Probing Correlated States in a Two-Subband Electron System

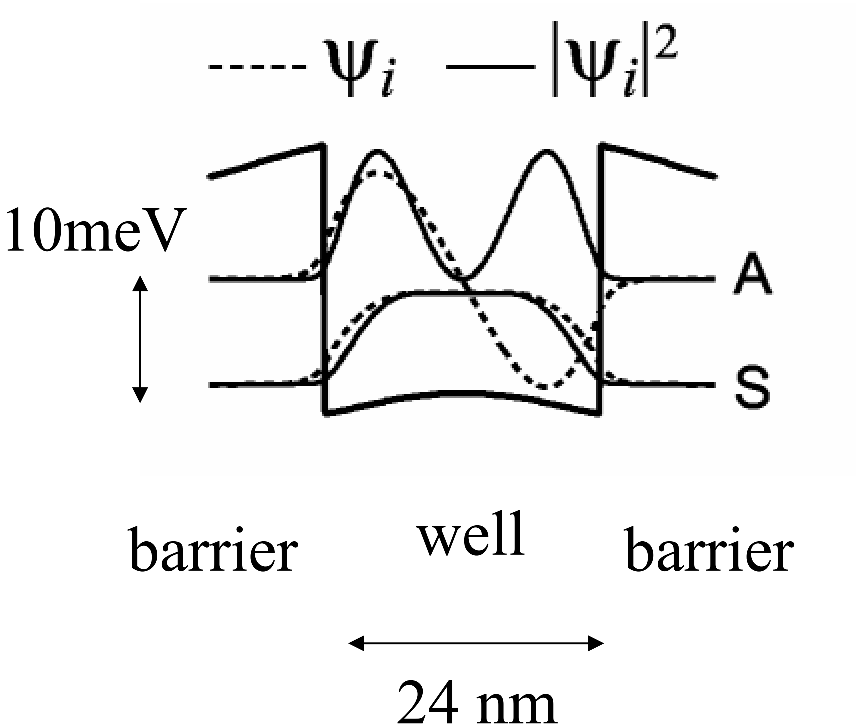
HongWen Jiang
UCLA, Department of Physics and Astronomy

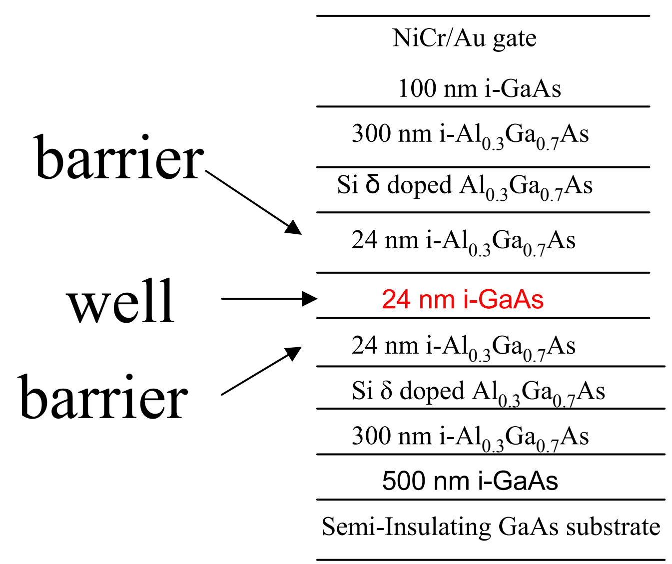
collaborators:
Xinchang Zhang (UCLA)
GuoPing Guo, and Tu Tao (USTC)

