Condensate and Quasiparticle Transport in a Bilayer Quantum Hall Excitonic Superfluid

Jim Eisenstein

Aaron Finck
Debaleena Nandi
Loren Pfeiffer
Ken West

ISSO-2012   St. Petersburg, July 2012
Outline of the talk

1. QHE & phase transition at $\nu_T = 1$
2. nature of the condensed phase
3. counterflow transport in Hall bars
4. pause…
5. counterflow transport in Corbino rings
6. perfect and imperfect Coulomb drag
7. dissipation in counterflow
phase transition
No QHE at half-filling of the lowest Landau level
QHE in Double Layer 2D Systems

\[ \nu_T = 1 \]

\[ \nu_T = \frac{1}{2} = \frac{1}{4} + \frac{1}{4} \]

\[ \nu_T = 1 = \frac{1}{2} + \frac{1}{2} \]
Phase Diagram at $\nu_T = 1$

Continuous evolution of QHE
Phase Diagram at $\nu_T = 1$

**NO QHE**

**QHE**

Tunneling Strength, $\Delta_{\text{SAS}} \left( \frac{e^2}{\varepsilon \ell} \right)$

- $d/\ell$

Al$_{0.9}$Ga$_{0.1}$As

$\Delta_{\text{SAS}} \sim 10 \ \mu\text{K} \sim 10^{-7} \frac{e^2}{\varepsilon \ell}$

**Extreme Coulomb limit**

Quantum critical point

layer spacing

$\nu_T = 1$

$\nu_T = 1/2 + 1/2$
Tunneling signature of transition
Tunneling signature of transition

Interlayer Voltage (mV)

Tunneling Conductance ($10^{-9} \Omega^{-1}$)

Coulomb gap replaced by resonant enhancement.
Josephson-like tunneling I-V

Onset coincident with appearance of QHE.
nature of the condensed phase
Halperin 111 state

Pure many-body effect

\[ \Psi \sim \prod_{i,\ldots,n} (z_i - z_j) (w_k - w_l) (z_m - w_n) \]

Laughlin-like intra- and inter-layer correlations

Essentially exact in the \( d/\ell \to 0 \) limit.
Easy-Plane Ferromagnet

layer index → pseudospin

\[ |\Psi\rangle = \prod_k |k\rangle \otimes \left( |\uparrow\rangle + e^{i\varphi} |\downarrow\rangle \right) \]

Exchange-driven “spontaneous interlayer phase coherence”

pseudospin waves (Goldstone modes)

charged vortices

Kosterlitz-Thouless transition
**Excitonic Bose Condensate**

Layer 1 + Layer 2

Electrons

Layer 2

Excitonic supercurrents

\[ |\Psi\rangle = \prod_k \frac{1}{\sqrt{2}} \left[ 1 + e^{i\phi} c_{k,1}^\dagger c_{k,2} \right] |\text{vac}^\rangle \]

Exciton creation operator

\[ \nabla \phi \rightarrow \text{excitonic supercurrents} \]
Two Transport Channels

1. Parallel Transport

\[ I_1 \quad I_2 \]

meron / anti-meron pair

quantized Hall effect
Two Transport Channels

2. Counterflow Transport

$\nabla \phi = \text{constant}$

$J_{ex} = \rho_s \nabla \phi$

collective exciton transport in condensate
counterflow in Hall bars
Counterflow Experiment
Counterflow Experiment
At $\nu_T = 1$, $R_{xy}^{CF} \to 0$ as $T \to 0$  

exciton transport
Counterflow Experiment

At $\nu_T = 1$: $R_{xy}^{CF} \rightarrow 0$ and $R_{xx}^{CF} \rightarrow 0$

Excitonic superfluidity?
Counterflow Experiment

\[ \sigma_{XX} \] (e^2/h)

\[ \sigma^{CF}_{XX} \]

\[ \sigma_{XX} \parallel (B = 0) \]

d/\ell = 1.5

Counterflow dissipation small but non-zero at all finite T.
Pause and reflect…

1. phase transition
2. QHE
3. tunneling anomaly
4. Goldstone modes (pseudospin waves)
5. quantized Hall drag
6. counterflow transport
7. etc.

Qualitatively, theory = experiment
Pause and reflect…

1. phase transition
2. QHE
3. tunneling anomaly
4. Goldstone modes (pseudospin waves)
5. quantized Hall drag
6. counterflow transport
7. etc.

Qualitatively, theory = experiment, but deep questions remain.
What is really going on?
Counterflow Experiment

Andreev reflection and exciton transport?

Su & MacDonald 2008
Counterflow Experiment

What role does the $\nu = 1$ edge state play?
Experiments on simply connected Hall bars cannot directly demonstrate bulk exciton transport.
counterflow in Corbino rings
Quantum Hall systems are topological insulators.

