Low energy physics of the integer quantum Hall regime

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The quantum Hall effect regime

Non interacting electrons $\rightarrow$ edge excitations $=$ chiral 1D fermions

Landau levels: $E_n(k) \approx (n+\frac{1}{2})\hbar eB \frac{m}{e} + V_{\text{conf}}(y_k)$ = $-k\frac{\hbar}{eB}$

$n_S \approx 2 \times 10^{15} \text{ m}^{-2}$, $T = 40 \text{ mK}$
The quantum Hall effect regime

Landau levels: \( E_n(k) \approx (n+1/2) \frac{\hbar eB}{m} + V_{\text{conf}}(y_k=-k \frac{\hbar}{eB}) \)

Non interacting electrons \( \rightarrow \) edge excitations = chiral 1D fermions

\( n_s \approx 2 \times 10^{15} \text{ m}^{-2}, \ T = 40\text{ mK} \)
Electrical analog of optical devices

Mach-Zehnder interferometer

Sample edge quantum point contact

QHR: large potential to investigate new quantum physics
Coulomb interaction in the QHR

Cb interaction ignored in most cases

Hall currents robust to microscopic details of EC

Recently: revealed by electronic MZI experiments

- Zoology of phenomenon not compatible with free chiral e⁻
- Theoretical controversy: No single model explains all observations

Ex: \( \phi \) fluctuations from low freq. noise

Seeling & Buttiker (PRB 2001); Roulleau et al. (PRL 2008)

Electronic excitations are edge magnetoplasmons

Wen (PRL 1990); Aleiner & Glazman (PRL 1994); Levkivskyi & Sukhorukov (PRB 2008)

\[ \delta \varphi(t) = \frac{1}{\hbar} \int_{t\pm\tau} eU_1(t)dt \]

\( \tau = L/v_D \)

Courtesy P. Roche et al. (SPEC)
Turning on interactions

Competition confinement - Coulomb interaction

Sharp confinement

\[ \exists \text{ edge instability} \quad \partial_y V_{\text{conf}} < \hbar \omega_c / 10 l_B \]

\[ l_B = \sqrt{\hbar/eB} \]

Chamon & Wen, PRB (1994)

Counter propagating modes

Not 1D fermions: \( \exists \) new excitations branches

Wide compressible EC (typical confinement)

\[ l_V \approx \frac{10}{\omega \hbar} \]

\[ \partial \Omega \]

CSG, PRB 46, 4026 (1992)

Transverse density oscillations

Aleiner & Glazman, PRL (1994)

New acoustic excitations predicted in realistic smooth edges
Problematic:
Nature of edge excitations & inelastic mechanisms

- Mechanism limiting Quantum coherence?
- Inelastic mechanism for energy exchanges?

Electronic excitations in QHR?

- free chiral Fermions
- charge & dipole EMP
Novel experimental approach to IQHR: Non equilibrium edge channel spectroscopy

Key ingredients

- New tool to probe $f(E)$
- Generate a tunable non-equilibrium situation
- Test the analogy QPC-beam splitter
- Measurement of energy exchanges

Viewpoint ≠ from dephasing: no contribution of low freq. noise
Energy distribution spectroscopy

Single active level in QD

Sequential tunneling:

\[ I_{\text{dot}}(V_G) = I_{\text{max}} \left\{ f_S(E_{\text{lev}}(V_G)) - f_D(E_{\text{lev}}(V_G)) \right\} \]

with \( E_{\text{lev}}(V_G) = E_0 - e\eta_G V_G \)

Quantum dot ◀️ Energy filter
Tunable non-equilibrium situation

In the quantum Hall regime

Free chiral 1D fermions model: $f_D = \tau f_{D1} + (1-\tau)f_{D2}$
Demonstrate experiment principle & Test QPC-beam splitter analogy

- Short distance QPC-QD
  - Reduces impact of propagation

- Test QPC-beam splitter analogy out-of-equilibrium
  - Hyp.: QD tunnel spectro insensitive to internal EC excitations
    - (Shown by linear I-V characteristics of QPCs in tunnel regime)

  - Probed excitations are chiral 1D fermions

  - Excited internal EC modes would appear as an energy loss
Experimental implementation

Propagation length: 0.8µm

\[ n_s \approx 2 \times 10^{15} \text{m}^{-2} \]
\[ T \approx 30 \text{mK} \]
\[ \nu = 2 \]