KITP Low Dimensional Electron Systems, February 10, 2009

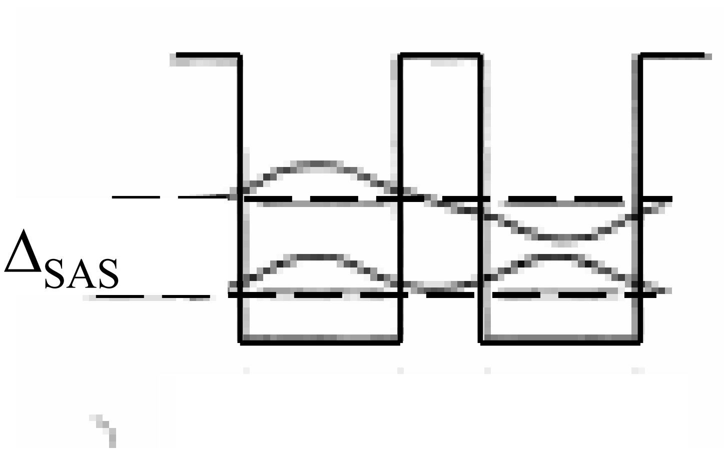
Two-Subband 2D Electron System

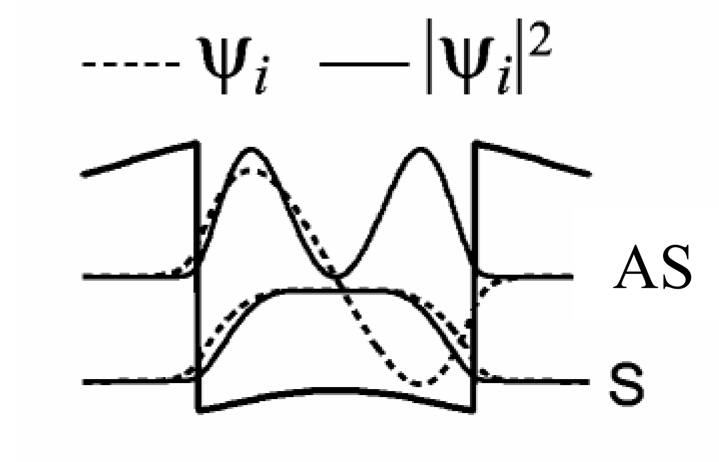
A single quantum well





Double-Layer System *vs.* Two-Subband System





The Hamiltonian of the two systems are mathematically identical

Quantitative difference:

electron density: $\sim 10^{11}/cm^2$ for double layer

$\sim 10^{12}/cm^2$ for two-subband

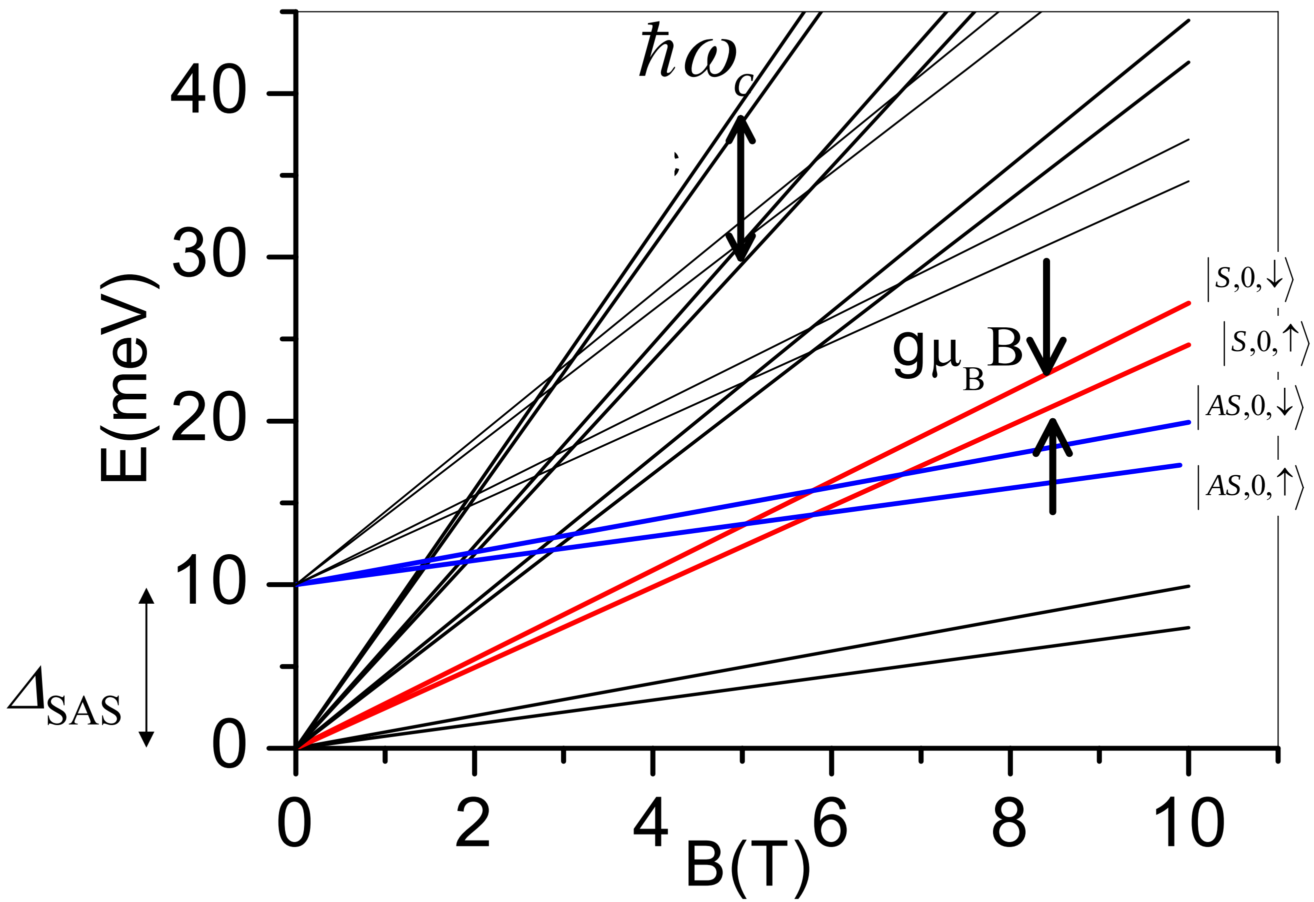
Gap Δ_{SAS} $\sim$ 1meV for double layer