Contacts on different edges are isolated.
Corbino geometry measures bulk conductivity

Bulk conductivity vanishes when QHE is well-developed.
Corbino Experiments
QHE suppresses parallel charge transport across the bulk

\[
\nu = 1
\]

\[
T = 25 \text{ mK}
\]

\[
d/\ell = 1.5
\]

No surprise here.
Tunneling configuration

![Graph showing current (nA) versus interlayer voltage (µV). The graph is nearly flat, indicating low current variation with voltage. The diagram on the right illustrates a tunneling configuration with interlayer voltage (V) and current (I).]
Tunneling configuration

Tunneling intentionally suppressed by tilting.
Remote short vastly enhances current.
A Paradox?

No current

Lots of current
How can it be?

No current

Enhanced tunneling?

Lots of current
How can it be?

No current

Counterflow?

Lots of current
How can it be?

Counterflow?

No current

Measure current here!

Lots of current
Measuring the shunt current

It IS counterflow.
Counterflowing electrical currents can cross the insulating bulk; parallel currents cannot.

Counterflow is an intrinsically bilayer phenomenon.

*Counterflow IS exciton transport.*
Excitons are launched and absorbed via Andreev reflection. Excitons transport energy but not charge.
Analogy to superconductivity

\[ \Delta \phi = \frac{eV}{\hbar} t + k x \]

two superconducting wires
Analogy to superconductivity

\[ \phi = \frac{eV}{\hbar} t + k x \]
Coulomb Drag

Usually a weak, perturbative effect.

\[ R_D = \frac{V}{I} \]
Coulomb drag in magnetic fields

Longitudinal drag

Hall drag
Drag Coefficients at $\nu_T = 1$

![Graph showing drag coefficients at $\nu_T = 1$](image-url)
Corbino Coulomb Drag

\[ V \quad R_1 \quad I_{\text{drive}} \quad R_2 \quad I_{\text{drag}} \]
Corbino Coulomb Drag:
Incoherent Phase

Negligible drag current when layers are independent.
Corbino Coulomb Drag: Coherent Phase

Significant drag only at $\nu_T = 1$

$T = 20 \text{ mK}$
$d/l = 1.5$
Corbino Coulomb Drag: Coherent Phase

Drag and drive currents equal at small V.
“Perfect” Coulomb Drag
Inducing exciton transport

Ideally, $I_1 = I_2$
Breakdown of Perfect Coulomb Drag

When $I_1 \neq I_2$, there is charge transport across annulus.
Su-MacDonald 1D model:

\[ \sigma_{xx}^{\text{CF}} = \infty \]
\[ \sigma_{xx}^\parallel = 0 \]
\[ R_1 + R_2 \geq 2h/e^2 \]

\[ I_2 = I_1 = \frac{V}{R_1 + R_2} \]
Modeling the Breakdown

Generalized Su-MacDonald model:

\[ \sigma_{xx}^{\text{CF}} = \infty \]

\[ \sigma_{xx}^{\parallel} > 0 \]

\[ R_1 + R_2 \geq 2h/e^2 \]

\[ I_2 = \frac{V}{R_1 + R_2 + R_1 R_2 \sigma_{xx}^{\parallel}} \]

\[ \frac{I_2}{I_1} = \frac{1}{1 + R_2 \sigma_{xx}^{\parallel}} \]
Charged quasiparticle transport

Charge gap $\Delta \approx 360 \text{ mK}$
Combined condensate and quasiparticle transport
dissipation in counterflow
Hall Bar Counterflow Experiment

But do Hall bars really detect bulk exciton dissipation?
Exciton dissipation masked by extrinsic series resistances

\[ V = I_1 R_1 + I_2 R_2 \]

\[ I_2 = I_1 = \frac{V}{R_1 + R_2} \]
Exciton dissipation masked by extrinsic series resistances

\[ I_2 = I_1 = \frac{V}{R_1 + R_2 + R_{\text{ex}}} \]

How can we determine \( R_1 \) and \( R_2 \)?
Tunneling: 2-terminal vs. 4-terminal

At $\theta = 0$, 2-terminal I-V dominated by series resistances.
Exciton dissipation “small”

Applied voltage
Extrinsic voltage drop (est.)

New, multi-terminal measurements needed.
Exciton dissipation “small”

New, multi-terminal measurements needed.
Conclusions

Direct observation of exciton transport across insulating bulk of the bilayer $\nu_T = 1$ QHE state.

Energy transport without charge transport.

“Perfect” Coulomb drag at low $T$, $d/l$, and $V$.

Questions

Dissipation in exciton transport is small, but how small? Can we detect the KT transition?

Exciton transport is coherent. But on what length scale?

Can we make an excitonic Josephson junction?