

## Equilibration between edge states in the fractional quantum Hall effect regime at high imbalances

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We experimentally study equilibration between edge states, copropagating at the edge of the fractional quantum Hall liquid, at high initial imbalances. We find an anomalous increase of the conductance between the fractional edge states at the filling factor  $\nu=2/5$  in comparison with the expected one for the model of independent edge states. We conclude that the model of independent fractional edge states is not suitable to describe the experimental situation at  $\nu=2/5$ .

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In the integer quantum Hall effect (IQHE) regime, edge states<sup>1</sup> (ES) are arising at the sample edge at the intersections of the Fermi level and Landau levels. Buttiker proposed a formalism,<sup>2</sup> that allows to calculate different transport characteristics of the sample by regarding the transport through ES. This picture was firmly confirmed in experiments with crossing gates (for a review see Ref. 3) and in the quasi-Corbino geometry.<sup>4</sup>

From the beginning, the fractional quantum Hall effect (FQHE) was understood as the many-body phenomenon.<sup>5</sup> Strongly interacting electron system forms a new ground state,<sup>5-7</sup> that, contains gapless excitation modes at the sharp sample edges—fractional ES.<sup>8,9</sup> While decreasing the sharpness of the edge potential profile, edge reconstruction occurs<sup>10</sup> and the sample edge is a set of incompressible (with constant fractional filling factor) and compressible electron liquids,<sup>11</sup> like in the integer case.<sup>12</sup> Fractional ES are arising at the edges of the incompressible stripes.<sup>10</sup> For the calculation of the transport along the fractional edge, Buttiker formulas can easily be modified.<sup>11</sup> These formulas were validated in experiments on the transport along the sample edge.<sup>13</sup>

From both the experimental and theoretical points of view, transport investigations *across* the sample edge should be important. Fractional ES can be regarded as the realization of the one-dimensional strongly correlated electron liquid,<sup>9</sup> as was confirmed in experiments on tunnelling into the fractional edge.<sup>14-17</sup> Except for the tunnelling, even the equilibration between the fractional ES in extended uniform junctions is a point of question. It was shown<sup>18</sup> to be sensitive to the internal structure<sup>10</sup> of the incompressible stripes. The authors in Ref. 19 concluded that interaction between ES can significantly affect on the maximum conductance of the line junction. Moreover, even the possibility to describe the interacting fractional ES at high imbalance in terms of the local electrochemical potentials is still an open question.<sup>20</sup> The fractional ES can be regarded as independent only for very smooth edge potential profile,<sup>11</sup> e.g., at the electrostatically defined edge.<sup>21,22</sup> The inter-ES interaction, however, cannot be neglected at stronger edge potentials, e.g., at etched mesa edges, where the reconstructed fractional edge<sup>10,18</sup> is expected.

Thus, to experimentally study the inter-ES equilibration, investigations at imbalances higher than the spectral gaps should be performed at etched mesa edge. This is impossible in the usual Hall-bar techniques,<sup>21-23</sup> but can be easily performed in the quasi-Corbino sample geometry.<sup>4,24,25</sup> Also, in view of the theoretical investigations,<sup>9,19</sup> inter-ES interaction differs qualitatively for different fractional fillings, so measurements at fifth fractions are important.

Here we experimentally study equilibration between the fractional ES, copropagating at the same sample edge, at high initial imbalances. We find an anomalous increase of the conductance between the fractional ES at the filling factor  $\nu=2/5$  in comparison with the expected one for the model of independent ES. We conclude that the model of independent fractional ES<sup>11</sup> is not suitable to describe the experimental situation at  $\nu=2/5$ .

Our samples are fabricated from molecular beam epitaxial-grown GaAs/AlGaAs heterostructure. It contains a 2DEG located 150 nm below the surface. The mobility at 4 K is  $1.83 \times 10^6$  cm<sup>2</sup>/V s and the carrier density  $8.49 \times 10^{10}$  cm<sup>-2</sup>, as was obtained from the usual magnetoresistance measurements. Also, magnetocapacitance measurements were performed to characterize the electron system under the gates. We use both these methods to check the contact resistances and the sample homogeneity. The cooling procedure with slow sample cooling was used to obtain the well-reproducible, stable, and homogeneous sample states, as was tested for four samples. This guarantees the reliability of the results, presented below.

An interplay between two ground states<sup>7</sup> [spin polarized (SP) at  $B=5.18$  T and spin unpolarized (SU) at  $B=4.68$  T] at  $\nu=2/3$  is well developed in our samples, permitting the measurements at different spin configurations of the  $\nu=2/3$  ground state.