$\sim$ 10 meV for two-subband

Motivation

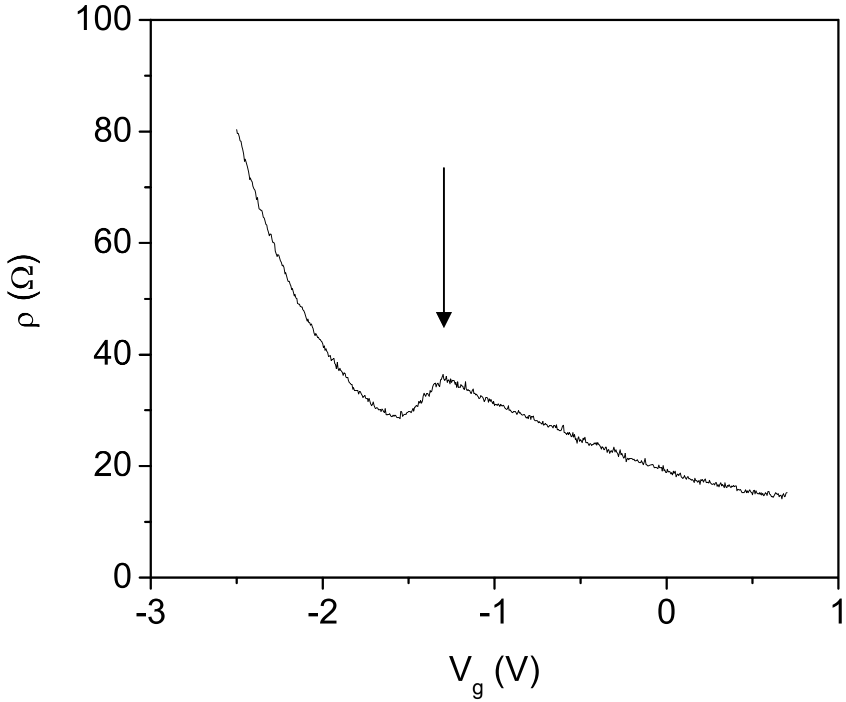
•The system can be tuned to degeneracy either by magnetic field or by density

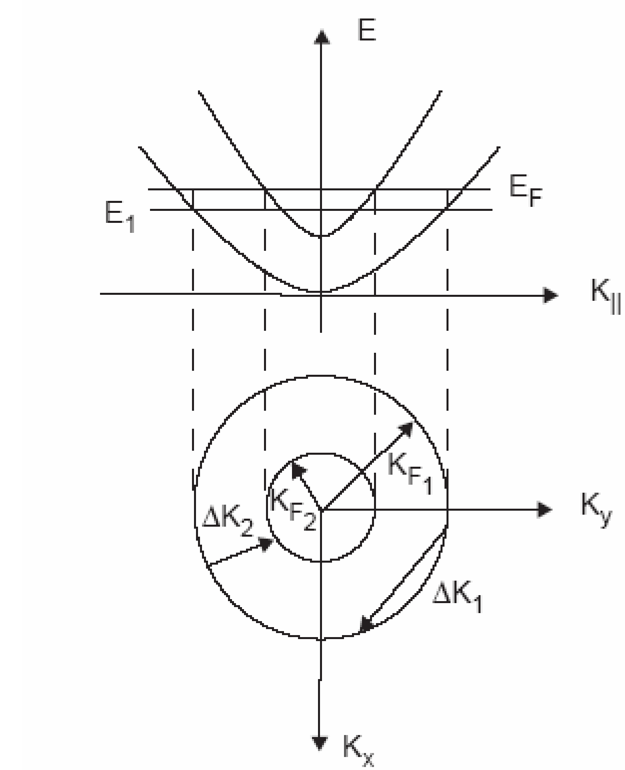
•Electronic systems with multi-fold degeneracy are interesting: competing orders and broken symmetry states



a state: $|i, N, \sigma\rangle$ $\quad i$: S, AS $\quad N$ = Landau level Indies $\quad \sigma: \uparrow, \downarrow$

