Quantum Hall circuits with variable geometry: study of the inter-channel equilibration by Scanning Gate Microscopy

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Electronic transport in the quantum Hall regime

Landau levels in a confined system

- Edge state picture: current is carried by chiral 1D channels

Backscattering is suppressed due to the large spatial separation between counter-propagating channels
Electronic transport in the quantum Hall regime

Landau levels in a confined system

Edge state picture:
 current is carried by chiral 1D channels

With a QPC we can intentionally induce backscattering, which provides us information about the edge properties

see papers by the NEST quantum transport group:
Roddaro et al.: PRL 90 (2003) 046805
Roddaro et al.: PRL 95 (2005) 156804
Roddaro, Paradiso et al.: PRL 103 (2009) 016802
Non-interacting VS interacting picture

• The self consistent potential due to e-e interactions modifies the edge structure

• For any realistic potential the density goes smoothly to zero.

• Alternating compressible and incompressible stripes arise at the sample edge

Incompressible stripes:
• The electron density is constant
• The potential has a jump

Compressible stripes:
• The electron density has a jump
• The potential is constant

Motivation: electronic quantum interferometry

The state of the art of electronic quantum interferometry

At the beam splitters the electrons are backscattered into the counter-propagating edge through two quantum point contacts (QPCs).
Motivation: a new architecture for QH interferometry

A simply connected QH interferometer: the proposal of Giovannetti et al.

Advantages:

• Simply connected topology (no air bridges)

• Very small $\Phi$ area, only a few flux quanta are involved

• The device is scalable: it is possible to put many devices in series
Motivation: a new architecture for QH interferometry

a simply connected QH interferometer: the proposal of Giovannetti et al.

Is it possible to study and image the microscopic details of the inter-channel backscattering?

The only elusive parts are the beam mixers between co-propagating channels.

coherent inter-channel mixing

PHYSICAL REVIEW B 77, 155320 (2008)

Multichannel architecture for electronic quantum Hall interferometry

Vittorio Giovannetti, Fabio Taddei, Diego Fristaglia, and Rosario Fazio
Motivation: fractional structures in integer edges

With transport measurements our group found evidences of fractional structure (Luttinger liquid-like) in a single edge (Fermi liquid).


How can we image the edge structure and in particular their fractional components?
Outline

- Scanning Gate Microscopy
- Imaging the edge channel structure
- SGM study of a beam mixer between co-propagating edges
- A simply connected Mach-Zehnder
- Imaging of fractional stripes in a single integer edge channel

Future directions: interferometry with fractional quasi-particles?
The SGM @NEST lab in Pisa

Setup:

- AFM non-optical detection scheme (tuning fork)
- With vibration and noise isolation system
- $^3$He insert (cold finger base temp. :300 mK)
- 9 T cryomagnet

Pioneering work by:

Tuning fork and sample holder

Tip – sample geometry

- Conductive tip glued on the TF
- Top
- Bottom
- Z coarse posit.
- X, Y coarse positioners
- XYZ scanner
- Thermometer

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SGM measurements on QPCs

The biased tip creates a depletion spot that we use to backscatter the electrons passing through the constriction.

The split gates define a constriction by depleting the 2DEG underneath.
In 1D systems the current is carried by a finite number of modes (arising from confined subbands). Each mode contributes two quantum of conductance.

First we fix the mode number (QPC setpoint), then we start scanning the biased tip at a fixed height.
QPC at 3rd plateau

$G = 6 \frac{e^2}{h}$

$G = 0$

$V_{\text{gate}} (V)$

$G (\frac{e^2}{h})$

Distance (μm)

600nm
QPC at 2nd plateau

- $G = 6 \, e^2/h$
- $G = 0$

Graphs showing the transition at the 2nd plateau with $V_{gate}$ vs. $G (e^2/h)$ and Distance vs. $G (e^2/h)$.
QPC at 1st plateau

G = 6 e²/h

G = 0

1st plateau

G (e²/h)

Distance (µm)

V_{gate} (V)

G (e²/h)
Branched flow and interference fringes

- QPC conductance $G = 6 \, e^2/h$ (3rd plateau)
- Tip voltage $V_{\text{tip}} = -5 \, V$, height $h_{\text{tip}} = 10 \, nm$

Fringe periodicity: $\lambda_F/2=20 \, nm$
Selective control of edge channel trajectories by SGM

**SGM technique:** we select individual channels from the edge of a quantized 2DEG, we send them to the constriction and make them backscatter with the biased SGM tip.

