Excitonic Superfluidity in Quantum Hall Bilayers

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---UT Condensed Matter---
New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance

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A small voltage of a two-dimensional electron gas formed in an InSb semiconductor field-effect transistor, and a spatially well-defined surface carrier density, provides a method for the determination of the fine-structure constant and speed of light. Preliminary data are reported.
Dissipationless Transport
Quantum Hall vs. Superfluid

Dissipationless Transport in Superconductors

Quasiparticles in Equilibrium
Condensate not in ground state

Quantum Hall Edge State Picture

Quasiparticles in local equilibrium
No condensate

Voltage Probe
Hall Bar

Landau Level

Edge State
Symmetric gating allows continuous tuning of effective layer spacing in a single sample.
Crossing the phase boundary

layer spacing

\( \nu_T = \frac{1}{2} + \frac{1}{2} \)

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

\[ \nu_T = 1 \]

\[ \nu_T = 1/2 + 1/2 \]

Coulomb gap replaced by resonant enhancement.
Two kinds of drag

Longitudinal drag

“Hall” drag
Transport coefficients

![Graph showing transport coefficients](image)

- **Hall Drag**

**Axes:**
- **Y-axis:** $R_{xx}$ & $R_{xx,D}$ (kΩ)
- **X-axis:** Magnetic Field (T)
Bilayer Quantum Hall Ferromagnet

• **WHAT?** Spontaneous Interlayer Coherence

\[ |\Psi[\hat{m}_X]\rangle = \prod_X \left( u_X c_{XT}^+ + v_X c_{XB}^+ \right) |0\rangle \]

**Gain in Interlayer Correlation Energy**

**exceeds**

**loss in Intralayer Correlation Energy**

• **WHY?**

**Horie Kuramoto**

**Yoshioka**

**Paquet Rice Ueda**

**Fertig Quinn**

**Wen Zee**

**Ezawa**

**Yang Moon**

...
Exciton Condensation = Spontaneous Coherence

\[ |\Psi\rangle = \prod_k \left( u_k c_{kc}^+ + v_k c_{kv}^+ \right) |0\rangle \]
Exciton Condensation in MSS

Keldysh 1968

Lezovik 1975

Kuramoto 1978

E_c + E_v

2D Bilayer

E_c + E_v

2D Bilayer in Field

3D
Lessons from the Quantum Hall Regime

Spontaneous Coherence within conduction band

Halperin 1982
Yoshioka & AHM 1990
Microscopic Physics of Spontaneous Interband Phase Coherence

Exchange-Correlation Hole
How to detect an excitonic BEC

A. H. MacDonald
Giovanni Vignale

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Drag in Paired Electron-Hole Layers

\[
\rho_{cd} = \frac{\rho_{ee} \rho_{hh} - (\rho_{eh})^2}{\rho_{ee} + \rho_{hh} - 2\rho_{eh}} = \frac{1}{\sigma_{ee} + \sigma_{hh} + 2\sigma_{eh}}
\]

No Odd Channel Resistivity
Two-Fluid Model

Hall Effect

Odd Channel Resistivity because of Vortex Flow
Vortex-flow resistivity

\[ J_0 = \frac{e^3}{\hbar l^2} \]
\[ \sim 80 \ \mu\text{A/µm B[Tesla]} \]

\[ J_0^{\text{exp}} \sim 10 \ \text{pA/µm} \]

\[ \Delta \sim T_c \ln(J_c/J) \]
Elementary Charged Excitation Cartoon

Murphy et al. PRL 94  
Moon et al. PRB 95

"Particles, particles, particles."
Vortex-Soup Cartoon

Stern et al. 2000, 2001
Order Parameter Dynamics and Tunneling

DC Josephson Effect: $\alpha_\phi = 0 \quad \alpha_z \neq 0$

$$\frac{\partial \Omega_z}{\partial t} = \frac{1}{\hbar} \left[ \frac{\Delta_t}{2} \sin \phi - 2\pi l^2 \rho_s \nabla^2 \phi \right] - \frac{4\pi l^2 \beta \alpha_z}{\hbar} \Omega_z + \frac{8\pi^2 l^4 \beta \sigma_z}{e^2 M_0} \nabla^2 \Omega_z$$

- Collective Tunneling
- Supercurrent
- Quasiparticle Current
Order Parameter Dynamics and Tunneling

\[ \alpha_z = 0 \quad \alpha_\phi \neq 0 \]

\[ \frac{\partial \Omega_z}{\partial t} = \frac{1}{\hbar} \left[ \frac{\Delta_t}{2} \sin \tilde{\phi} - 2\pi l^2 \rho_s \nabla^2 \tilde{\phi} \right] - \frac{4\pi l^2 \beta \alpha_z}{\hbar} \Omega_z + \frac{8\pi^2 l^4 \beta \sigma_z}{e^2 M_0} \nabla^2 \Omega_z \]

Collective Tunneling
Supercurrent
Quasiparticle Current
Joglekar TDHFA+SCBA

\[
\Sigma = \triangle + \text{SCBA + HF}
\]

The diagram shows the decomposition of the self-energy into various corrections, labeled as Vertex Corrections, GRPA, and SCBA + HF, as indicated in the image.
Conclusions

Double Layer 2D Electron Systems Support Excitonic Bose Condensation

- Josephson-like tunneling $\rightarrow$ spontaneous phase coherence.
- Quantized Hall drag.
- Direct evidence of counterflow superfluidity.

No Quantitative Understanding of Tunneling or Drag