Selective Population and Detection of Edge Channels in the Fractional Quantum Hall Regime

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Transport in the fractional-quantum-Hall-effect (FQHE) regime is studied in a two-dimensional electron gas (2DEG) employing adjustable barriers as current and voltage probes. We find a fractionally quantized Hall conductance for integer filling factor in the bulk of the 2DEG, as a consequence of the fractional filling factor in the probes. We argue that this effect is the first manifestation of adiabatic transport in the FQHE. The results are in agreement with a proposed Landauer-Büttiker formula in which each fractional edge channel contributes a conductance $\frac{1}{3}e^2/h$.

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The similarity in experimental appearance between the integer quantum Hall effect (IQHE) and the fractional quantum Hall effect (FQHE) is striking in view of their theoretically different origins. While a single-particle description can be used for the IQHE, the FQHE originates from a many-body interaction.[1]

A clear picture of the IQHE in terms of edge channels[2] has recently gained much attention, both theoretically and experimentally. The transport in the IQHE regime can then be described within the Landauer-Büttiker formalism.[3-5] Recent experiments have demonstrated that edge channels can be selectively populated and detected by current and voltage contacts.[6,7] The experiment of Ref. 7 shows that scattering between edge channels can be very weak on length scales of the order of a micrometer. On these lengths scales the IQHE can be described in terms of adiabatic transport in edge channels, which can be viewed as independent current channels.

In the IQHE, edge channels are located at the boundary of the two-dimensional electron gas (2DEG), where the Landau levels intersect the Fermi energy. It is not obvious how to generalize this definition of edge channels to the FQHE, where a single-particle description no longer applies. The existing many-body theory[1,8] based on Laughlin's trial wave function essentially considers a homogeneous system. The partially depleted region at the 2DEG boundary, where in the IQHE regime the edge channels are located, was not considered in these theories for the FQHE.

In this Letter we study the transport along the boundary of a 2DEG having an integer filling factor, using adjacent current and voltage probes whose filling factors can be varied. From the observation of a fractional quantum Hall conductance which is completely determined by the filling factor in the probes, we conclude that adiabatic transport can occur in the FQHE regime. To describe our results we propose that fractional edge channels exist at the 2DEG boundary, which can be selectively populated and detected by current and voltage probes, similar to the edge channels in the IQHE regime.[7] A Landauer-Büttiker formula generalized to the FQHE provides quantitative agreement with the measurements. This generalization as well as the concept of fractional edge channels is supported by a recent theoretical paper by Beenakker.[9]

Chang and Cunningham[10] recently studied the transmission probabilities between regions with filling factor $\nu = 1$ and $\frac{2}{3}$, and between regions with $\nu = \frac{2}{3}$ and $\frac{1}{3}$. They showed that their results could be described by the Landauer-Büttiker formalism if the electron charge e was replaced by e^*, the fractional charge of the quasiparticles in the FQHE. The results of these barrier-resistance measurements are consistent with an interpretation in terms of transmission and reflection of edge channels, but do not demonstrate adiabatic transport in the FQHE, i.e., the crucial issue of whether or not the fractional edge channels can be treated as independent current channels on appropriate length scales. To demonstrate adiabatic transport, two spatially separated barriers are required, which can act as injector and detector of edge channels—as in the experiment presented in this Letter.

The inset of Fig. 1 schematically shows the geometry of the double-barrier device. A Hall bar is etched in a high-mobility GaAs/AlGaAs heterostructure to which Ohmic contacts, labeled from 1 to 6, are attached. The electron density of the 2DEG is $1.8 \times 10^{15}/m^2$ and the mean free path is 9 μm. On top of the heterostructure three gates are fabricated. The voltage on the black center gate is kept fixed at a negative value of -3 V, in this way creating a sufficiently extended depletion region

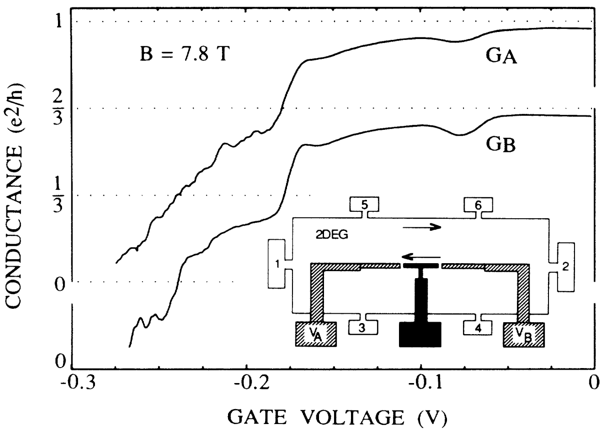

FIG. 1. Barrier conductances G_A and G_B as a function of gate voltage at a field of 7.8 T. The curve G_B has been offset for clarity. The double-barrier geometry defined by three different gates is shown in the inset. The arrows indicate the direction of electron flow along the sample edges.

