Interedge Strong-to-Weak Scattering Evolution at a Constriction in the Fractional Quantum Hall Regime

Stefano Roddaro, Vittorio Pellegrini, and Fabio Beltram
NEST-INFM, Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy

Giorgio Biasiol[1] and Lucia Sorba[1,2]
[1]*NEST-INFM and Laboratorio Nazionale TASC-INFM, Area Science Park, I-34012 Trieste, Italy*
[2]*Università di Modena e Reggio Emilia, Modena I-34012, Italy*
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Gate-voltage control of interedge tunneling at a split-gate constriction in the fractional quantum Hall regime is reported. Quantitative agreement with the behavior predicted for out-of-equilibrium quasiparticle transport between chiral Luttinger liquids is shown at low temperatures at specific values of the backscattering strength. When the latter is lowered by changing the gate voltage, the zero-bias peak of the tunneling conductance evolves into a minimum, and a nonlinear quasiholelike characteristic emerges. Our analysis emphasizes the role of the local filling factor in the split-gate constriction region.

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Scattering amplitudes between highly correlated electronic states are providing some of the most fascinating manifestations of electron-electron interaction effects in condensed matter [1]. Two-dimensional electron systems (2DES) under the application of magnetic fields (B) and at low temperatures are the ideal experimental arena where these phenomena can be induced and experimentally studied. This extreme quantum limit is characterized by integer and fractional quantum Hall (QH) states [2]. For integer or peculiar fractional ratios of the filling factor $\nu = nh/eB$ (n is the charge density), the 2DES becomes insulating and charges can propagate only in chiral one-dimensional (1D) states at the edges of the QH liquid. Wen demonstrated that at fractional ν's these 1D channels lead to a remarkable realization of nonfermionic states [3–5] identified as chiral Luttinger liquid (CLL). Several theoretical investigations predicted nonlinear tunneling between two such CLLs or between a metal and a CLL [3–12]. These results motivate an intense on-going experimental effort [1,13,14].

Experimentally, interedge tunneling between two CLLs can be induced at a quantum point contact (QPC) constriction defined by gating [15–22]. The split-gate QPC has two main effects. By locally depleting the 2DES it controls the edge separation and, consequently, the interedge interaction strength. It also modifies the local filling factor (ν^*). At gate-voltage (V_g) values corresponding to the formation of the constriction ν^* is still equal to ν. By further reducing V_g the local filling ν^* decreases and becomes zero at pinch-off.

Two separate interedge scattering regimes can be identified [6]. In the strong backscattering limit, the constriction is approaching pinch-off ($\nu^* \approx 0$) and scattering is associated to tunneling of electrons between two disconnected QH regions. For simple fractions such as $\nu = 1/q$ where q is an odd integer, theory predicts that when the tunneling voltage V_T (voltage difference between the two fractional edge states) goes to zero the tunneling current I_T vanishes as V_T^{2q-1}. In the opposite limit of weak backscattering, the QH fluid is weakly perturbed by the constriction ($\nu^* \approx \nu$) and tunneling is associated to scattering of Laughlin quasiparticles with fractional charge e/q. In the $T = 0$ limit, the tunneling current diverges as V_T tends to zero. At small but finite temperatures and below a critical tunneling voltage I_T reverts to a linear Ohmic behavior. This leads to a zero-bias peak in the differential tunneling conductance dI_T/dV_T whose width is proportional to qkT/e. We recently observed an unexpected suppression of the tunneling conductance in the low-temperature weak-backscattering limit and the appearance of the interedge tunneling zero-bias peak only above a critical value of temperature [18,19]. This low-temperature suppression has been recently ascribed to interedge interactions across the split gate [23].

The crossover between the strong and the weak regime and the role of temperature are nonequilibrium quantum transport phenomena largely unexplored experimentally. Fendley *et al.* [7,8] provided a unified theoretical framework of nonequilibrium transport between CLLs applicable to these different regimes. They demonstrated the existence of an exact duality between weak and strong backscattering, i.e., between electron and Laughlin quasiparticle tunneling [7–9]. Recent microscopic calculations emphasized the impact of electron-electron interactions [12,24].