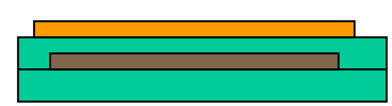
Transport at B=0



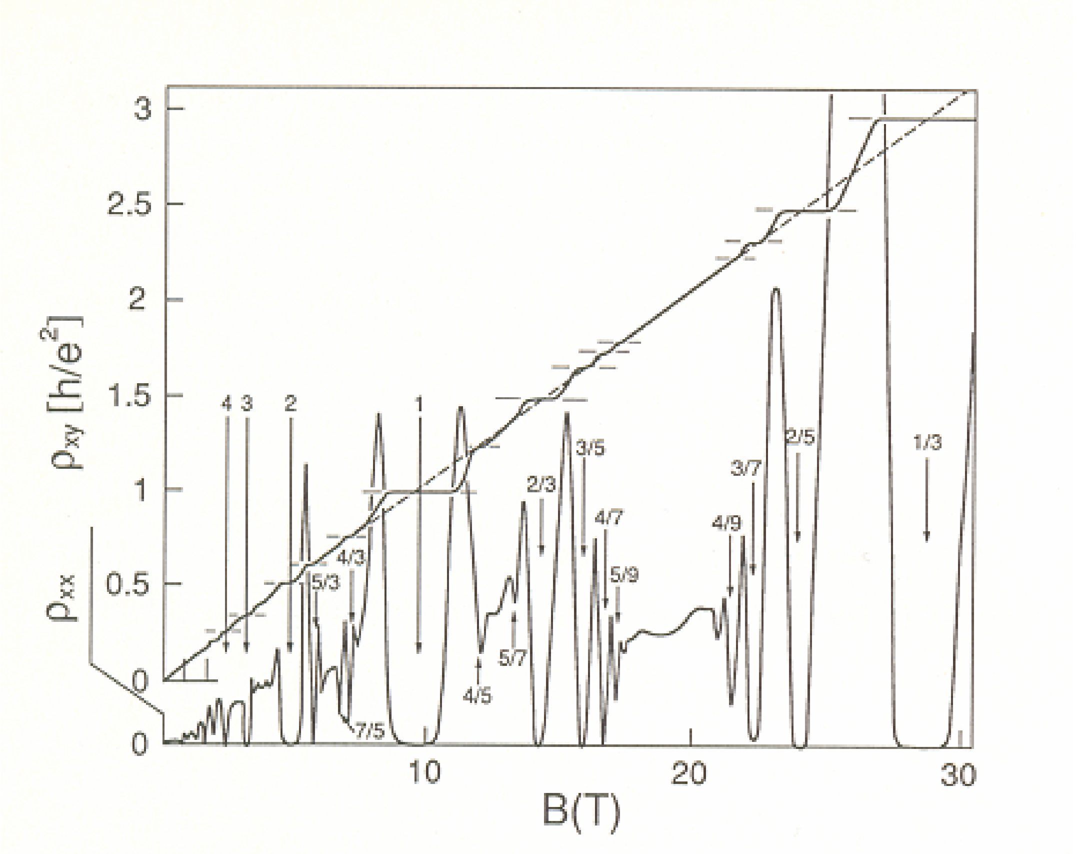


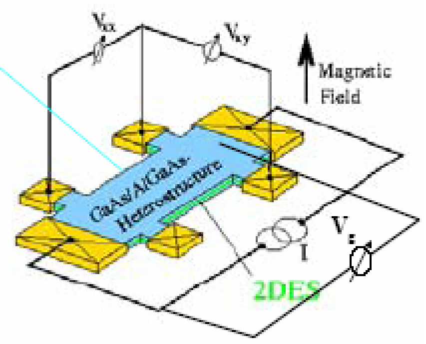
n →

V_g



QHE: two characteristic properties





1. $R_{xx} \to 0$ as $T \to 0$
2. Hall resistance is quantized as $R_{xy} = \frac{h}{e^2 \nu}$