- Bulk filling factor \( v = 4 \)
- \( B = 3.04 \) T
- 2 spin-degenerate edge channels
- gate-region filling factors \( g_1 = g_2 = 0 \)

*N. Paradiso et al., Physica E 42 (2010) 1038.*
How we probe incompressible stripes

Self-consistent potential

Landau levels inside the constriction

\( \hbar \omega_c \)

tip induced potential

tip position

conductance \((e^2/h)\)
tip position (nm)

-100 0 100 200 300 400 500 600 700 800

0

1

2

3

4

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How we probe incompressible stripes

conductance ($e^2/h$) vs. tip position (nm)

backscattering

↑ tip position
How we probe incompressible stripes

conductance \( (e^2/h) \)
tip position (nm)

-100 0 100 200 300 400 500 600 700 800

conductance (e^2/h)
tip position (nm)

300nm

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How we probe incompressible stripes

Energy gap: $\hbar\omega = 5.7$ meV
Plateau width: 60 nm
Incompr. stripe width: $\approx 30$ nm
Asymmetrical gate bias

From QPCs to QH interferometry

Present technology: beam mixers are obtained by means of QPCs

at the beam splitters the electrons are backscattered into the counter-propagating edge through two QPCs

New architecture: beam splitters induce mixing between co-propagating edge channels
Studying the inter-channel equilibration

Edge states in the regimes of integer and fractional quantum Hall effects

E V Deviatov

Physics – Uspekhi 50 (2) 197 – 218 (2007)

\[ \mu_{\text{in}} - \mu_{\text{out}} = eV_{\text{bias}} \]
Studying the inter-channel equilibration

Edge states in the regimes of integer and fractional quantum Hall effects

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*Physics – Uspekhi* 50 (2) 197–218 (2007)

devices with fixed interaction length $d$:
elusive determination of the microscopic details of the equilibration mechanisms

$\mu_{in} - \mu_{out} = eV_{bias}$
The opportunity of the Scanning Gate Microscopy

Our technique allows to selectively control the channel trajectory

Our idea: exploit the mobile depletion spot induced by the SGM to continuously tune $d$

$v_{\text{bulk}} = 4$

two spin degenerate edges

$v=0$
$v=2$
$v=4$
Experimental setup

- Tip voltage = -10 V

**2DES**
- Mobility = $2.3 \times 10^6 \text{cm}^2/\text{Vs}$
- Electron density = $3.2 \times 10^{11} \text{cm}^{-2}$
- Depth = 55 nm

**Scheme of the electronic setup**
- **Transmitted component**
- **Reflected component**
- **Source bias** $V = V_{AC} + V_{DC}$
- **Edge-selector gate**
- **Tip**

**SEM micrograph of the device**

$\nu = 0$
$\nu = 2$
$\nu = 4$
Calibration step

Topography scan

Calibration SGM scan

\[ \nu_{\text{bulk}} = 4 \]

\[ I_A \]

\[ I_B \]
Calibration step

Topography scan

Calibration SGM scan

the edges meet here
Imaging the inter-channel equilibration

By grounding the upper contact an imbalance is established between the edges.

SGM map of the $I_B$ signal: direct imaging of the equilibration process.

Source bias: $V_{AC}=50\mu V, V_{DC}=0mV$
Imaging the inter-channel equilibration

The profiles of $G_B(d)$ along the trajectory show a strict dependance on the local details.

Source bias: $V_{AC}=50\mu V, V_{DC}=0mV$
Imaging the inter-channel equilibration

The profiles of $G_B(d)$ along the trajectory show a strict dependence on the local details.