In this Letter, we show the experimental evolution of the out-of-equilibrium interedge tunneling conductance dI_T/dV_T for different values of V_g and T at $\nu = 1/3$. We find that at $\nu^* = 1/5$ the dI_T/dV_T versus V_T characteristic displays a sharp zero-bias peak at low temperatures and two well-resolved minima at positive and negative V_T values. Both width and amplitude of the zero-bias peak

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are found to saturate for temperatures below $T = 100$ mK. The shape of the tunneling conductance and its temperature dependence are successfully compared with the predictions by Fendley *et al.* [7,8]. Our experiments and analysis thus provide further evidence for the non-Fermi-liquid nature of fractional QH edge states.

As the backscattering strength is lowered by changing V_g, we find first a suppression of the nonlinearity of the tunneling conductance at $\nu^* \approx 1/4$, and then the emergence of a Fendley-like minimum at V_g corresponding to approximately $\nu^* = 2/7$. When $\nu^* = \nu = 1/3$, we recover a zero-bias minimum in agreement with previous results [18,22]. A similar evolution is also found at a bulk filling factor $\nu = 1$, in this case centered on $\nu^* = 1/2$. This latter result unambiguously establishes the role of the local filling factor ν^* in the interedge tunneling, even in a configuration where the bulk is a Fermi-liquid state. We believe that the observed values of ν^* associated to the peak-to-minimum crossover point at an interpretation in terms of particle-hole conjugation around the metallic state of composite fermions. Andreev-like processes of fractional quasiparticles at the interface between the bulk and the constriction region [25] and intra- and interedge interaction effects [12,23,24] could also play a significant role.

The measured devices were processed from a 150 nm deep $GaAs/Al_{0.15}Ga_{0.85}As$ heterojunction with carrier density $n = 7\text{–}9 \times 10^{10}$ cm^{-2} (depending on the cooldown procedure) and mobility exceeding 10^6 cm^2/V s. QPC gates were fabricated by e-beam lithography, metallization, and lift-off. Figure 1(a) shows a scanning electron microscopy image of the QPC superimposed to the multiterminal configuration used. Measurements were carried out by injecting a current I with both ac and dc components into contact 1. This current is partially reflected at the constriction: The backscattered fraction (I_T) is collected by Ohmic contact 2 while the transmitted one ($I - I_T$) is collected by contact 3. With this configuration, the potential difference between the two edges propagating towards the constriction is given by $V_T = \rho_{xy} I$ ($\rho_{xy} = h/\nu e^2$). Finite-bias phase-locked four-wire measurements were performed with the ac component of the current down to 20 pA. When the 2DES outside the QPC is in a QH state, the longitudinal-resistance drop across the constriction (dV/dI, the quantity measured in the experiment) is related to dI_T/dV_T through the relation

$$\frac{dV}{dI} = \rho_{xy}\frac{dI_T}{dI} = \rho_{xy}^2\frac{dI_T}{dV_T}. \tag{1}$$

Given the direct proportionality between these two quantities, in what follows the differential tunneling conductance characteristics will be presented as dV/dI resistance curves. The mismatch between bulk and constriction filling factors yields an additional V_T-independent longitudinal resistance drop due to the extra backscattered Landauer-Büttiker current. In the setup adopted in our experiments, this mismatch leads to