ν = integer: IQH, ν = fractional=p/q : FQHE

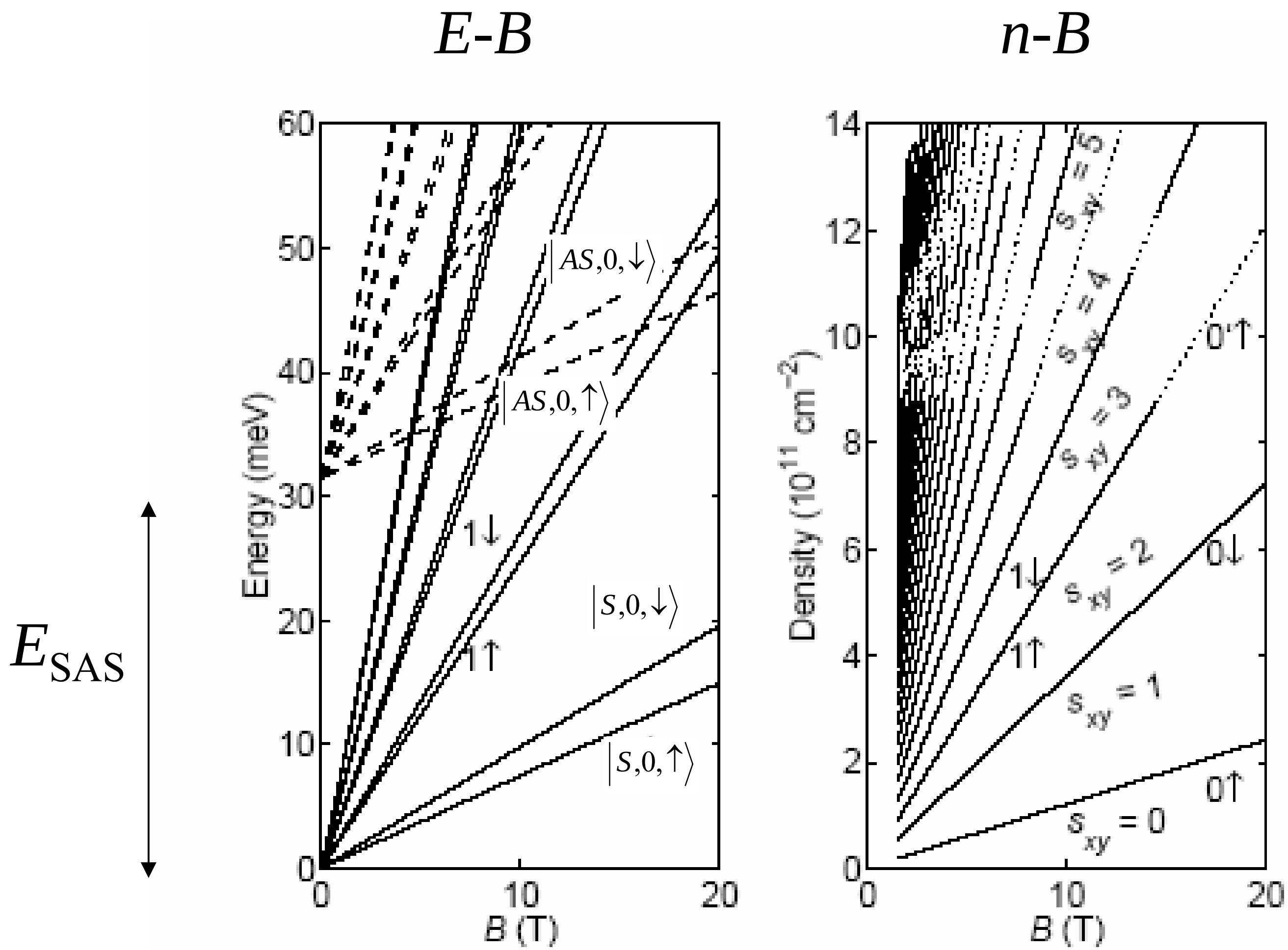
Identify three type of phases in a QHE system