The quasi-Corbino sample geometry<sup>4,24,25</sup> is modified for these measurements, see Fig. 1. Mesa of the square form ( $1.2 \times 1.2$  mm<sup>2</sup>) has a rectangular ( $810 \times 600$   $\mu$ m<sup>2</sup>) etched region inside it. Ohmic contacts are made to both, the inner and the outer, mesa edges. Two Schottky gates of the special form are placed on the top of the crystal, allowing to diminish the electron concentration under the gates. In the quantizing magnetic field at filling factor  $\nu$ , the number of ES at

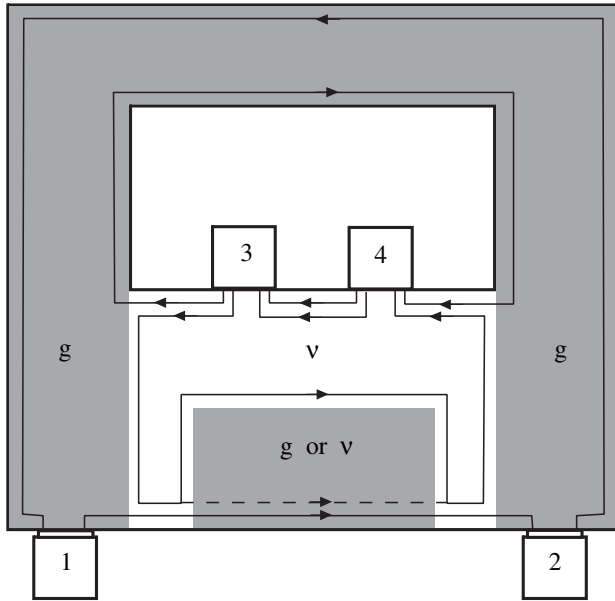


FIG. 1. Schematic diagram of the sample. Bold lines show etched mesa edges. Bars with numbers denote the ohmic contacts. The light gray areas represent the Schottky gates. Arrows indicate the direction of electron drift in the edge states.  $\nu, g$  indicates the filling factor in the corresponding region.

the ungated mesa edges are equal to  $\nu$ . By depleting 2DEG under the main gate to the filling factor  $g$ , some of ES (the number is  $\nu - g$ ), are redirected to the other mesa edge. Thus, ES from independent ohmic contacts run together along the outer etched edge of the sample in the gate-gap region, as depicted in Fig. 1. In the quantum Hall effect regime (at integer or fractional  $\nu, g$ ), a current between the outer and inner ohmic contacts can only flow across the sample edge in the gate gap, because of the zero dissipative conductivity. Auxiliary Schottky gate ( $800 \times 200 \mu\text{m}^2$ ) is placed into the gate gap, allowing to control the width of the interaction region. By depleting 2DEG to the same filling factor  $g$ , it separates two groups of ES in the gate gap by the macroscopic distance ( $200 \mu\text{m}$ ). ES are running together in two narrow ( $5 \mu\text{m}$ ) independent regions. As a result, there are two regimes of operation: (i) a negative bias is applied to both gates, the interaction region is narrow ( $2 \times 5 \mu\text{m} = 10 \mu\text{m}$ ); (ii) a negative bias is applied only to the main gate, the auxiliary gate is grounded, the interaction region is wide ( $810 \mu\text{m}$ ).

We study  $I$ - $V$  curves of the gate-gap region in the four-point configuration,<sup>4</sup> that allows to exclude any contact effects. We apply dc current  $I_{24}$  between the contacts 2 and 4 (grounded) and measure dc voltage  $V_{13}$  between the contacts 1 and 3, see Fig. 1. For the case of full equilibration between ES we can expect a linear  $I$ - $V$  with the equilibrium resistance that can be determined in our geometry from Buttiker formulas for integer<sup>2,4</sup> or fractional<sup>11,18</sup> fillings:  $R_{\text{eq}} = h/e^2 \nu/g(\nu - g)$ . We use a constant current mode to carefully study linear regions of  $I$ - $V$  (the resistances are in the range  $1.5 - 28 h/e^2$ ) and exclude contact resistances ( $0.5 \text{ k}\Omega$ ), while a constant voltage mode is more appropriate for