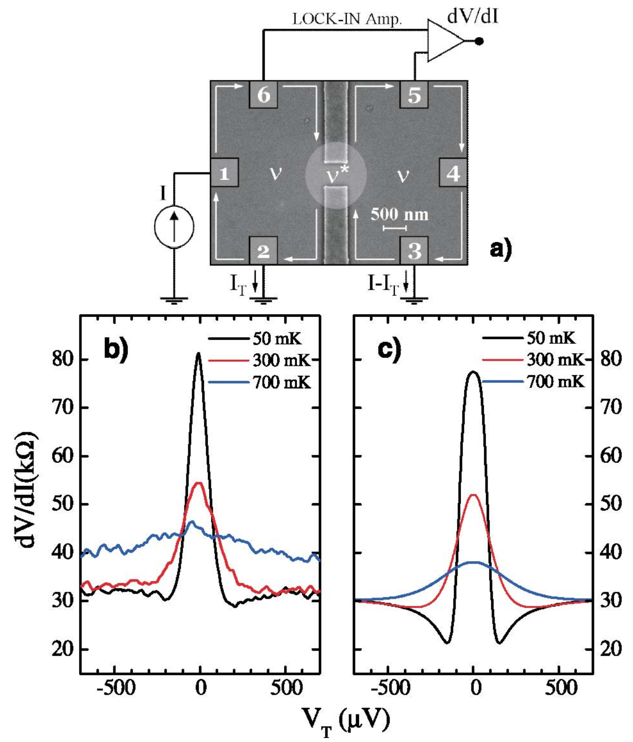

FIG. 1 (color). (a) Scanning electron microscope image of the quantum point contact (QPC) and setup of differential conductance. The geometrical sizes of the QPC constriction are 600 nm wide and 500 nm long. Bias current I is injected at the contact 1 and partially reflected at the constriction. The backscattering current I_T leaves the device through the contact 2, the transmitted one ($I - I_T$) through the contact 3. The measurement is performed in a four-wire scheme. The resistance drop dV/dI is measured between contacts 5 and 6. (b) Experimental dV/dI tunneling curves as a function of temperatures. $I_{ac} = 20$ pA. (c) Calculated dV/dI curves as a function of temperature according to Refs. [7,8].

$\frac{dV}{dI}|_{BG} = h/\nu e^2[1 - \nu^*/\nu]$. This relation was used to estimate ν^* from the measured resistance at large V_T.

Figure 1(b) shows representative finite-bias dV/dI measurements at a background value $\frac{dV}{dI}|_{BG} \approx 32$ kΩ, corresponding to $\nu^* = 1/5$. At low temperatures, the tunneling conductance displays a sharp (full width at half maximum ≈ 100 μV) zero-bias peak and two minima at positive and negative voltage bias (the peak resistance value is set by the quantized transverse resistance $3h/e^2 \approx 77.4$ kΩ [26]). The tunneling conductance presents a marked temperature dependence, and the nonlinearity altogether disappears for T exceeding 700–800 mK. These data can be analyzed within the framework proposed by Fendley *et al.* [8]. Figure 1(c), in particular, reports a set of calculated differential interedge tunneling characteristics at filling factor 1/5 [8]. To allow the comparison with the experimental data, a constant background of 32 kΩ was added to the calculated curves. The only free parameter in the calculation is the so-called impurity or point-contact interaction strength T_B, and the best agreement was found for $T_B = 500$ mK.

This strengthens the interpretation of the nonlinear tunneling curve in terms of quasiparticle tunneling between fractional quantum Hall edge states at filling factor $1/5$. It is worth noting that the two lateral minima present at the lowest temperature are purely nonequilibrium transport effects in the interedge tunneling conductance.

Further support to this interpretation stems from the temperature dependence of width and intensity of the zero-bias tunneling peak. Experimental data (open circles) are plotted in Fig. 2 together with the results of the theoretical prediction in the weak-backscattering limit [4,5] (dotted lines) and with the exact results of Fendley *et al.* [8] (solid lines). We should like to emphasize the low- and high-T behavior in Fig. 2. At low T, the weak-backscattering theory predicts a width proportional to $kT/\nu^* e$, vanishingly small when $T \rightarrow 0$. On the contrary, the exact nonequilibrium results yield a saturation below $T \approx 100$ mK in agreement with our experimental results [27]. A similar saturation was found for the intensity of the zero-bias tunneling peak. This behavior signals the evolution of the tunneling characteristics from the weak- to the strong-backscattering regime as T is lowered. In the high-T weak-backscattering regime, on the other hand, the T dependence of the peak intensity is compatible with $T^{-8/5}$ [see the inset of Fig. 2(b) where the experimental data are plotted in a log-log scale together with a straight line with slope $-8/5$] consistently with the CLL prediction of $T^{(2\nu^*-2)}$ at $\nu^* = 1/5$.