easy to identify in a magneto-transport experiment

transport coefficients in various phase as $T \to 0$

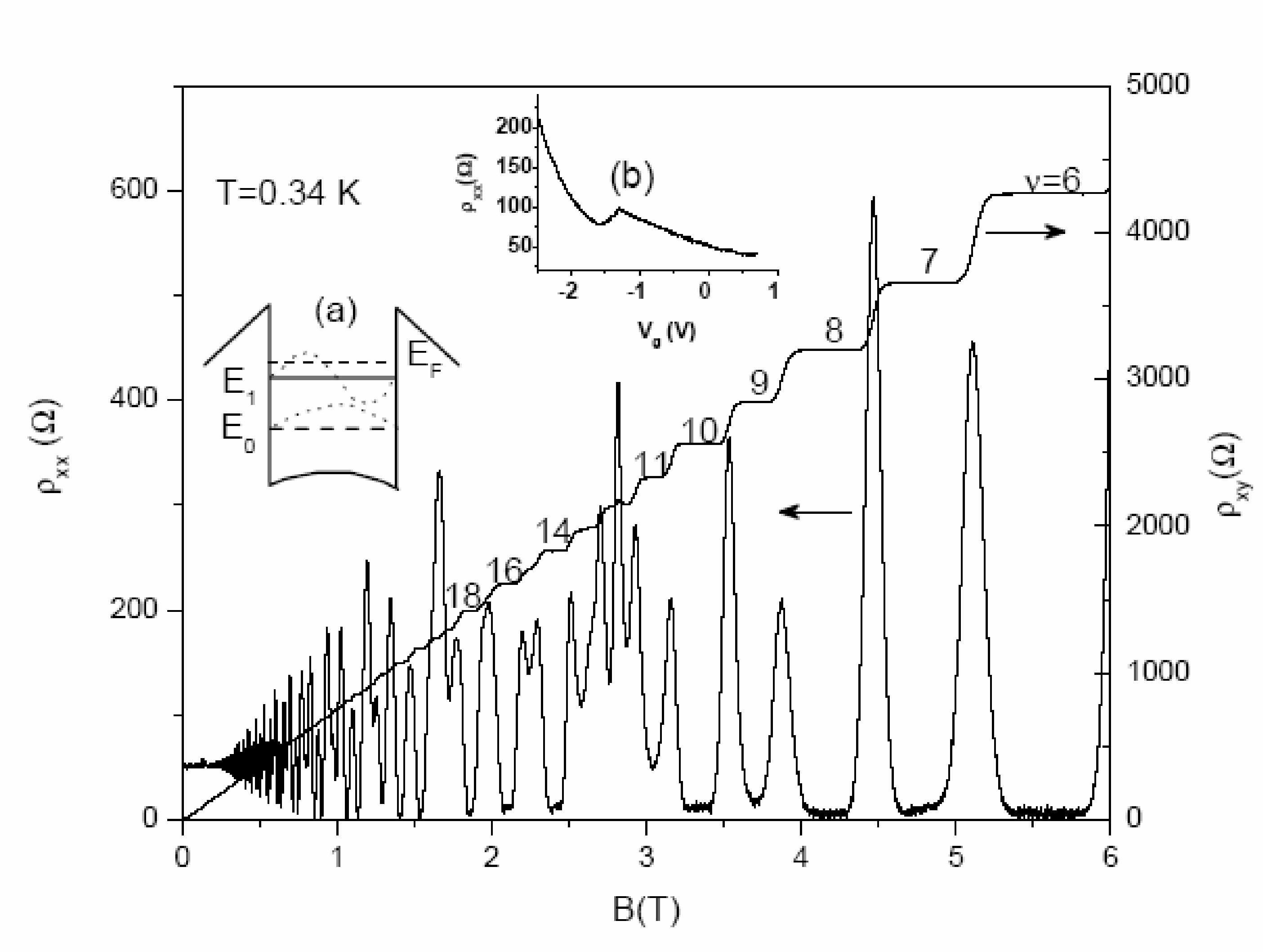
	ρ_{xx}	ρ_{xy}	σ_{xx}	σ_{xy}
insulator	∞	const.	0	0
quantum Hall liquid	0	$(h/e^2)/S_{xy}$	0	$S_{xy}(e^2/h)$
metal	const.	const.	const.	const.

Single particle diagram (“Landau fans”)

