Pseudospin Soliton in the ν =1 Bilayer Quantum Hall State

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N. Kumada (NTT Basic Res. Lab.)

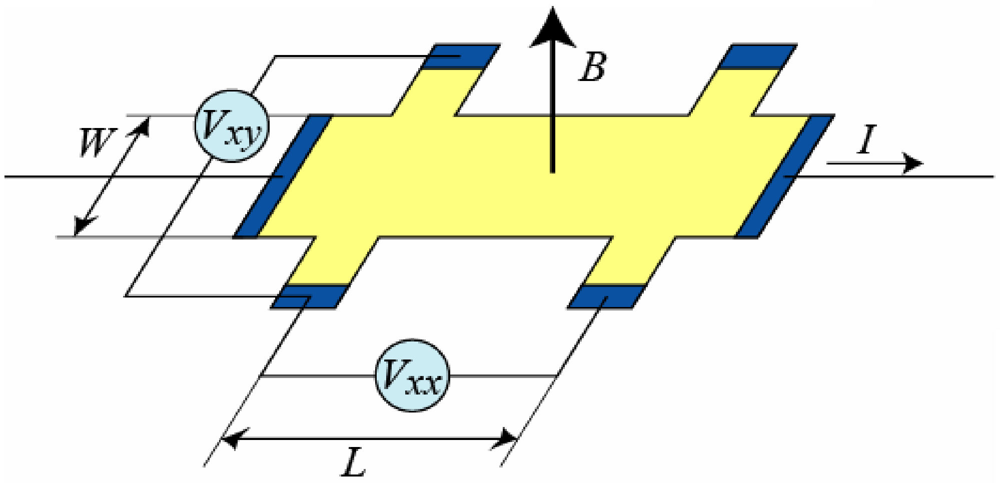
In press A. Fukuda *et al*. Phys. Rev. Lett.
Cond-mat/0711.1216

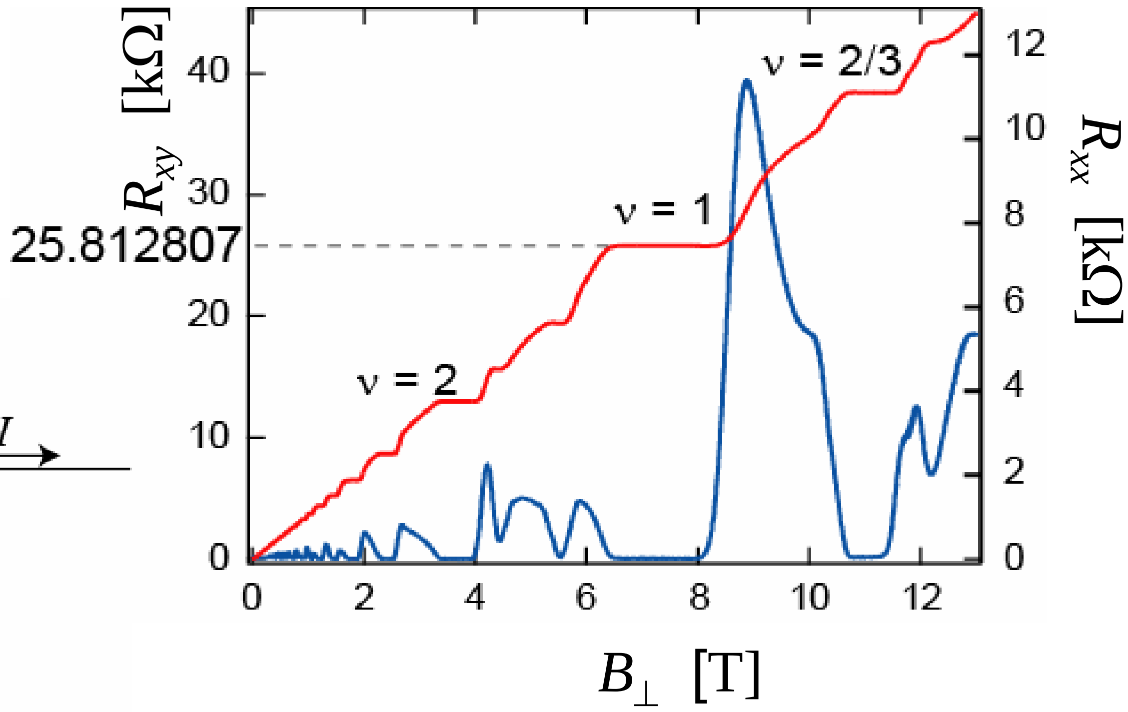
Introduction – Quantum Hall Effect

2-D Electron System

Low Temperature

High Magnetic Field





Hall Resistance $R_{xy} = V_{xy}/I$ → $h/\nu e^2$ Quantized

ν:Landau Level Filling Factor

Integer or Fractional

Magnetoresistance $R_{xx} = V_{xx}/I$ → 0

Composite Boson Model

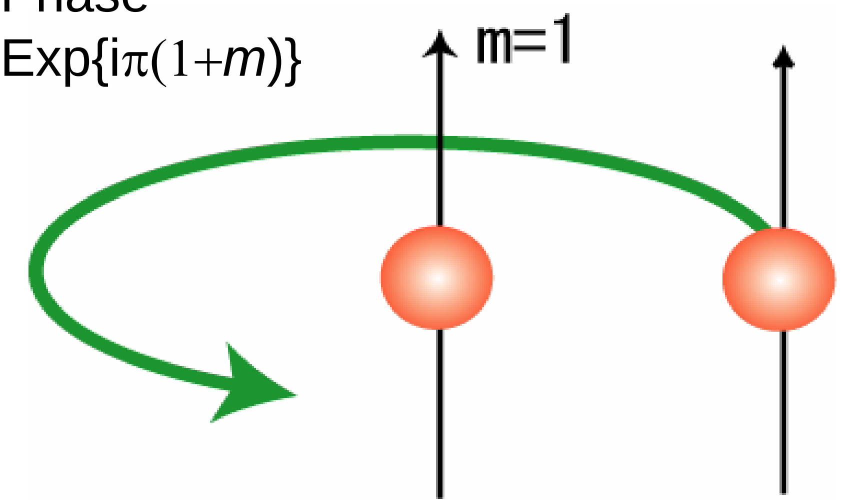
Composite Boson＝One Electron＋Odd Number Flux Quanta

Girvin and MacDonald Phys. Rev. Lett. **58**, 1252(1987)
Ezawa *et al*. Phys. Rev. **46**, 7765(1992).

Exchange Symmetry

Phase
Exp{i$\pi(1+m)$}

Aharonov-Bohm Effect



Quantum Hall State is incompressible (100K)

$\Delta n \Delta \phi \geqq$ h Δn=0, $\Delta \phi = \infty$,

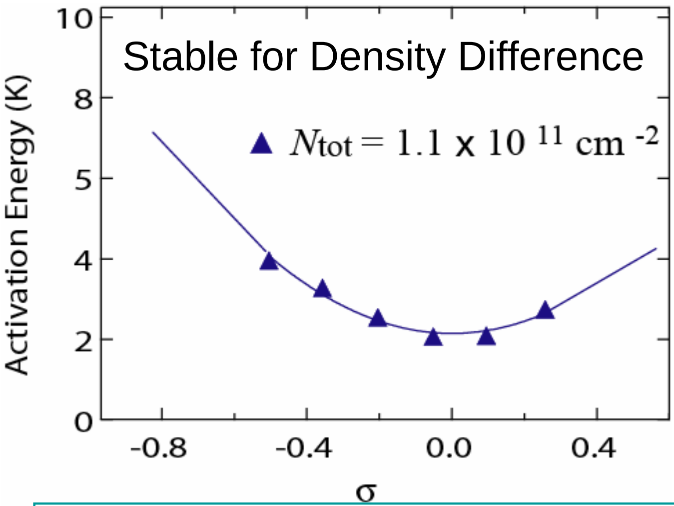
no coherence, no superconductivity

Bilayer System

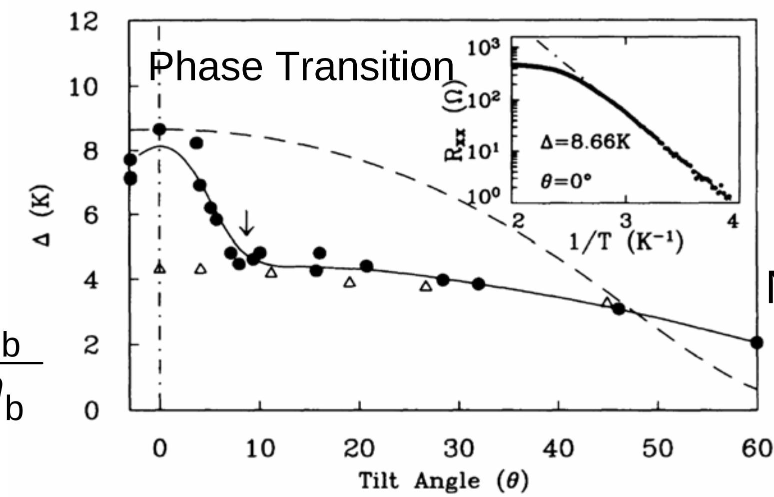
$\Delta n_d \Delta \phi_d \geqq h$
Density Difference $\Delta n_d \neq 0$
Phase Difference $\Delta \phi_d \neq \infty$
Macro Coherence arise

Wen and Zee Phys. Rev. Lett. **69**, 1811(1992)
Ezawa and Iwazaki, Phys. Rev. B **48**, 15189(1993)

Experiments of ν=1 bilayer QHE



$$\sigma = \frac{n_f - n_b}{n_f + n_b}$$



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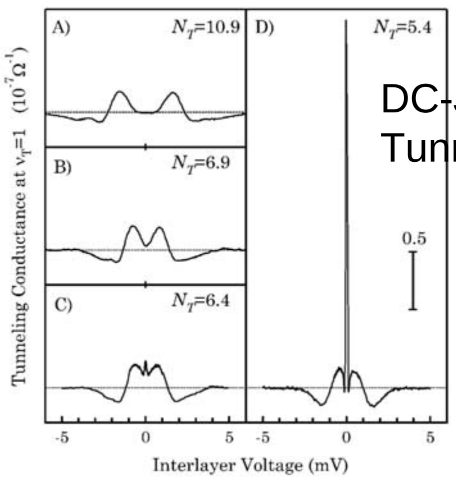
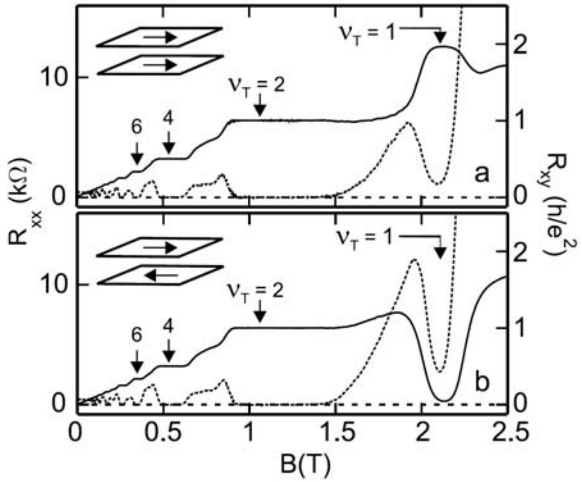
A. Sawada *et al.* Phys. Rev. Lett 80 4534(1998)

