Experiments on a Quantum Hall Exciton Condensate

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Intrinsic semiconductor at $T = 0$
Add light

$hv$
Only electrons
Particle-hole transformation on valence band

Electrons

+  

Holes

Excitons!

Embarrassing relative
A different way: Doped bilayer semiconductor
Discard the valence band

Layer 1

Layer 2
Add a magnetic field

Layer 1

Layer 2

$N = 3$

$2$

$1$

$0$

$\hbar \omega_c$

conduction band Landau levels
A bigger magnetic field: One filled Landau level

Analogous to intrinsic semiconductor at $T = 0$, but no gap!
Transfer charge by doping or gating

\[ N = 0 \]

Layer 1  Layer 2

Total number of electrons unchanged
Particle-hole transformation on lowest Landau level in layer 2

Layer 1

$N = 0$

electrons

Layer 2

+ holes

excitons!

Embarrassing relative
No QHE at half-filling of the lowest Landau level
Double Layer Two-Dimensional Electron Gas
QHE in Double Layer 2D System

\[ v_T = 1 = \frac{1}{2} + \frac{1}{2} \]
Single Particle and Many-body Origins for $\nu_T = 1$ QHE

1. Single Particle Tunneling

2. Pure Many-body Effect

$$\Psi \sim \prod_{i,,n} (z_i - z_j) (w_k - w_l) (z_m - w_n)$$
Phase Diagram

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

$QHE$ persists in zero tunneling limit
Bilayer $\nu_T = 1$ QHE with Nearly Zero Tunneling

$\Delta_{SAS} \approx 90 \mu K \approx 1.2 \times 10^{-6} \left( \frac{e^2}{\varepsilon \ell} \right)$

$\Delta = 0.34 \text{K}$

Quantum critical point

Layer spacing

$\nu_T = 1$  $\nu_T = 1/2 + 1/2$
Easy-Plane Ferromagnet

Layer index → pseudospin

\[
\Psi = \prod_{k} |k\rangle \otimes \frac{1}{\sqrt{2}} \left[ |\uparrow\rangle + e^{i\phi} |\downarrow\rangle \right]
\]

Spontaneous interlayer phase coherence and “which layer” uncertainty.

Pseudo-spin waves, charged vortices, etc.

\[ \nabla \phi \] dissipationless pseudo-spin currents
Pseudospin Textural Phase Transition

\[ \lambda = \frac{h}{eB||d} \]

Increasing \( B|| \)

\[ H = \frac{\rho_s}{2} |\nabla \varphi|^2 - \frac{\Delta_{SAS}}{4\pi \ell^2} \cos(\varphi - Qx) \]

\[ Q = \frac{eB||d}{\hbar} \]
Excitonic Bose Condensate

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

exciton creation operator

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

1. Parallel Transport

- vortex charged excitations above gap
- edge states
- quantized Hall effect
- dissipation $\sim \exp\left(-\frac{\Delta}{T}\right)$
Two Transport Channels

2. Counterflow Transport

\[ \nabla \phi = \text{constant} \]

\[ J_{\text{ex}} = \rho_s \nabla \phi \]

- collective exciton transport \textit{in condensate}
- bulk flow
- zero dissipation for \( T < T_{KT} \)
The really cool physics is in the antisymmetric channel!

counter-flow transport

interlayer tunneling

separate layer contacts are essential
Symmetric gating allows continuous tuning of effective layer spacing in a single sample.
Crossing the phase boundary

Zero bias tunneling heavily suppressed by *intra*-layer correlations.
Crossing the phase boundary

Coulomb gap replaced by resonant enhancement.
Magnetic Field and Temperature Dependences

![Graphs showing magnetic field and temperature dependences.](image)

- Magnetic Field (Tesla)
- Temperature (K)
- $G_0 (10^{-7} \Omega^{-1})$
- $G_0$ (mho)

- $\nu_T = 1$

- Small $d/\ell$
- Large $d/\ell$
Extremely Narrow Resonance

\[ \frac{dI}{dV} \quad (10^{-6} \Omega^{-1}) \]

\[ \Gamma \approx 1 \mu \text{eV} \]

Counter-flow superfluidity rapidly relaxes charge defects created by tunneling.
Collective Modes

pseudo-spin waves

Fertig ‘89
Wen & Zee ‘92

Tunneling detects the Goldstone mode of the broken symmetry ground state.
Parallel Field Spectroscopy

$dI/dV (10^{-6} \Omega^{-1})$

$V (\mu V)$

$B_\parallel = 0$

$B_\parallel = 0.6 T$

Peak is suppressed and satellites appear.