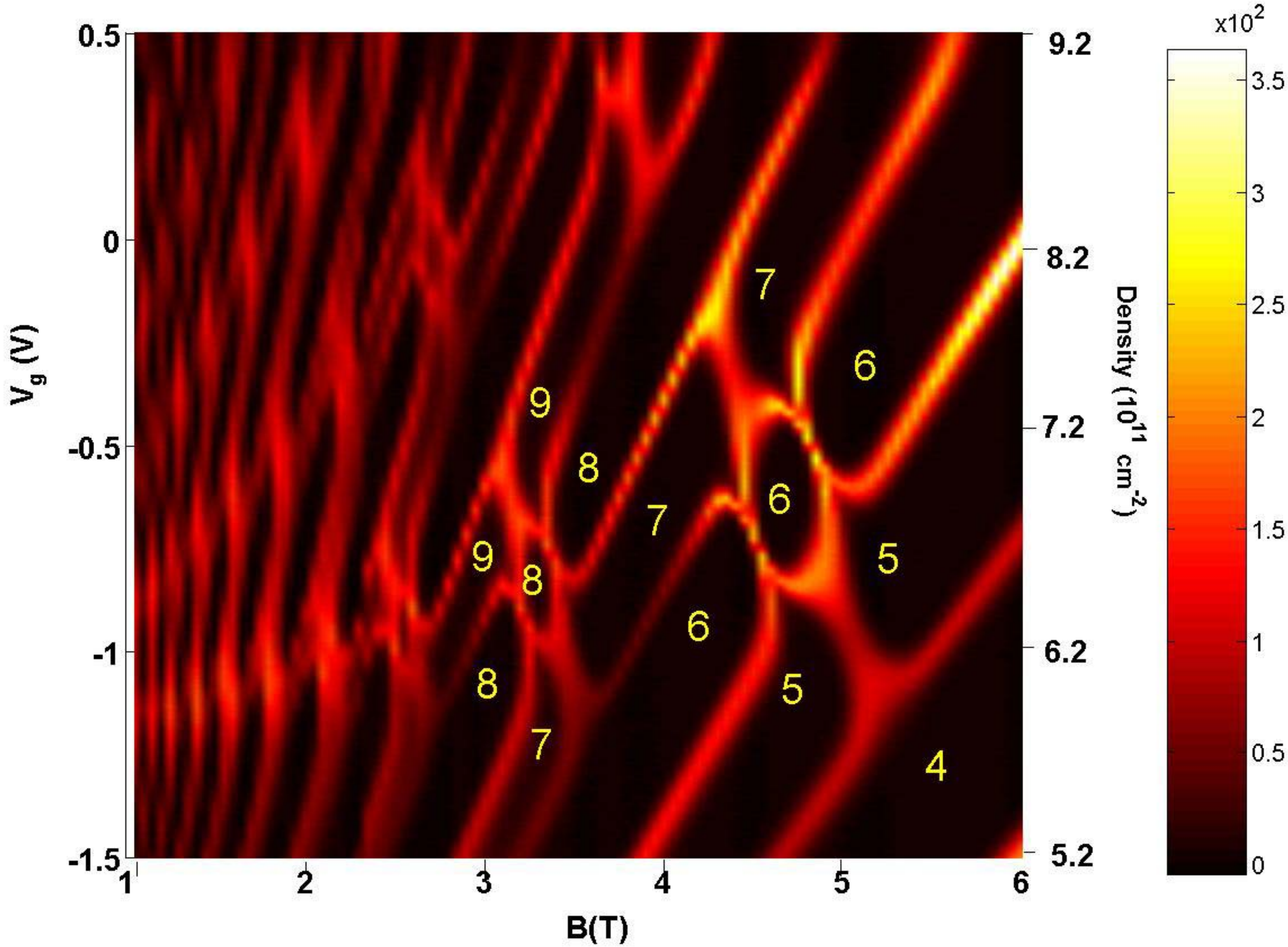


a state: $\left|i, N, \sigma\right\rangle$ i: S, AS N = Landau level Indies $\sigma: \uparrow, \downarrow$