S.Q. Murphy *et al.* Phys. Rev. Lett 72 728(1994)



DC-Josephson like Tunnel Conductance



Disappearance of Hall Resistance

I.B. Spielman *et al.* Phys. Rev. Lett 84 5808(2000)

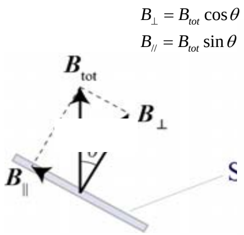
M. Kellogg *et al.* Phys. Rev. Lett 93 036801(2004)

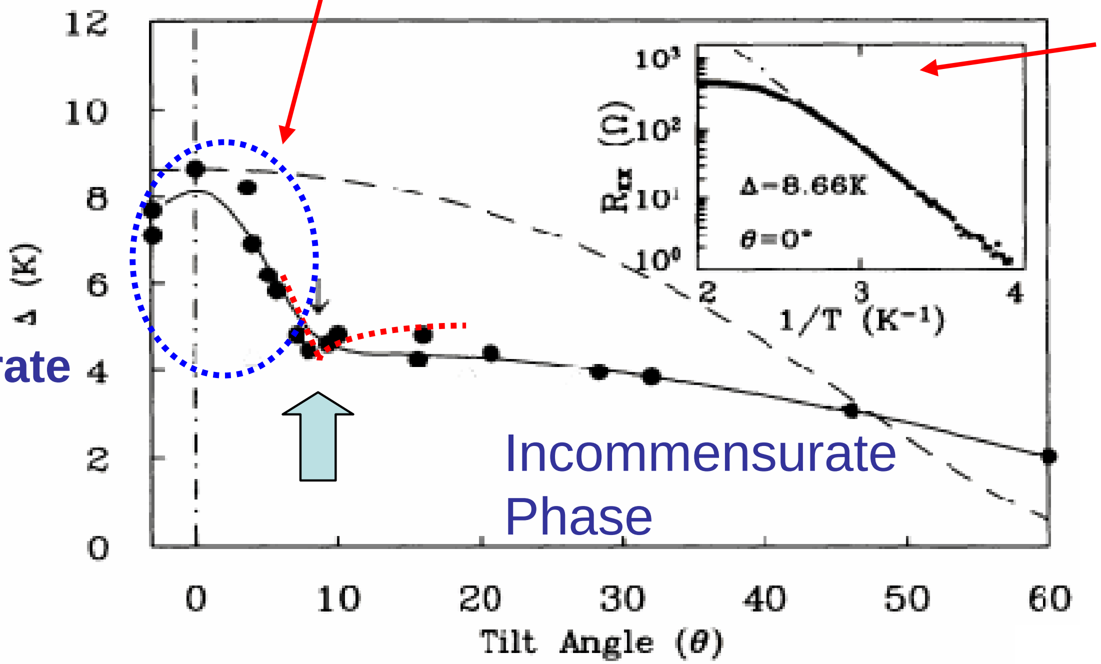
Bilayer ν =1 Quantum Hall Effect
- In-plane Field Effect -

$$\Delta_{\mathrm{SAS}}(\theta) = \Delta_{\mathrm{SAS}}(0)\exp(-d^2\tan^2\theta/4\ell^2)$$

Excitation Gap Δ

$R_{xx} \propto \exp(-\Delta/2T)$





Commensurate Phase

Coherence
C-IC Phase Transition

K. Yang et al. Phys. Rev. Lett. 72, 732(1994)

Pokrovsky-Talapov Form

Phase Transition for In-plane Field

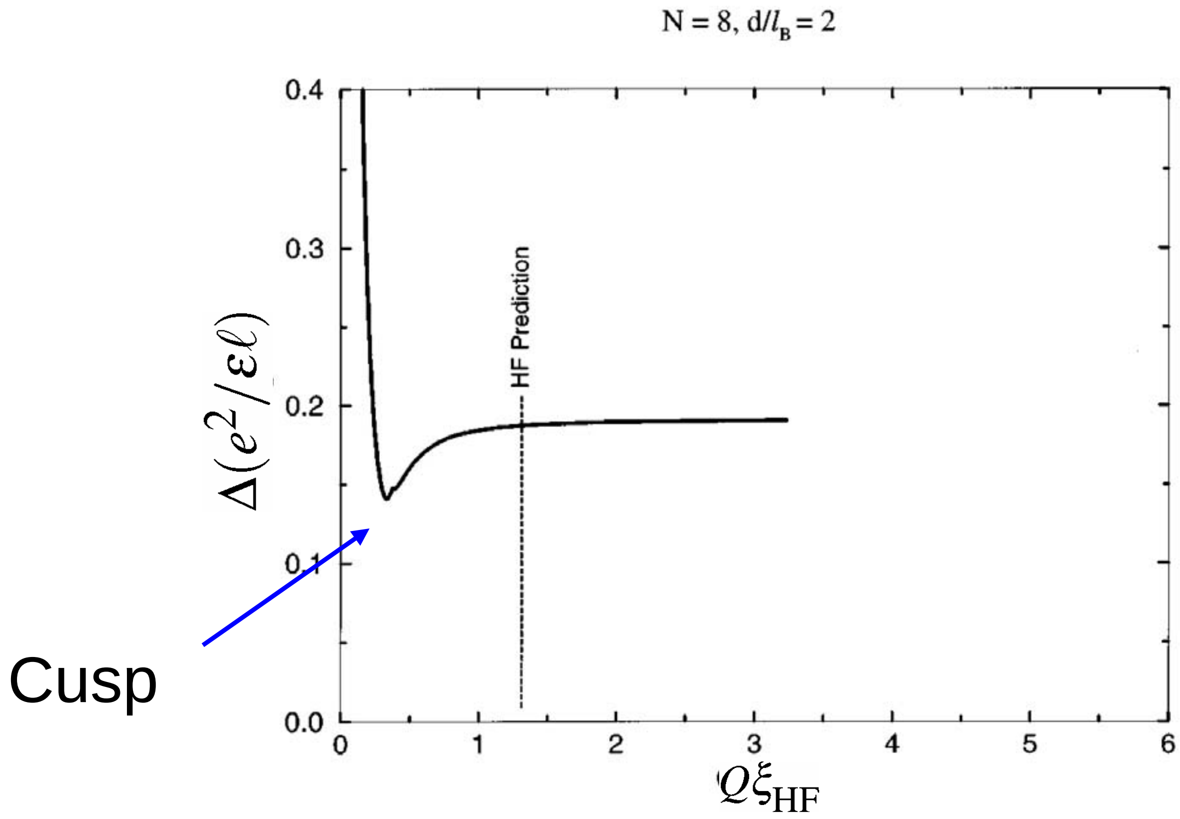
$$\mathcal{E} = \int d^2r\left[\frac{1}{2}\rho_s(\nabla\theta)^2 - \frac{t}{2\pi l^2}\cos(\theta + \mathbf{Q}\cdot\mathbf{r})\right].$$

Incommensurate	Commensurate
θ=const.	θ=-***Qr***

S. Q. Murphy *et al.* Phys. Rev. Lett., **72** 728 (1994)

Theory

Exact Diagonalization
8 Electron, d/l=2



More precise measurement

K. Yang *et al*., *Phys. Rev. B*, **54** 11644 (1996)

$$Q\xi = \frac{2\pi d \ell B_{||}}{\phi_0}\sqrt{\frac{2\pi\rho_{ps}}{t}}$$

ξ : String Size

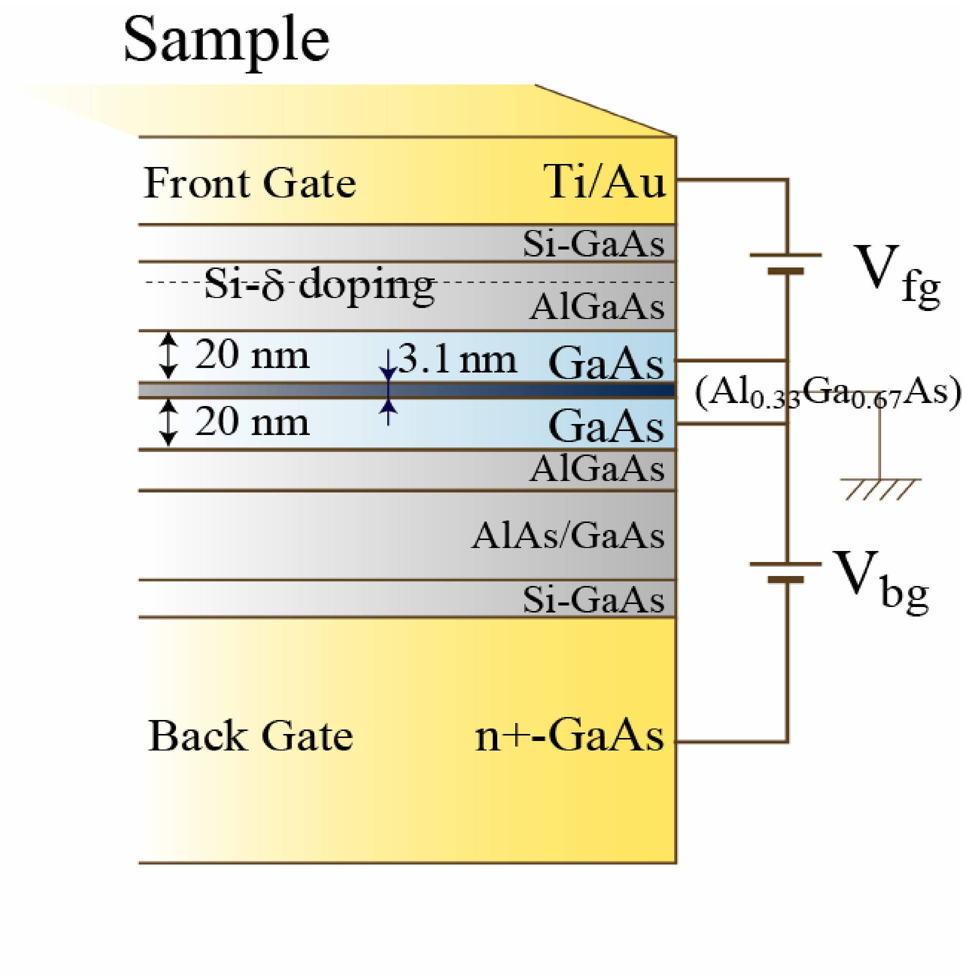
ρ_{ps} is Hartree-Fock value

4. Experimental System

Dilution Refrigerator

- Lowest Temperature 6 mK
- Cooling Power（@100 mK）400 μW
- Highest Magnetic Field 15 T
- Electrical Transport
- Rotation of Sample

