Condensate and Quasiparticle Transport in a Bilayer Quantum Hall Excitonic Superfluid

Jim Eisenstein

Aaron Finck

Debaleena Nandi

Loren Pfeiffer

Ken West

California Institute of Technology 1891

Princeton University

U.S. DEPARTMENT OF ENERGY: BASIC ENERGY SCIENCE

Division of Materials Sciences

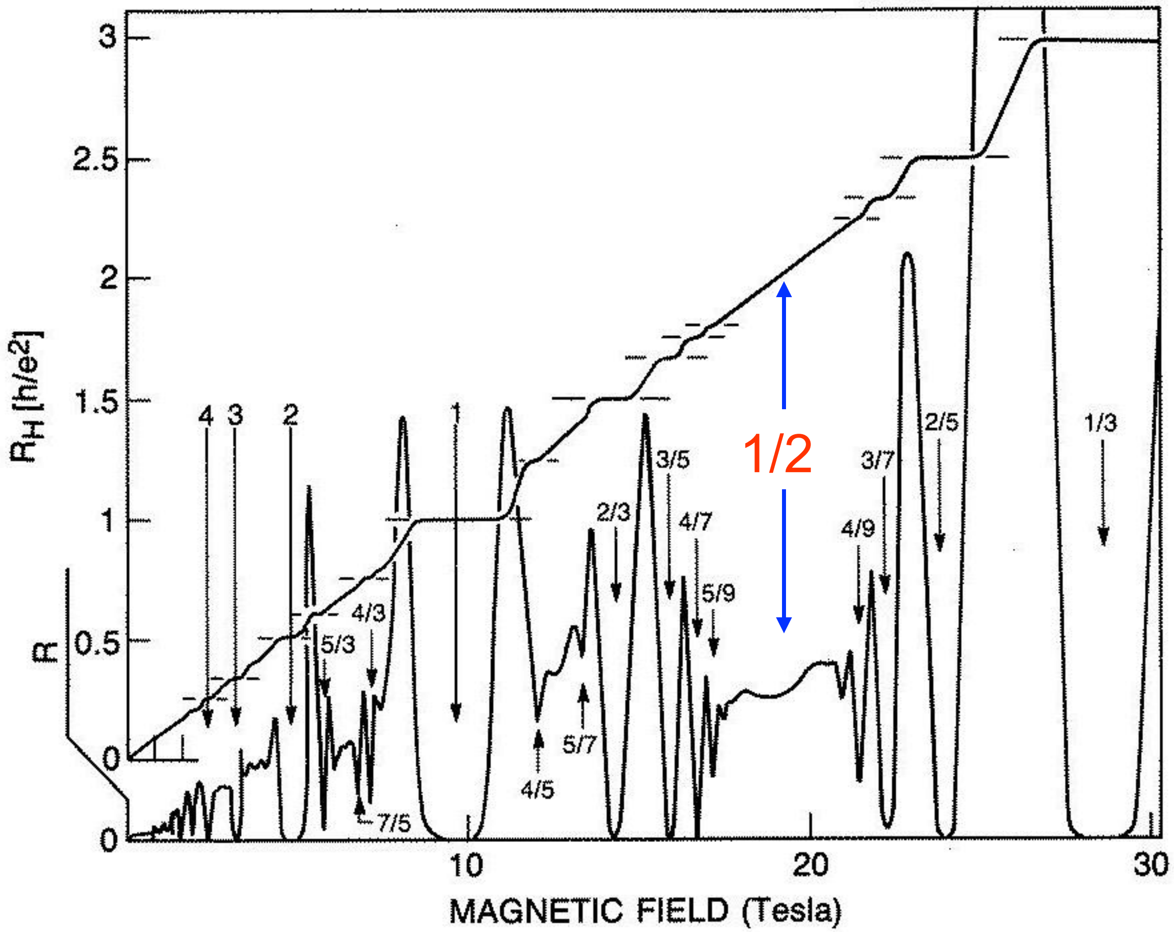
ISSO-2012 St. Petersburg, July 2012

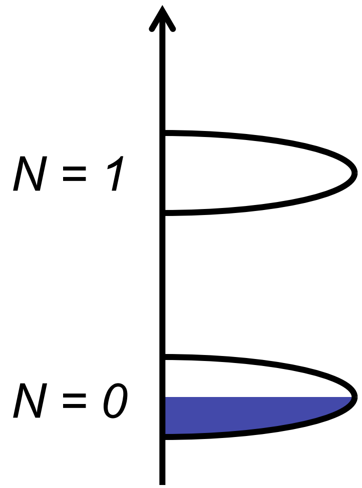
Outline of the talk

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

Quantum Hall Effect in a Single Layer 2D System

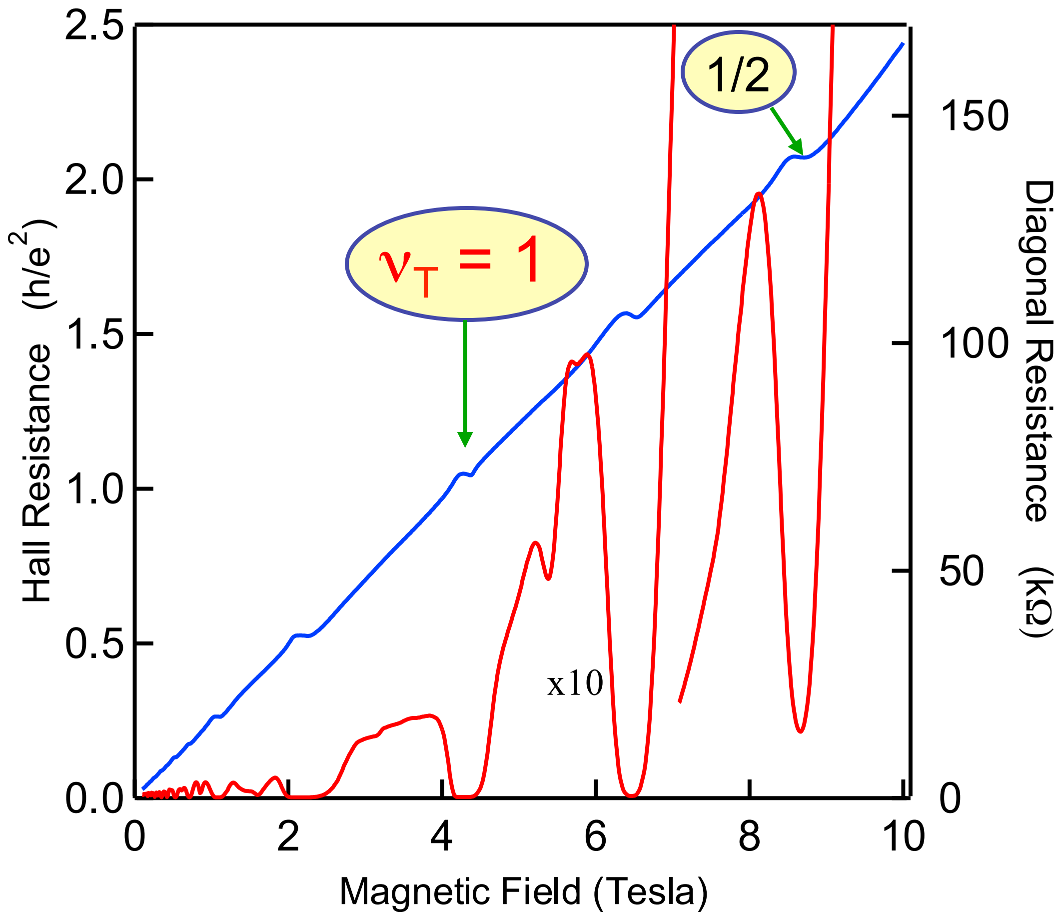




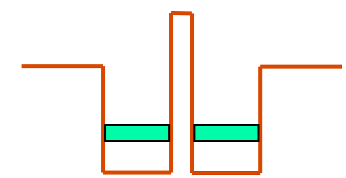
$\nu = ½$

No QHE at half-filling of the lowest Landau level

QHE in Double Layer 2D Systems

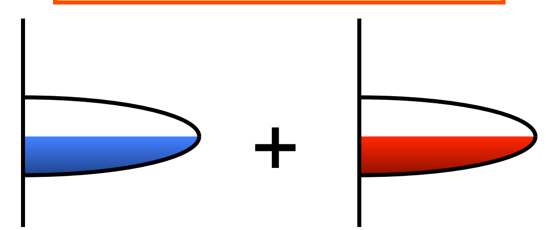


$\nu_T = \nu_1 + \nu_2$

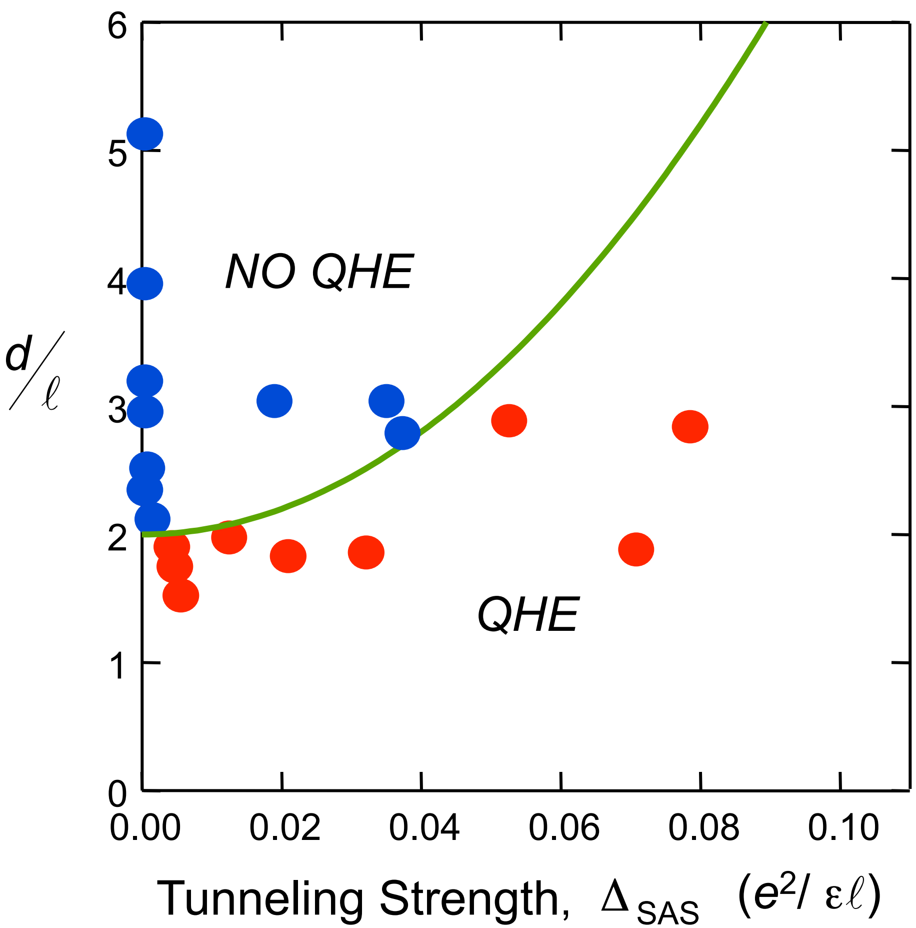


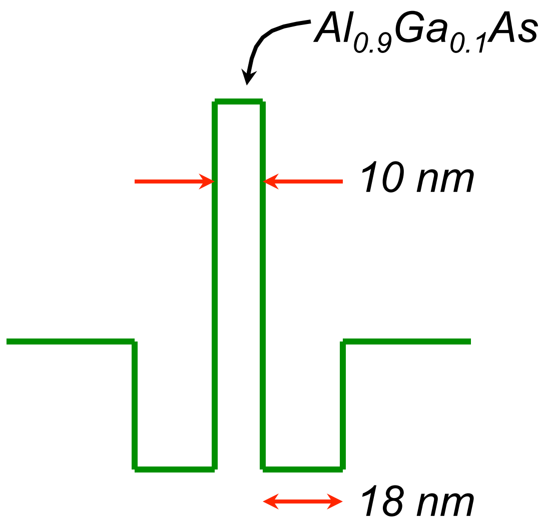
$\nu_T = ½ = ¼ + ¼$

$\nu_T = 1 = ½ + ½$



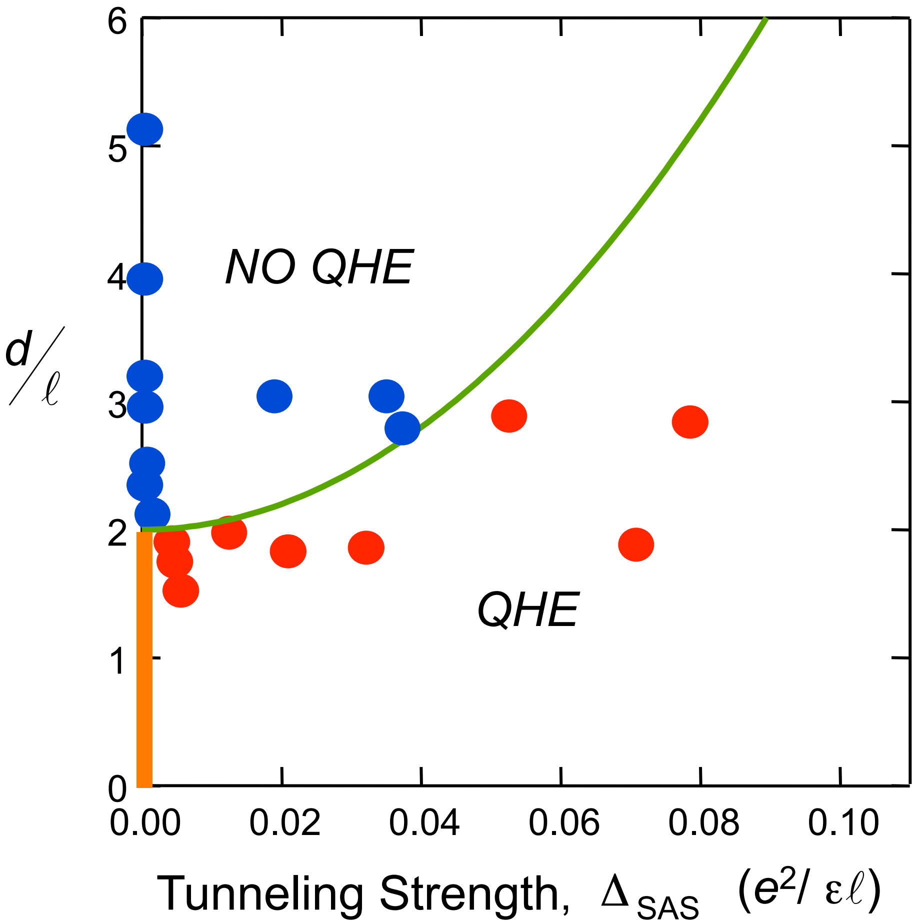
Phase Diagram at $\nu_T = 1$

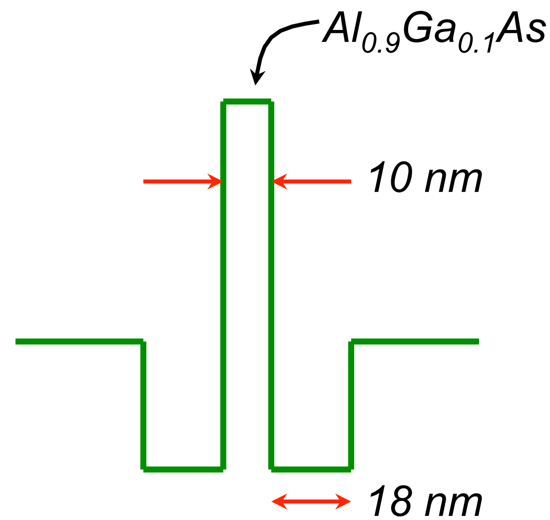




Continuous evolution of QHE

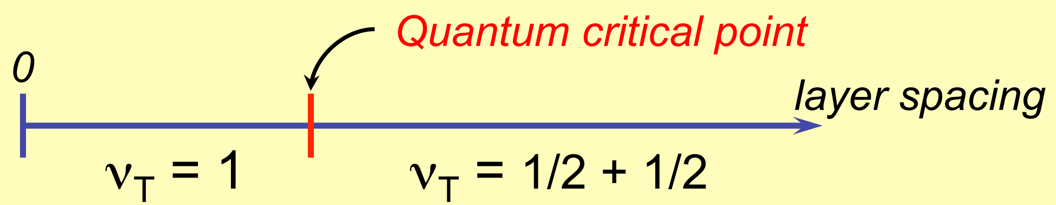
Phase Diagram at $\nu_T = 1$



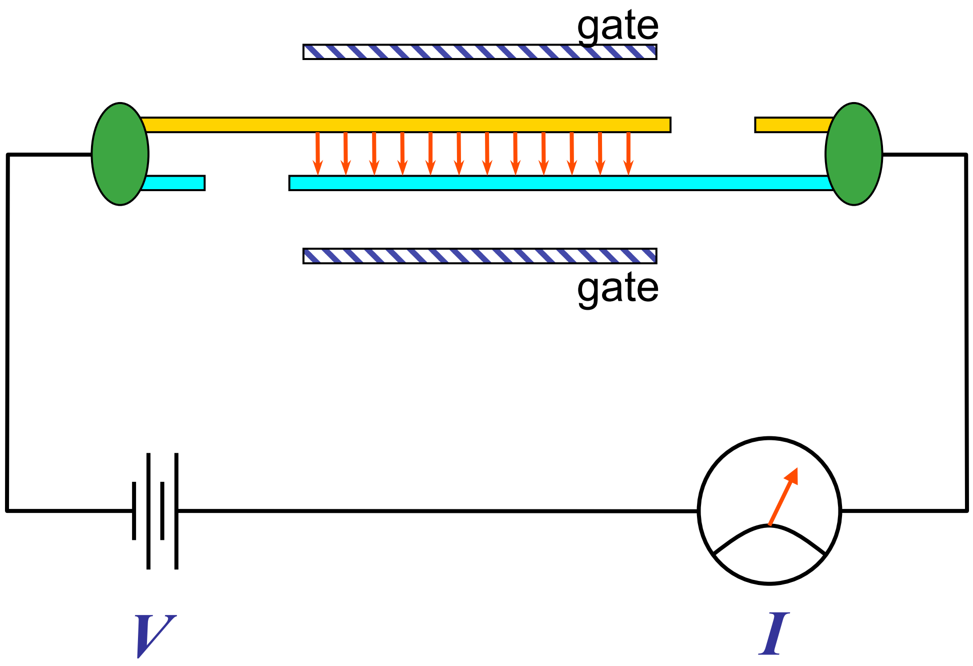


$\Delta_{SAS} \sim 10\ \mu K \sim 10^{-7}\ e^2/\varepsilon\ell$

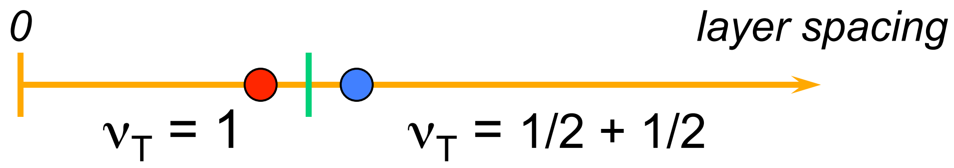