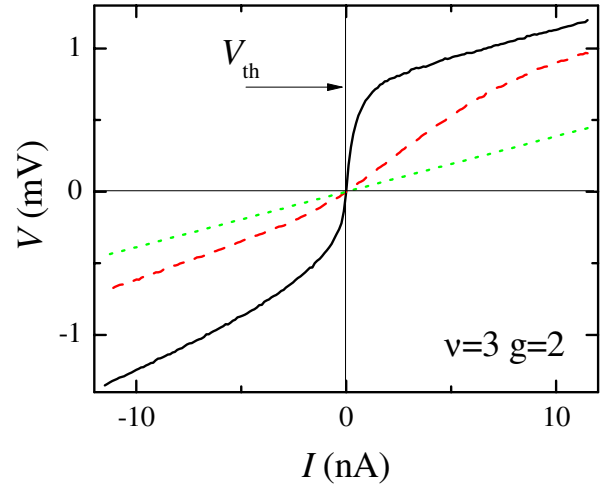


FIG. 2. (Color online)  $I$ - $V$  curves for integer filling factors  $\nu=3$ ,  $g=2$  for narrow ( $10 \mu\text{m}$ , solid line) and wide ( $800 \mu\text{m}$ , dashed line) interaction regions. Equilibrium curve (with  $R_{\text{eq}}=1.5h/e^2$ ) is shown by dots. Magnetic field  $B$  equals  $1.1 \text{ T}$ .

strongly nonlinear  $I$ - $V$ . We checked that the interchange of the current and voltage probes does not affect the results presented here, confirming reliability. The experiment is performed in the dilution refrigerator with the base temperature of  $30 \text{ mK}$ , equipped with the superconducting solenoid.

We start from the well-known situation<sup>4,25</sup> of integer fillings.  $I$ - $V$  curves for the integer filling factors  $\nu=3$ ,  $g=2$  are presented in Fig. 2. The experimental curve for the narrow gate gap is strongly nonlinear and asymmetric. The positive branch is of threshold behavior, the threshold value  $V_{\text{th}}=0.73 \text{ meV}$ . After the threshold, the positive branch goes with the constant slope, and is parallel to the fully equilibrated ( $R_{\text{eq}}=1.5h/e^2$ ) theoretical line. The slope of the negative branch of the  $I$ - $V$  trace is always higher than the equilibrium  $R_{\text{eq}}$ . The experimental  $I$ - $V$  curve for the wide gate gap is also presented in the figure. The threshold on the positive branch is still present, but is smaller and not so well defined as in the previous case. The positive branch itself is parallel to the equilibrium line at high currents. The negative branch of the  $I$ - $V$  is still nonparallel to the equilibrium line.

For the fractional filling factor combination  $\nu=2/3$ ,  $g=1/3$ ,  $I$ - $V$  curves are shown in Fig. 3 for both gate-gap widths.  $I$ - $V$ 's are presented in two panels, (a) and (b), for the two different spin configurations of the  $\nu=2/3$  ground state. For the narrow gate gap,  $I$ - $V$  curves are nonlinear and close to be symmetric. In contrast to the integer case, they have a linear region near the zero without any threshold and two nonlinear branches. The central linear region with roughly equilibrium slope, is clearly defined in the spin-polarized (high-field) state, but not so pronounced in the spin-unpolarized (low-field) state. Nonlinear branches disappear with increasing the temperature up to  $T=195 \text{ mK}$ , leaving the slope of the linear central part to be unchanged. At the wide gate gap the nonlinear branches are not present even at minimal temperature.  $I$ - $V$  curves for both gate-gap widths coincide near the zero, the experimental slope is not differ from the equilibrium  $R_{\text{eq}}=6h/e^2$  within 3%, see Fig. 3.

The most intriguing experimental result is the evolution of

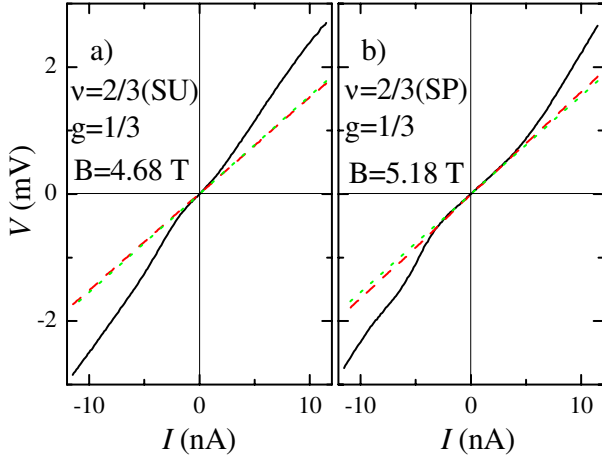


FIG. 3. (Color online)  $I$ - $V$  curves for fractional filling factors  $\nu=2/3$ ,  $g=1/3$  for narrow ( $10 \mu\text{m}$ , solid line) and wide ( $800 \mu\text{m}$ , dashed line) interaction regions, for two spin configurations of  $\nu=2/3$ : (a) spin unpolarized (SU) state ( $B=4.68 \text{ T}$ ); (b) spin polarized (SP) state ( $B=5.18 \text{ T}$ ). Equilibrium curve (with  $R_{\text{eq}}=6h/e^2$ ) is shown by dots.