Sample



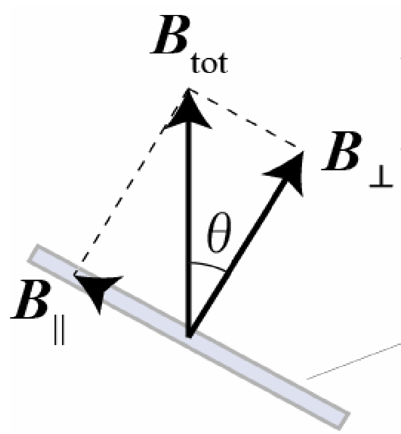
Sample Parameter

Layer Distance d = 23.1 nm

Tunneling Energy Δ_{SAS} = 11 K

Mobility (@ $n_T = 1.0 \times 10^{11}$ cm^{-2})

1.0 x 10^6 cm^2 /Vs



$$B_\perp = B_{tot} \cos\theta$$

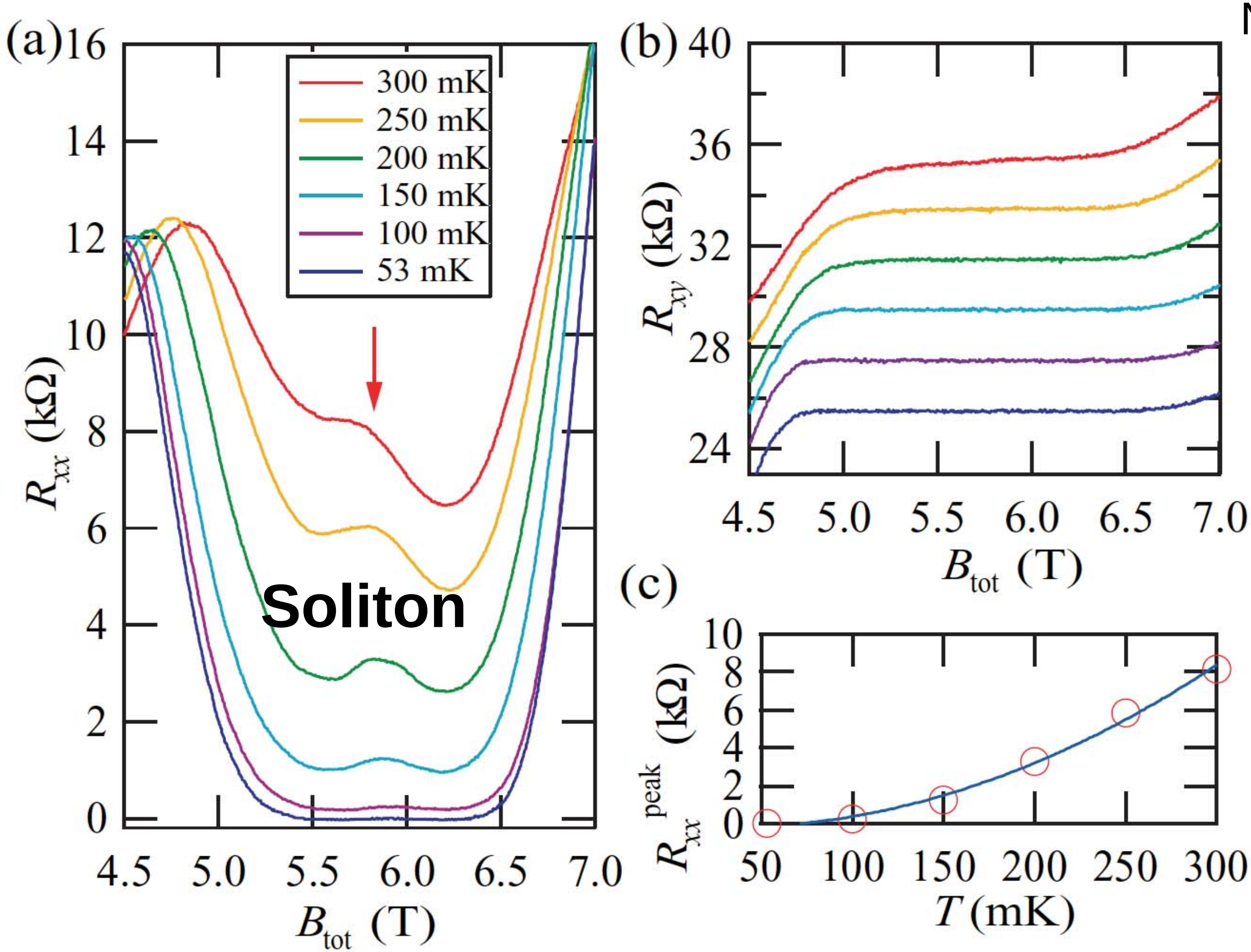
$$B_{//} = B_{tot} \sin\theta$$

Magneto and Hall Resistance Field Dependence

$N_t = 0.95 \times 10^{11}$ cm^{-2}

$\Theta = 50.3°$

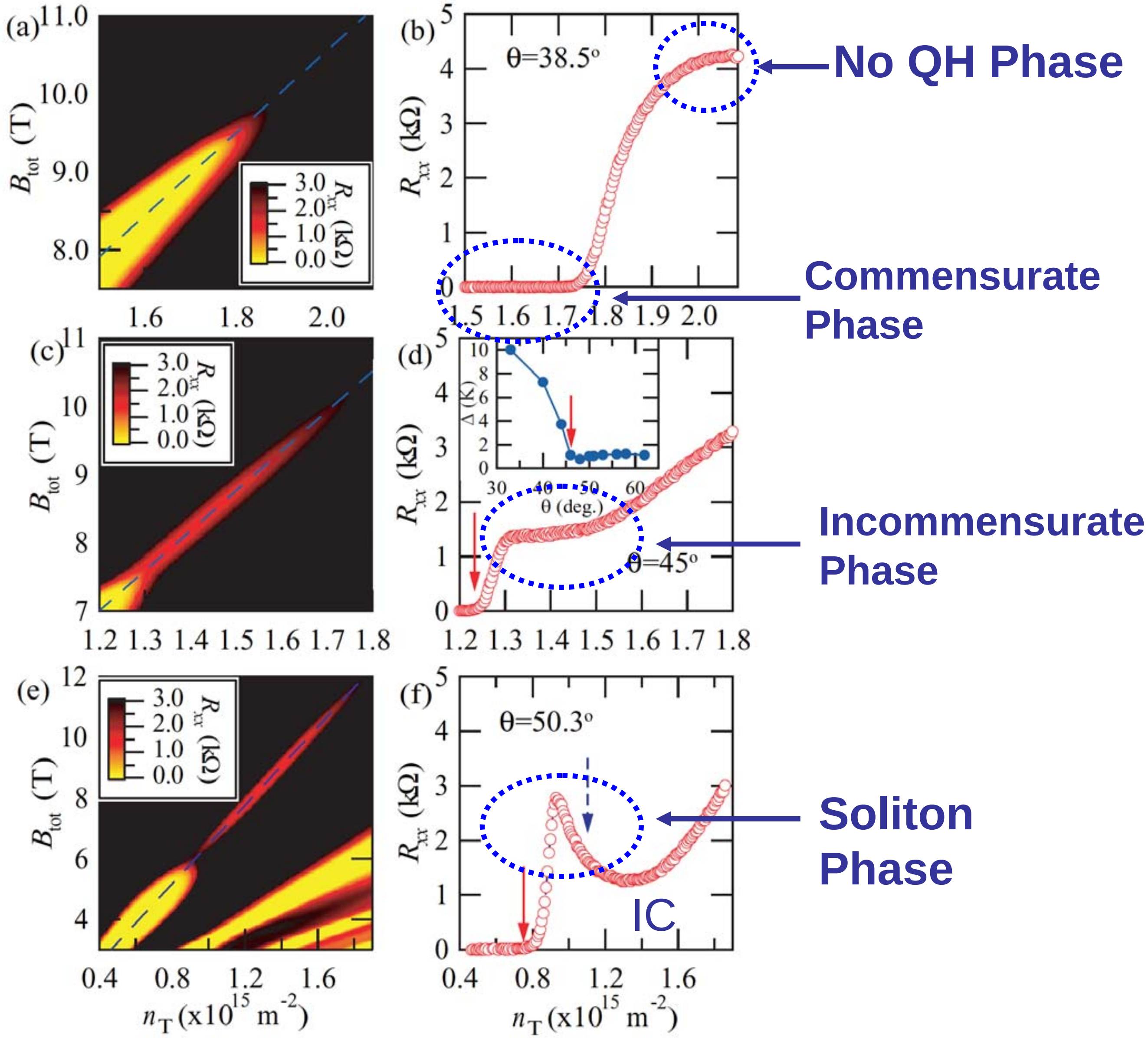
$\Theta_C = 46.2°$



Offset by 2kΩ

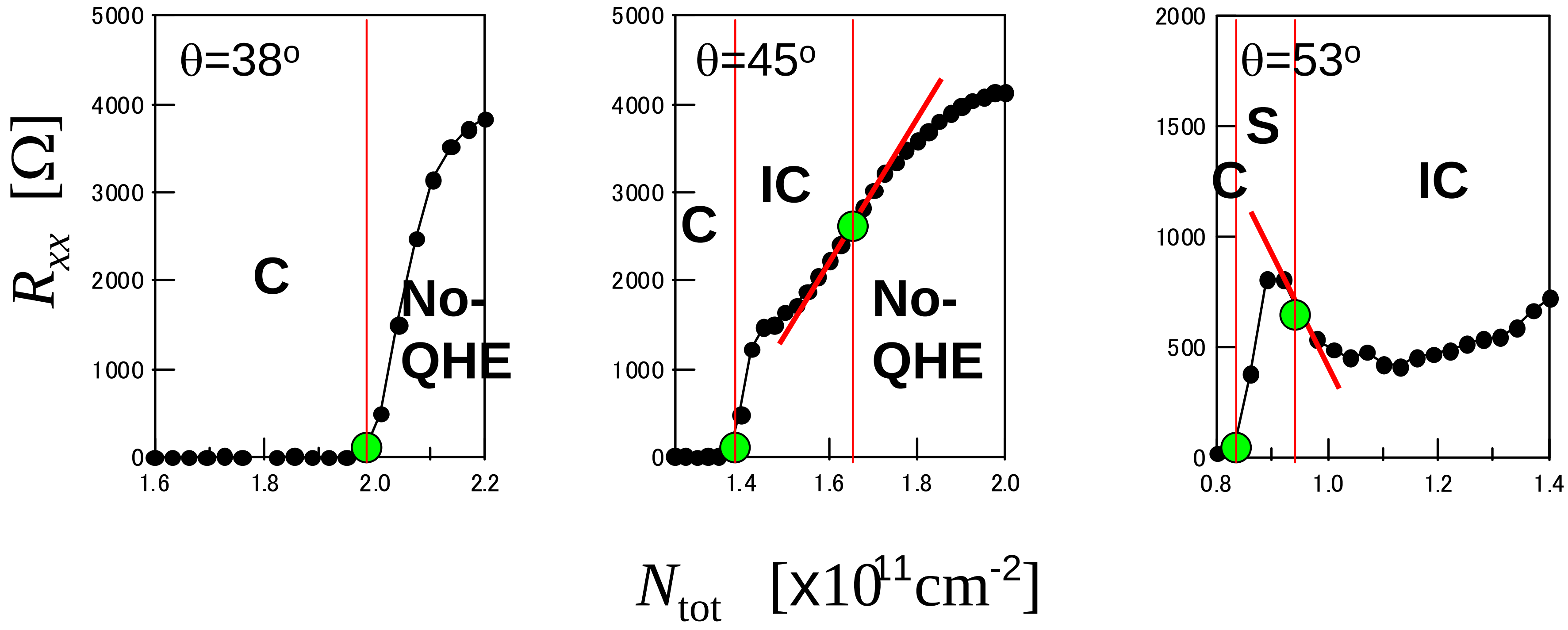
What is the peak?