Extreme Coulomb limit

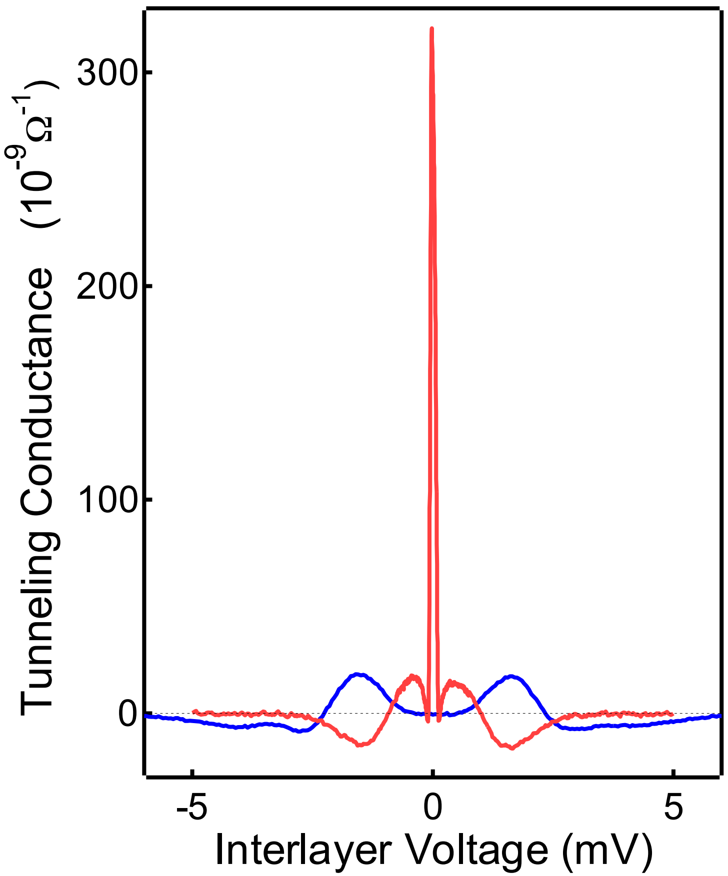


Tunneling signature of transition



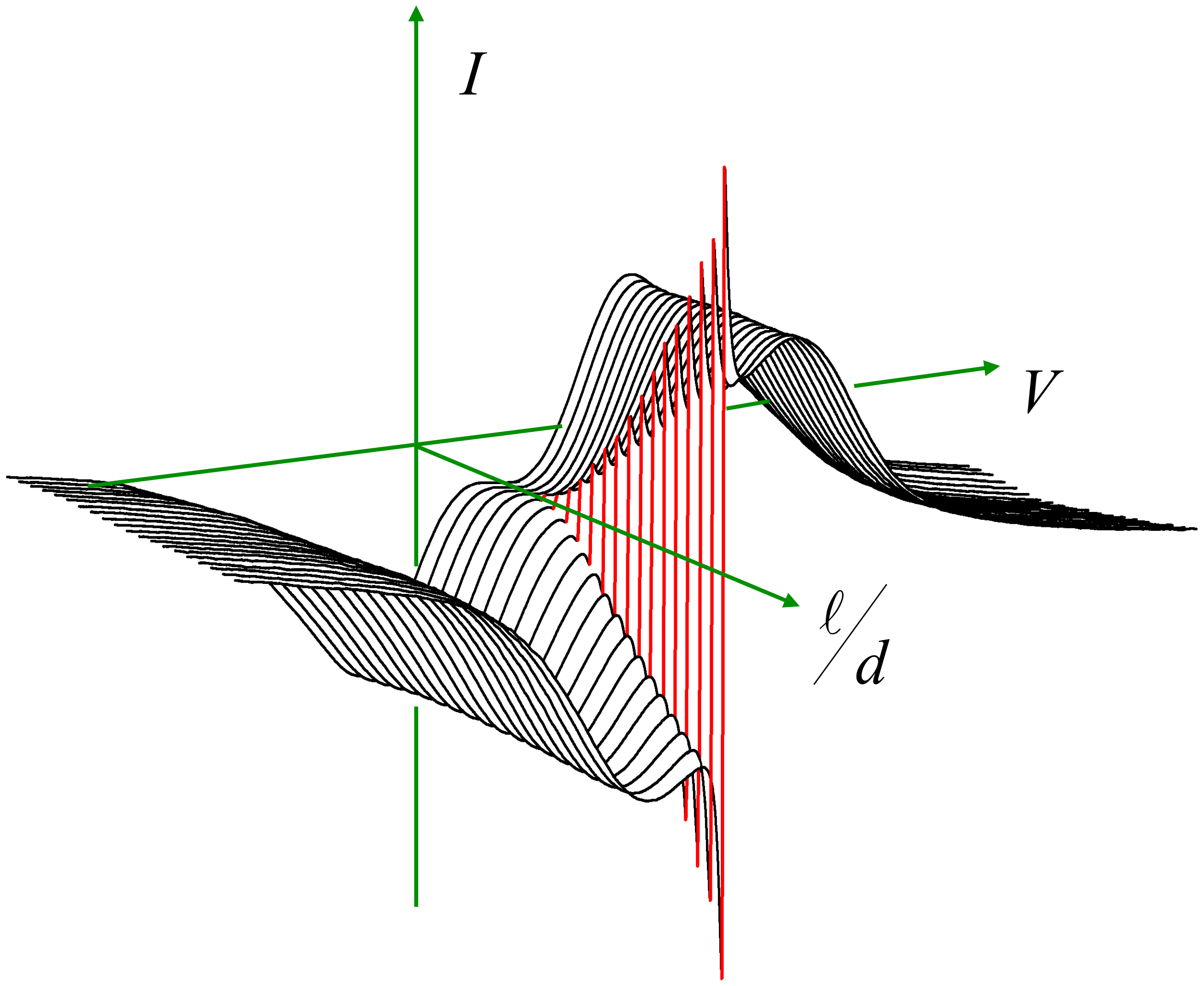
Tunneling signature of transition





Coulomb gap replaced by resonant enhancement.

Josephson-like tunneling I-V

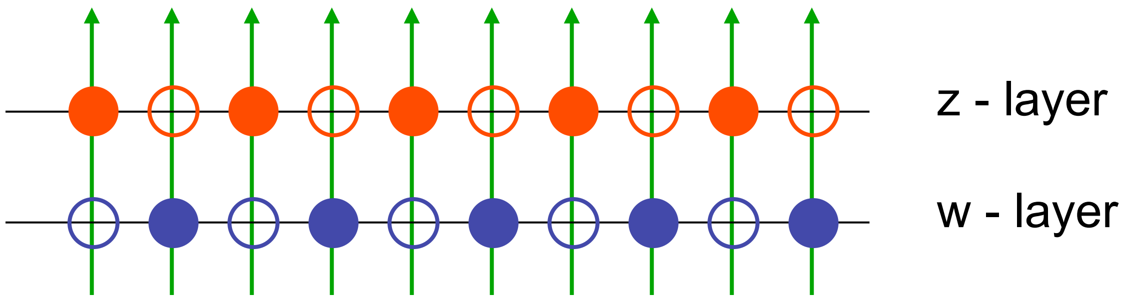


Onset coincident with appearance of QHE.

nature of the condensed phase

Halperin 111 state

Pure many-body effect



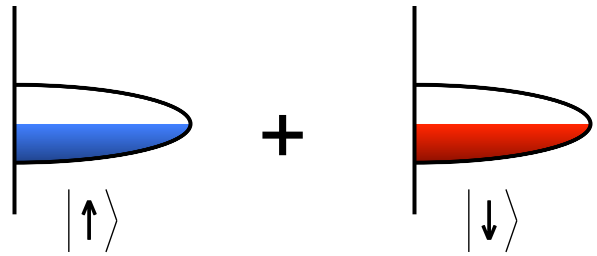
$$\Psi \sim \prod_{i,..,n} (z_i - z_j)\ (w_k - w_l)\ (z_m - w_n)$$

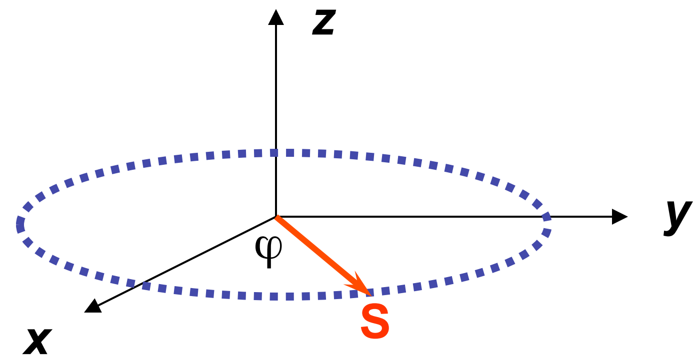
Laughlin-like intra- and inter-layer correlations

Essentially exact in the $d/\ell \rightarrow 0$ limit.

Easy-Plane Ferromagnet

layer index → *pseudospin*





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

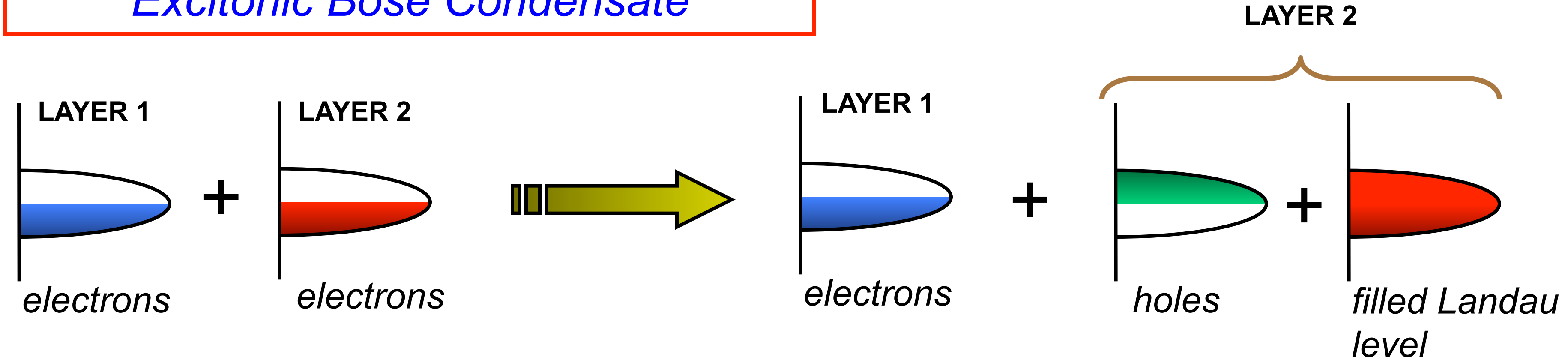
Exchange-driven "spontaneous interlayer phase coherence"

pseudospin waves (Goldstone modes)

charged vortices

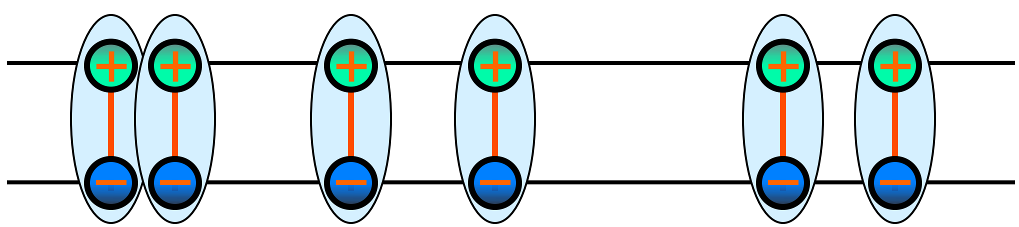
Kosterlitz-Thouless transition

Excitonic Bose Condensate



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

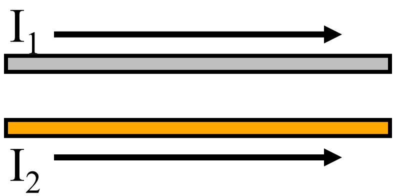
exciton creation operator



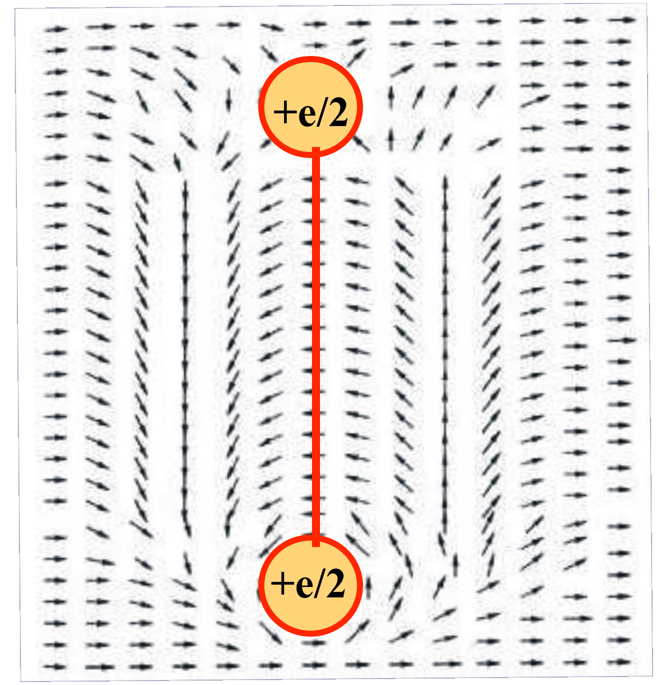
$\nabla\phi$ → *excitonic supercurrents*