Inner EC (not shown) reflected

Free 1D fermions model

\[ f_D \]
\[ \tau \]
\[ -eV_{D2} - eV_{D1} \]
\[ E \]

\[ V_{D2} \]
\[ V_{D1} \]
\[ 200 \text{nm} \]

\[ B = 4.25 \text{T} \]

Free 1D fermions model

\[ I_{\text{dot}} \]
\[ V_G \]
Equilibrium spectroscopy

QD gate voltage-to-energy calibration

$T_{fit}=T \quad \eta_G=0.057 \pm 10\%$

Consistent with Coulomb diamonds
Non-equilibrium spectroscopy
Of an EC tuned out-of-eq. with the QPC bias voltage $\delta V_D$

several $\delta V_D$
$\tau=0.5$
$0.8\mu$m

$\eta_G \delta V_{FIT} = \delta V_D \pm 5\mu V$
Non-equilibrium spectroscopy
Of an EC tuned out-of-equ. with the QPC transmission $\tau$

$\delta V_D = 36 \mu\text{V}$

several $\tau$

$0.8 \mu\text{m}$

$\frac{\partial I}{\partial V_G}(\text{mV}^{-1})$

$V_G (\text{mV})$

$\tau = 0$

$G_{\text{QPC}} [\frac{\text{e}^2}{\text{h}}]$

$G_{\text{QPC}} [\frac{\text{e}^2}{\text{h}}]$

$\tau_{\text{fit}} = \frac{G_{\text{QPC}}}{\text{h/e}^2} \pm 0.03$
Total energy of probed excitations

Extracting $E_{qp}$ from $f(E)$

\[
\frac{E_{qp}}{V_F} = \int_{-\infty}^{\infty} (E - \mu) \delta f(E) dE
\]

\[
T_{qp} = \sqrt{\frac{E_{qp}}{V_F} \frac{6}{\pi^2 k_B^2}}
\]

\[
J_Q = \frac{\nu V_F}{1/h} \frac{E_{qp}}{V_F} = \frac{\pi^2}{6 \hbar} (k_B T_{qp})^2
\]

Power balance considerations

\[
J_Q^{\text{edge excitations}} (T=0) = \frac{(e \delta V_D)^2}{2 \hbar} \tau (1-\tau)
\]

$\exists$ energy transported by internal modes

$J_Q^{\text{edge excitations}} > J_Q^{\text{meas.}} \iff T_{qp}^{\text{meas.}} < \sqrt{T^2 + \frac{3e^2 \delta V_D^2}{\pi^2 k_B^2}} \tau (1-\tau)$
Total energy of probed excitations

$L=0.8\mu m, \tau=0.5, T=30mK$

\[ T_{qp, pred} = \sqrt{T[\delta V_D=0]^2 + \frac{3e^2}{\pi^2 k_B^2} \delta V_D^2 \tau (1-\tau)} \]

QPC $\longleftrightarrow$ beam splitter

NO FIT PARAMETERS!
Check-point summary

QD : tool to measure $f(E)$

Beyond QHR, opens new windows for
- energy transport experiments
- out-of-equ physics

Voltage biased QPC in QHR: tunable non-eq. source

QPC analogue to optic beam splitter for 1D chiral fermions

Internal EC modes harmless to electronic analogue of quantum optics devices

Now ready for

Step 2:

Energy exchanges in the QHR

Probed from $f(E)$ vs propagation length
Changing the propagation length

\[ I_{\text{dot}}(V_G) \]

\[ V_{D1} \]

\[ V_{D4} \]

L=0.8\( \mu \)m

Inner EC reflected
Changing the propagation length

$V_{D4}$

$L = 2.2 \mu m$

$V_{D2}$

$I_{dot}(V_G)$

Inner EC reflected
Changing the propagation length

L = 10 µm

I_{dot}(V_G)

Inner EC reflected
f(E) vs propagation length

$\delta V_D = 36 \mu V$, $\tau \sim 0.5$, several L

$\left(\frac{\partial I_{\text{dot}}}{\partial V_G}\right)_{\text{max}}$ (mV$^{-1}$)

- $0.8 \mu m$
- $2.2 \mu m$
- $4 \mu m$
- $10 \mu m$
- $30 \mu m$

$\delta V_D = 36 \mu V, \tau \sim 0.5$

- $f(E)$ relaxation!
- $L_{\text{inelastic}} \sim 3 \mu m$
- $f(E)$ saturates to a "hot" Fermi function: inner EC?
Total energy within probed outer edge channel

\[ T_{\text{EXCESS}} \equiv \sqrt{T_{\text{inj}}^2 - T(\delta V_D=0)^2} \]

\[ \delta V_D \quad (\mu V) \]

\[ 0.8\mu m \quad 2.2\mu m \quad 4\mu m \quad 10\mu m \quad 30\mu m \]