Color-scale Plots of Magnetoresistance
as a Function of Magnetic Field and Electron Density



Phase Boundaries

Definition of Boundaries

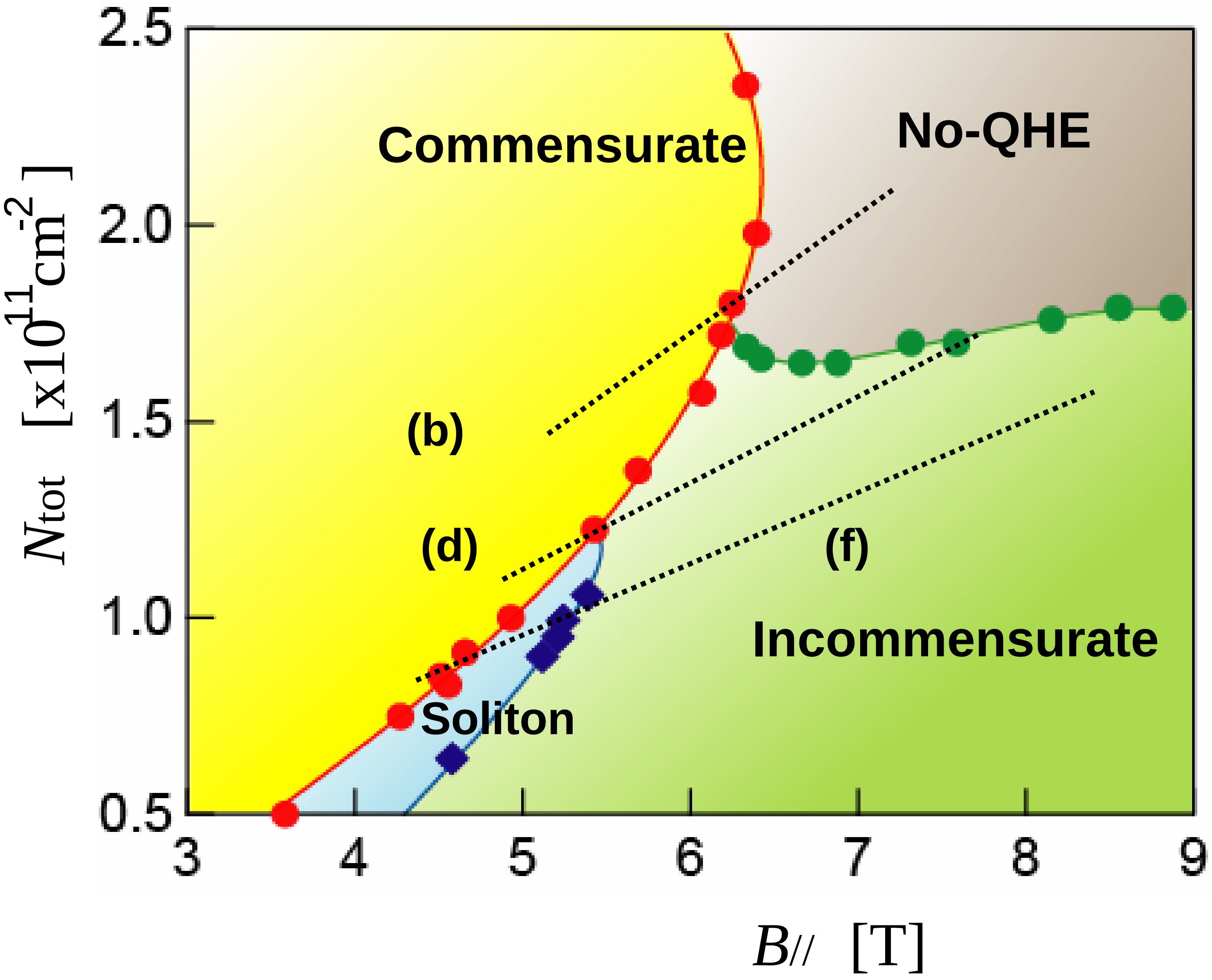


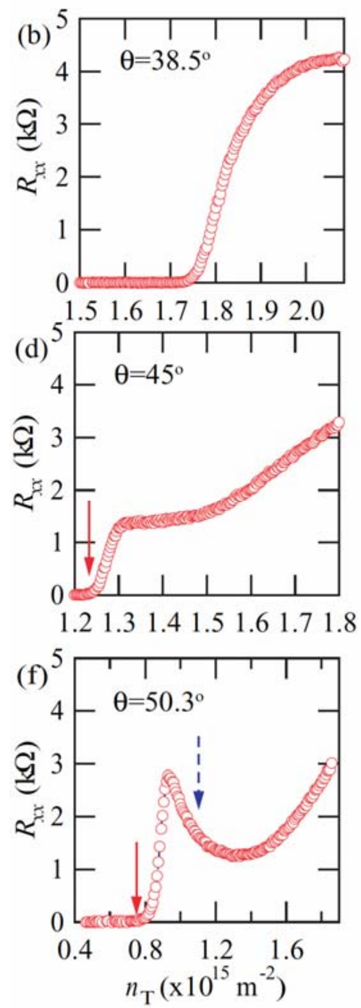
Transition from C Phase **Clear** ⇒ **Increase of Resistance**

IC ⇒ No-QHE, S⇒IC Transition, **No Clear** ⇒ **Maximum of Gradient**

Phase Diagram

In-plane Field and Electron Density Space





Related Theoretical Papers

Coherent System Pokrovsky-Talapov Form

$$\mathcal{E}=\int d^2r\left[\frac{1}{2}\rho_s(\nabla\theta)^2-\frac{t}{2\pi l^2}\cos(\theta+\mathbf{Q}\cdot\mathbf{r})\right].$$ **+Capacitance energy**

Soliton State

Charge Imbalance

A) C.B. Hanna, *et al*., Phys. Rev. B 63, 125305(2001).

A) E. Papa and A.M. Tsvelik, Phys. Rev. 66, 155304(2002).

A) S. Park, *et al*., Phys. Rev. B 66, 153318(2002).

A) S. Park and K. Moon, Solid State. Comm. 132, 851(2004).

A) Z.F. Ezawa, *et al*., Physica E in press.

B) C.B. Hanna, Phys. Rev. B 66, 165325(2002).

B) L.R. Radzihovsky Phys. Rev. Lett. 87, 236802(2001).

B) M. Abolfath, *et al*. Phys. Rev. B 65, 233306(2002).

Soliton Phase

$$\mathcal{E}=\int d^2r\left[\frac{1}{2}\rho_s(\nabla\theta)^2-\frac{t}{2\pi l^2}\cos(\theta+\mathbf{Q}\cdot\mathbf{r})\right].$$

$$\nabla^2\tilde{\theta}=\frac{1}{\xi^2}\sin\tilde{\theta},\qquad \tilde{\theta}_{ss}(\mathbf{r})=4\arctan[e^{\pm\hat{\mathbf{e}}_1\cdot(\mathbf{r}-\mathbf{r}_0)/\xi}]$$

Soliton: Solution of sine-Gordon EQ
Part of 2π Phase Slip

$\phi=\varphi-Qx$

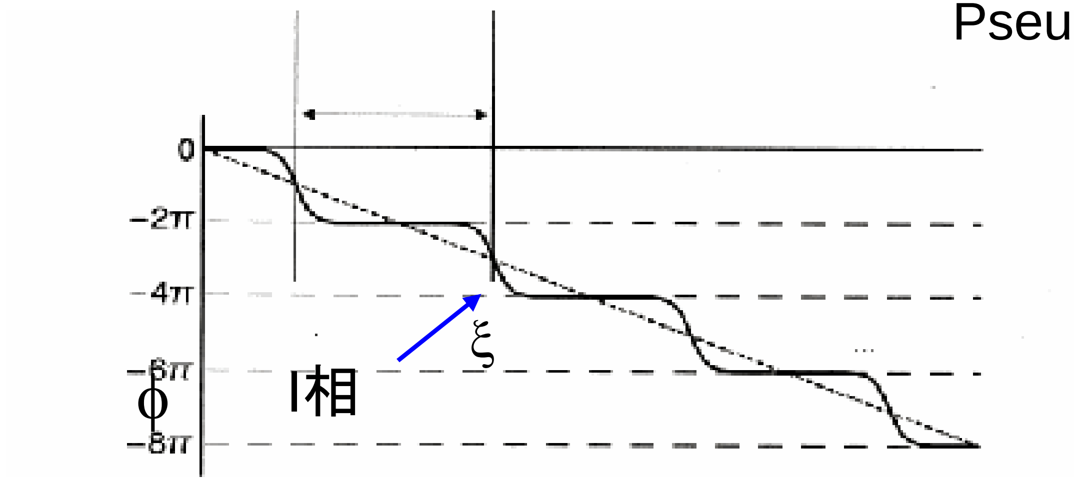
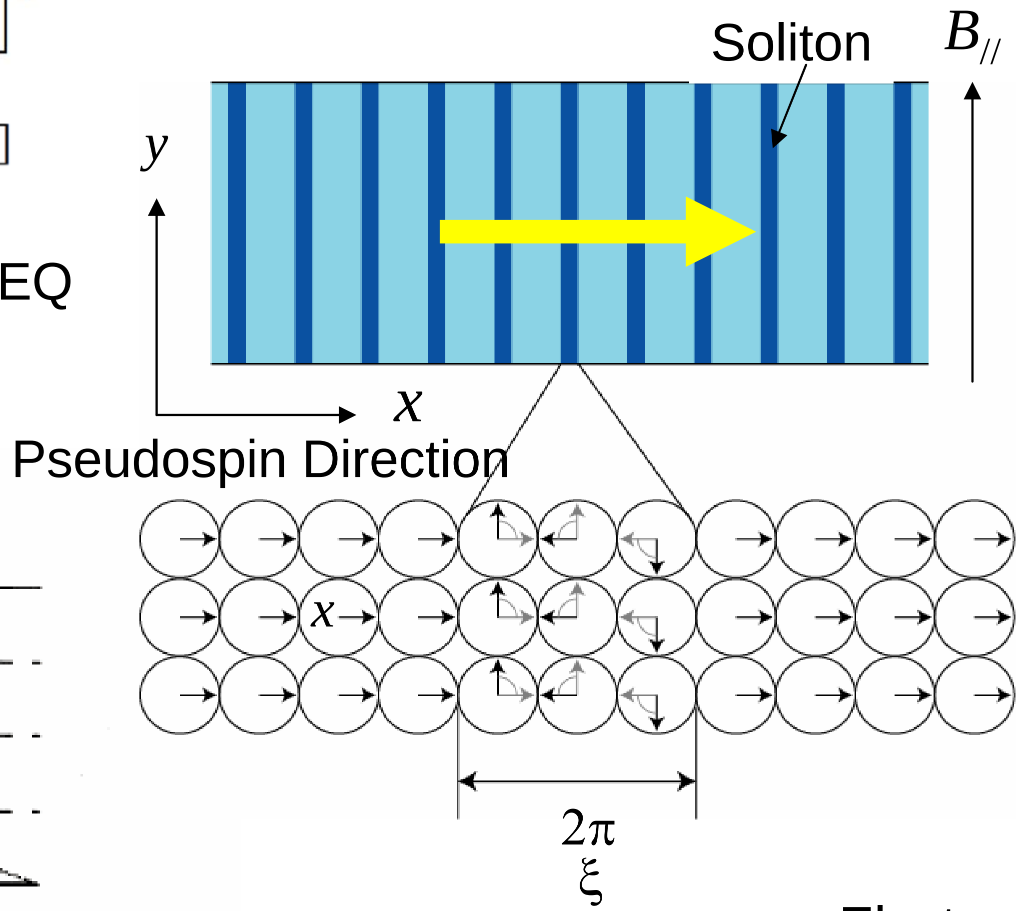