Two Transport Channels

1. Parallel Transport



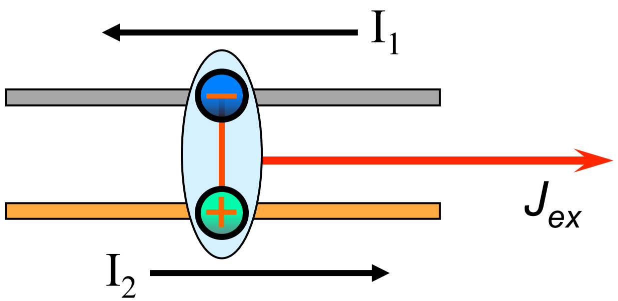
meron / anti-meron pair



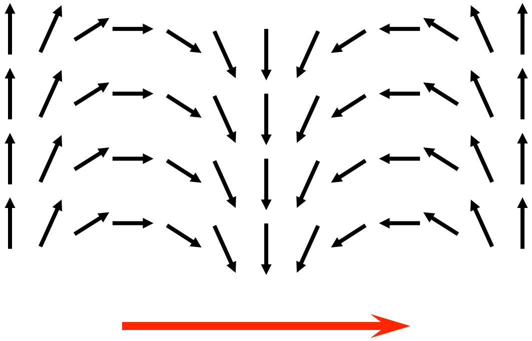
quantized Hall effect

Two Transport Channels

2. Counterflow Transport



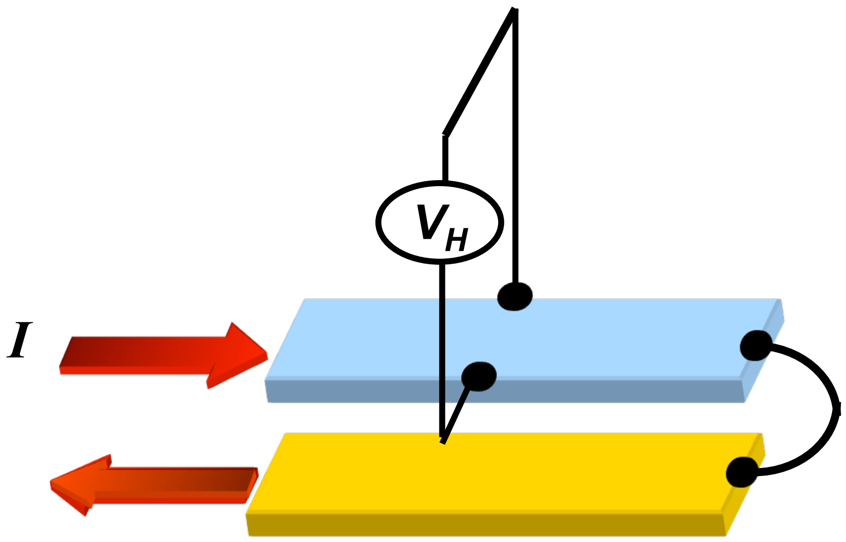
$\nabla \phi$ = *constant*



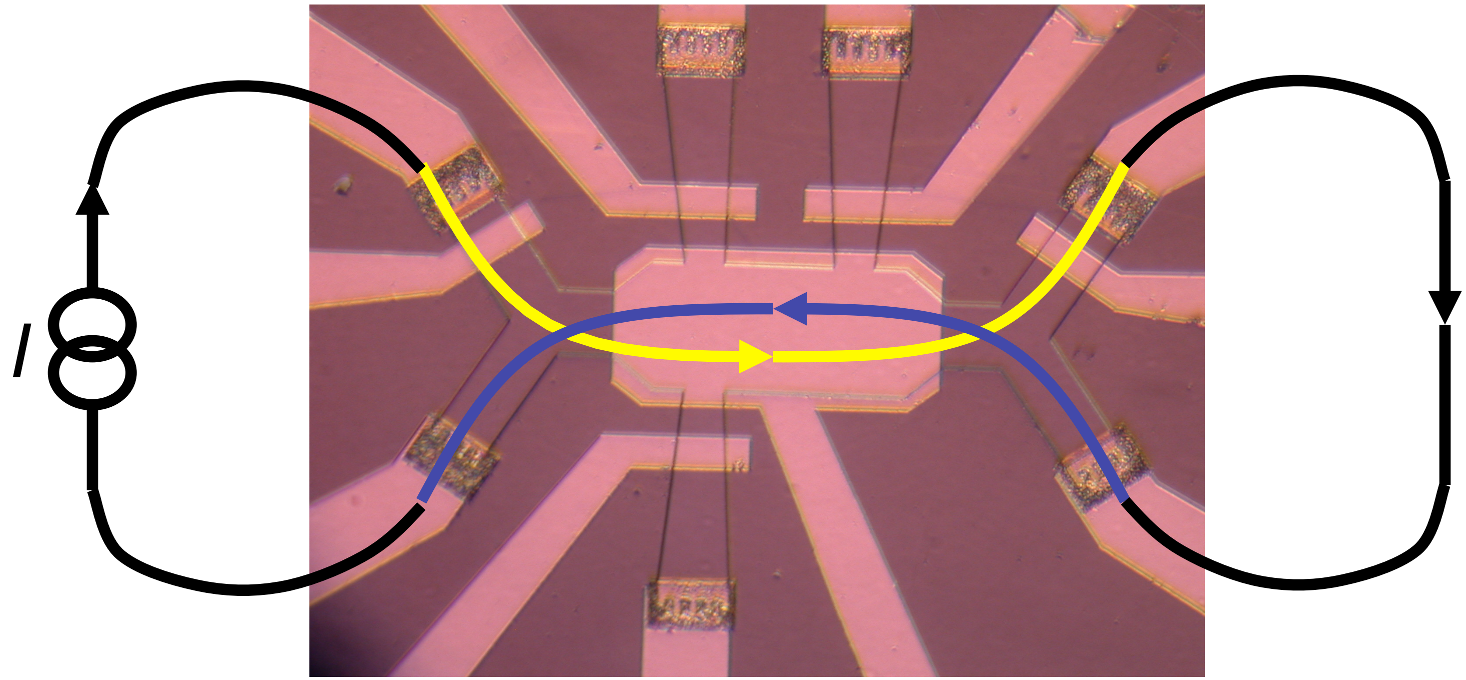
$J_{ex} = \rho_s \nabla \phi$

collective exciton transport in condensate counterflow in Hall bars

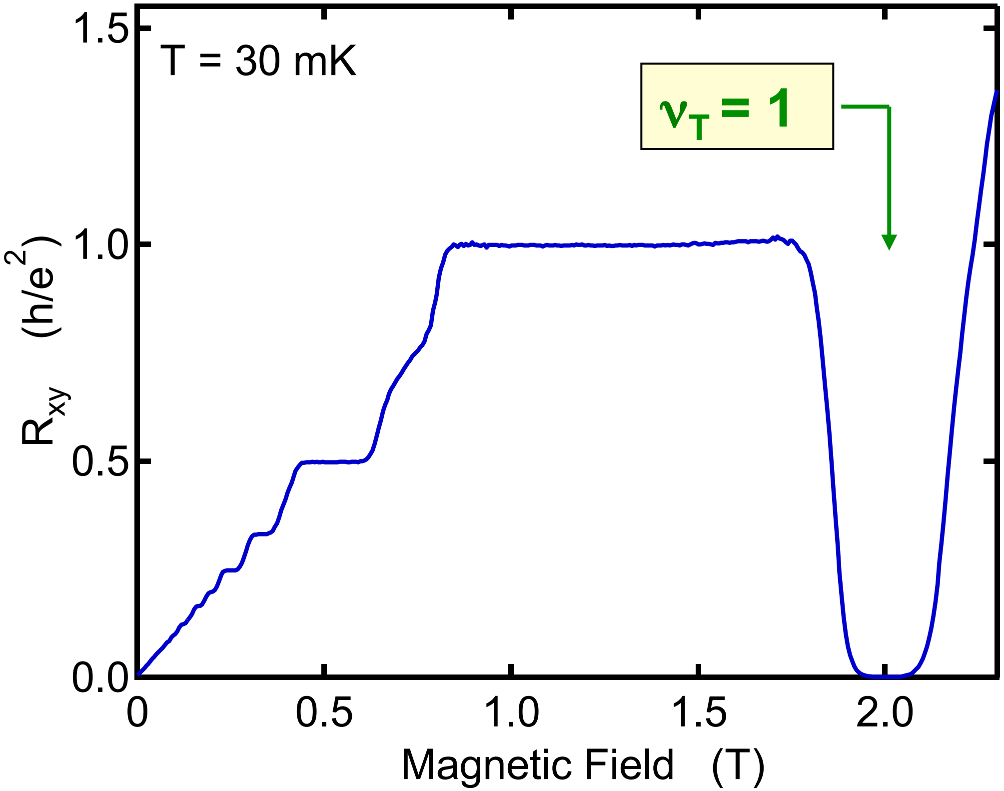
Counterflow Experiment

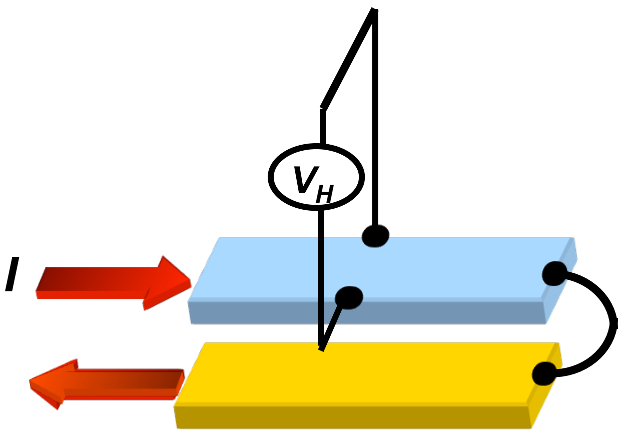


Counterflow Experiment



Counterflow Experiment

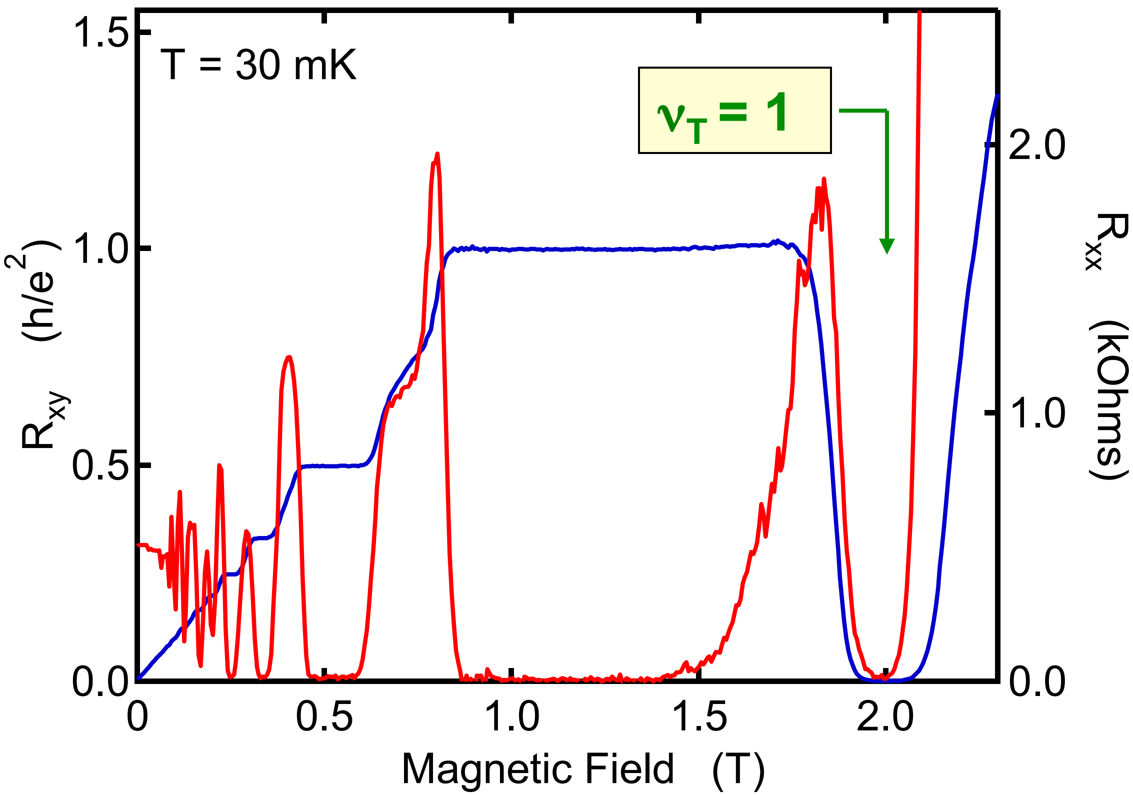


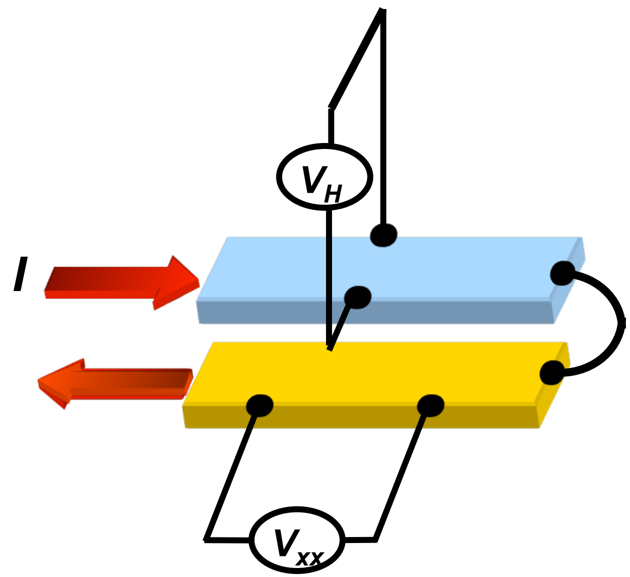


Kellogg 2004
Tutuc 2004

At $\nu_T = 1$ $R_{xy}^{CF} \to 0$ *as* $T \to 0$ → *exciton transport*

Counterflow Experiment



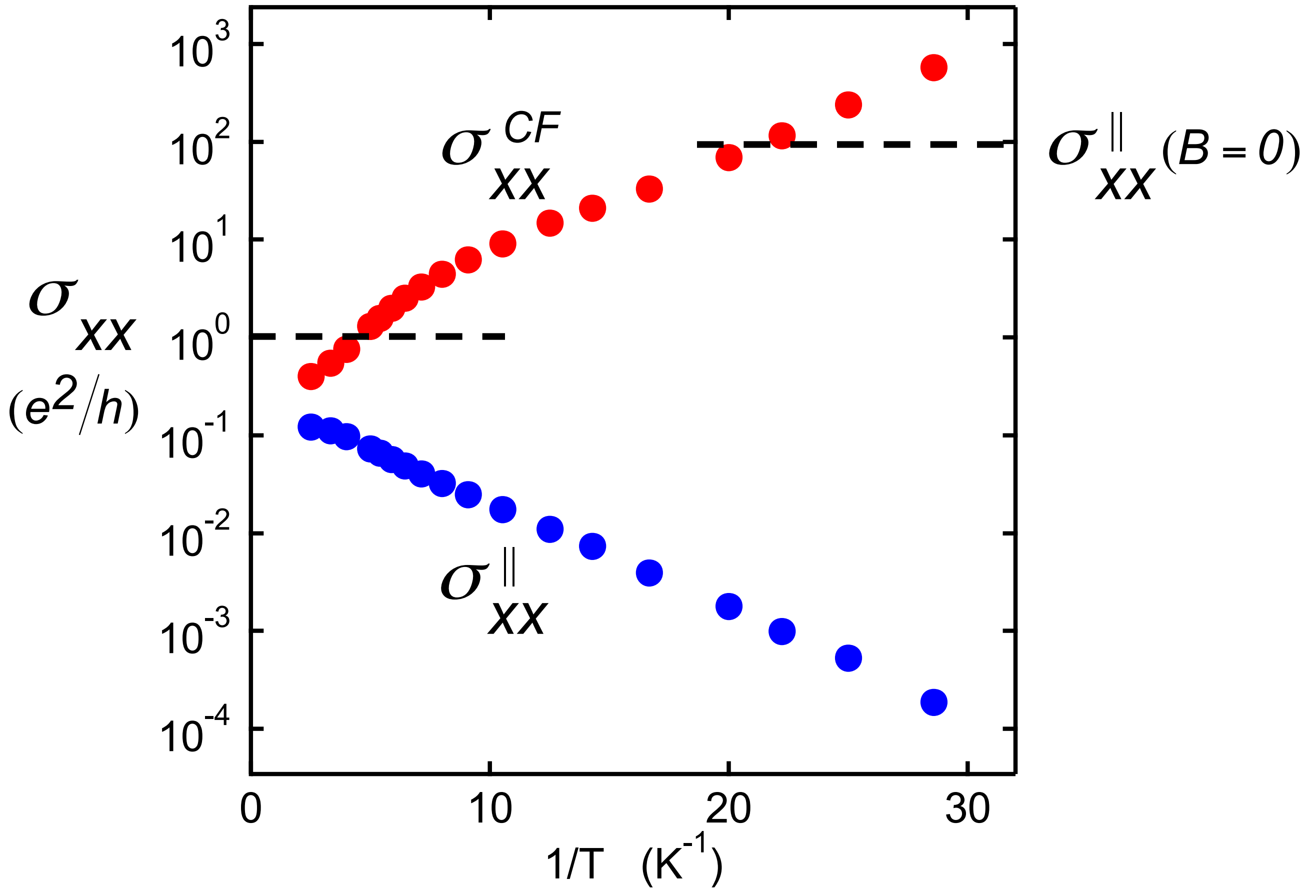


At $\nu_T = 1$: $R^{CF}_{xy} \rightarrow 0$ *and* $R^{CF}_{xx} \rightarrow 0$

Excitonic superfluidity?

Counterflow Experiment

$d/\ell = 1.5$



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.

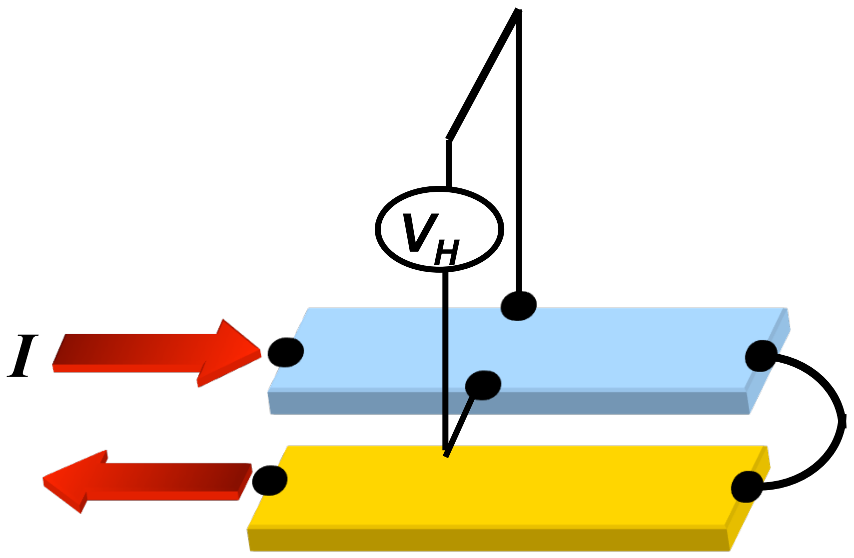
Qualitatively, theory = experiment

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.

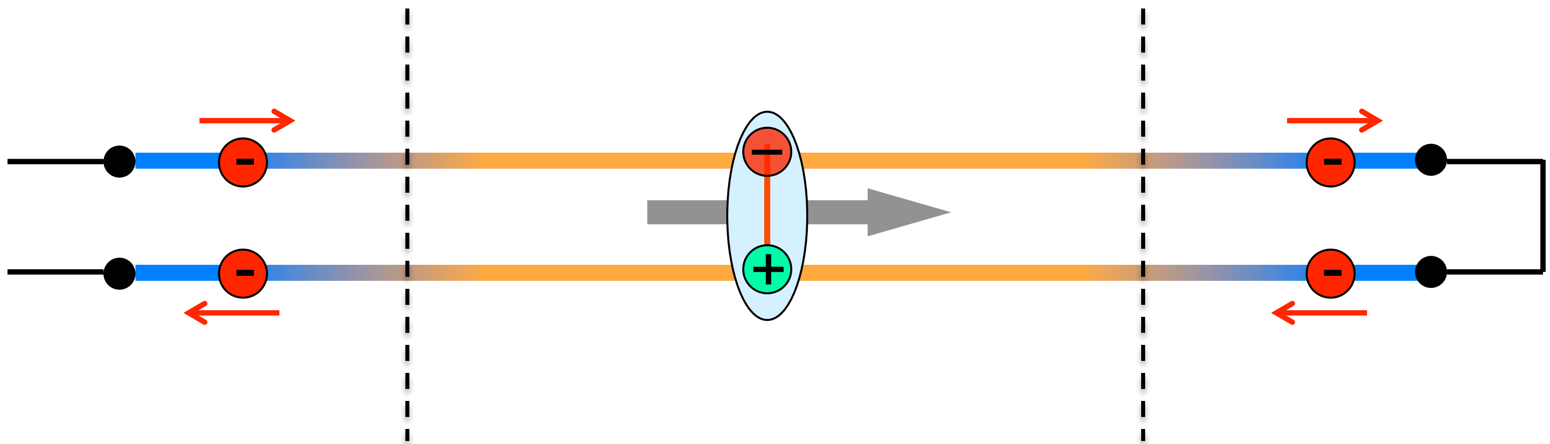
Qualitatively, theory = experiment,
but
deep questions remain.

Counterflow Experiment



What is really going on?

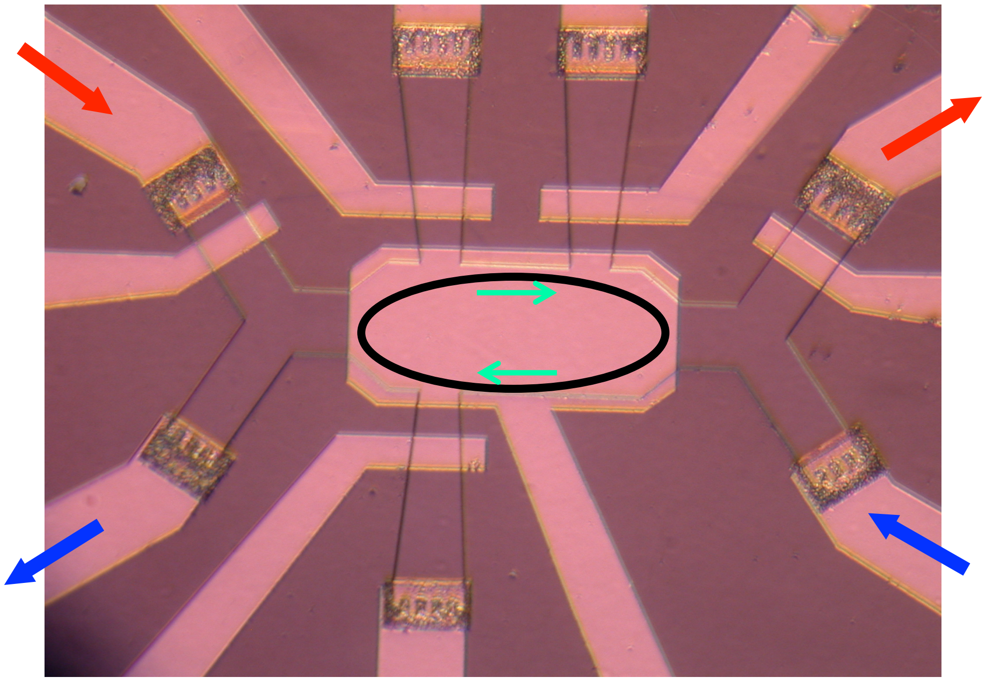
Counterflow Experiment



Andreev reflection and exciton transport?