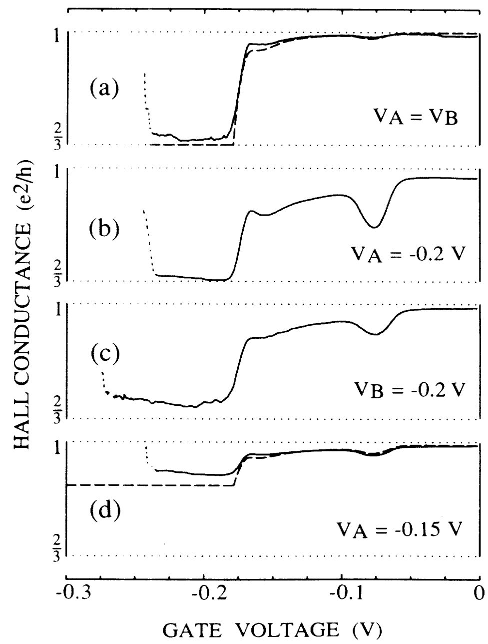

FIG. 2. Hall conductances as a function of gate voltage at a field of 7.8 T. In (a) both gate voltages V_A and V_B are varied simultaneously and in (b)–(d) one gate voltage is kept fixed. The rapidly rising parts (dotted) are measurement artifacts due to barrier pinchoff. The dashed lines are calculated from Eqs. (1), see text.

in the 2DEG to prevent conduction through the two narrow openings (width = 300 nm) separating the different gates (see also Fig. 3). A negative voltage V_A or V_B on the hatched gates (width = 0.5 μm and length = 40 μm of the smaller-width section) creates a potential barrier underneath them, which locally reduces the electron density n_s and consequently the filling factor $\nu = hn_s/eB$.

Figure 1 shows the two-terminal conductances[11] of the barriers as a function of gate voltage measured at 20 mK and at a fixed magnetic field of 7.8 T. At this field the filling factor of the bulk 2DEG is slightly less than 1, which can be seen in Fig. 1 at zero gate voltage. The decreasing gate voltage gradually reduces the conductance of each barrier until pinchoff occurs at -0.27 V. Although the observed fractional plateaus are not fully developed, the change in slope at a gate voltage of -0.175 V can be attributed to the $\frac{2}{3}$ fractional state, as we will discuss below.

Figure 2 shows the Hall conductances measured at $B = 7.8$ T, employing barrier A as the voltage probe and barrier B as the current probe. The Hall conductance is defined as $G_{H;14,23}$ indicating that the current flows from contact 1 to 4 and the voltage is measured between contacts 2 and 3. Figure 2(a) shows the Hall conductance as a function of equal voltage on both gates A and B. Although the filling factor in the bulk 2DEG is unchanged in the fixed magnetic field, the Hall conductance drops from e^2/h to $\frac{2}{3}e^2/h$ at -0.175 V. A similar behavior is seen if one gate voltage is kept fixed and the other is varied. In Figs. 2(b) and 2(c) one voltage is fixed at -0.2 V and in Fig. 2(d) the voltage on gate A is fixed at -0.15 V. The dashed lines in Figs. 2(a) and 2(d) are calculated from the barrier conductances G_A and G_B (see Fig. 1), which will be discussed below.

The Hall conductance $G_{H;23,14}$ measured by interchanging the current and voltage probes, did not show the anomalous drop to the $\frac{2}{3}$ plateau. Instead, $G_{H;23,14}$ was independent of the gate voltage and corresponded with the filling factor in the bulk 2DEG.

To describe our results we propose the existence of fractional edge channels, which follow different equipotential lines along the boundary of the sample. The adjustable barriers used as current and voltage probes in the experiment provide a selective coupling to these fractional edge channels. Coupling to a certain edge channel occurs if this channel follows an equipotential line which is higher than the probe potential barrier. Fractional edge channels following equipotential lines which are lower than the barrier potential of the probe are not transmitted over the barrier and thus will not be populated by a current probe nor detected by a voltage probe. Each populated or detected fractional edge channel is assumed to contribute $\frac{1}{3}e^2/h$ to the Hall conductance (for simplicity only the $p/3$ fractional channels are considered, with $p = 1,2,3$). However, if no coupling of the current probe or the voltage probe exists to a particular fractional edge channel, and interedge channel scattering between the probes is absent, this channel will be irrelevant for transport measurements. In this way deviations in the measured Hall conductance from the expected bulk value are a direct demonstration of adiabatic transport in fractional edge channels over the distance between the current and the voltage probe.

Selective population and detection of edge channels has been investigated in the integer quantum Hall regime.[6,7] Reference 7 gives a derivation of the Hall conductance depending on the transmission properties of the current and voltage probes. It follows from this derivation, which included only integer edge channels, that this Hall conductance cannot be smaller than e^2/h, even when the filling factors of the probes are less than 1. The observation of a Hall conductance below e^2/h therefore indicates the failure of the integer formalism. For describing our present results we include the fractional edge channels proposed above in the derivation of Ref. 7. Considering only the $p/3$ fractions we obtain

$$G_H = \begin{cases} \dfrac{e^2}{3h}\max(N_I+T_I, N_V+T_V) & \text{if } N_I \neq N_V\,, \quad \text{(1a)} \\ \dfrac{e^2}{3h}\dfrac{(N+T_I)(N+T_V)}{N+T_I T_V} & \text{if } N_I = N_V = N\,. \quad \text{(1b)} \end{cases}$$

N_I and N_V denote the number of fully transmitted fractional channels through the current and the voltage probe, respectively. T_I and T_V are the transmission probabilities ($0 \le T_I, T_V \le 1$) through the current and the voltage probe, respectively, of the partially transmitted upper channel. Note that Eqs. (1) are independent of the filling factor of the bulk 2DEG, but are completely determined by the transmission properties of the current and voltage probes. Consequently, the fractional quantization of the Hall conductance is determined by the filling factors in the probe barriers. A prerequisite for the validity of Eqs. (1) is the occurrence of adiabatic transport, requiring the absence of scattering between adjacent channels over the distance between the current and voltage probes (> 2 μm in our device).

In Fig. 3 we have illustrated the electron flow for the case of three fractional edge channels in the bulk 2DEG. The current probe populates only two of them ($N_I = 2$, $T_I = 0$) and the voltage probe detects two fractional edge channels ($N_V = 2$, $T_V = 0$). According to Eqs. (1) the

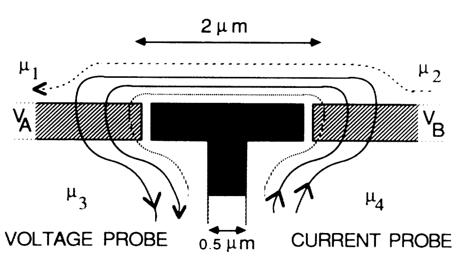

FIG. 3. Illustration of the selective population and detection of the first and second fractional edge channels. In this case the third channel does not contribute to the Hall conductance. The dotted line along the black center gate indicates the depletion area induced by the center gate voltage, which prevents conduction through the narrow openings separating the different gates.

Hall conductance for this case is equal to $\frac{2}{3}e^2/h$, which corresponds to the experimental situation of $V_A \approx V_B \approx -0.2$ V.

To compare the proposed description quantitatively with the measurements we have calculated the Hall conductance with the measured barrier conductances G_A as voltage-probe conductance and G_B as current-probe conductance (see Fig. 1) substituted in Eqs. (1). The results are shown in Figs. 2(a) and 2(d) (dashed lines) demonstrating a good agreement with the measured Hall conductances. Note again that an integer calculation would give a constant Hall conductance at e^2/h. The Hall conductance in Fig. 2(a) is calculated from Eq. (1b) with a fixed equal number of fully transmitted channels ($N_I = N_V = 2$) and the measured transmission of the third fractional channel of each barrier between 0 and 1, i.e., $\frac{2}{3}e^2/h < G_A, G_B < e^2/h$ (Fig. 1). Figure 2(d) shows that the Hall conductance can also be fixed at a value in between the plateaus, whenever the largest barrier conductance is fixed and not quantized (in this case $N_I < N_V = 2$ and $T_V = 0.62$ when $V_B < -0.175$ V). In the region $-0.175\text{ V} < V_B < 0$ V the Hall conductance is determined by both barrier transmissions ($N_I = N_V = 2$ and $T_I, T_V \neq 0$). The curves in Figs. 2(b) and 2(c) can be compared directly with Fig. 1 because in these cases one probe is kept fixed at the $\frac{2}{3}$ quantized value. According to Eq. (1a), Fig. 2(b) should follow the current-probe conductance G_B for $V_B > -0.175$ V ($N_I = N_V = 2$, $T_V = 0$, and $T_I \neq 0$) and be equal to $\frac{2}{3}e^2/h$ for lower V_B ($N_V = 2 > N_I$). In Fig. 2(c) the Hall conductance should follow the voltage-probe conductance G_A for $V_A > -0.175$ V ($N_V = N_I = 2$, $T_I = 0$, and $T_V \neq 0$) and be equal to $\frac{2}{3}e^2/h$ for lower V_A ($N_I = 2 > N_V$). Comparing Figs. 2(b) and 2(c) with Fig. 1 it can be seen that there is good agreement between the proposed description and the experiment. Similar measurements as in Figs. 2(b) and 2(c) for a number of fixed voltages on one single gate between -0.19 and -0.22 V did not show any dependence of the measured Hall conductance on this gate voltage. This indicates that in this range of gate voltage the barrier conductances G_A and G_B are indeed quantized at the $\frac{2}{3}$ fraction. The fact that the measured barrier conductances G_A and G_B do not show well-defined fractional plateaus may be related to scattering in the not fully quantized bulk 2DEG, which is measured in series.

The observation that $G_{H;23,14}$ (i.e., with current and voltage probes interchanged) is independent of V_A and V_B and equal to the bulk 2DEG value can also be understood within the proposed description. In this case the Ohmic contact 1 (see inset of Fig. 1) is the relevant voltage probe,[7] which will couple equally to all edge channels in the 2DEG. The Hall conductance should now correspond to the bulk filling factor, as is found experimentally. Note that complete equilibration over the long distance from probe A to Ohmic contact 1 yields the same result.

The agreement between the proposed description in terms of fractional edge channels and the experiment demonstrates that adiabatic transport occurs over the distance between the current and voltage probes. Apparently, the boundary defined by the center gate (black gate in Fig. 3) is sufficiently smooth that scattering between the second and third fractional edge channels is suppressed. The fact that we did not observe a Hall conductance quantized at $\frac{1}{3}$ may indicate that the boundary is not sufficiently smooth to suppress scattering between the first and second fractional channels. Although the energy separations between the first and second and between the second and third fractional channels are expected to be equal, the separation in space may differ when the boundary potential changes nonlinearly. We have studied the influence of the smoothness of the boundary in more detail in a second sample of identical design, but with a higher electron density of $2.3\times10^{14}/\mathrm{m}^2$. With -3.0 V applied to the center gate this sample did not show a deviation of the Hall conductance from the bulk 2DEG value, indicating that all channels are completely mixed. However, at lower voltages applied to the center gate, the Hall conductance showed quantization at anomalous values. With -4.5 V on the center gate the $\frac{2}{3}$ fractional value was almost reached. Hall-conductance measurements performed on this sample at a center-gate voltage of -4.5 V confirmed the results presented in Fig. 2. Apparently a lower center-gate voltage increases the depletion region until a sufficiently smooth boundary potential is formed at -4.5 V. Here the mixing between the second and third fractional channels is almost absent. It is difficult to determine quantitatively, including screening, the spatial locations of the fractional edge channels. However, the strong influence of the boundary potential evident from this experiment clearly shows that the properties of the boundary are of prime importance for the anomalous fractional quantization of the Hall conductance, in accordance with the proposed description in terms of fractional edge channels.[12]

In a recent paper Beenakker[9] extends the Landauer-Büttiker formalism to include the FQHE regime. He also theoretically demonstrates the formation of edge channels in the FQHE regime in a slowly varying boundary potential. The ith edge channel corresponding to the fractional filling factor ν_i contributes $(\nu_i-\nu_{i-1})e^2/h$ to the conductance, where ν_{i-1} is the lower filling factor corresponding to the next separated edge channel. If only the $p/3$ states are considered, Eqs. (1) can be derived from the multiterminal generalization given in Ref. 9.

In summary, transport in edge channels in the fractional quantum Hall regime has been studied experimentally by using two closely spaced adjustable barriers as current and voltage probes. By selectively populating and detecting these fractional edge channels, adiabatic transport over a distance exceeding 2 μm has been demonstrated. These results are in quantitative agreement with the generalized Landauer-Büttiker formalism for the fractional quantum Hall regime derived in Ref. 9.

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[11]The experiments are performed with two adjacent Ohmic contacts on either side of the barrier. The configuration of voltage and current contacts was such that effectively the two-terminal conductance is measured.

[12]The strong influence of the boundary potential explains why we did not observe an anomalous fractional quantized Hall effect in a device with two adjacent point contacts, as used in Ref. 7.