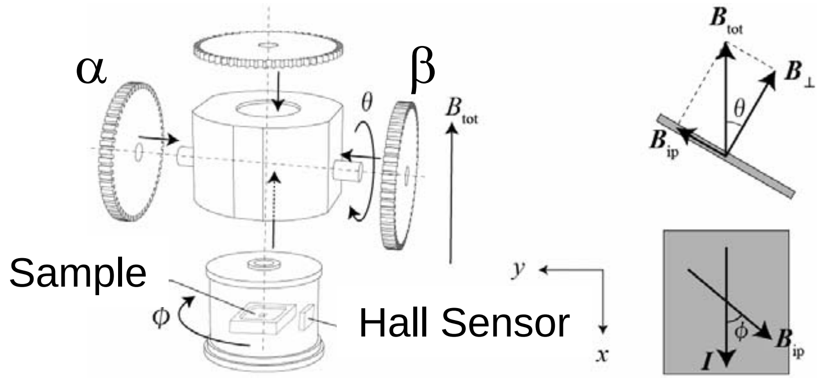
Image of Soliton Phase

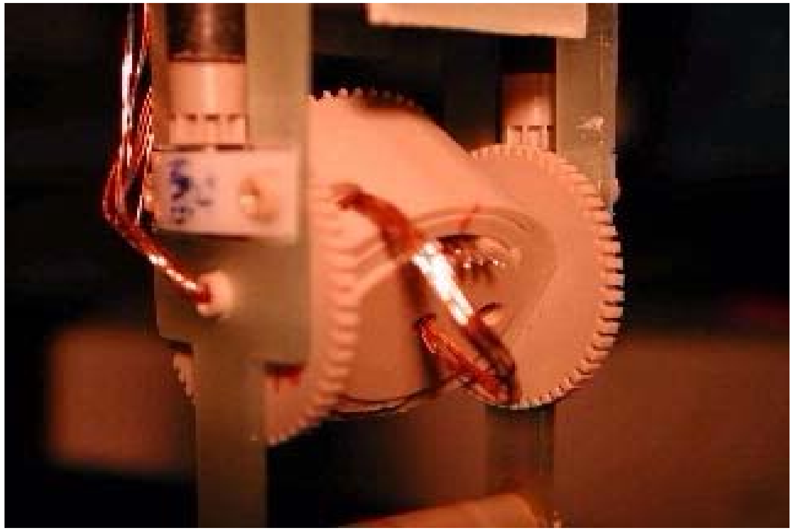


Electron
Pseudospin up : Front Layer
down : Back Layer

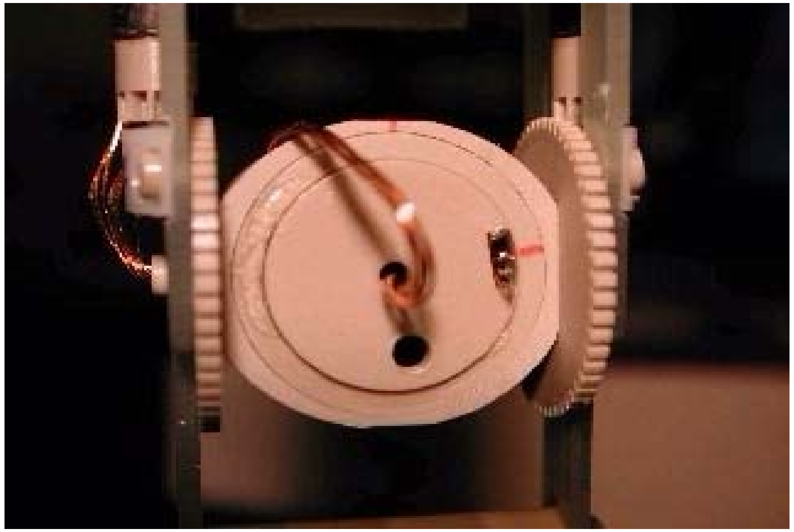
Like Pseudospin Domain State

Two-axis Goniometer In Mixer of Dilution Refrigerator





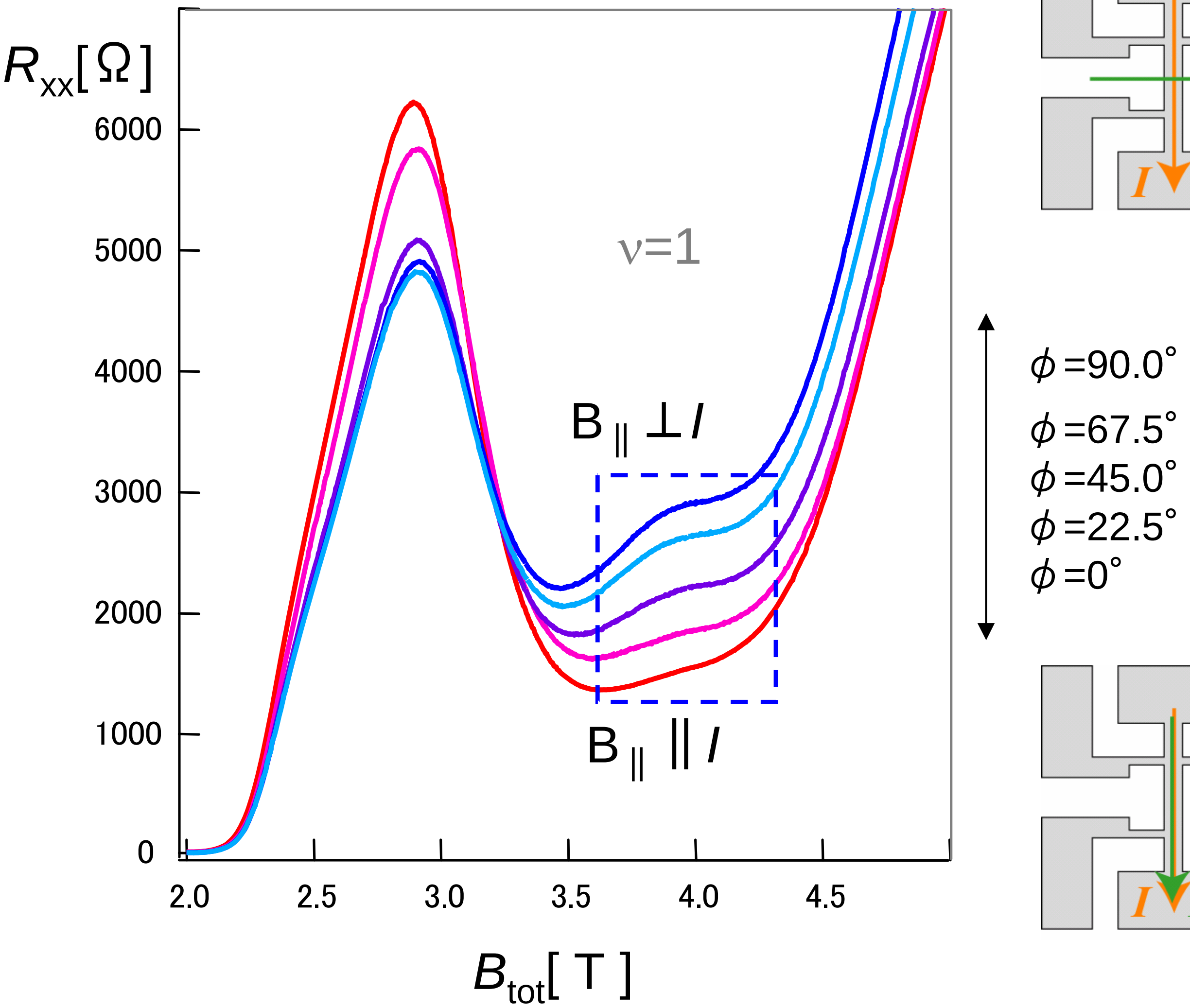
Rotation of θ-Axis

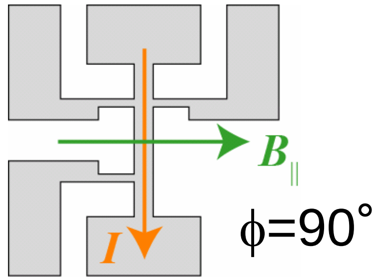


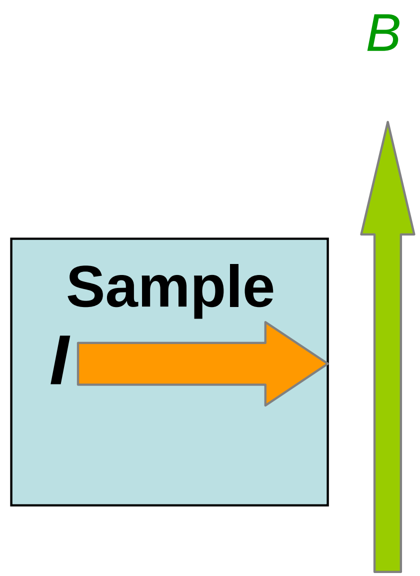
Rotation of ϕ-Axis

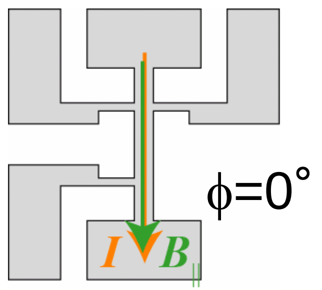
Anisotropic Conductance

$n_t = 0.55 \times 10^{11} cm^{-2}$, $\theta = 53.5°$, $T = 0.32K$

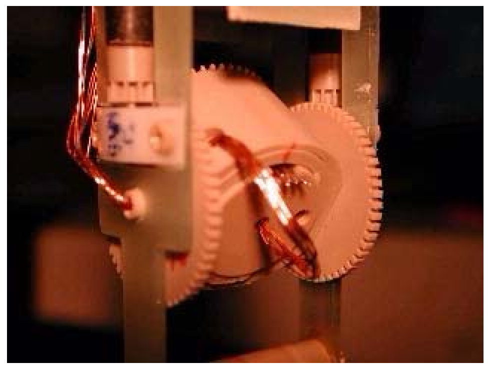






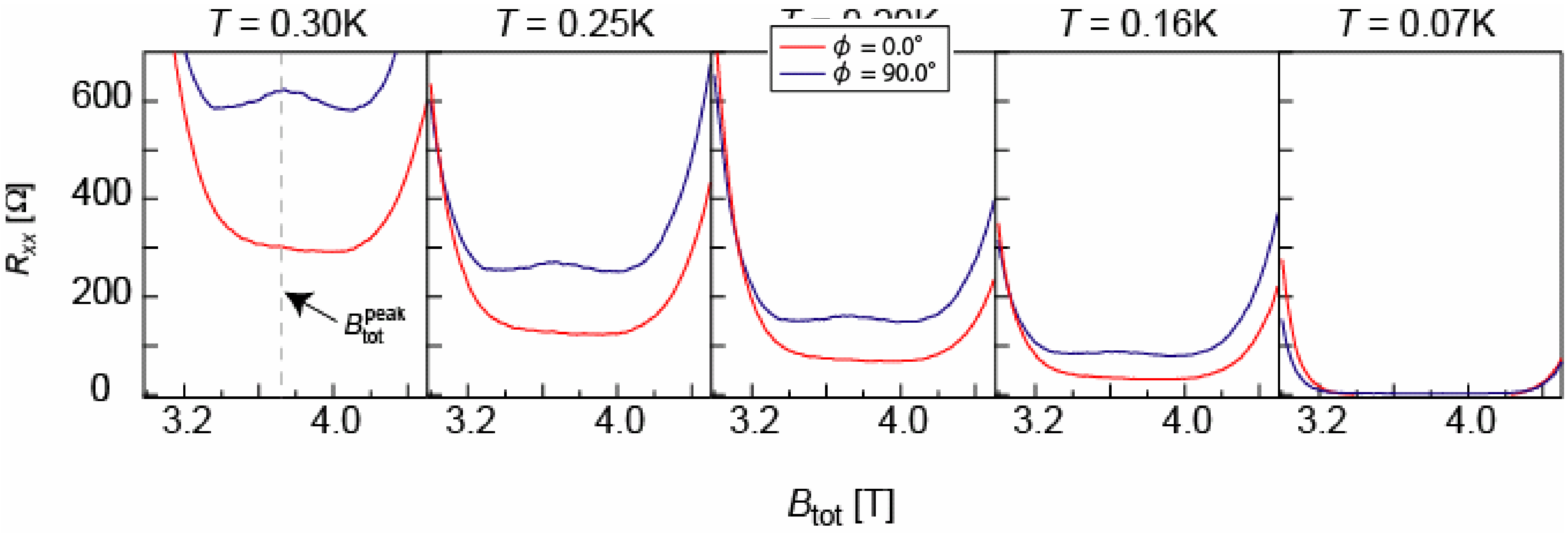


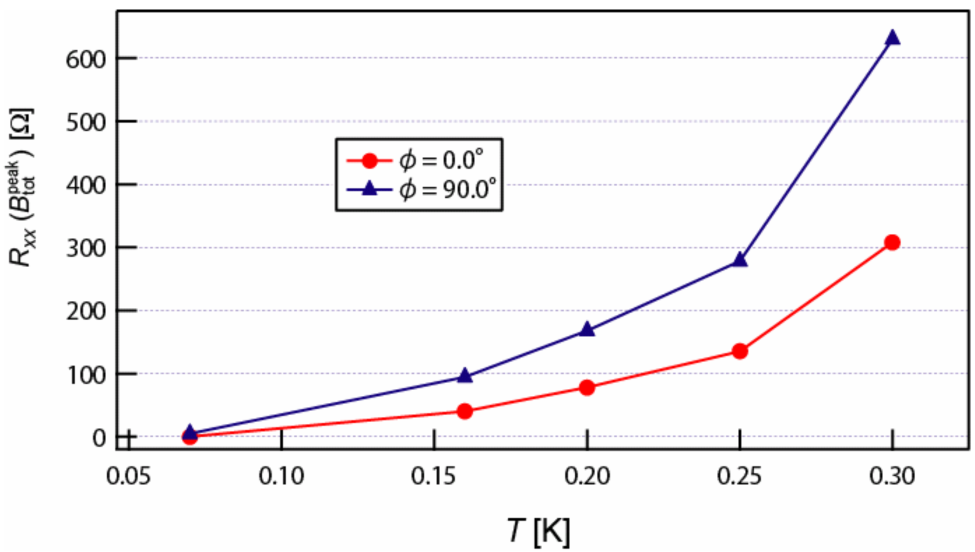
Two Axis Goniometer



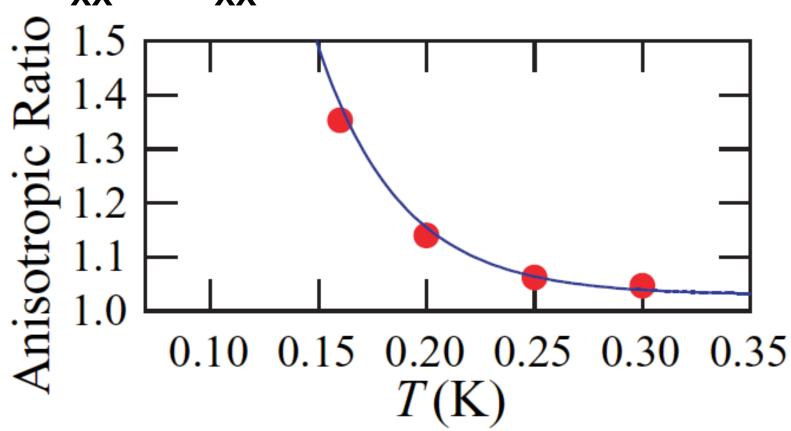
Temperature Dependence of Anisotropy

$n_t = 0.50 \times 10^{11}$ cm^{-2}, $\sigma = 0.0$, $\theta = 54.0°$

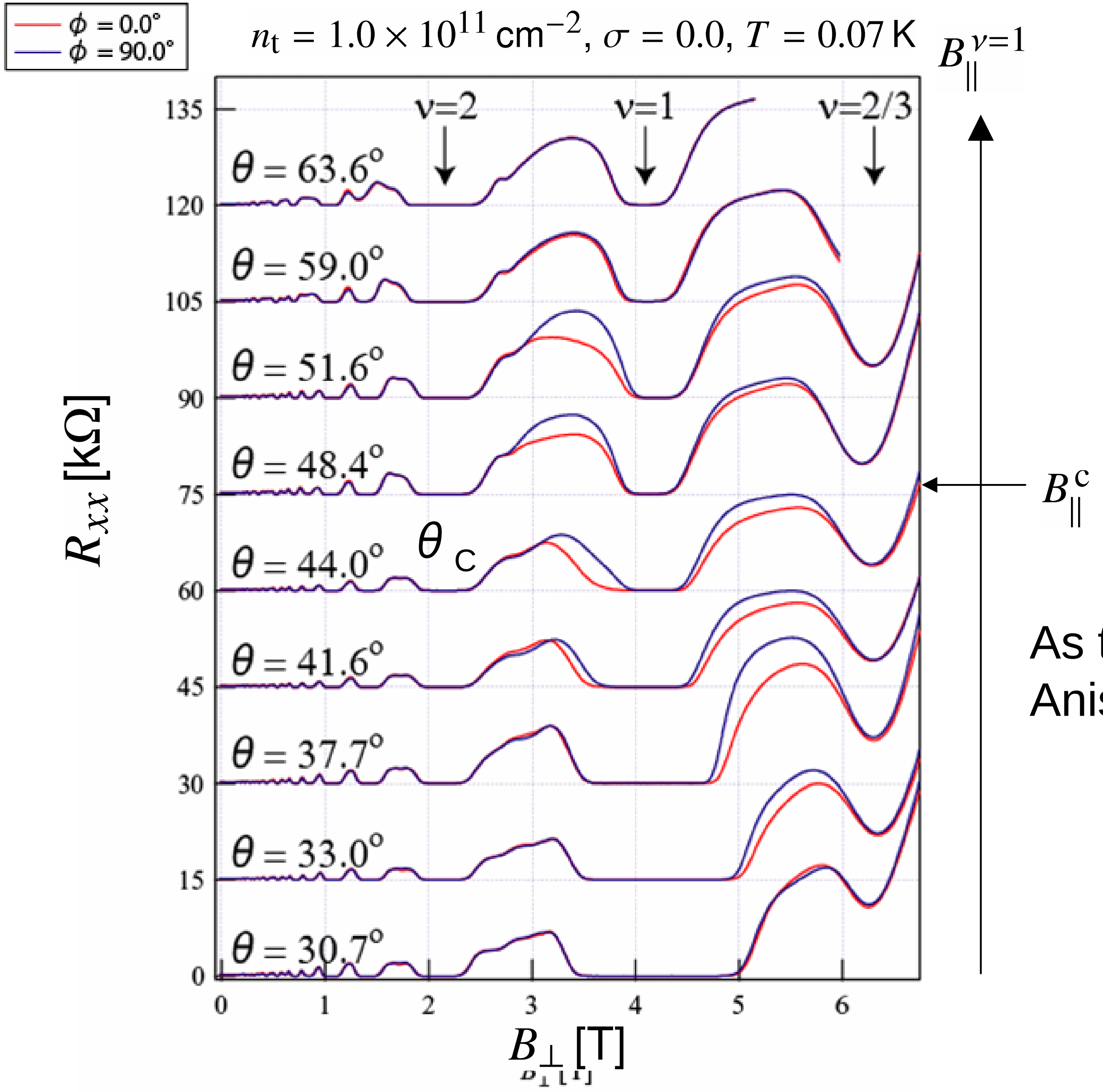




R_{xx}^{90}/R_{xx}^{0}



In-plane Field Dependence of Anisotropy



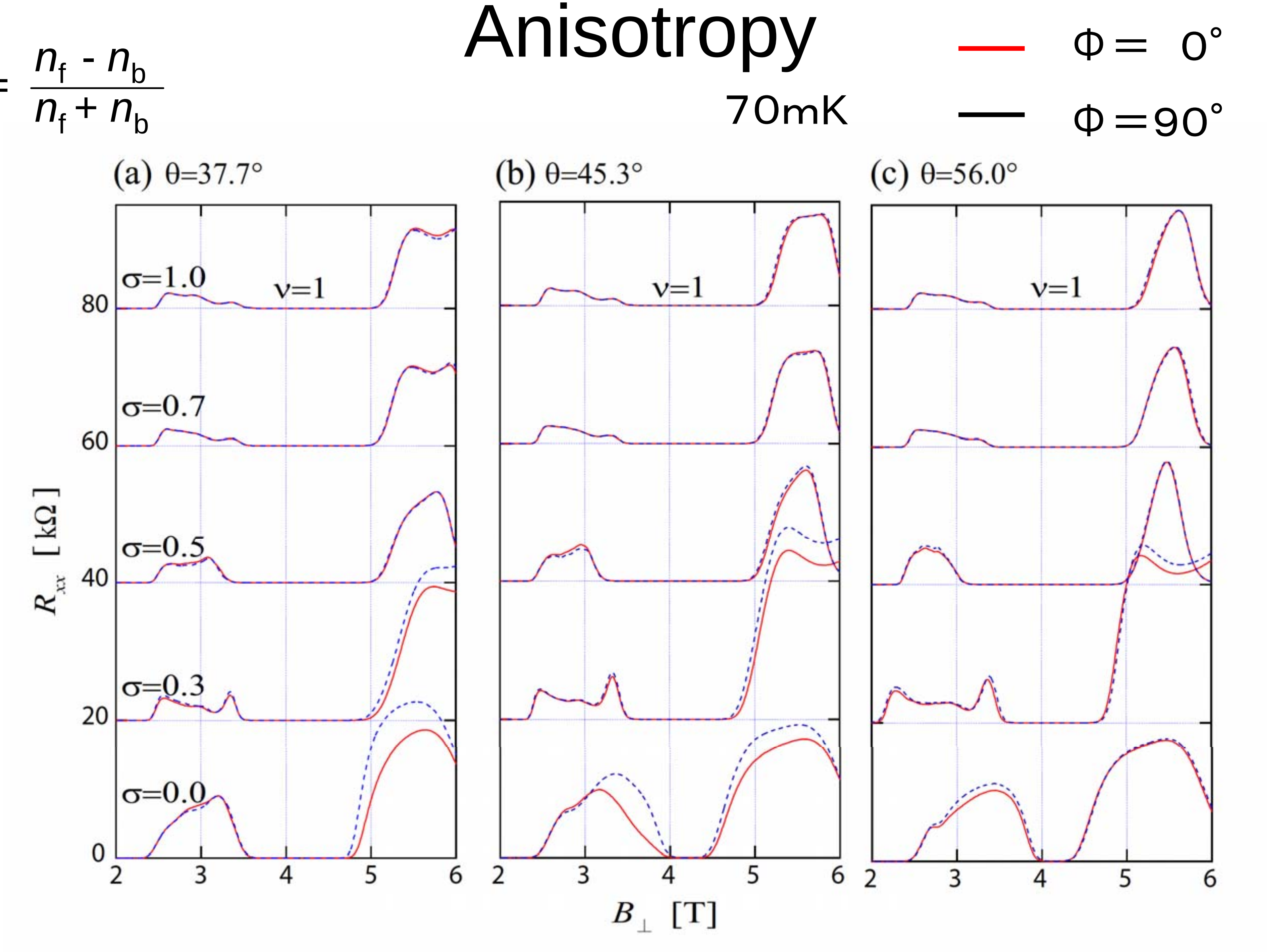
Anisotropy appear
Near C-IC Transition Point

As temperature is low,
Anisotropy at ν=1 is disappear.

Density Difference Dependence of Anisotropy

$$\sigma = \frac{n_f - n_b}{n_f + n_b}$$

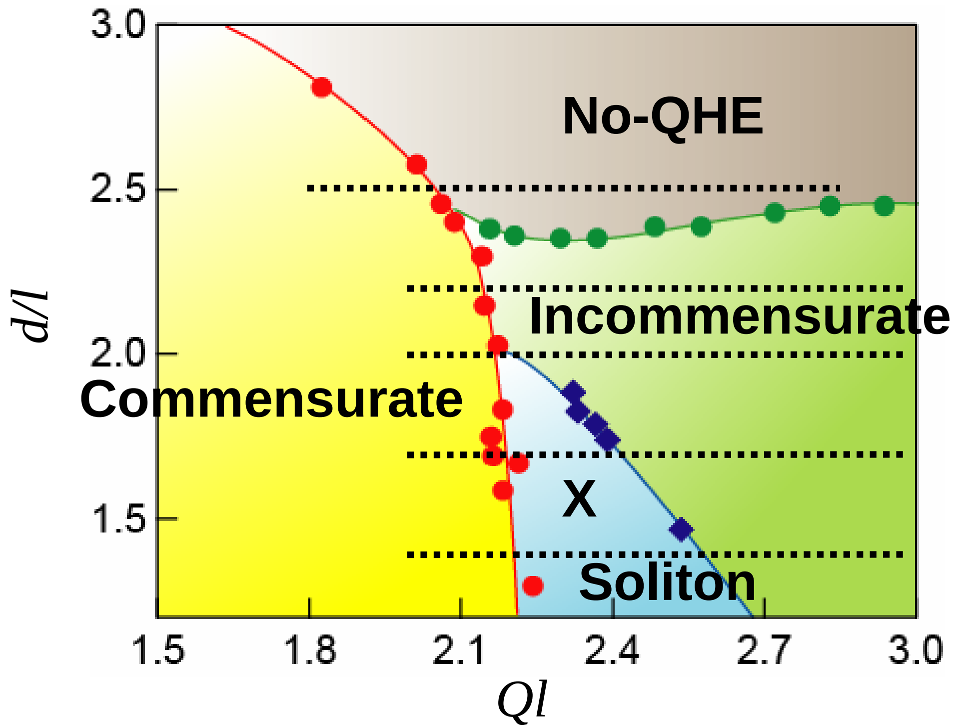
70mK

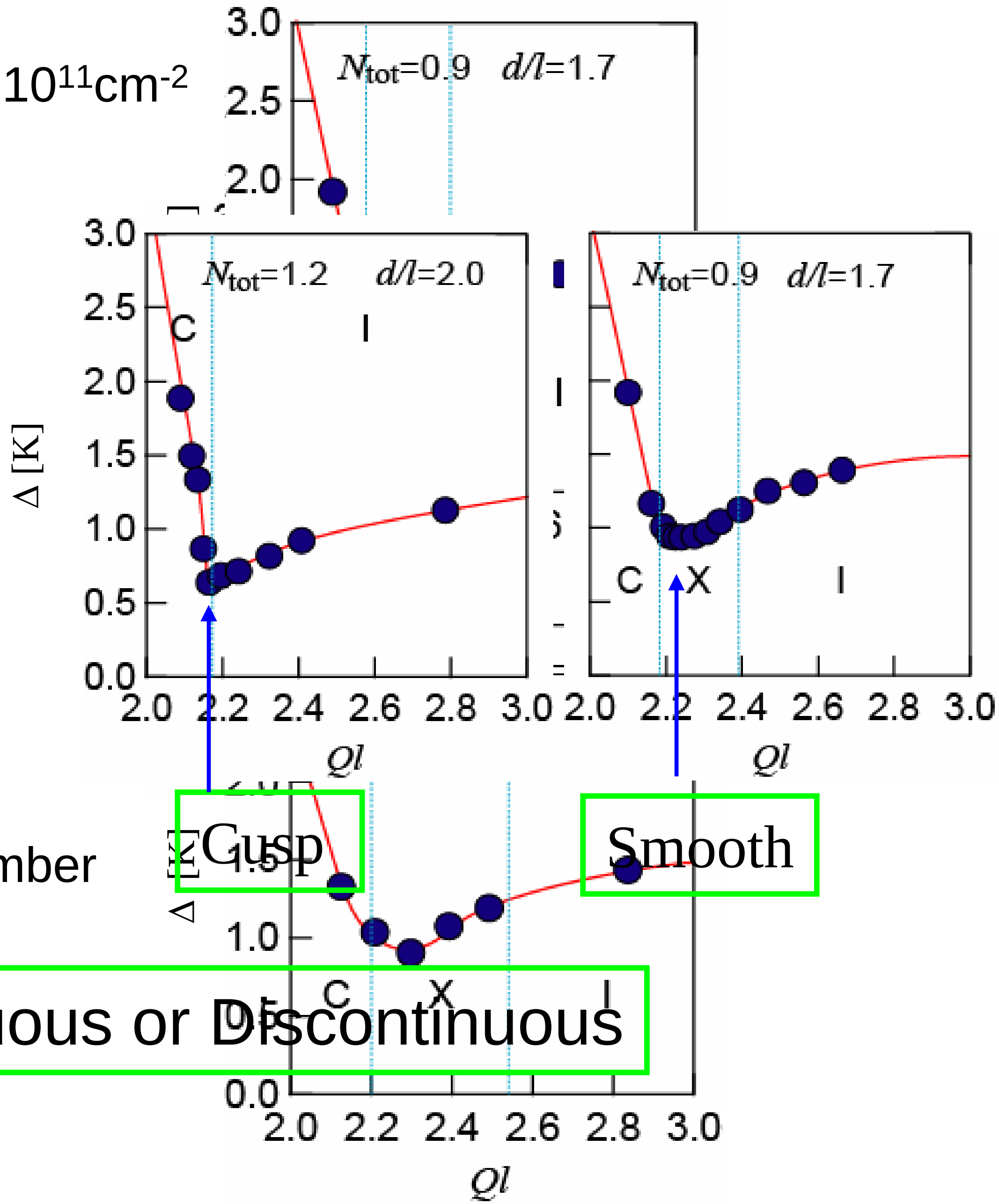


Activation Energy

Total Density and In-plane Field Dependence

Unit of N_{tot}: $10^{11}\mathrm{cm}^{-2}$





Cusp

Smooth

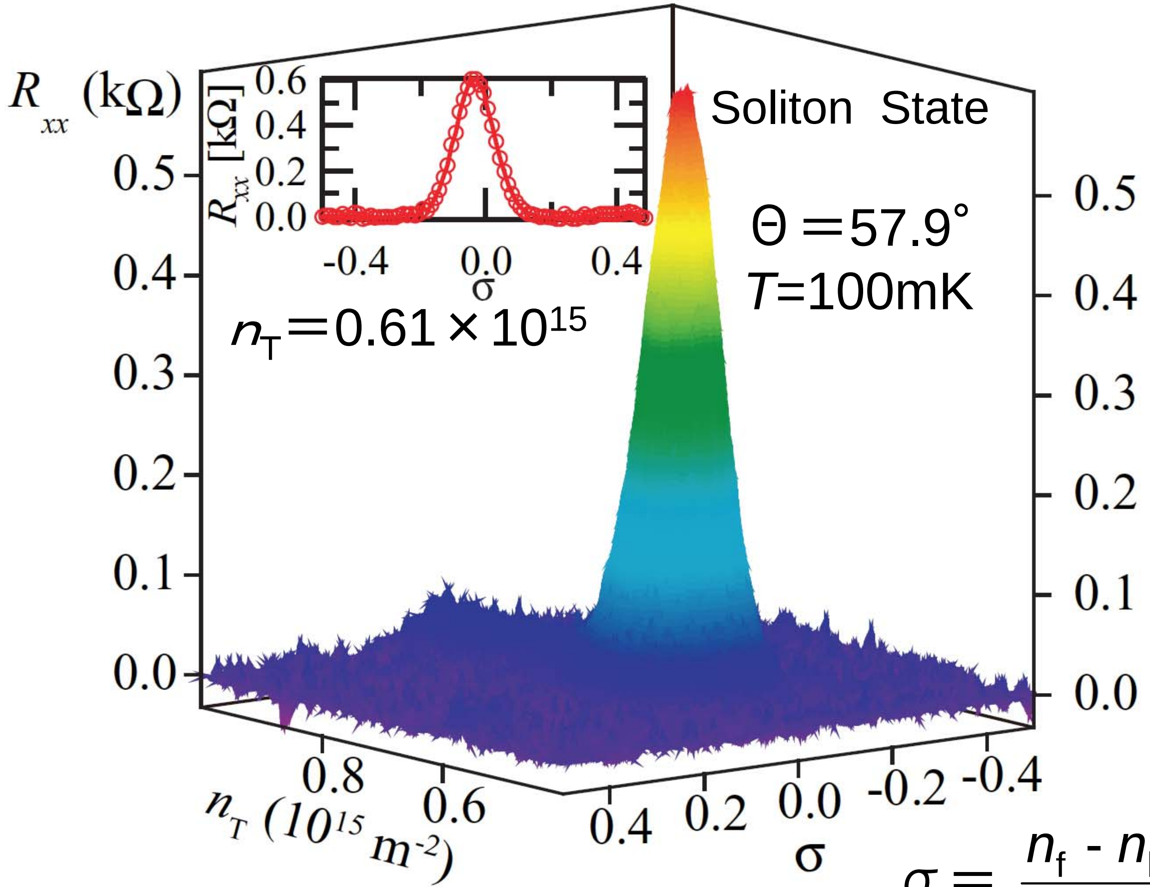
$Q=(2\pi d/\phi_0)B$: In-plane Field Wave Number

$l=(h/2\pi eB_\perp)^{1/2}$: Magnetic Length

$$d\Delta/d(Q\ell)$$

Continuous or Discontinuous

Magnetoresistance as a Function of Density Imbalance Parameter and Total Density

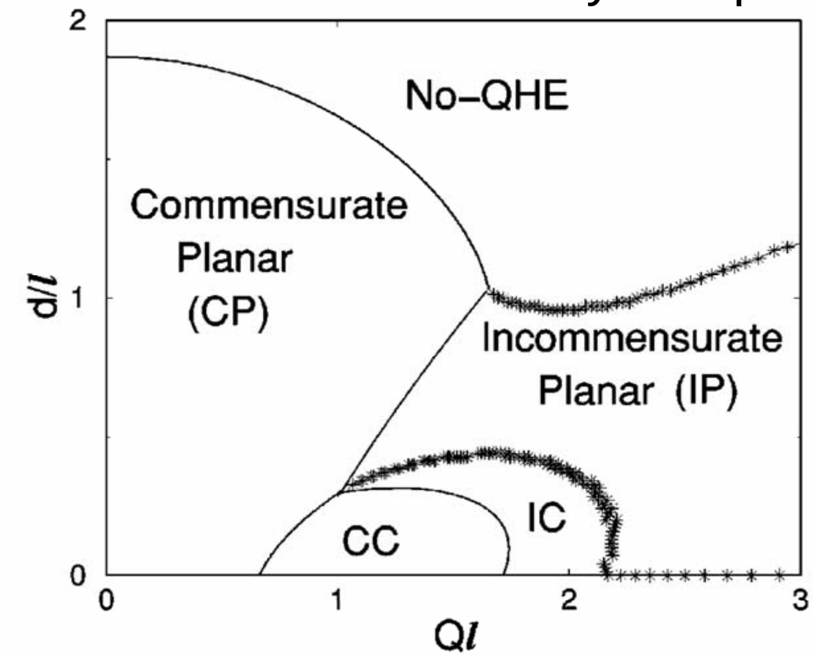


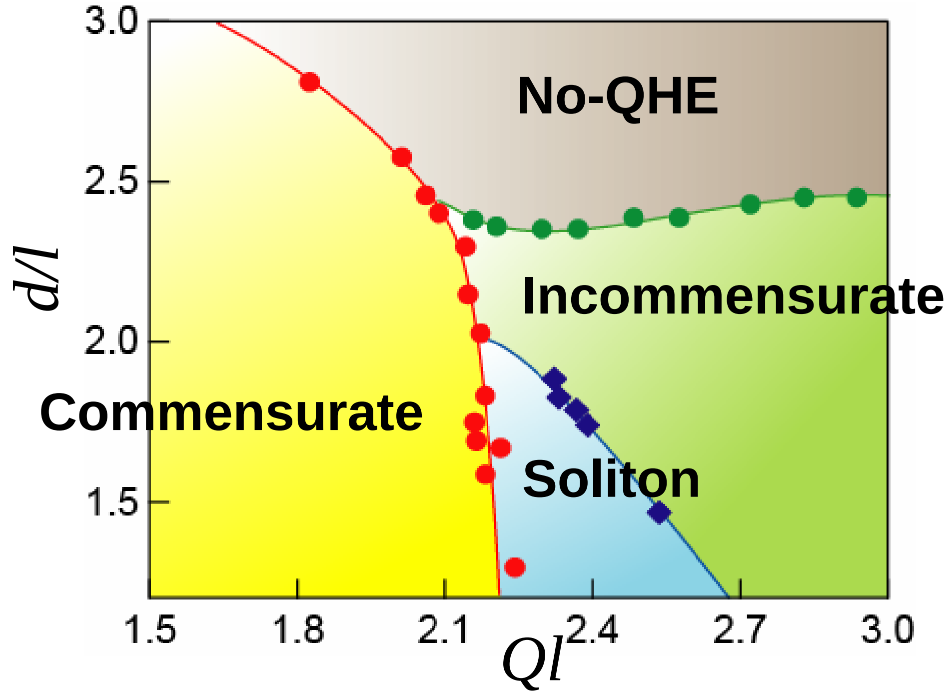
$$\sigma = \frac{n_f - n_b}{n_f + n_b}$$

Phase Diagram
Theory and Experiment

$$H = \int d^2\boldsymbol{r}\left[\frac{1}{2}\varepsilon_c\sigma^2 + \frac{1}{2}\rho_{ps}|\nabla\varphi|^2 - \frac{t}{2\pi l^2}\cos(\varphi(\boldsymbol{r}) + Qx)\right]$$

Pokrovsky-Talapov Form





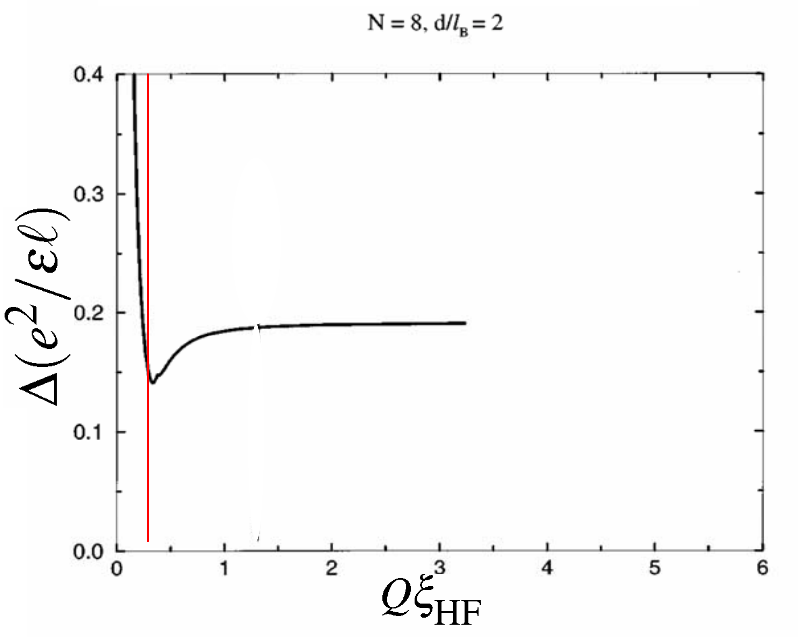
CC: Commensurate Canted

IC: Incommensurate Canted

L. Radzihovsky, Phys. Rev. Lett., 87 236802(2001)
M. Abolfath *et al.*, Phys. Rev. B, **65** 233306 (2002)

Exact Diagonalization Calculation of Ground State Energy

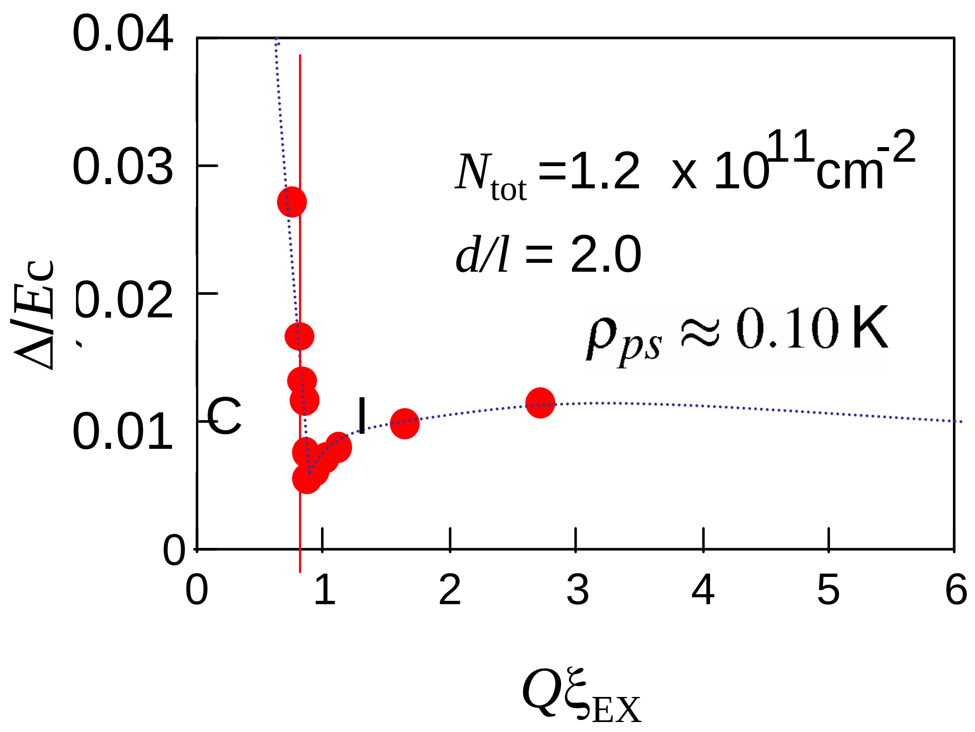
Exact Diagonalization
8 Electron, d/l=2



K. Yang *et al.*,
Phys. Rev. B, **54** 11644 (1996)

$$Q\xi = \frac{2\pi d\ell B_{||}}{\phi_0}\sqrt{\frac{2\pi\rho_{ps}}{t}}$$

ρ_{ps} is Hartree-Fock value



Similar experimental result,
Transition point, different

Summary

•Magnetoresistance Peak (Soliton Phase) in Bilayer   ν=1 Quantum Hall State

•Phase diagram of Bilayer ν=1 Quantum Hall State in $B_{//} – n_{\mathrm{t}}$ space

•Anisotropic Magnetotransport to angle between $B_{//}$ and I

→ Soliton Lattice Phase or Charge Imbalanced Phase

•Soliton Phase is unstable when the density imbalance is large

•Charge imbalance exist or not?