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Conduction through point contacts in fractional quantum Hall liquid

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Abstract

We have investigated conductance spectrum through a quantum point contact in a fractional quantum Hall liquid. The width of resonant peaks near the pinch-off shows temperature dependence suggestive of a non-Fermi liquid nature of the edge channel. Observation of well-defined fractional plateaus corresponding to filling factors different from the bulk implies complicated multiple edge channel structure for a smooth confinement. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Although the edge channel model has proved extremely successful in explaining many aspects of transport in the integer quantum Hall effect (IQHE) [1], its extension to the case of fractional quantum Hall effect (FQHE) seems by no means straightforward. As long as one considers only the IQHE states, there is clear one-to-one correspondence between each edge channel and a bulk Landau level. By contrast, once the FQHE states are considered, the structure of edge channels becomes a subtle issue.

The first step to this problem were made by Beenakker [2] and by MacDonald [3] independently, however leading to different conclusions due to different assumptions on the boundary condition. In either case, fractional edge may consist of multiple edge channels *with fractional conductance* (in unit of e^2/h) but the concept of edge channel is quite different. In Beenakker's edge channel picture, which is appropriate for a smooth confinement potential, the fractional edge consists of compressible strips sandwiched between incompressible liquids of different filling factors. Thus, the construction of the edge channels depends on the stability of each compressible strip as well as the smoothness of the confining potential. In MacDonald's picture, which is appropriate for a sharp confinement potential, the structure of the edge channels directly reflects the hierarchy of the FQH state so the edge channel construction is determined solely by the FQH state itself. In addition, this picture also considers the existence of edge

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channels with hole-like character, which travel in opposite direction to the ordinary particle-like edge channels. For example, edge channels for $\nu = \frac{2}{3}$ FQH state consists of one particle-like edge channel with conductance e^2/h and one hole-like edge channel with conductance $-\frac{1}{3}e^2/h$, giving a net conductance $G = \frac{2}{3}e^2/h$.

Wen [4] has shown in his pioneering work that the dynamical feature of the current-carrying edge excitation of FQH liquid is that of chiral Tomonaga–Luttinger (TL) liquid, which is a variation of the model for an interacting one-dimensional electron gas. In the simplest case of Laughlin state (i.e. $\nu = 1/(2n + 1)$), correlation exponent K_ρ which characterizes the TL liquid coincides with the Landau level filling factor ν of the FQH state:

$$K_\rho = \nu. \quad (1)$$

Based on this model, transport properties of FQH edge channels were studied intensively [5–7]. The novel feature of the chiral TL liquid is predicted to show up in the transport through a point contact as a power law dependence of conductance to energy parameters such as temperature or source-drain voltage. Although this idea seems to have been confirmed experimentally for $\nu = \frac{1}{3}$ FQH state [8], both structure and dynamics of edge channels for hierarchial FQH states such as $\nu = \frac{2}{3}$ are still unclear. Here we present experimental results which shed some light on the edge state construction in $\nu = \frac{2}{3}$ FQH state.

2. Experiment

Our samples are GaAs/AlGaAs heterostructure two-dimensional electron gas (2DEG) with Hall bar geometry. The 2DEG which is located 90 nm away from the surface of the device has a carrier density $n = 2.2 \times 10^{15}\ \mathrm{m}^{-2}$ and a mobility $\mu = 65\ \mathrm{m}^2/\mathrm{V\,s}$. A gold split gate with an opening of 200 nm is fabricated on top of the Hall bar by electron beam lithography and vacuum deposition. A negative voltage applied to the split gate defines a point contact in the 2DEG. The sample is set in the mixing chamber of a dilution refrigerator placed in a 15 T superconducting solenoidal magnet and is cooled down to 30 mK. The conductance of the 2DEG across the split gate is measured using the standard AC lock-in technique. At zero magnetic field, quantum point contact is defined when the gate bias voltage is about $V_g < -0.3$ V, showing a series of conductance plateaus at $G = 2Ne^2/h$ until the point contact is completely pinched off at about $V_g = -1.0$ V. The magneto- and Hall resistance of the 2DEG show a clear signature of $\nu = \frac{2}{3}$ FQH state at around $B = 14.0$ T and some IQH plateaus at lower magnetic fields.