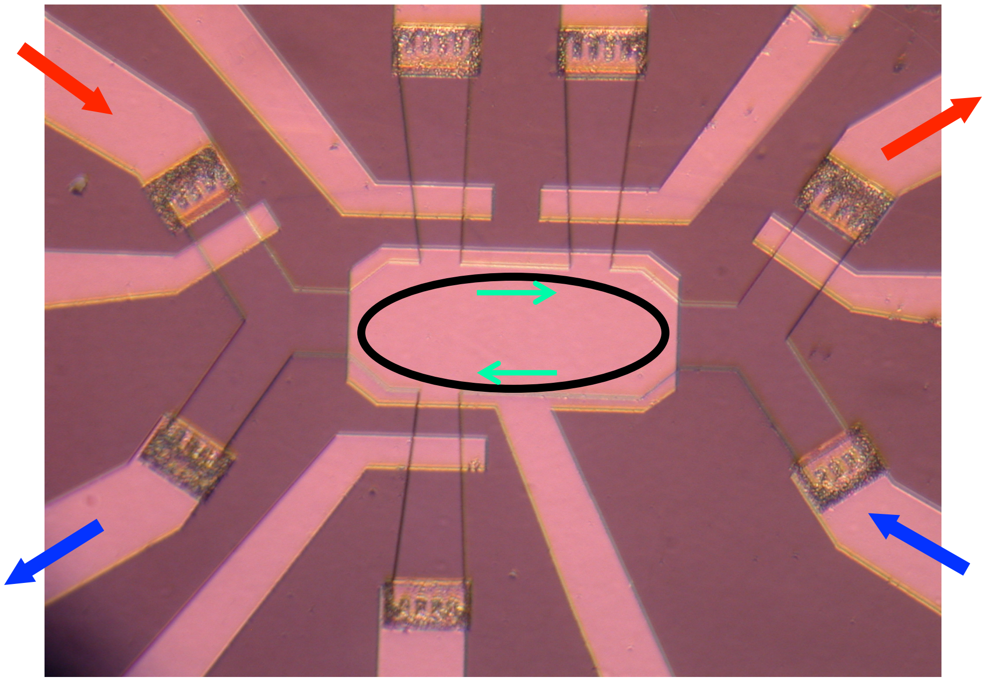
Su & MacDonald 2008

Counterflow Experiment



What role does the $\nu = 1$ edge state play?

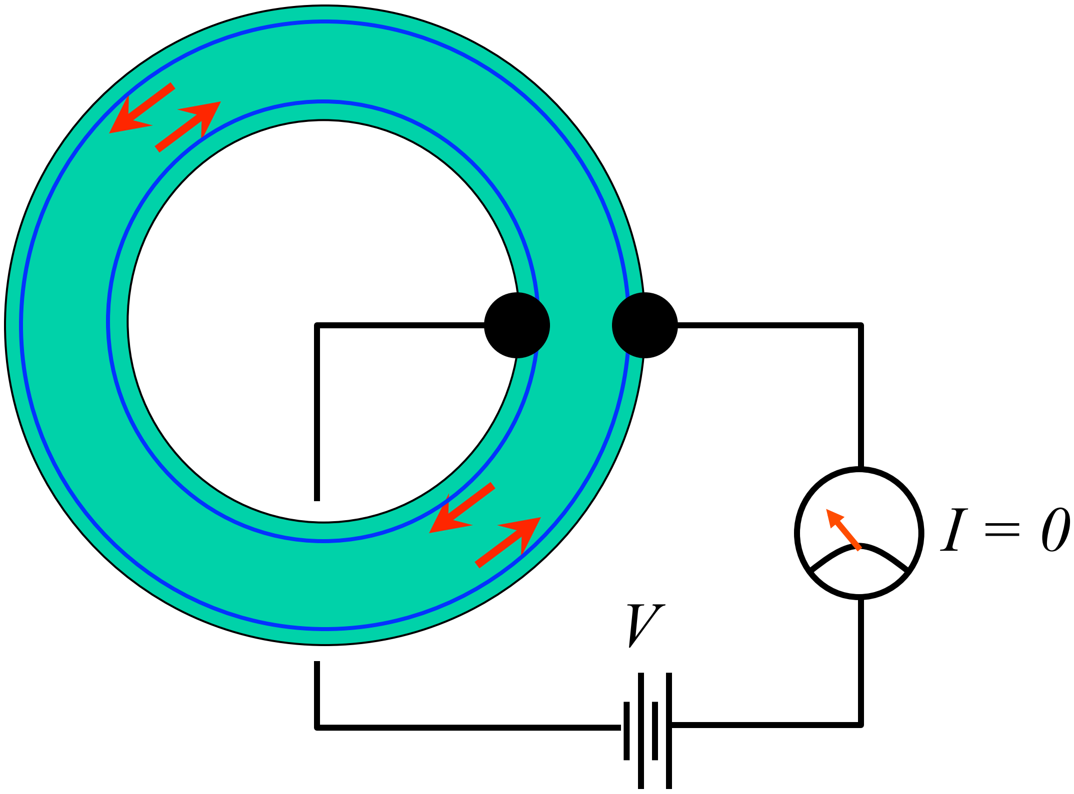
Counterflow Experiment



Experiments on simply connected Hall bars cannot directly demonstrate bulk exciton transport.

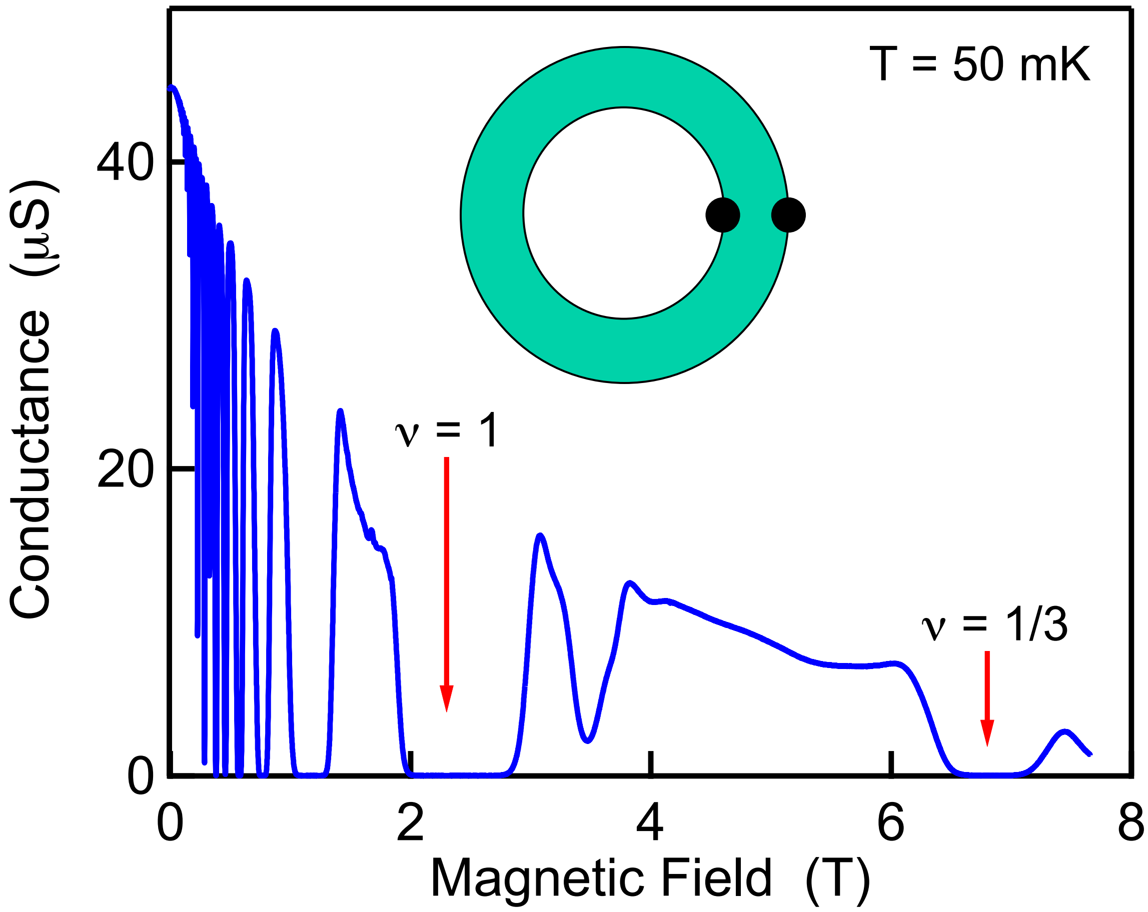
counterflow in Corbino rings

Quantum Hall systems are topological insulators



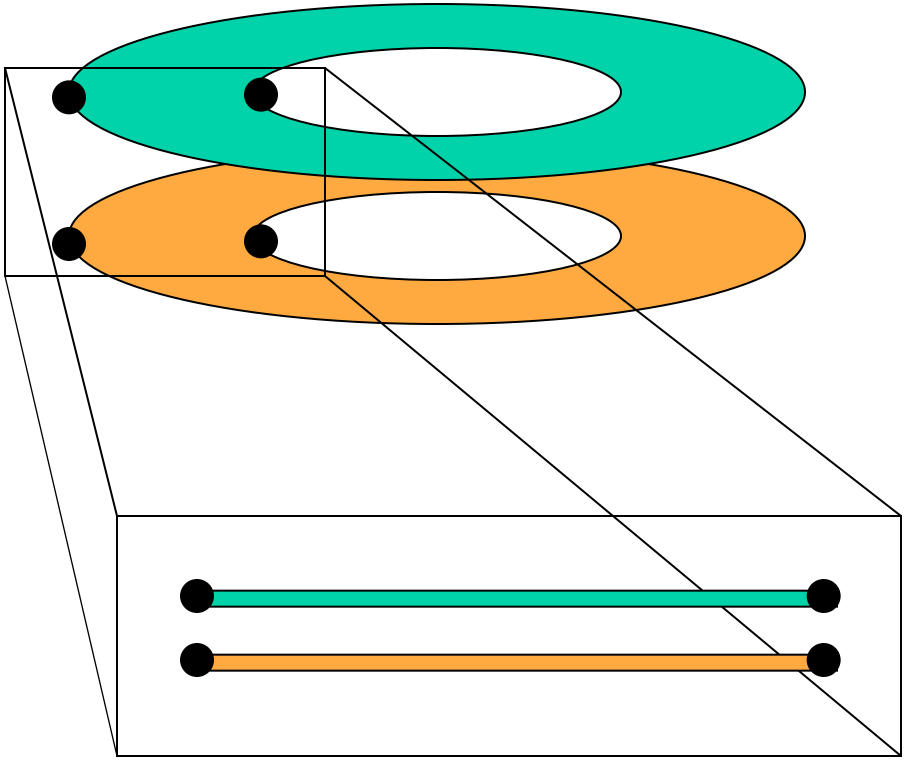
Contacts on different edges are isolated.

Corbino geometry measures bulk conductivity

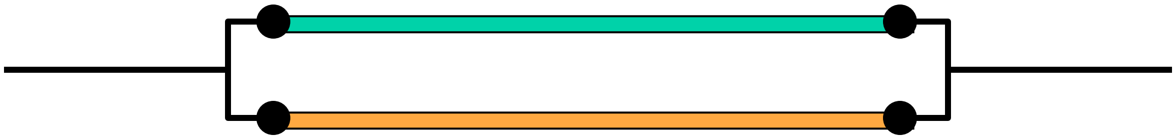


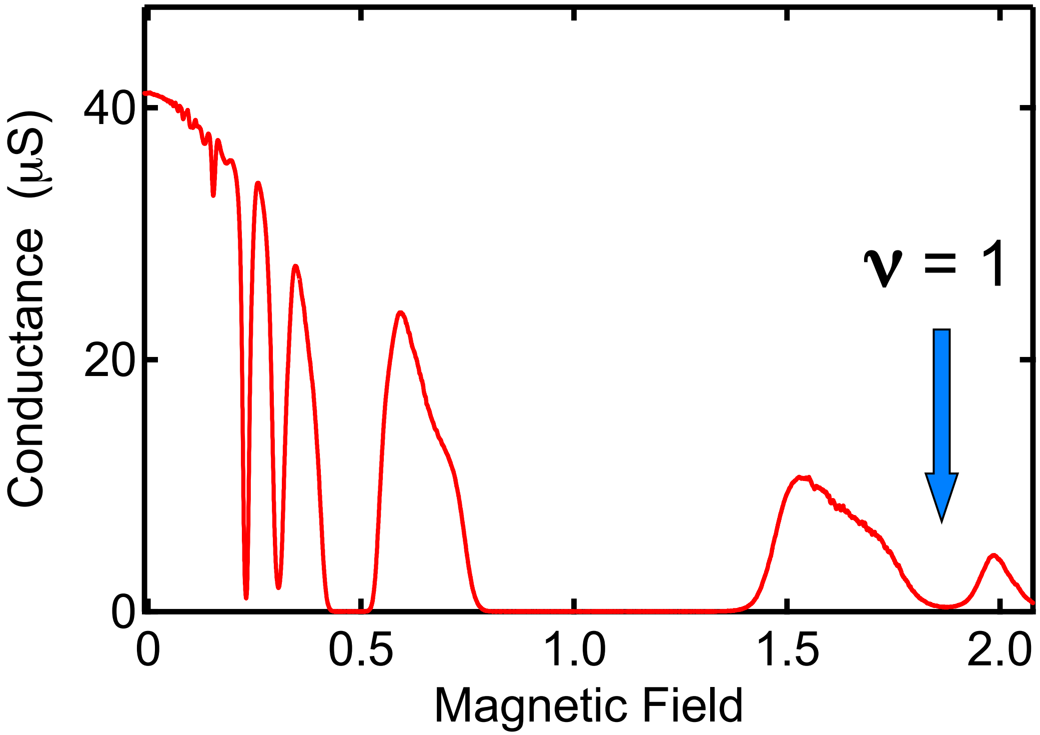
Bulk conductivity vanishes when QHE is well-developed.

Corbino Experiments



QHE suppresses parallel charge transport across the bulk



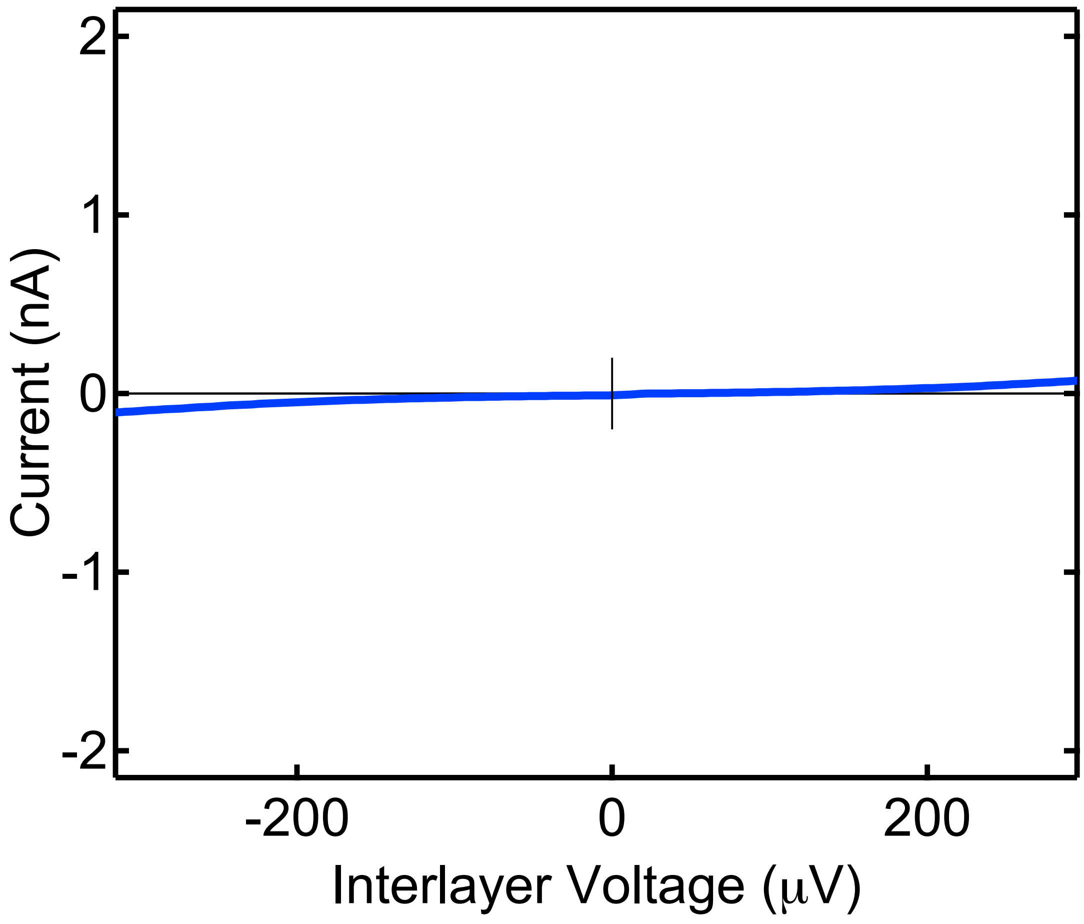


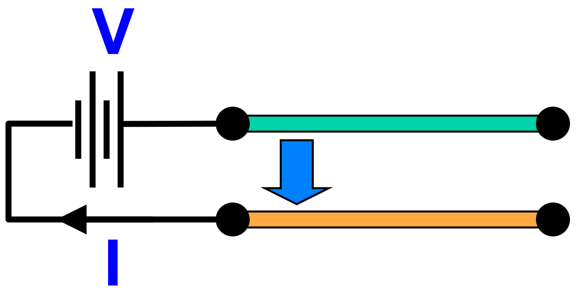
T = 25 mK

d/ℓ = 1.5

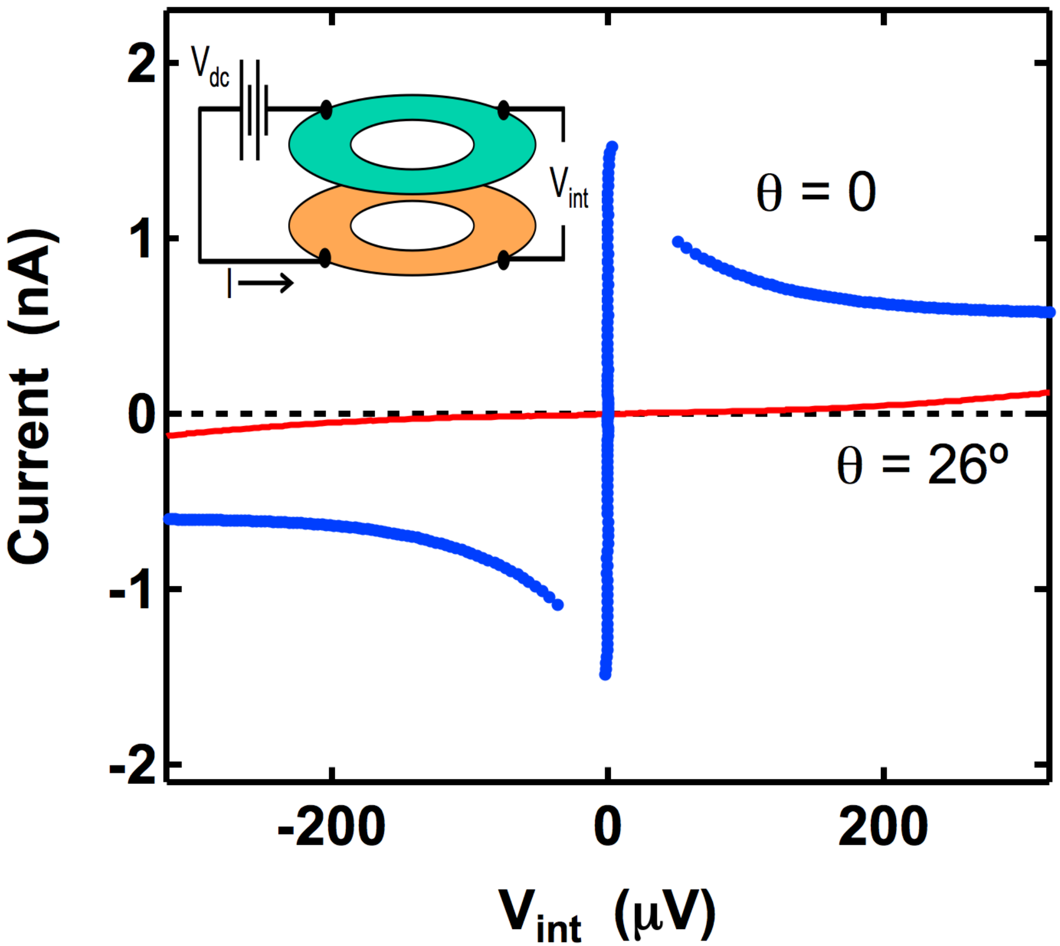
No surprise here.