Injected energy redistributed with a co-propagating excitation branch:

Inner EC?  Internal EC modes?
Test of energy exchanges between ECs

Energy injection in inner EC

$f(E)$ meas. in outer EC ($L=2.2\mu m$)
Test of energy exchanges between ECs

Energy injected in inner EC, f(E) measured in outer EC

$\delta V_D = 36 \mu V$, $\tau \sim 0.5$

$\exists$ energy exchanges between ECs!
Test energy exchanges with "rest of the world"

Closed loop inner EC

no loss of energy in outer EC resulting from coupling with inner EC
Test energy exchanges with "rest of the world"

Closed loop inner EC

Energy in outer EC is conserved

No energy exchanges with "rest of the world"!
Main experimental observations:
- ECs are exchanging energy
- No energy exchange with rest of the world

No significant energy exchanges with:
internal outer EC modes, phonons, top metal gates, other deg of freedom

Most likely mechanism: strong inter ECs Coulomb interactions (as in MZI)

Observed typical inelastic length:

\[ L_{\text{in}}[T_{qp}=125\text{mK}] \sim 2.5\mu\text{m} \]

Similar to MZI dephasing: \( L_\phi \sim 20\mu\text{m}/(T/20\text{mK}) \Rightarrow L_\phi[125\text{mK}] \sim 3\mu\text{m} \)

1D chiral Fermions in EC not well defined excitations:
Heisenberg time-energy uncertainty ⇒
\[ \Delta E[125\text{mK}] > \frac{h}{4\pi \tau_{\text{in}}} \approx 150\text{mK} \quad (v_D \approx 10^5\text{m/s}) \]
Turning on interactions
Beyond perturbation

Non-perturbative \textit{inter} EC $\rho$-$\rho$ interactions ($\nu=2$)

$$H = \pi \hbar \nu_{\text{inner}} \int dx \, \rho_{\text{inner}}^2(x) + H_{\text{outer}} + \pi \hbar \nu_{\text{int}} \int dx \, \rho_{\text{inner}}(x) \rho_{\text{outer}}(x)$$

$$\Rightarrow \quad H = \pi \hbar \nu \rho_{\text{C}} \int dx \, \rho_{\text{C}}^2(x) + \pi \hbar \nu \rho_{\text{S}} \int dx \, \rho_{\text{S}}^2(x)$$

Free bosons delocalized on both ECs $\neq$ quasiparticles

Simple limit: $v_{\text{inner}} = v_{\text{outer}}$

$\rho_C = \frac{1}{\sqrt{2}}(\rho_{\text{inner}} + \rho_{\text{outer}})$

$\rho_S = \frac{1}{\sqrt{2}}(\rho_{\text{inner}} - \rho_{\text{outer}})$

\textbf{spin-charge separation}

Wen (PRL 1990); Levkivskyi & Sukhorukov (PRB 2008)
Energy exchanges within the edge magnetoplasmons model

\( \nu = 2 \), strong ECs interaction

Levkivskyi & Sukhorukov (PRB 2008)

\( QPC \) excites 1 EC

\[
\frac{1}{\sqrt{2}} \left( \begin{array}{c}
\text{charge mode} \\
\text{(fast)}
\end{array} \right) + \left( \begin{array}{c}
\text{dipole mode} \\
\text{(slow)}
\end{array} \right)
\]

Time evolution:

\exists \text{ energy in inner EC!}
Tuning down interactions
By closing the inner EC on a smaller loop (7.5µm)

Level quantization in closed inner EC

$L_{\text{loop}}=7.5\mu m$, $V_{\text{drift}}=10^5\text{m/s} \Rightarrow \Delta E=55\mu\text{eV}$
Tuning down interactions

\[ \delta V_D = -36\mu V, \; \tau \sim 0.5 \]

\[ \left( \frac{\partial I}{\partial V_G} \right)_{\text{max}} \frac{\delta V_D}{I_\text{dot}} \text{ [mV}^{-1}] \]

\[ V_G \text{ [mV]} \]

Strongly reduced energy redistribution!
Practical implementation

Experimental implementation on MZI in progress…

(coll. P. Roche et al.)
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