the  $I$ - $V$  curve for the fractional filling factor combination  $\nu=2/5$ ,  $g=1/3$ , as shown in Fig. 4. The experimental curve for the narrow gate gap consists from two slightly nonlinear branches and is situated above the equilibrium line ( $R_{\text{eq}}=18h/e^2$ ). It is similar to Fig. 3(a), but the central linear region is not developed at all. Increasing the gate-gap width leads to the  $I$ - $V$  curve, which is situated *below* the equilibrium one, see Fig. 4, with 28% lower resistance. This curve is still nonlinear and can be scaled to one for the narrow gate gap by dividing the current by factor  $q=2.35$ , see inset to Fig. 4. Increasing the temperature up to  $T=0.62 \text{ K}$  results in linear  $I$ - $V$  traces with the slope, which is equal to  $5.1h/e^2 \ll R_{\text{eq}}=18h/e^2$  for both gate-gap widths. In other words, the scaling coefficient  $q$  approaches 1 by increasing the temperature.

Thus, we have two most important experimental results: (i) for the narrow gate gap ( $10 \mu\text{m}$ ),  $I$ - $V$  curves are nonlinear for both the integer and fractional fillings, but differ in the symmetry and the zero-bias behavior; (ii) for the wide gate gap ( $800 \mu\text{m}$ ) the slope of the fully equilibrated curve is significantly *smaller* than the calculated equilibrium one for the fractional filling factors  $\nu=2/5$ ,  $g=1/3$ , in contrast to the integer case and the simple fractional  $\nu=2/3$ ,  $g=1/3$  fillings.

At real edge profiles, the edge of the sample is a set of compressible and incompressible electron liquids in both the IQHE (Ref. 12) and FQHE (Refs. 10 and 11) regimes. Applying a voltage between the outer and inner ohmic contacts leads to the electrochemical potential imbalance across the incompressible stripe at the “injection” corner of the gate-gap (the left-hand one in Fig. 1). While going along the sample edge in the gate gap, this imbalance is diminishing with some characteristic equilibration length  $l_{\text{eq}}$ . We can consider two limits: (i) the gate-gap width  $W$  is much higher than the equilibration length,  $W \gg l_{\text{eq}}$ . The  $I$ - $V$  curve is determined by the equilibrium redistribution of the applied electrochemical potential difference between ES in the gate gap. The  $I$ - $V$  trace can be expected to be linear<sup>4</sup> with the equilib-

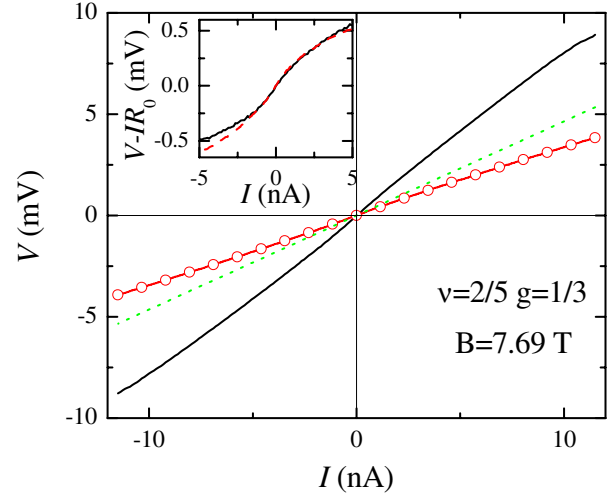


FIG. 4. (Color online)  $I$ - $V$  curves for fractional filling factors  $\nu=2/5$ ,  $g=1/3$  for narrow ( $10 \mu\text{m}$ , solid line with open circles) and wide ( $800 \mu\text{m}$ , dashed line with open circles) interaction regions. Equilibrium curve (with  $R_{\text{eq}}=18h/e^2$ ) is shown by dots. The inset shows the wide-region curve (dashed), scaled to the narrow-region one (solid) in  $x$  direction. The linear dependence  $IR_0$  with  $R_0=28h/e^2$  is subtracted to highlight the nonlinear behavior. Magnetic field  $B$  equals to  $7.69 \text{ T}$ .

rium Buttiker slope  $R_{\text{eq}}$ . (ii) In the opposite case  $W \ll l_{\text{eq}}$ , the charge transfer can be neglected and the applied voltage  $V$  directly affects the potential barrier between ES. The  $I$ - $V$  trace can be expected to be strongly nonlinear<sup>4</sup> and asymmetric, because of the intrinsic asymmetry at the sample edge.

From our experimental results for the narrow gate gap we can conclude that the latter situation is realized for the integer filling factors  $\nu=3$ ,  $g=2$ , while for the fractional ones an intermediate regime  $W \sim l_{\text{eq}}$  takes place.

Nonlinear  $I$ - $V$  curves at integer fillings  $\nu=3$ ,  $g=2$  can be explained in terms of the single-particle Landau levels, bent up by the smooth edge potential,<sup>12</sup> as it was reported before.<sup>4,25</sup> The full equilibration can be achieved only after the threshold voltage  $V_{\text{th}}$  for both gate-gap widths. It is worth to note, that we cannot expect and do not see in the experiment  $I$ - $V$  slopes smaller than the equilibrium  $R_{\text{eq}}$ , which would correspond to the additional charge transfer between ES.

For the FQHE regime, the full equilibration at  $W \sim l_{\text{eq}}$  can be achieved at low bias  $V$  (at low initial imbalances) while the rest electrochemical imbalance at the “rejection” corner of the gate gap is smaller than the temperature. While increasing the initial bias  $V$ , it becomes higher than the temperature, disturbing the full equilibration and leading to the nonlinear branches. Thus, the range of the linear behavior allows to estimate the equilibration length for fractional fillings:  $l_{\text{eq}} \leq 10 \mu\text{m}$  for  $\nu=2/3$ ,  $g=1/3$  with spin-polarized  $\nu=2/3$ ;  $l_{\text{eq}} \sim 10 \mu\text{m}$  for  $\nu=2/3$ ,  $g=1/3$  with spin-unpolarized  $\nu=2/3$ ;  $l_{\text{eq}} > 10 \mu\text{m}$  for  $\nu=2/5$ ,  $g=1/3$ . These estimations for  $l_{\text{eq}}$  at third fractions are in good coincidence with ones, reported before<sup>21–23</sup> for  $\nu=2/3$ ;  $1/3$ , that support our analysis.

The situation for the wide gate gap is more sophisticated. The experimental  $I$ - $V$  traces indicate the full equilibration

between the fractional ES at  $\nu=2/3$ . In contrast, the  $I$ - $V$  trace is still nonlinear at  $\nu=2/5$ , and is situated significantly *below* the calculated line for the full equilibration, see Fig. 4. The former could be expected for  $W < l_{\text{eq}}$ , while the latter cannot be expected for any relation between  $W$  and  $l_{\text{eq}}$ . In terms of the picture of independent fractional ES in the gate gap,<sup>11</sup> it means that there is some additional charge transfer between ES and they are leaving the gate-gap region with different electrochemical potentials. It seems to be impossible, because of the macroscopic gate-gap width  $W=800 \mu\text{m} \gg l_{\text{eq}} \sim 10 \mu\text{m}$ . From both this fact and the scaling between nonlinear  $I$ - $V$ 's with scaling coefficient  $q=2.35 \ll W_{\text{wide}}/W_{\text{narrow}}=81$  and its temperature behavior, we should conclude, that the model of independent ES in the gate gap<sup>11</sup> does not describe the equilibration process at the FQHE edge at  $\nu=2/5$ . We should mention here, that non-ideal contacts could not affect the presented result. Nonideal contacts would lead to the nonperfect mixing of the electrochemical potentials in contacts,<sup>2,3</sup> and, thus, to rising resistance *above* the equilibrium value.

Our experiment could be compared with the picture of interacting fractional ES in line junction,<sup>19</sup> where the influence on the equilibrium conductance is expected, different for  $\nu=1/3$  and  $\nu=1/5$ . However, the exact calculation<sup>19</sup> was performed for the junction between two quantum Hall liquids at principal filling factors  $\nu_{\pm}=1/(2m_{\pm}+1)$ ,  $m_{\pm}=0,1,\dots$ . In our experiment, we are working with *nonprincipal* fractional fillings and with equilibration at the reconstructed FQHE edge. Both points are crucial for Ref. 19, preventing us from the direct comparison. We hope that this experiment will stimulate further theoretical investigations.

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