We can directly image the potential induced by the most important defects by means of a scan at zero magnetic field.

Source bias: $V_{AC}=50\mu V$, $V_{DC}=0mV$

SGM scan at zero magnetic field

Correlation found
Tight binding simulations

Pictorial model for the disorder potential
- tip potential
- "big impurities" potential
- background potential

SGM map of the inter-channel equilibration in another device

Simulations made by the theoretical group of Scuola Normale Superiore (Pisa, Italy)
D. Venturelli, F. Taddei, V. Giovannetti and R. Fazio

- Experimental data
- Tight binding simulations

scatter centers

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Next step: a simply connected MZI

If the electron mixing is coherent, it is possible to build an interferometer just by adding another selector gate.

Our idea to implement the Mach-Zehnder interferometer proposed by Giovannetti et al.
Nonlinear regime

The backscattered current is a function of the local imbalance $\Delta V(x)$ that depends on the specific scattering process.

$$\frac{dI}{dx} = -\frac{e^2}{\hbar} \frac{d}{dx} \Delta V(x) = \Phi(\Delta V(x))$$
Two mechanisms for the inter-channel scattering

For low bias the only relevant mechanism is the elastic scattering induced by impurities, which determines an ohmic behavior (linear I-V):

\[ dI = \frac{2eT_0}{h} \int_{-\infty}^{\infty} (f_{\mu_i, \tau}(\epsilon) - f_{\mu_{io}, \tau}(\epsilon))d\epsilon = \frac{2e^2T_0}{hv_d} \Delta V(x) \]

At high bias (\( \Delta \mu \approx \hbar \omega_c \)) vertical transition with photon emission are enabled (threshold and saturation):

\[ dI = \frac{2eT_i}{h} \int_{-\infty}^{\infty} [f_{\mu_i, \tau}(\epsilon)(1 - f_{\mu_{io}, \tau}(\epsilon - \hbar \omega_c))]d\epsilon = \frac{2eT_i}{h} \left( \frac{e\Delta V(x) - \hbar \omega_c}{1 - e^{-\frac{\hbar \omega_c - e\Delta V(x)}{k_BT}}} \right) \]

![Graph](attachment://graph.png)
Impact of the electron heating

Electron heating due to injection of hot carriers:

\[
\frac{d}{dx} T(x) = \frac{3e^2}{4\pi^2 k_B^2 \ell_{eq}} \frac{\Delta V^2(x)}{T(x)}
\]

The relaxation of hot carriers induces a dramatic temperature increase. This is why the transition is smoothened and the threshold voltage reduced for high \(d\).
Conclusions

- We explored the use of the Scanning Gate Microscope to selectively control the edge channel trajectories.

- Control of the edge channel trajectory allowed us to study their structure.

- We built size-tunable QH circuits to directly image the equilibration between imbalanced co-propagating edges.

- The comparison with the SGM scan at zero magnetic field revealed a correlation between the local potential and steps in the $G_B(d)$ curve.

- Shift of the threshold voltage for the onset of photon emission is explained by a simple model for the electron heating.

- Our last measurements on $v=1$ samples managed to image the fractional incompressible stripes within a single integer edge channel.
Novel results: fractional structures in integer channels

Beenakker* suggested that at the edge of a smooth integer edge a series of compressible/incompressible fractional stripes can occur. We used the SGM technique to image them.

*C. W. J.Beenakker, PRL 64, 216 (1990)

Even though the electron temperature is quite high (400 mK), nonetheless the more robust fractions (1/3, 2/5) are visible.

N. Paradiso et al., PRB (submitted).
Summary and outlook

The SGM technique allows us to individually control the edge channel trajectory and study their structure.

With this extra degree of freedom we can build size-tunable QH circuits that allowed us to study the inter-channel mixing.

Coherent mixers can be exploited to implement a new class of quantum interferometers.

Future directions: Interference of fractional quasi-particles?
Thank you for your attention!

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References:


