_{QPC} = 4$ in both the 1.2 $\mu$m and 0.8 $\mu$m QPCs which remains unexplained. At higher magnetic fields (Fig. 3c and Fig. 3d), $R_D$ and $R_L$ show FQHE plateaus while the bulk is quantized at the IQHE value $\nu_{bulk} = 2$.

We now concentrate on the range $\nu_{QPC} = 3$ to $\nu_{QPC} = 2$ with $\nu_{bulk} = 3$ (Fig. 4). Plateau-like structure near $\nu_{QPC} = 5/2$ is evident in the 1.2 $\mu$m and 0.8 $\mu$m QPCs, but is not seen in the 0.5 $\mu$m QPC. Near $\nu_{QPC} = 21/3$ we also see plateau-like behavior in the 1.2 $\mu$m QPC, and somewhat less well developed plateaus in the 0.8 $\mu$m QPC (although $\nu_{bulk}$ is not on a plateau when $\nu_{QPC} \sim 21/3$), but again these features are suppressed in the 0.5 $\mu$m QPC.
FIG. 4: Typical magnetoresistance from \( \nu = 3 \) to \( \nu = 2 \), measured concurrently in the QPC (a) and the bulk (b). In (a), the \( R_D \) curves are from three different QPCs, of lithographic size 0.5 \( \mu \text{m} \) (black), 0.8 \( \mu \text{m} \) (red) and 1.2 \( \mu \text{m} \) (blue). The colored stripes highlight regions in field where the resistance in the 1.2 \( \mu \text{m} \) and 0.8 \( \mu \text{m} \) QPCs forms a plateau-like feature near \( \nu_{\text{QPC}} = \frac{5}{2} \) with \( \nu_{\text{bulk}} = 3 \). The applied gate voltages \( V_g \) are -2.2, -2.0 and -1.9 V for the 1.2, 0.8 and 0.5 \( \mu \text{m} \) QPCs and the ac lock-in excitation is 0.86 nA. All data is for \( T \sim 8 \text{ mK} \).

QPC. We do not observe any plateaus near \( \nu_{\text{QPC}} = 2/3 \) in any of the QPCs. The reentrant integer quantum Hall effect features, which are clearly visible in the bulk, do not survive at all in the QPCs.

We interpret the plateau-like features in the two larger QPCs as indicating that the incompressible states at \( \nu_{\text{QPC}} = 5/2 \) and \( \nu_{\text{QPC}} = 21/3 \) are not destroyed by the confinement. The linear, plateau-less behavior in the 0.5 \( \mu \text{m} \) QPC is reminiscent of a classical Hall line, suggesting that no incompressible states survive in this QPC.

Temperature dependence for a representative \( V_g \) setting of the 1.2 \( \mu \text{m} \) QPC is shown in Fig. 5. Below 30 mK, a distinct plateau-like feature is evident. This plateau disappears between 30 to 70 mK, consistent with the disappearance of the plateaus in the bulk. However, unlike the bulk, where the \( 5/2 \) plateau disappears symmetrically around a stationary point at \( R_{\text{xy}} = 0.4 \text{ h/e}^2 \) as temperature increases, in the QPC there is an additional resistance: \( R_D \) exceeds the quantized value of 0.4 h/e\(^2\) by 26 \( \Omega \) ± 5 \( \Omega \). We also note that the the extra resistance on the plateau decreases as the temperature increases, behavior consistently observed in both the 0.8 \( \mu \text{m} \) and 1.2 \( \mu \text{m} \) QPCs. We interpret this as indicating that the temperature dependence comes not only from the thermal excitation of quasiparticles, but also from the temperature dependence of their backscattering.

The dependence of the differential resistance on dc source-drain bias \( I_{\text{dc}} \) (Fig. 6) provides additional insight into this excess resistance. At base temperature, the resistances \( R_D \) vs \( I_{\text{dc}} \) near \( \nu_{\text{QPC}} = 5/2 \) and \( \nu_{\text{QPC}} = 21/3 \) in the 1.2 \( \mu \text{m} \) (Fig. 6a) and 0.8 \( \mu \text{m} \) (not shown) QPCs show pronounced peaks at \( I_{\text{dc}} = 0 \), a dip at intermediate values, and saturation to a constant value at high currents. In these QPCs, the \( I_{\text{dc}} \) behavior near \( \nu_{\text{QPC}} = 2/3 \) (not shown) is inverted, with a pronounced dip at \( I_{\text{dc}} = 0 \) a peak at intermediate values, and high-current saturation. In the 0.5 \( \mu \text{m} \) QPC the \( I_{\text{dc}} \) traces are flat for all filling fractions between \( \nu_{\text{QPC}} = 3 \) and \( \nu_{\text{QPC}} = 2 \). All the traces in Fig. 6 are measured with an ac-lock-in excitation \( I_{\text{ac}} = 0.2 \text{ nA} \), (while the data in all other figures have been measured with \( I_{\text{ac}} = 0.86 \text{ nA} \)).

Fig. 6 provides a key point of comparison to previous experimental and theoretical work on the FQHE. In a recent experiment [23], a QPC is used to measure tunneling differential resistance characteristics (\( I_{\text{dc}} \) curves) for \( \nu_{\text{QPC}} < 1 \) while \( \nu_{\text{bulk}} \) is fixed on an IQHE plateau. Our \( I_{\text{dc}} \) data for \( 2 < \nu_{\text{QPC}} < 3 \) and \( \nu_{\text{bulk}} = 3 \), with a distinct peak at zero bias and dips at intermediate biases, resembles the \( I_{\text{dc}} \) curves in that work. In Ref. [28] it is
convincingly argued that the $I_{dc}$ curves are a signature of quasiparticle tunneling between the FQHE edge states, based on quantitative comparison to applicable theory. That theory states that the characteristic for tunneling between FQHE edge states \cite{27,37,50} is expected to have a peak at zero bias and a minimum at intermediate biases, whereas tunneling between IQHE edge channels is expected to yield a flat (ohmic) curve. The data we present for $\nu_{QPC} = 5/2$, both the temperature dependence and the $I_{dc}$ curves, are consistent with the formation of a FQHE state with tunneling-related backscattering.

We interpret that a mechanism for the deviation of $R_D$ from $0.4 \hbar/e^2$ near $5/2$ and $21/3$, as well as the peak-and-dip behavior of the $I_{dc}$ data, could be tunneling between edge channels on opposite sides of Hall bar in the vicinity of the QPC. We do not believe the data can be explained by transport via thermally excited particles through the (small) bulk region of the QPC, since this process would be expected to have the opposite temperature dependence.

We gratefully acknowledge helpful discussions with M. Fisher, B. Halperin, A. Johnson, E. Kim, B. Rosenow, A. Stern, X.-G. Wen and A. Yacoby. Research supported in part by Microsoft Corporation Project Q, and HCRP at Harvard University, and ARO (W911NF-05-1-0062), the NSEC program of the NSF (PHY-0117795) and NSF (DMR-0353209) at MIT.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6.pdf}
\caption{Dependence upon dc current bias of the 5/2 and 21/3 states in the 1.2 $\mu$m QPC. The main panel (a) shows the $R_D$ data as a function of magnetic field; each trace represents a different $I_{dc}$ from 0 nA to 3 nA. $R_D$ as a function of $I_{dc}$ for selected magnetic fields (indicated by the color-coded arrows) are shown in (b) and (c). The dotted grey lines in the insets indicate resistance values of $\nu h/e^2$ (b) and $\nu h/e^2$ (c). All traces are measured at $T \sim 8$ mK with $V_{g} = -2.4$ V and an ac lock-in excitation of 0.2 nA. $\nu_{bulk} = 3$ for all fields shown in this figure.}
\end{figure}

\begin{thebibliography}{99}
\bibitem{1} Willett R. et al., \textit{Phys. Rev. Lett.} \textbf{59} 1776 (1987).
\bibitem{2} Eisenstein J.P. et al., \textit{Phys. Rev. Lett.} \textbf{61} 997 (1988).
\bibitem{3} Eisenstein J.P. et al., \textit{Surf. Sci.} \textbf{229} 31 (1990).
\bibitem{4} Pan W. et al., \textit{Phys. Rev. Lett.} \textbf{83} 3530 (1999).
\bibitem{5} Pan W. et al., \textit{Phys. Rev. Lett.} \textbf{83} 820 (1999).
\bibitem{6} Lilly M.P. et al., \textit{Phys. Rev. Lett.} \textbf{83} 824 (1999).
\bibitem{7} Haldane F.D.M. and Rezayi E.H., \textit{Phys. Rev. Lett.} \textbf{60} 956 (1988).
\bibitem{8} Morf R.H., \textit{Phys. Rev. Lett.} \textbf{80} 1505 (1998).
\bibitem{9} Rezayi E.H. and Haldane F.D.M., \textit{Phys. Rev. Lett.} \textbf{84} 4685 (2000).
\bibitem{10} Moore G. and Read N., \textit{Nucl. Phys. B} \textbf{360} 362 (1991).
\bibitem{11} Greiter M., Wen X.G. and Wilczek F., \textit{Phys. Rev. Lett.} \textbf{66} 3205 (1991).
\bibitem{12} Read N. and Green D., \textit{Phys. Rev. B} \textbf{61} 10267 (2000).
\bibitem{13} Scarrola V.W., Park K. and Jain J.K., \textit{Nature} \textbf{406} 863 (2000).
\bibitem{14} Nayak C. and Wilczek F., \textit{Nuclear Physics B} \textbf{479} 529 (1996).
\bibitem{15} Tserkovnyak Y. and Simon S.H., \textit{Phys. Rev. Lett.} \textbf{90} 016802 (2003).
\bibitem{16} Stern A., von Oppen F. and Mariani E., \textit{Phys. Rev. B} \textbf{70} 205338 (2004).
\bibitem{17} Stern A. and Halperin B.I., \textit{Phys. Rev. Lett.} \textbf{96} 016802 (2006).
\bibitem{18} Bonderson P., Kitaev A. and Shtengel K., \textit{Phys. Rev. Lett.} \textbf{96} 016803 (2006).
\bibitem{19} Hou C.Y. and Chamon C., \textit{Phys. Rev. Lett.} \textbf{97} 146802 (2006).
\bibitem{20} Chung S.B. and Stone M., \textit{Phys. Rev. B} \textbf{73} 245311 (2006).
\bibitem{21} Feldman D.E. and Kitaev A., \textit{Phys. Rev. Lett.} \textbf{97} 186803 (2006).
\bibitem{22} Kitaev A., \textit{Ann. Phys. (N.Y.)} \textbf{332} (2006).
\bibitem{23} Bonesteel N.E. et al., \textit{Phys. Rev. Lett.} \textbf{95} 140503 (2005).
\bibitem{24} Das Sarma S., Freedman M. and Nayak C., \textit{Phys. Rev. Lett.} \textbf{94} 166802 (2005).
\bibitem{25} Harju A., Saarikoski H. and Räsänen E., \textit{Phys. Rev. Lett.} \textbf{96} 126805 (2006).
\bibitem{26} Töke C. and Jain J.K., \textit{Phys. Rev. Lett.} \textbf{96} 246805 (2006).
\bibitem{27} Fendley P., Ludwig A.W.W. and Saleur H., \textit{Phys. Rev. B} \textbf{52} 8934 (1995).
\bibitem{28} Roddaro S. et al., \textit{Phys. Rev. Lett.} \textbf{95} 156804 (2005).
\bibitem{29} Fendley P., Fisher M.P.A. and Nayak C., \textit{Phys. Rev. Lett.} \textbf{97} 036801 (2006).
\bibitem{30} D’Agosta R., Vignale G. and Raimondi R., \textit{Phys. Rev. Lett.} \textbf{94} 086801 (2005).
\bibitem{31} Büttiker M., \textit{Phys. Rev. Lett.} \textbf{57} 1761 (1986).
\bibitem{32} Beenakker C.W.J. and van Houten H., \textit{Solid State Physics} \textbf{44} 1 (1991), see discussions in Secs. IV.B and IV.C. Our $R_D$ corresponds to $R_D^2$ in this reference.
\bibitem{33} Beenakker C.W.J., \textit{Phys. Rev. Lett.} \textbf{64} 216 (1990).
\bibitem{34} MacDonald A.H., \textit{Phys. Rev. Lett.} \textbf{64} 220 (1990).
\bibitem{35} Chang A.M. and Cunningham J.E., \textit{Solid State Comm.} \textbf{72} 651 (1989).
\bibitem{36} Kouwenhoven L.P. et al., \textit{Phys. Rev. Lett.} \textbf{64} 685 (1990).
\end{thebibliography}
[37] Wen X.G., *Phys. Rev. Lett.* **64** 2206 (1990).
[38] Wang J.K. and Goldman V.J., *Phys. Rev. Lett.* **67** 749 (1991).
[39] Würtz A. *et al.*, *Physica E* **22** 177 (2004).
[40] van Wees B.J. *et al.*, *Phys. Rev. B* **38** 3625 (1988).
[41] Alphenaar B.W. *et al.*, *Phys. Rev. Lett.* **64** 677 (1990).
[42] Alphenaar B.W. *et al.*, *Phys. Rev. B* **45** 3890 (1992).
[43] Lal S., condmat/0611218 (2006).
[44] Saminadayar L. *et al.*, *Phys. Rev. Lett.* **79** 2526 (1997).
[45] de Picciotto R. *et al.*, *Nature* **389** 162 (1997).
[46] Camino F.E., Zhou W. and Goldman V.J., *Phys. Rev. Lett.* **95** 246802 (2005).
[47] Das Sarma S., in S. Das Sarma and A. Pinczuk, eds., *Perspectives in Quantum Hall Effects*, Wiley, New York (1997).
[48] Eisenstein J.P. *et al.*, *Phys. Rev. Lett.* **88** 076801 (2002).
[49] Xia J.S. *et al.*, *Phys. Rev. Lett.* **93** 176809 (2004).
[50] Moon K. *et al.*, *Phys. Rev. Lett.* **71** 4381 (1993).