3. Results and discussion

With the magnetic field fixed at FQH state $\nu = \frac{2}{3}$, conductance is measured as a function of the gate voltage. As the gate bias is swept towards pinch-off, the conductance decreases from the quantized Hall conductance $G = \frac{2}{3}e^2/h$ towards zero, but not monotonically. Instead, the conductance draws a reproducible curve as shown in Fig. 1. Although the detailed conductance pattern was found to vary from sample to sample, some features as given below are commonly observed in many samples: (1) a small dip at about $V_g = -0.2$ V, (2) a plateau around $V_g = -0.5$ V with conductance value $G = \frac{1}{3}e^2/h$ as indicated by dashed line, (3) a series of peak structures near the pinch-off voltage.

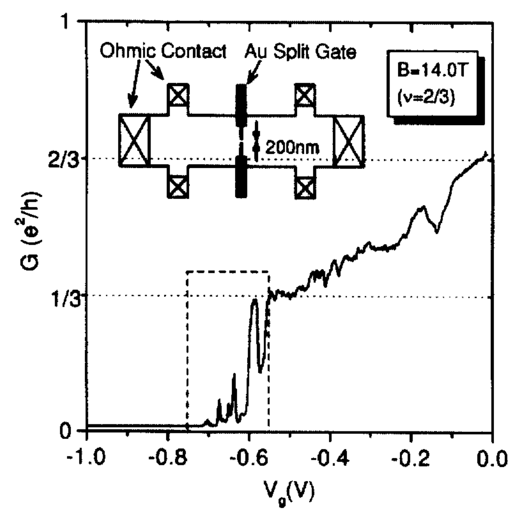

Fig. 1. Conductance versus gate voltage at $\nu = 2/3$. Inset: schematic view of the sample structure.

By attributing the peak structures near the pinch-off to resonant tunneling at some impurity state near the point contact, we can attempt to compare the temperature dependence of the peak widths with the prediction based on chiral TL liquid theory. The widths of resonant tunneling peaks between TL liquids and the values of off-resonant conductance are predicted to have power law dependence on temperature where those for non-interacting system does not have a strong temperature dependence [6]. The exponent of this temperature dependence is related to the correlation exponent K_ρ in a simple manner. Thus, the TL liquid nature of the fractional edge channel can be tested by studying such temperature dependence. Shown in Fig. 2a are detailed traces of conductance for $-0.75\ \mathrm{V} < V_g < -0.55\ \mathrm{V}$ at 90 and 350 mK. Evidently, the peaks at 350 mK are wider than the corresponding peaks at 90 mK. Fig. 2b is a plot of width of three peaks indicated in Fig. 2a at seven different temperatures. For all three peaks the peak width tends to increase with increasing temperature, which is suggestive of a non-Fermi liquid nature of the edge channel. Quantitative discussion on this temperature dependence, however, needs a more careful measurements at $T < 100$ mK. Unfortunately we experienced a long term drift of unknown origin in the conductance spectrum, and that troubled a systematic data collection.

The $G = \frac{1}{3}e^2/h$ plateau around $V_g = -0.5$ V may give insight into the structure of edge channels. As shown in Fig. 3, this plateau is observed clearer in some other samples. Similar plateaus with conductance values different from the quantized Hall conductance $\nu e^2/h$ are also observed in other

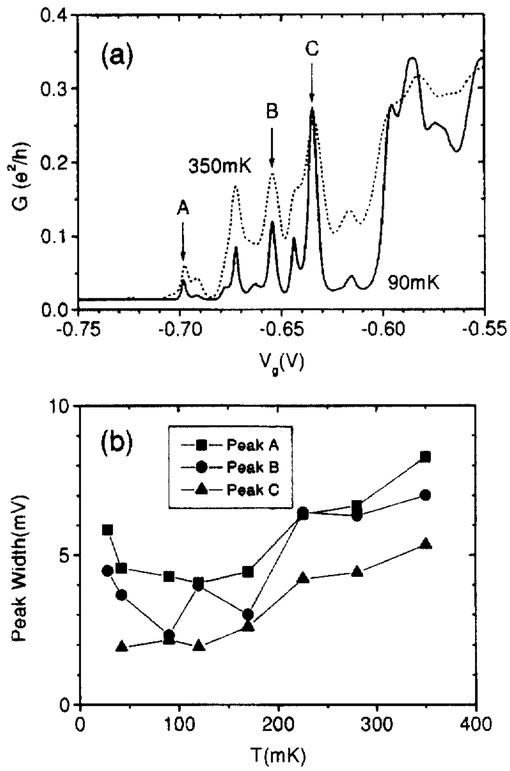

Fig. 2. (a) Detailed trace of conductance for $-0.75\ \mathrm{V} < V_g < -0.55\ \mathrm{V}$ (the boxed region in Fig. 1) at two different temperatures; (b) Temperature dependence of the widths of three representative resonance peaks.

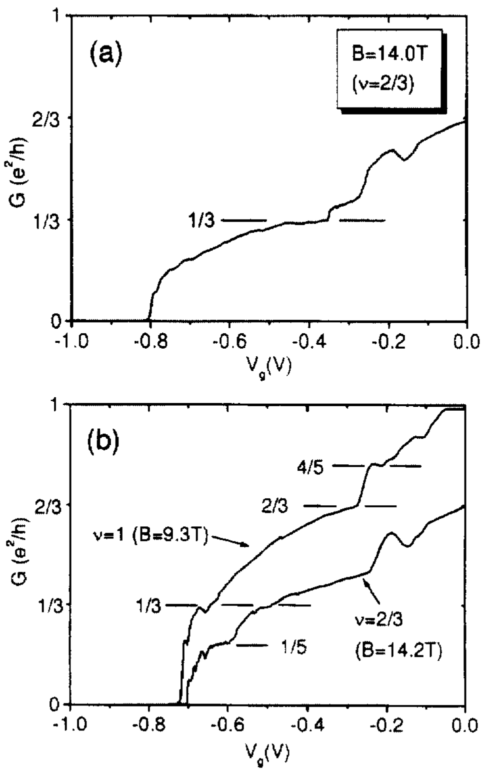

Fig. 3. (a) Conductance versus gate voltage at $\nu = 2/3$ for a sample different from Fig. 1 and Fig. 2; (b) Similar data at $\nu = 2/3$ and $\nu = 1$ for still another sample. $G = (1/3)e^2/h$ plateau is observed clearly.

combination of filling factors ν and plateau conductance values G. In Fig. 3, one can find plateaus at $G = \frac{1}{3}$ and $\frac{1}{5}$ in $\nu = \frac{2}{3}$ state and $G = \frac{4}{5}, \frac{2}{3}$ and $\frac{1}{3}$ in $\nu = 1$ state. Since a well-defined conductance plateau is usually taken as a signature of well-separated channels, the above results may imply existence of such complicated edge state structure. Particularly, the fact that such fractional plateaus are observed for a $\nu = 1$ state seems to suggest that the confinement potential is rather smooth and the spatial variation of the electron density is gradual. The TL liquid theory predicts that the behavior of tunneling conduction between edge channels depends highly on its structure [7]. Therefore it is necessary to elaborate the model of the edge channel in comparing the edge transport with the chiral Tomonaga–Luttinger theory.

In summary, we have observed some structures in the conductance through a quantum point contact in a FQH liquid which can be understood with edge channel picture. The clear $G = \frac{1}{3}e^2/h$ plateau manifests the existence of well-separated edge channels in the $\nu = \frac{2}{3}$ FQH liquid. The temperature dependence of the resonant peak structure may be due to the non-Fermi liquid nature of the edge channels.

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