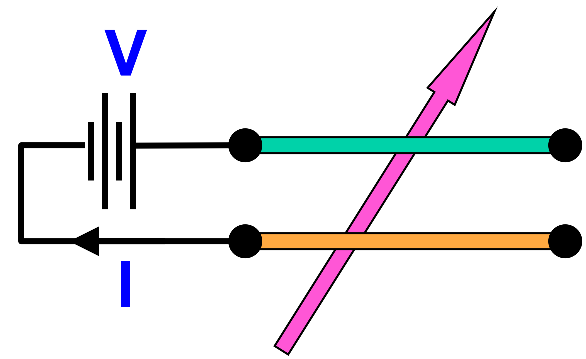
Tunneling configuration





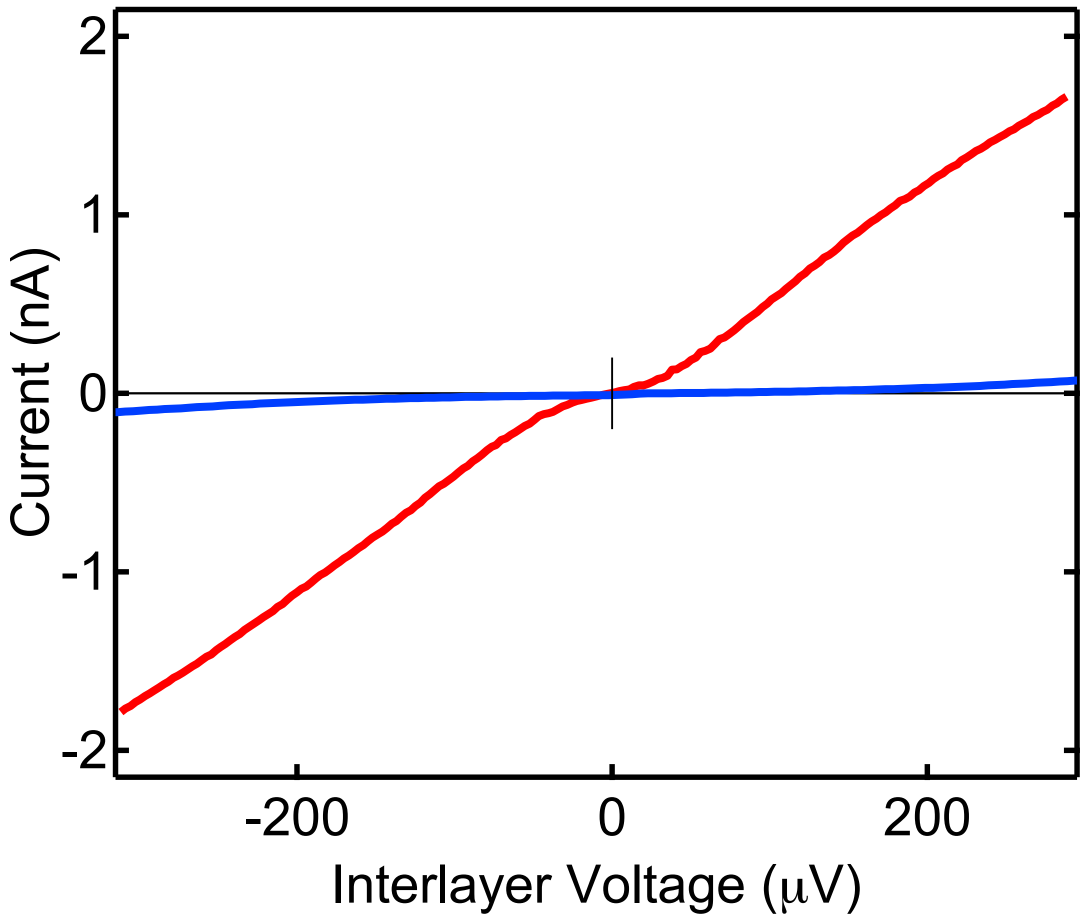
Tunneling configuration

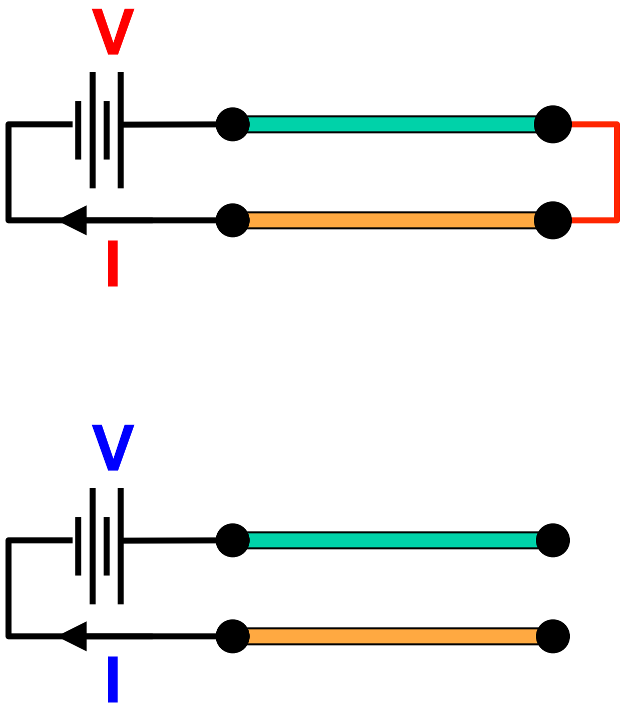




Tunneling intentionally suppressed by tilting.

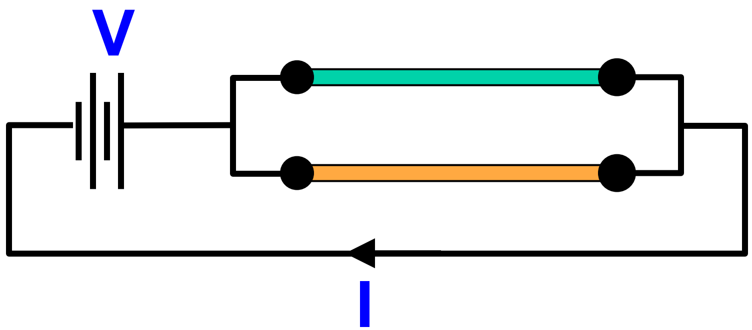
Tunneling vs. Corbino counterflow



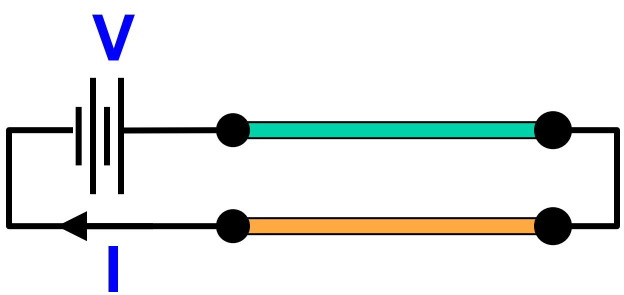


Remote short vastly enhances current.

A Paradox?

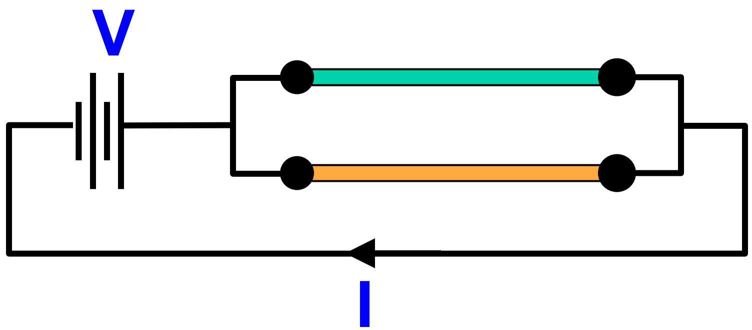


No current

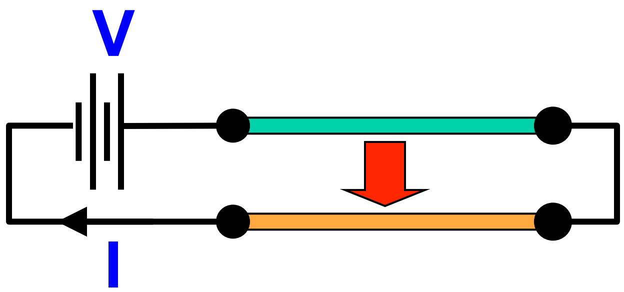


Lots of current

How can it be?



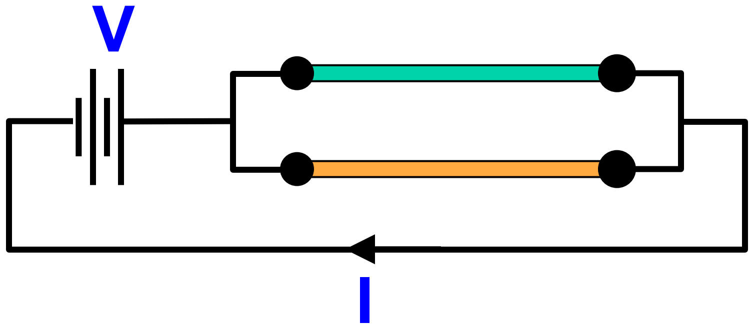
No current



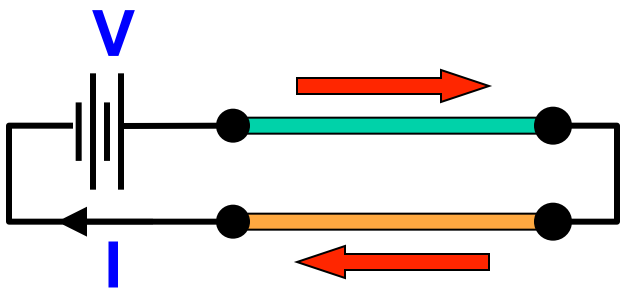
Lots of current

Enhanced tunneling?

How can it be?



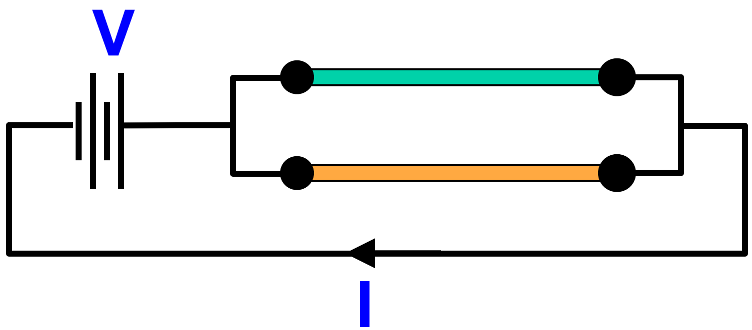
No current



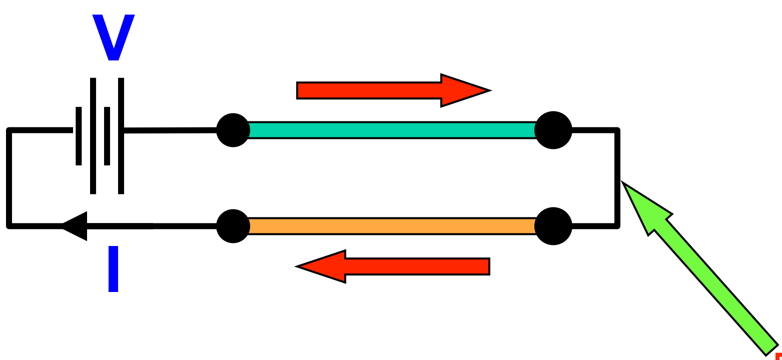
Lots of current

Counterflow?

How can it be?



No current

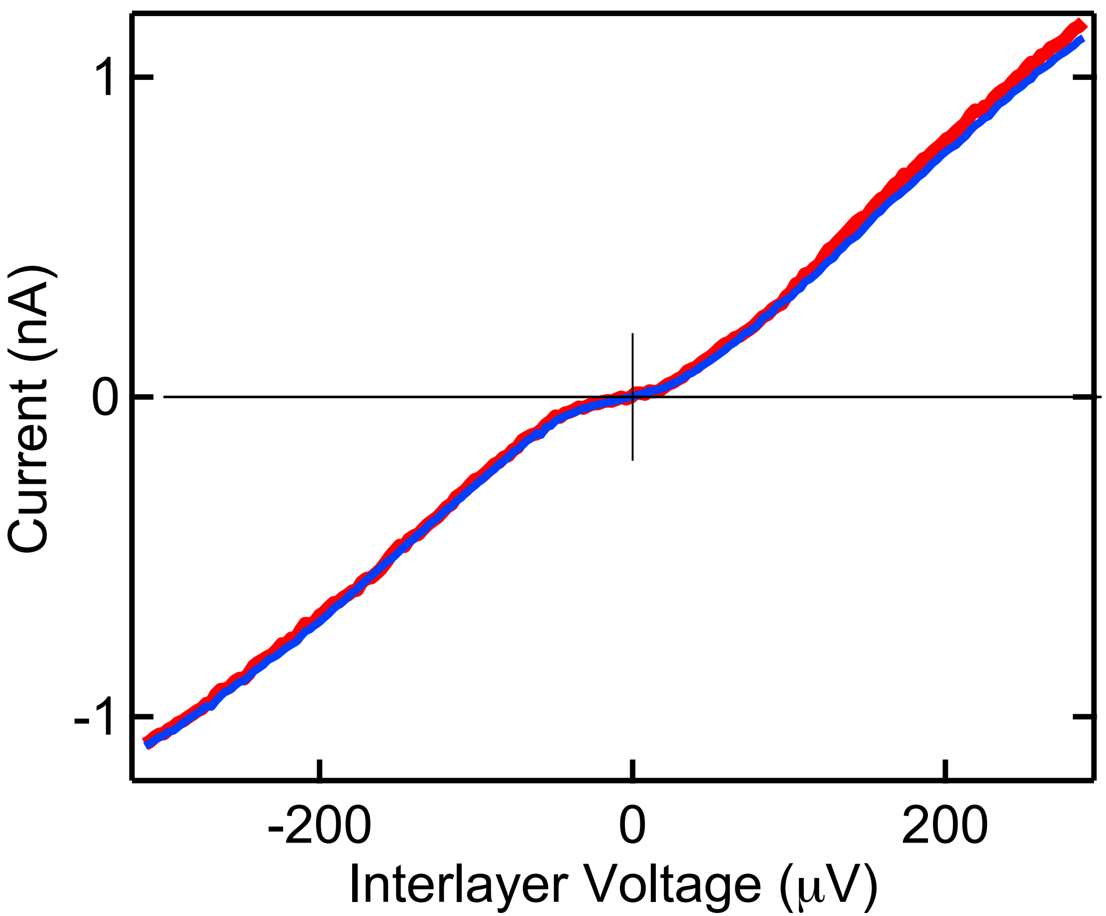


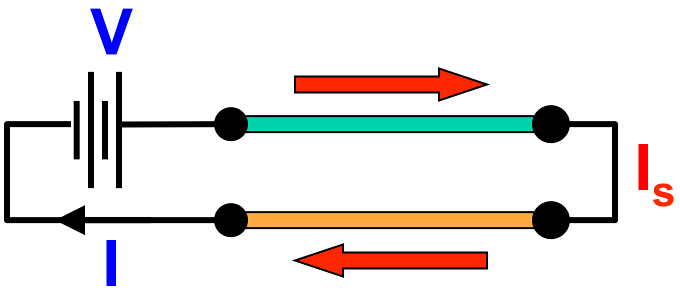
Lots of current

Measure current here!

Counterflow?

Measuring the shunt current





It IS counterflow.

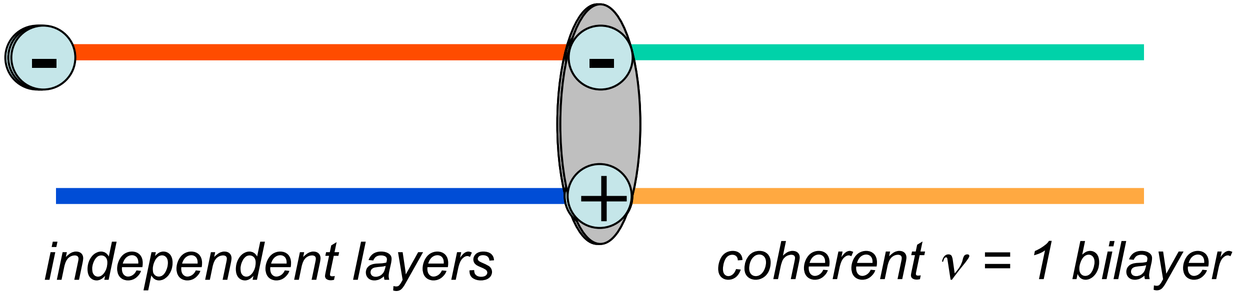
What we now know…

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

Counterflow is an intrinsically bilayer phenomenon.