Let us move on to the evolution of interedge tunneling conductance as a function of V_g. Figure 3 reports representative results obtained with a relatively high excitation current $I_{ac} = 200$ pA. Two qualitatively different behaviors emerge: For high backscattering strength (high $|V_g|$ values) conductance curves display a maximum at zero bias [see also Fig. 1(b)]; for lower $|V_g|$ values the maximum evolves into a minimum. This behavior was consistently observed at different charge densities (and magnetic fields). In all measurements we found that the minimum-to-maximum transition occurs at a resistance value of about 20 kΩ where a flat linear characteristic is found. It is intriguing to note that this resistance value corresponds to $\nu^* = 1/4$. Here a Fermi-liquid state of composite fermions with four flux quanta h/e attached is realized within the constriction region. A similar evolution is observed at $\nu = 1$ (see inset of Fig. 3): The crossover in this case occurs at $\nu^* = 1/2$. This latter result highlights the impact of the local filling factor ν^* on the tunneling characteristics.

A careful analysis of the tunneling conductance characteristics under low excitation current (20 pA) reveals an unexpected behavior. First, the line shapes of maxima change significantly as the gate voltage is varied close to $\nu^* = 1/5$ as shown in Fig. 4(a). In addition, at the specific background resistance value of about 11 kΩ ($\nu^* = 2/7$), we observed a sharp zero-bias dip with a line shape similar to the one observed at $\nu^* = 1/5$. Figure 4 [panels (b)–(e)] compares the evolution of the tunneling conductance peak (at $\nu^* = 1/5$) and dip (at $\nu^* = 2/7$) as a function of T. The behavior in the high temperature limit is associated to the breakdown of the QH state outside the QPC: In both cases the contribution of this additional

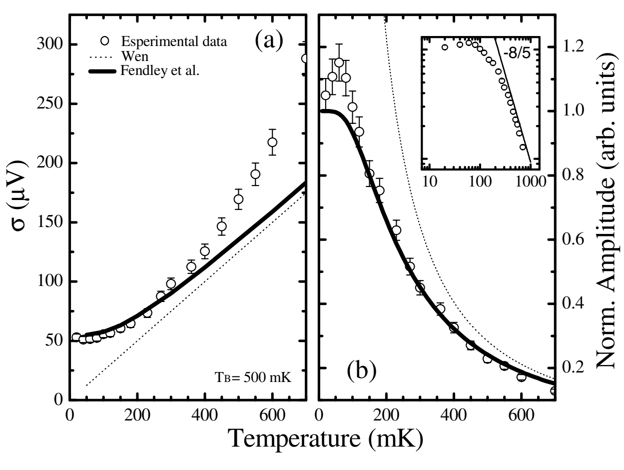

FIG. 2. (a) Standard deviation parameter σ of the Gaussian fit to the zero-bias tunneling conductance peak versus temperature. Experimental data (open circles), theoretical calculation at filling factor $1/5$ following Wen (Ref. [3], dotted line), and Fendley *et al.* (Ref. [8], solid line) with $T_B = 500$ mK. (b) Same as in (a) but for the peak intensity (normalized in terms of the reflection coefficient for the local filling ν^* [29]). The inset reports the experimental points in a log-log scale together with a straight line with slope $-8/5$.