$q = e B_{\parallel} d / \hbar$
Measured Collective Mode Dispersion

Direct observation of linearly dispersing Goldstone mode.

- red curves: A.H. MacDonald

$v \sim 15$ km/sec
A quantum phase transition

Demonstration of spontaneous interlayer phase coherence.
Josephson Effect in a Non-Superconductor?

dc Josephson effect in a superconductor:

\[ J_T = J_c \sin \Delta \phi \]

Interlayer tunneling in \( \nu_T = 1 \) bilayer QHE:

\[ J_T = \frac{e}{4\pi \ell^2 \hbar} \Delta_{\text{SAS}} \sin \phi \]

QHE critical current:

\[ I_c = \frac{eA}{4\pi \ell^2 \hbar} \Delta_{\text{SAS}} \approx 50 \mu A \]

Suggests that pseudospin field is heavily disordered on macroscopic scales

cf. Fertig and Straley, cond-mat/0301128
**Coulomb Drag at B=0**

\[ N_1 = N_2 = 1.4 \times 10^{11} \text{ cm}^{-2} \]

\[ d = 300 \text{ Å} \]
Two Kinds of Coulomb Drag in a Magnetic Field

Longitudinal drag

“Hall” drag
Transport coefficients

\[ R_{xx} \quad (\text{k}\Omega) \]

\[ \nu_T = 1 \]

\[ R_{xx} \]

Magnetic Field (T)
Transport coefficients

![Graph showing transport coefficients](image)

Longitudinal Drag
Transport coefficients
Transport coefficients

Exact quantization of Hall drag.
In a drag measurement, current flows only in one layer:

The $\nu = 1$ excitonic state supports two kinds of transport: charged quasiparticle currents and neutral excitonic superflow.
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The $\nu = 1$ excitonic state supports two kinds of transport: charged quasiparticle currents and neutral excitonic superflow.

\[ I_1 = I_{qp} + I_{ex} = I \]
\[ I_2 = I_{qp} - I_{ex} = 0 \]
It’s stranger still...

Same Hall voltages no matter how current is divided between the layers!
Counterflow Experiment
Counterflow Experiment
Counterflow Experiment - cartoon

Hall Voltage vs. Magnetic Field
Counterflow Experiment - cartoon

![Diagram showing the relationship between Hall Voltage and Magnetic Field, with an arrow labeled \( V_H \) and current arrows labeled \( I \).]
Charge neutral excitons should feel no Lorentz force!
At $v_T = 1$, $R_{xy}^{CF} \to 0$ as $T \to 0$.

exciton transport dominates counterflow
Counterflow Experiment - reality

At $\nu_T = 1$: $R^{CF}_{xy} \rightarrow 0$ and $R^{CF}_{xx} \rightarrow 0$
Parallel vs. Counterflow Transport

\[ \sigma_{xx} = \frac{R_{xx}}{R_{xx}^2 + R_{xy}^2} \]

\[ R_{xx}^{||} \to 0 \quad \text{and} \quad R_{xy}^{||} \to h/e^2 \quad \Rightarrow \quad \sigma_{xx}^{||} \to 0 \]

\[ R_{xx}^{CF} \to 0 \quad \text{and} \quad R_{xy}^{CF} \to 0 \quad \Rightarrow \quad \sigma_{xx}^{CF} \to ? \]
Temperature Dependences

\[ d/\ell = 1.5 \]
Conductivities

Counterflow dissipation small but non-zero at all finite $T$. 

$d/\ell = 1.5$
Results

In closely-spaced bilayer 2D electron systems at $\nu_T = 1$:

Tunneling reveals a phase transition to an interlayer phase coherent state and unveils the Goldstone mode.

Counterflow and Coulomb drag reveal collective transport of excitons. Dissipationless as $T \rightarrow 0$. 
Puzzles

- tunneling conductance peak too small
- $B_\parallel$-dependence of tunneling not understood
- no non-linearity observed in counterflow transport
- thermally-activated dissipation suggests $T>T_{KT}$

Disorder induced free vortices present at all temperatures.
Quantum Hall Excitonic Bose Condensate

Start with a double layer 2D electron gas

Add a magnetic field

Presto! A BCS-like superfluid comprised of interlayer excitons.

Keldysh and Kopaev 1964; Lozovik and Yudson; Shevchenko 1976