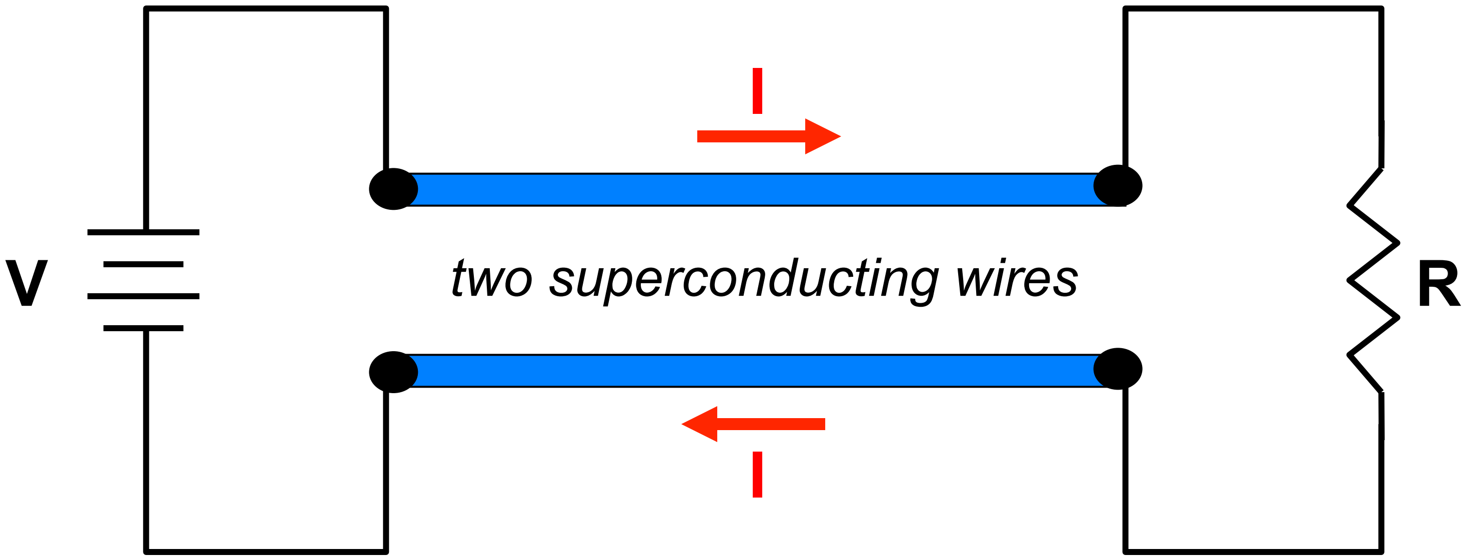
Counterflow IS exciton transport.

The mechanism



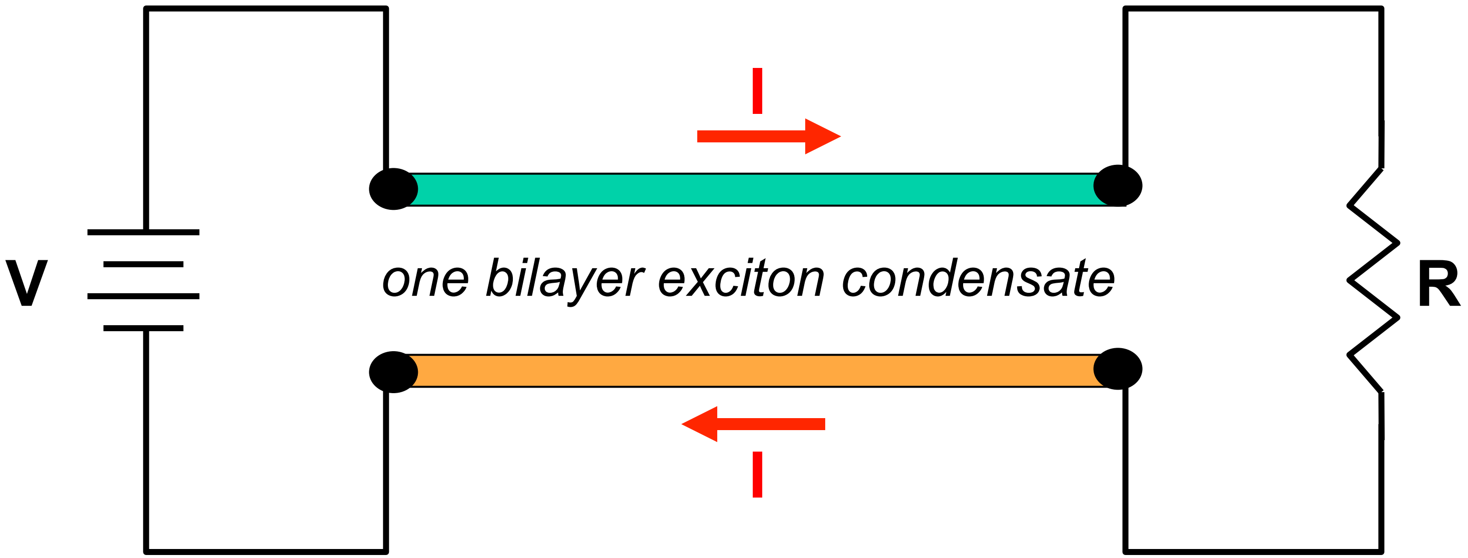
Excitons are launched and absorbed via Andreev reflection.
Excitons transport energy but not charge.

Analogy to superconductivity



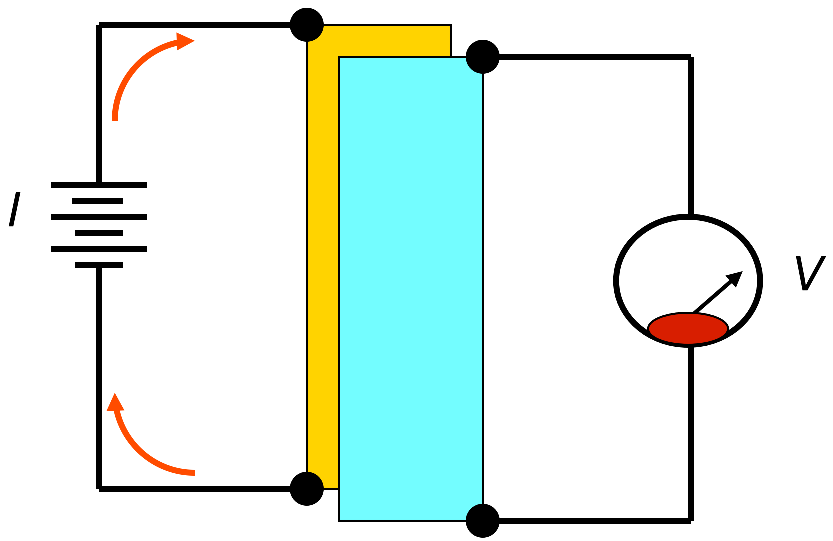
$$\Delta\phi = \frac{eV}{\hbar}t + k\,x$$

Analogy to superconductivity



$$\phi = \frac{eV}{\hbar} t + k\, x$$

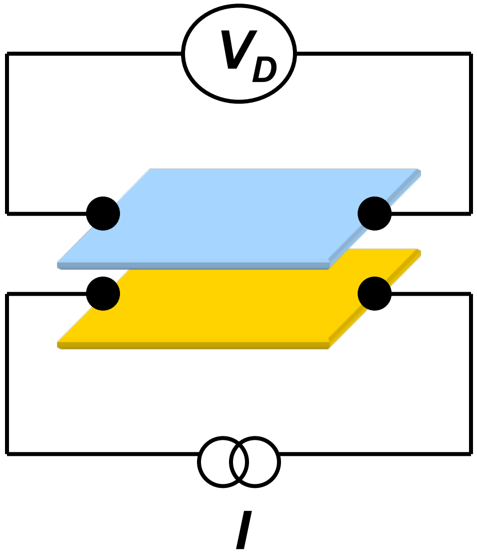
Coulomb Drag



$$R_D \equiv \frac{V}{I}$$

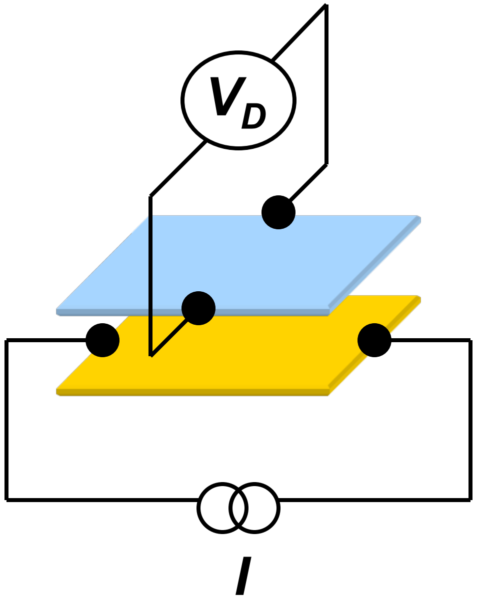
Usually a weak, perturbative effect.

Coulomb drag in magnetic fields

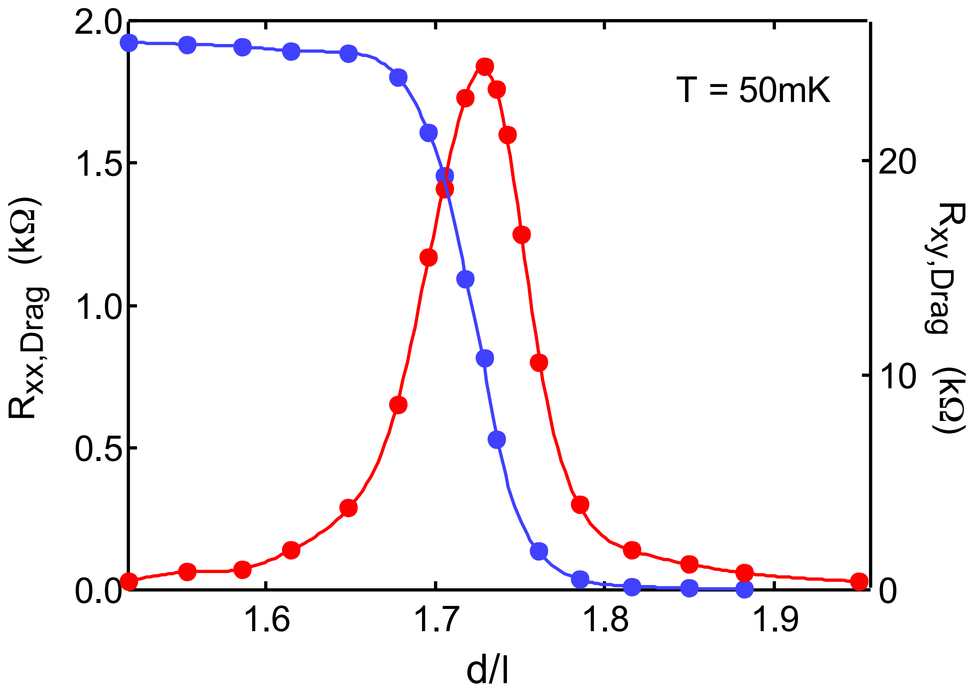


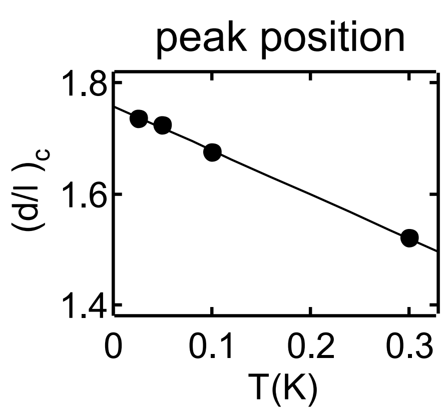
Longitudinal drag

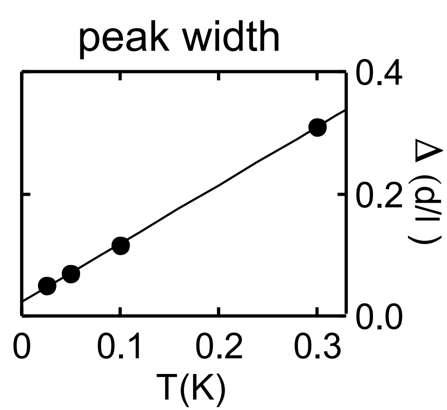
Hall drag



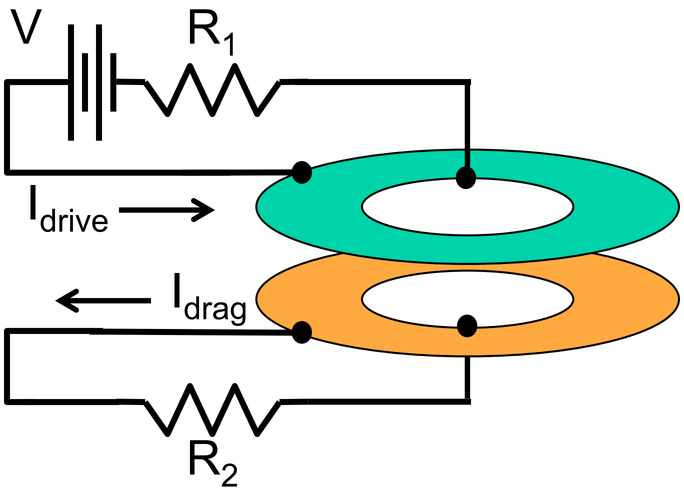
Drag Coefficients at $\nu_T = 1$





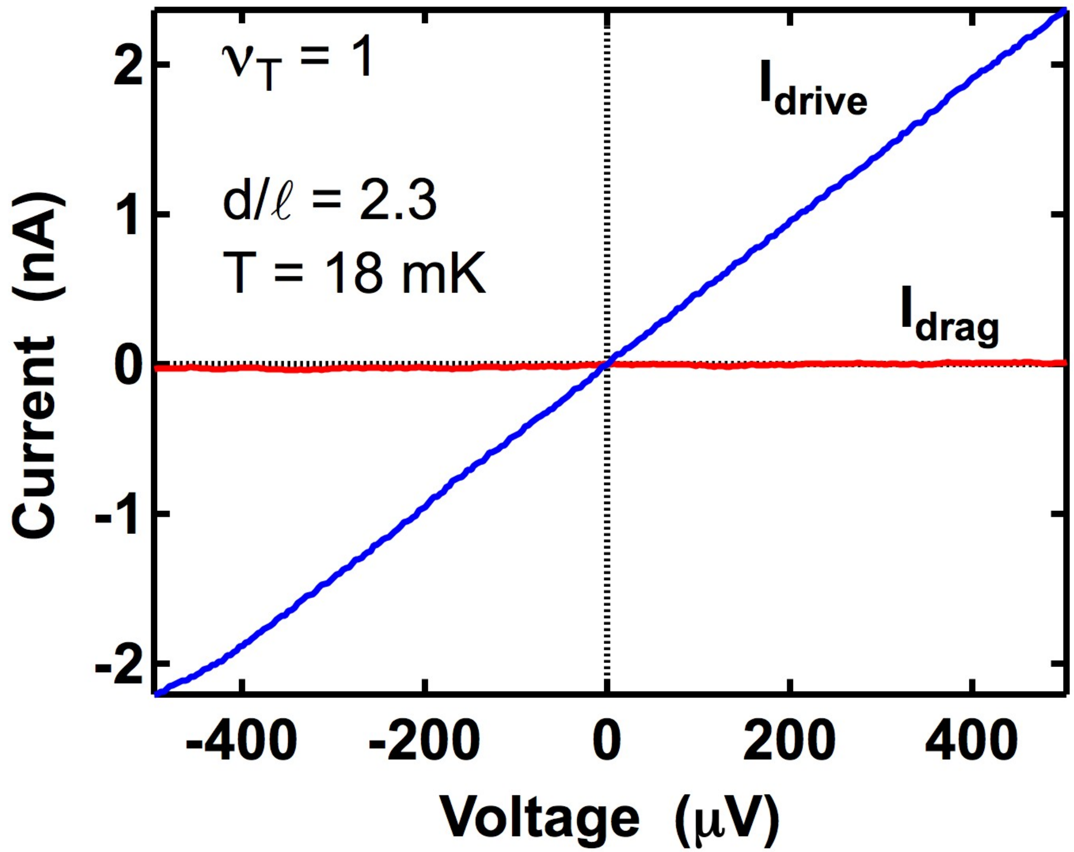


Corbino Coulomb Drag



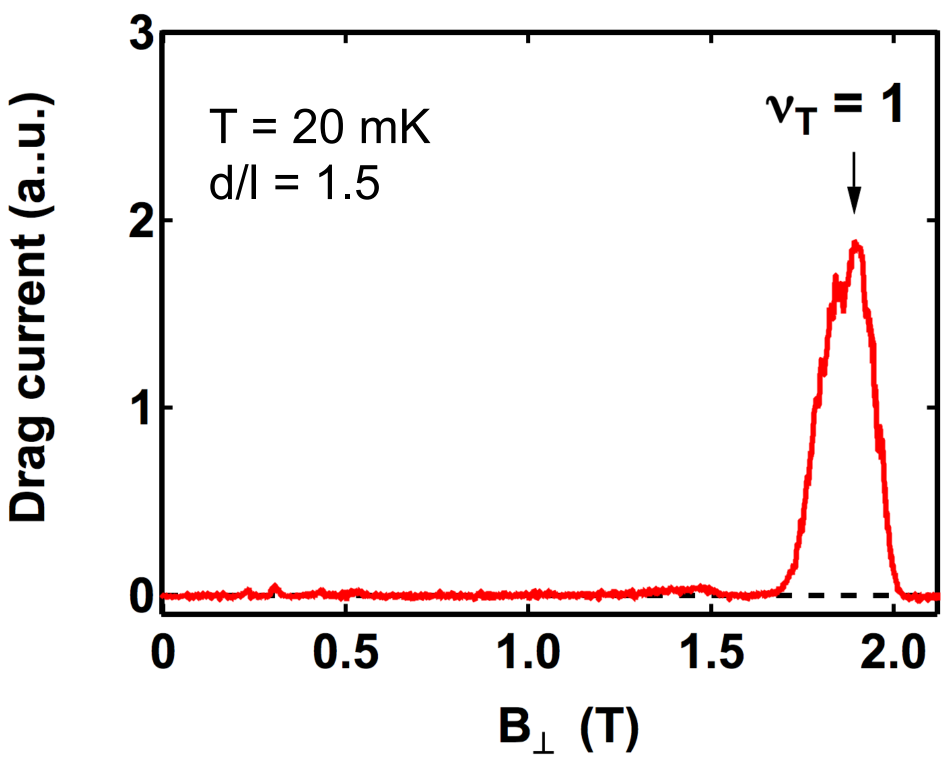
Su & MacDonald 2008

Corbino Coulomb Drag:
Incoherent Phase



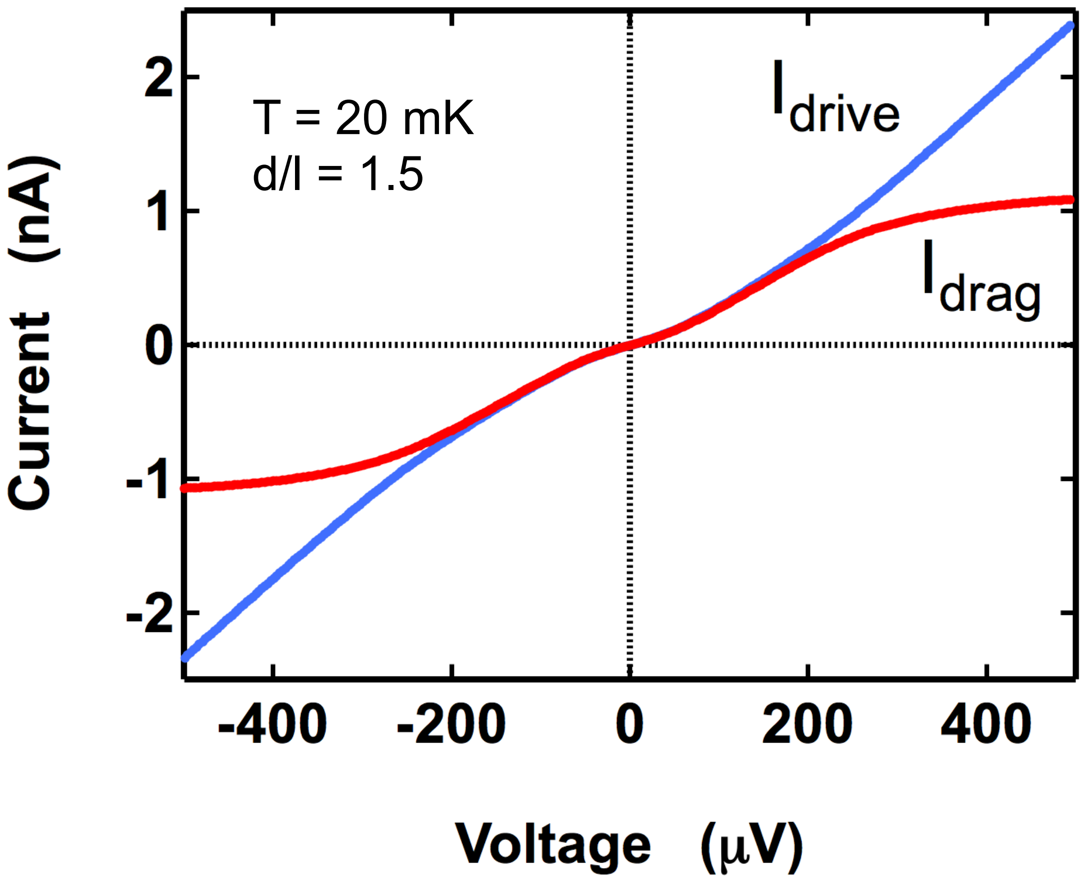
Negligible drag current when layers are independent.

Corbino Coulomb Drag: Coherent Phase



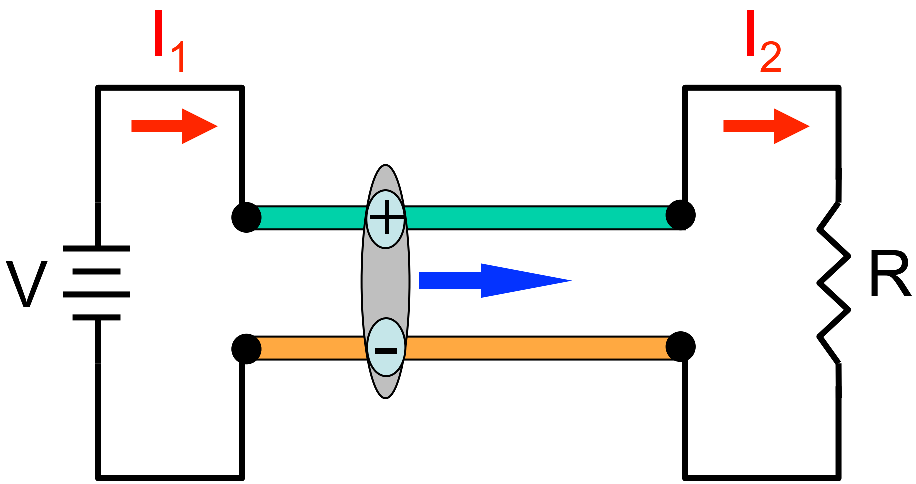
Significant drag only at $\nu_T = 1$

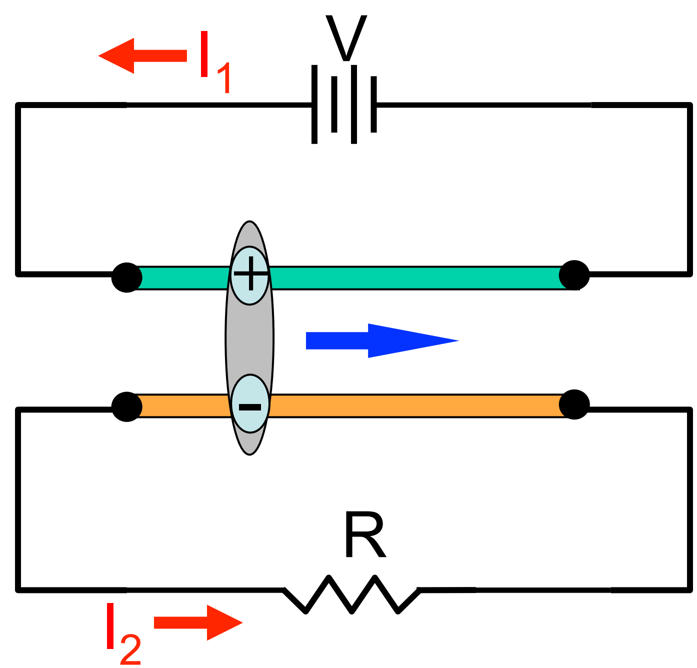
Corbino Coulomb Drag: Coherent Phase



Drag and drive currents equal at small V.
"Perfect" Coulomb Drag

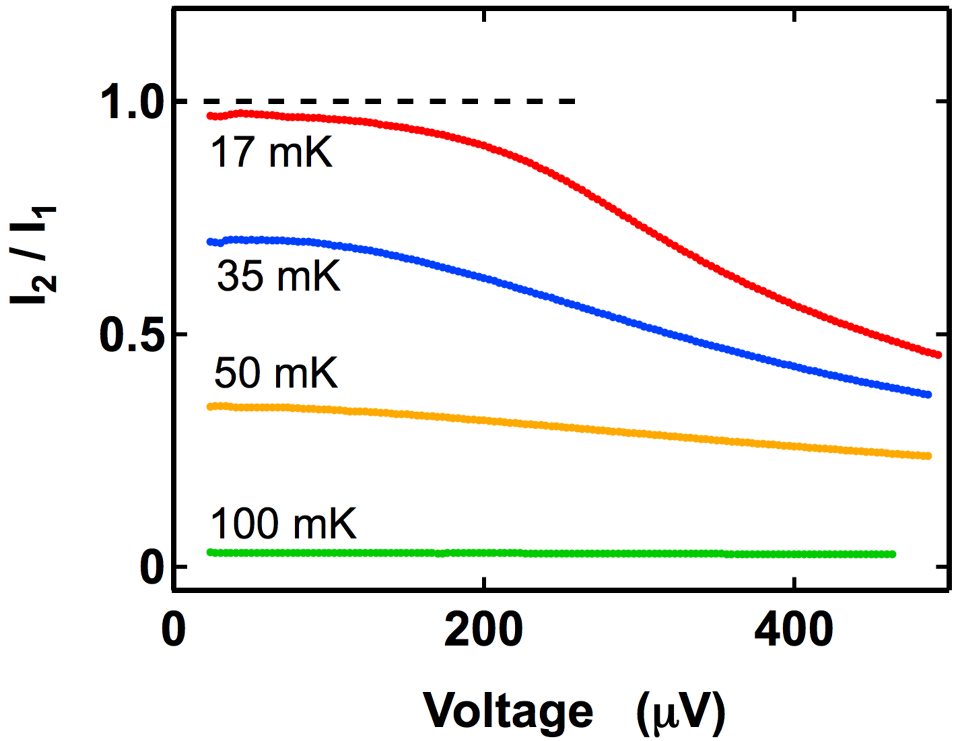
Inducing exciton transport





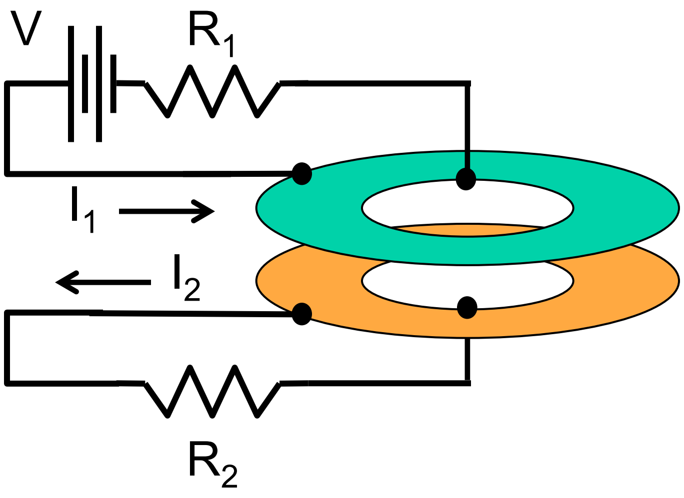
Ideally, $I_1 = I_2$

Breakdown of Perfect Coulomb Drag



When $I_1 \neq I_2$, there is charge transport across annulus.

Modeling the Breakdown



Su-MacDonald 1D model:

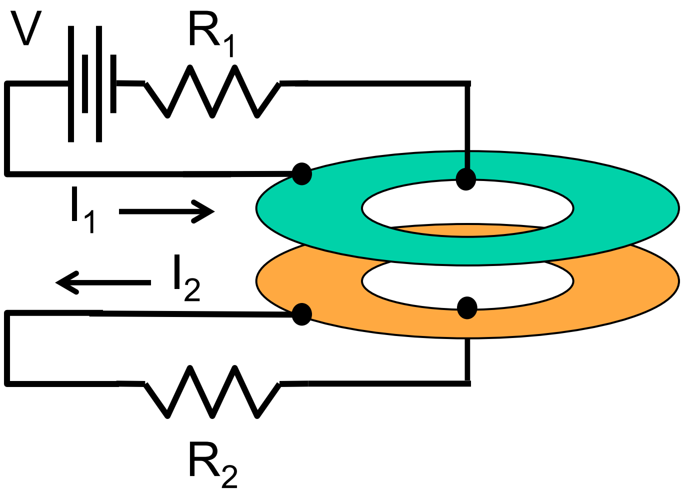
$$\sigma_{xx}^{CF} = \infty$$

$$\sigma_{xx}^{\parallel} = 0$$

$$R_1 + R_2 \geq 2h/e^2$$

$$I_2 = I_1 = \frac{V}{R_1 + R_2}$$

Modeling the Breakdown



Generalized Su-MacDonald model:

$$\sigma_{xx}^{CF} = \infty$$

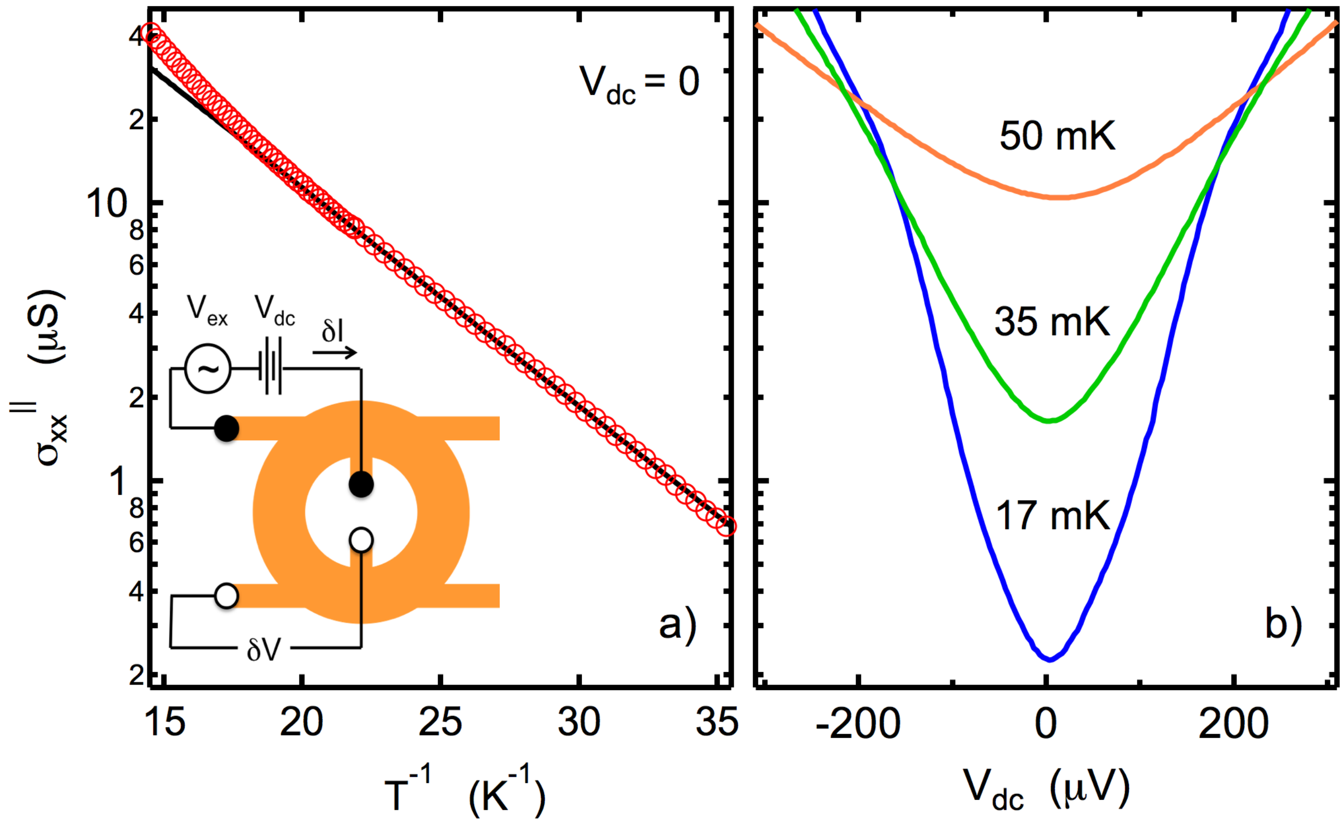
$$\sigma_{xx}^{\parallel} > 0$$

$$R_1 + R_2 \geq 2h/e^2$$

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

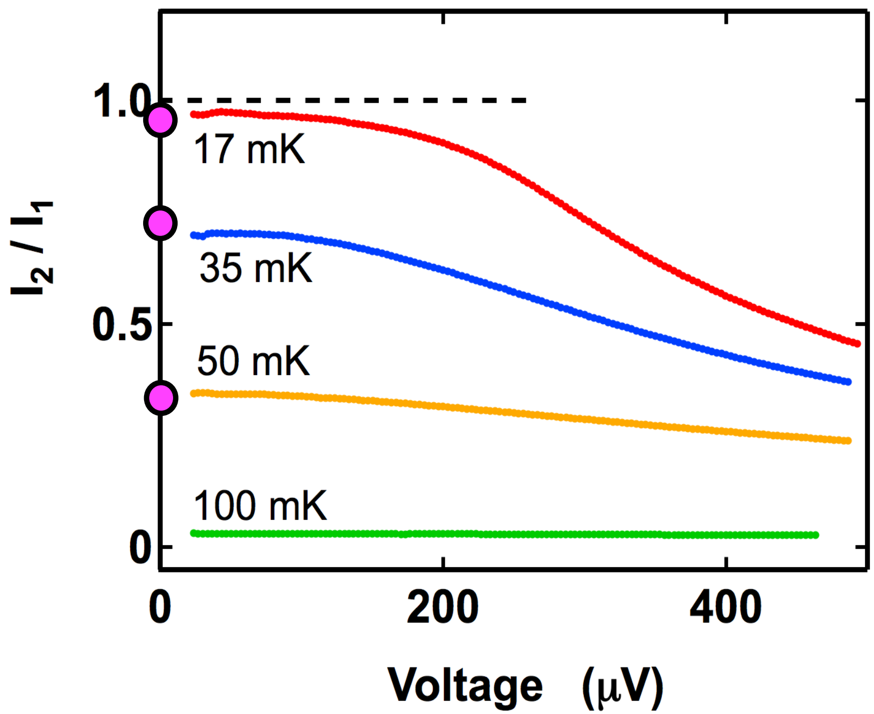
$$\frac{I_2}{I_1} = \frac{1}{1 + R_2 \sigma_{xx}^{\parallel}}$$

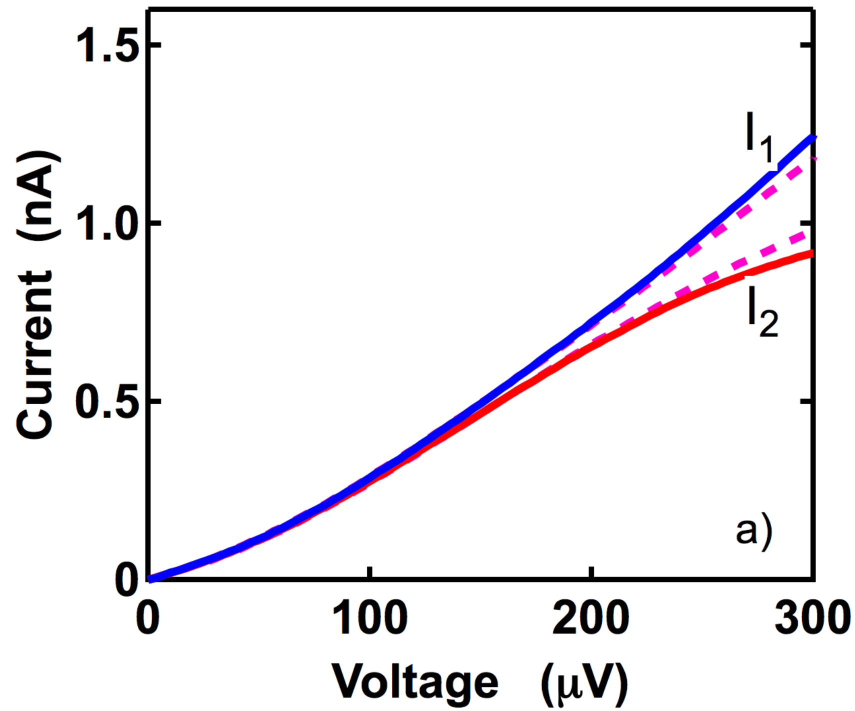
Charged quasiparticle transport



Charge gap $\Delta \approx 360$ mK

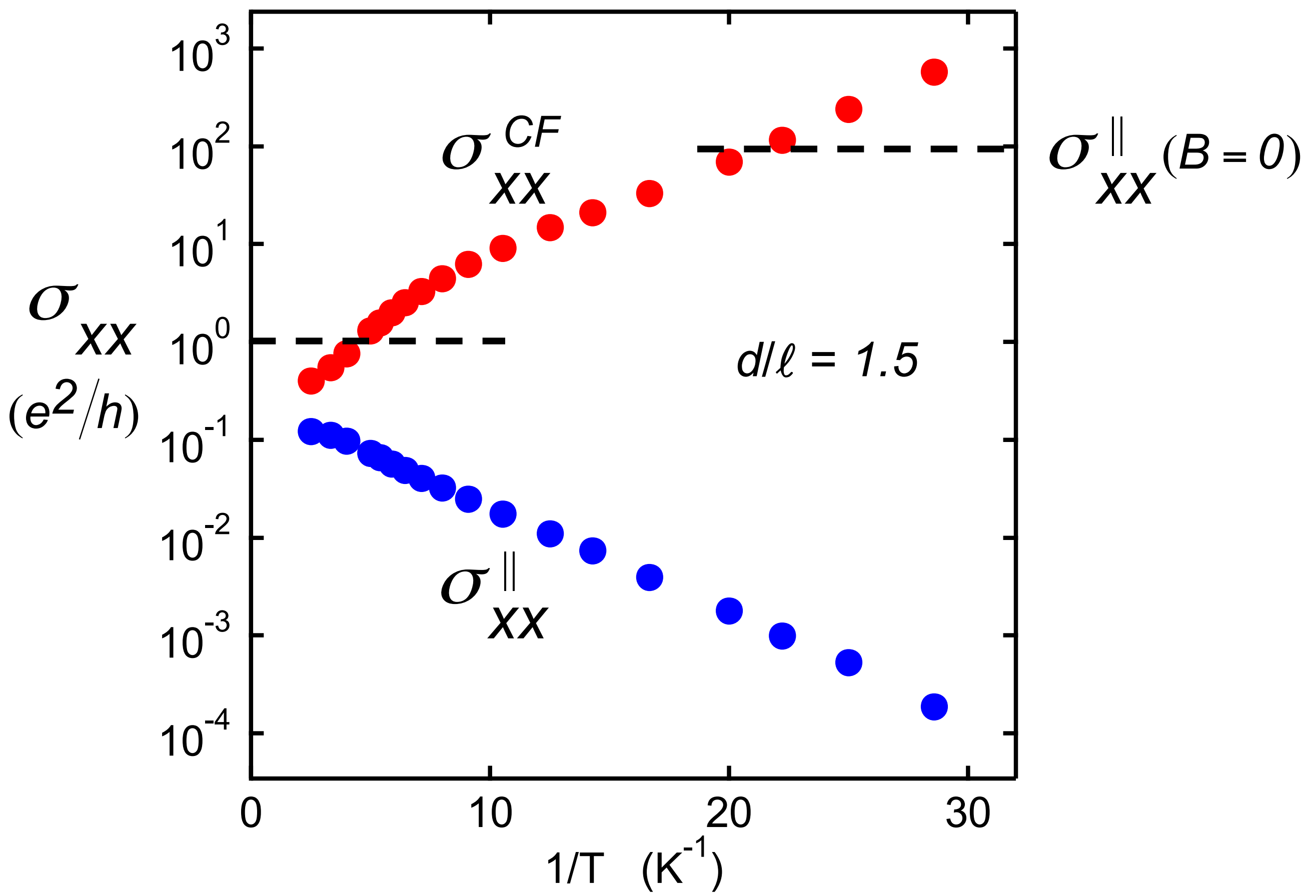
Model vs. Experiment





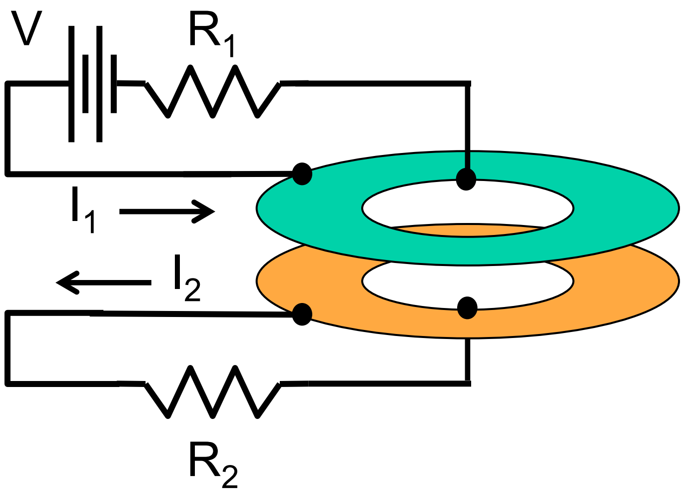
Combined condensate and quasiparticle transport dissipation in counterflow

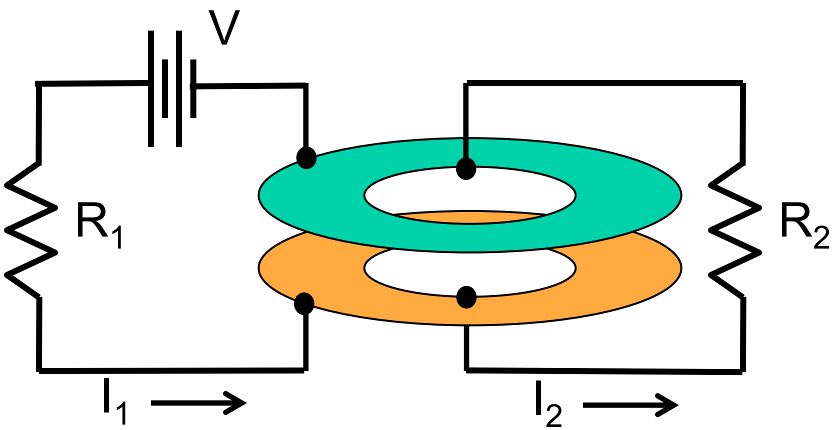
Hall Bar Counterflow Experiment



But do Hall bars really detect bulk exciton dissipation?

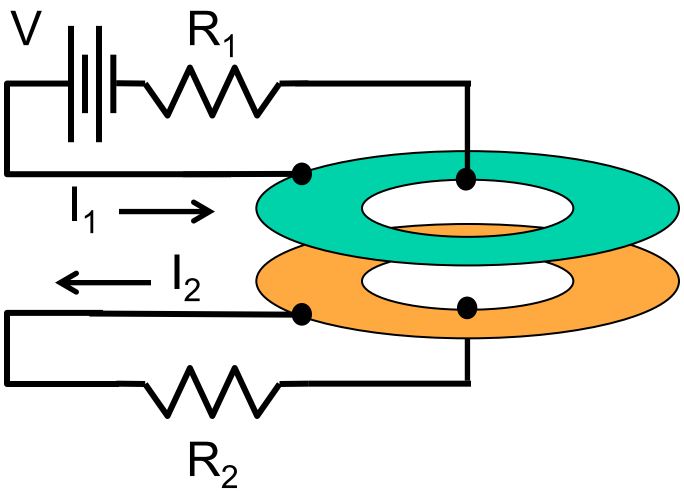
Exciton dissipation masked by extrinsic series resistances

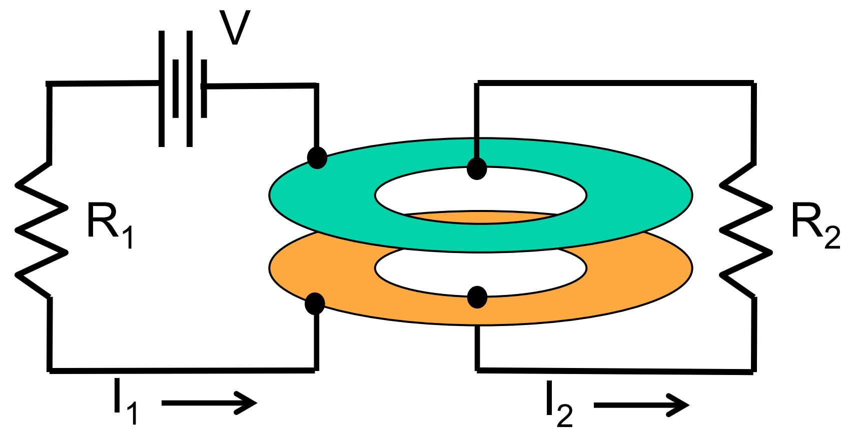




$$I_2 = I_1 = \frac{V}{R_1 + R_2}$$

Exciton dissipation masked by extrinsic series resistances

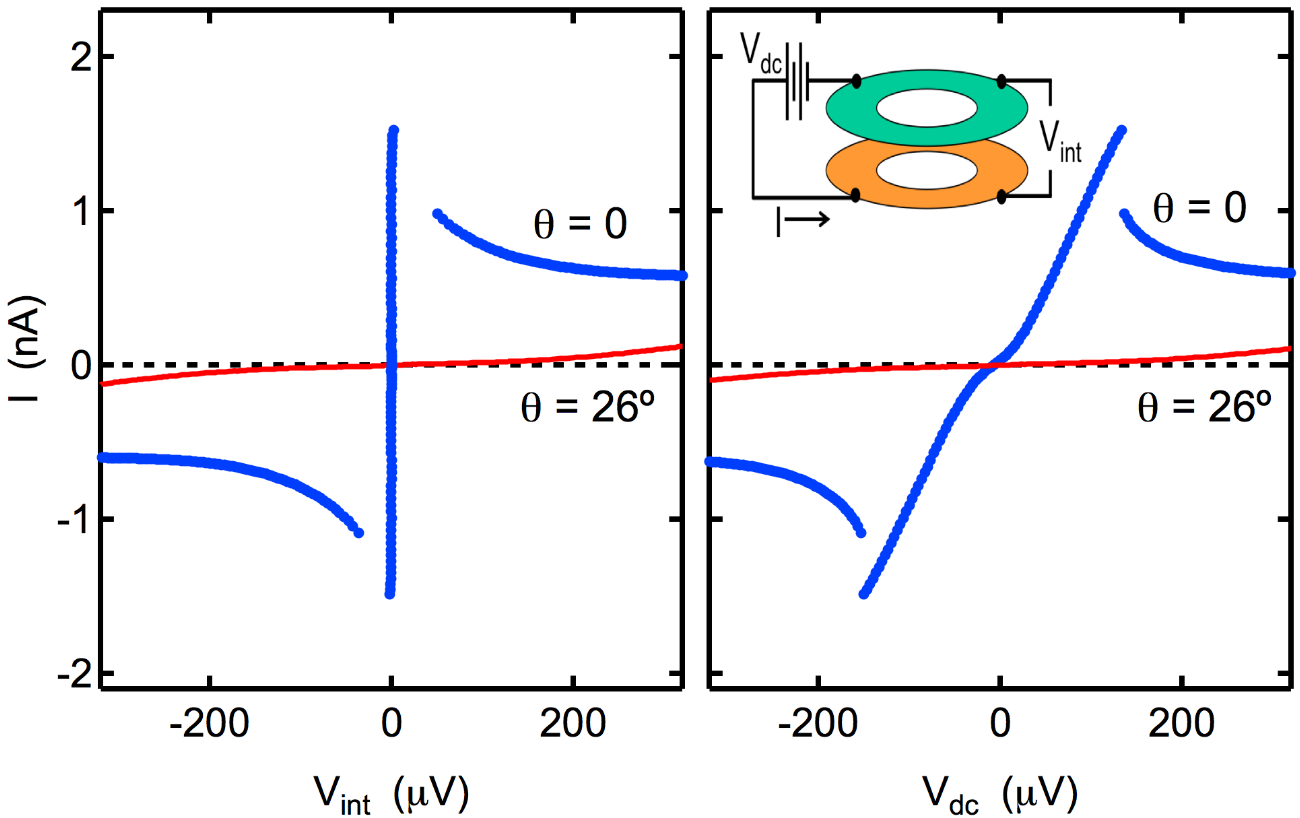




$$I_2 = I_1 = \frac{V}{R_1 + R_2 + R_{ex}}$$

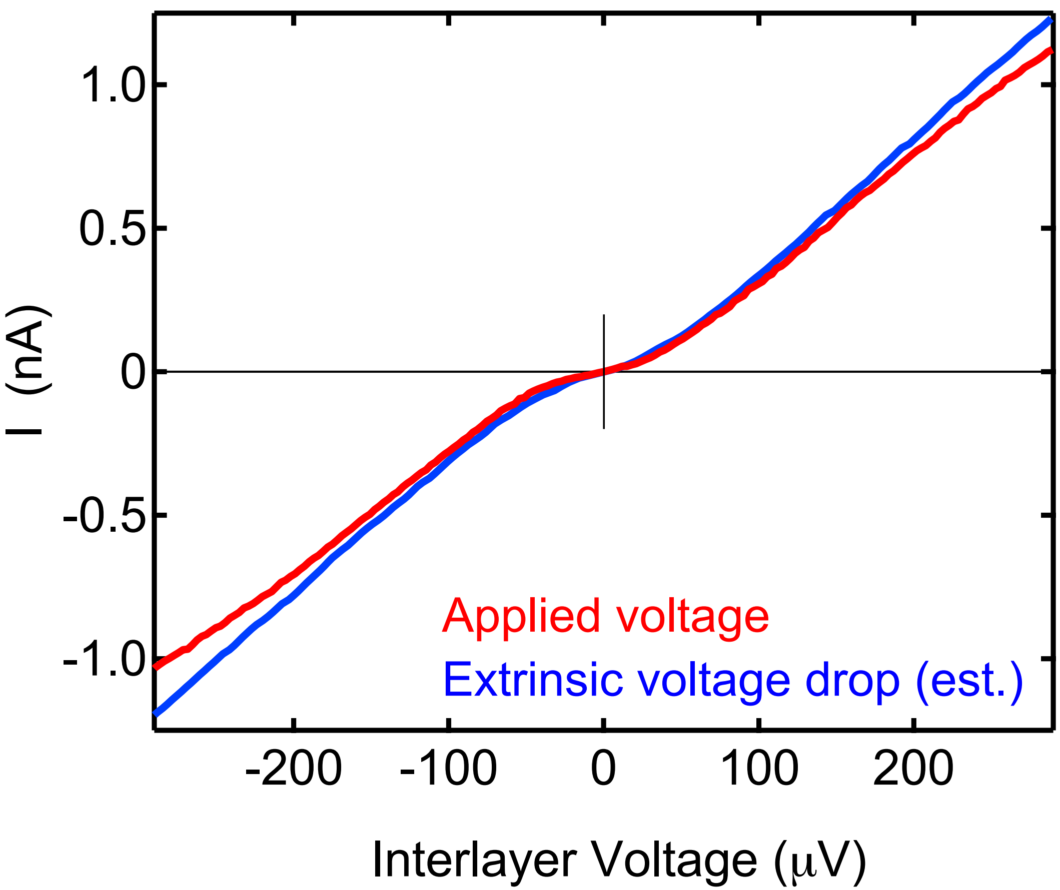
How can we determine R_1 and R_2?

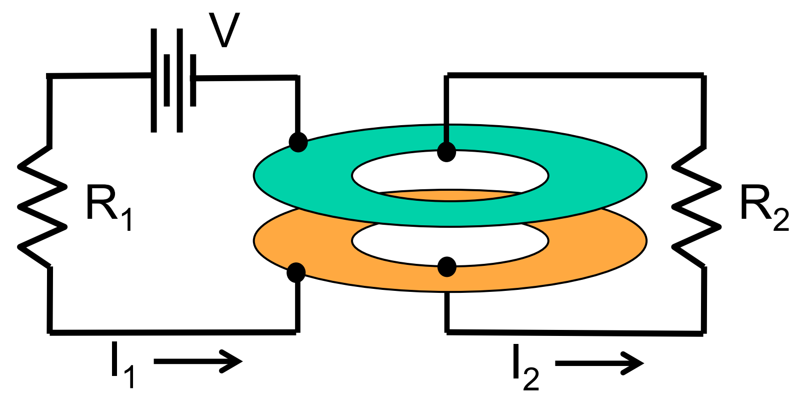
Tunneling: 2-terminal vs. 4-terminal



At θ = 0, 2-terminal I-V dominated by series resistances.

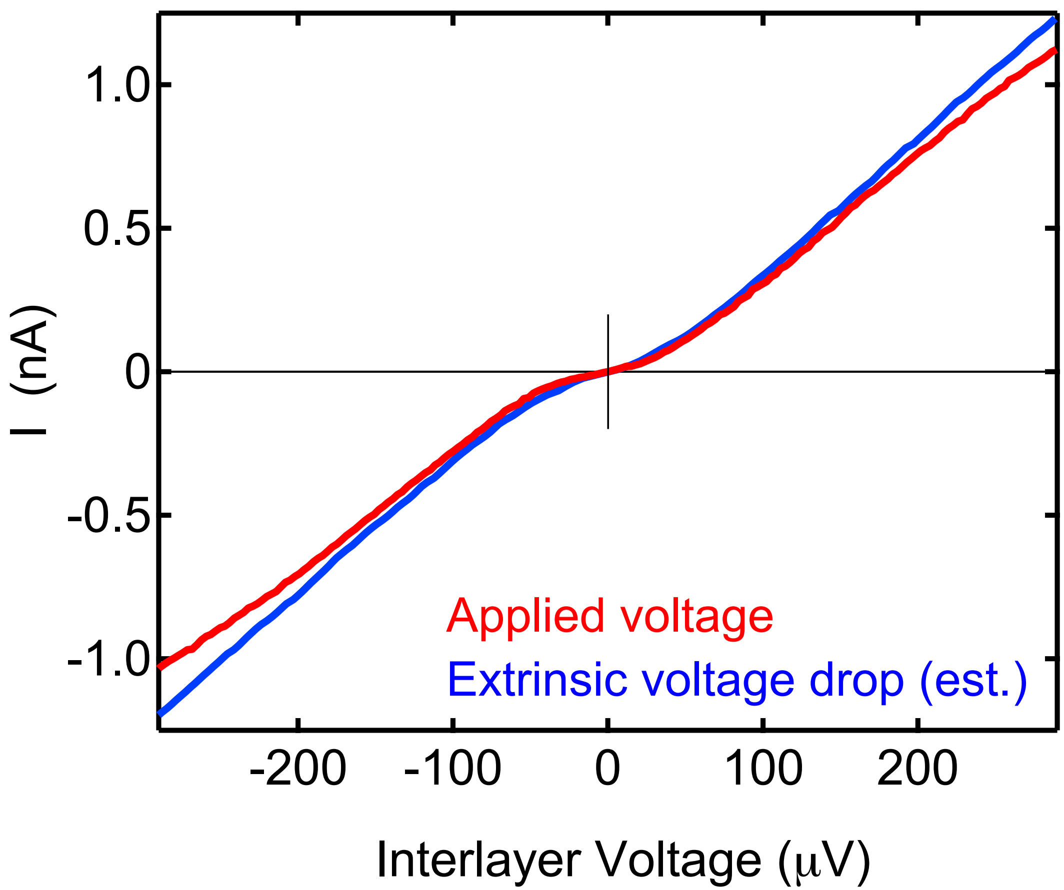
Exciton dissipation "small"

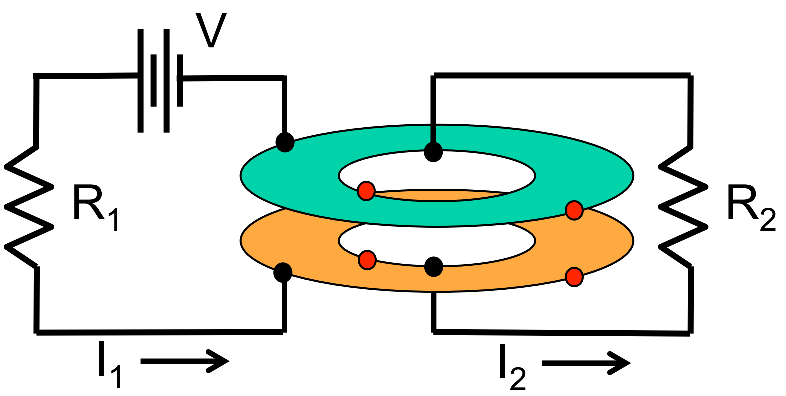




New, multi-terminal measurements needed.

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?