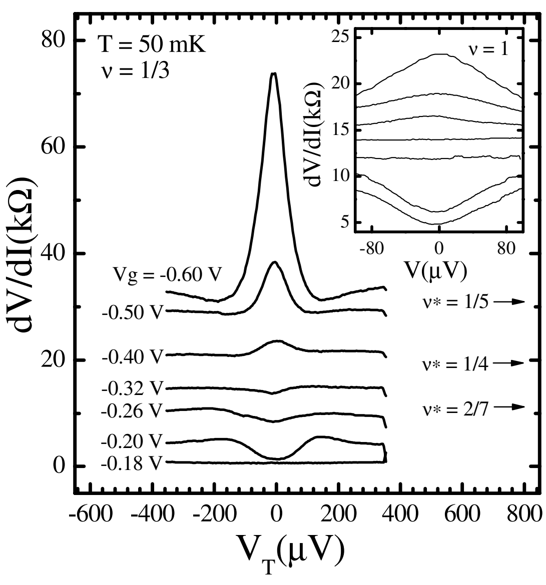

FIG. 3. Evolution of tunneling conductance versus gate voltage at $T = 50$ mK and $\nu = 1/3$. The background resistance values associated to relevant filling factors inside the constriction region ν^* are indicated by the arrows. The inset shows the behavior at the bulk filling factor $\nu = 1$. Here the crossover occurs at ≈ 12 kΩ which corresponds to $\nu^* = 1/2$, and the saturation is at the transverse resistance $h/e^2 \approx 25.8$ kΩ. The excitation current is $I_{ac} = 200$ pA.

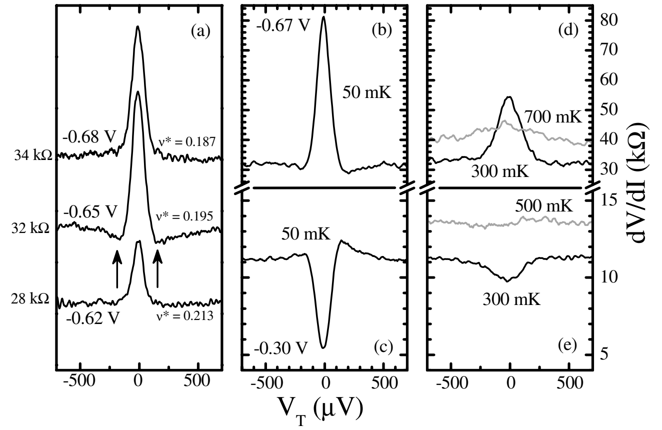

FIG. 4. (a) Evolution of the differential tunneling conductance versus V_g. At the background resistance value of ≈ 32 kΩ ($\nu^* = 1/5$), finite-bias minima (indicated by arrows) are observed in agreement with [7,8]. The excitation current is $I_{ac} =$ 20 pA. (b),(d) Evolution of the differential tunneling conductance characteristics corresponding to $\nu^* = 1/5$ at three different values of the temperature. (c),(e) Same as (b) and (d) but for the background resistance of 11 kΩ (corresponding to $\nu^* = 2/7$).

backscattering simply increases the overall resistance drop. As expected, the weaker QH 2/7 state reflects into a more pronounced temperature dependence. A large sensitivity to the electrostatic configuration of the split gate was found close to the weak 2/7 QH state, thus preventing a detailed study of line shape evolution at the required low values of the excitation current.

The observation of symmetric peak and dip line shapes compatible with the theory of Refs. [7,8] is intriguing. Given the values of ν^*'s, it is tempting to link these data to particle-hole conjugation around the metallic state of composite fermions at 1/4. In this framework, the tunneling peak could be related to quasiparticle tunneling between $\nu^* = 1/5$ edge states, and the dip would be due to quasihole tunneling at $\nu^* = 2/7$, the latter leading to an increase of the total transmission coefficient at the QPC constriction (i.e., reduction of the measured resistance drop dV/dI). In the Fermi-liquid state corresponding to $\nu^* = 1/4$, the V_T-dependent nonlinear tunneling current vanishes as observed experimentally. The complex structure of edge states in the rather smooth potential profile of the split-gate QPC should be taken into account [28]. Moreover, quasiparticle Andreev-like processes due to the mismatched filling factors at the QPC [25] and interaction effects intraedge and across the split gate [23,24] may also play a role. Further experimental and theoretical analysis is therefore needed.

In conclusion, we reported the evolution of interedge scattering at a split-gate QPC constriction when the bulk is at $\nu = 1/3$. Gate bias allows one to control the interedge coupling by changing both the interedge distance and the filling factor ν^* within the QPC region. At a local filling factor $\nu^* = 1/5$ and $T = 50$ mK, we observed a zero-bias differential tunneling-conductance peak consistent with the prediction of out-of-equilibrium quasiparticle transport between CLLs. The gate-voltage-induced evolution of tunneling around $\nu^* = 1/4$ suggests an unexpectedly complex phenomenology in quasiparticle transport through a QPC in the QH regime.

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