Typical Rxx and Rxy

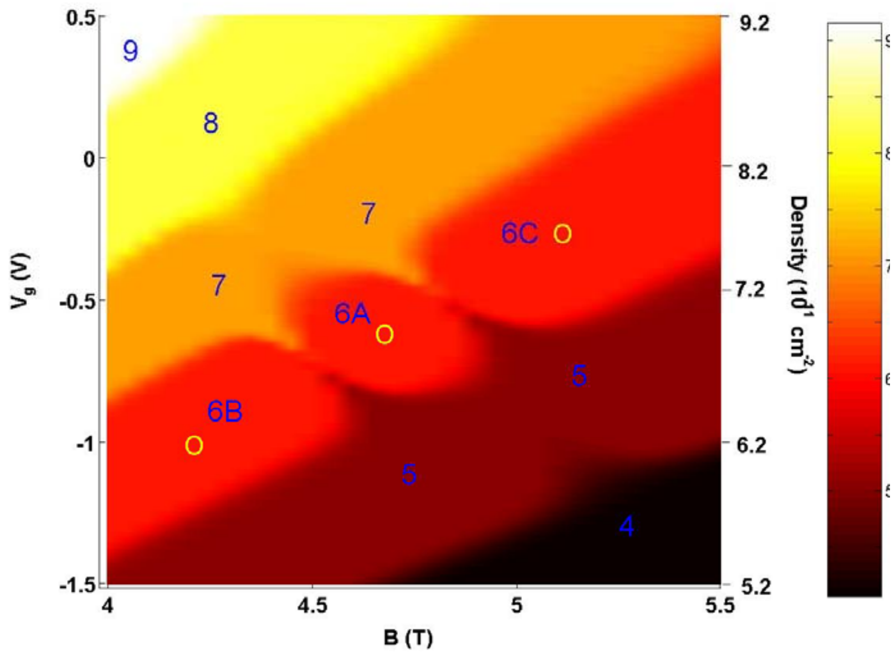


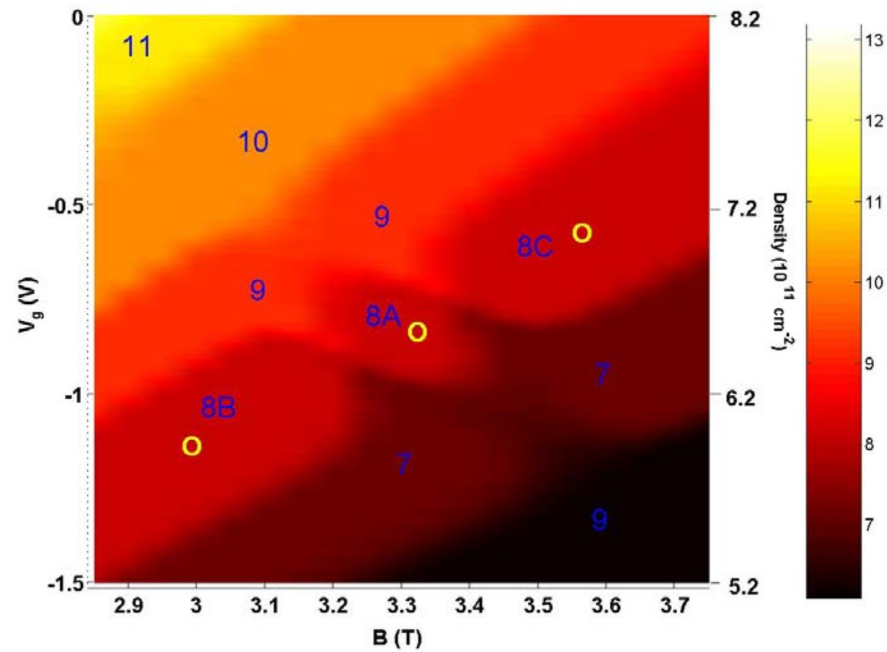
Phase-diagram in *n*-*B* plane



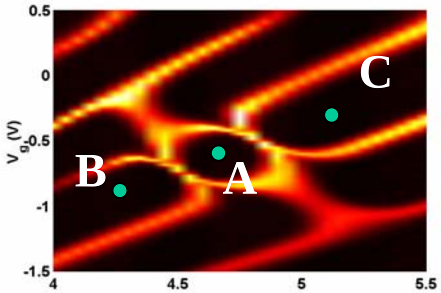
X. C. Zhang, R. F. Faulhaber, and H. W. Jiang, PRL 95, 216801 (2005).

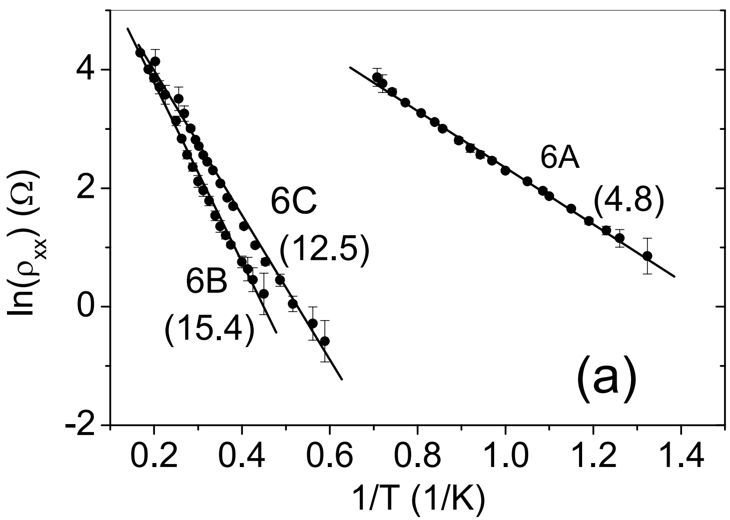
Multiple Phases with the Same Quantized Hall Conductance

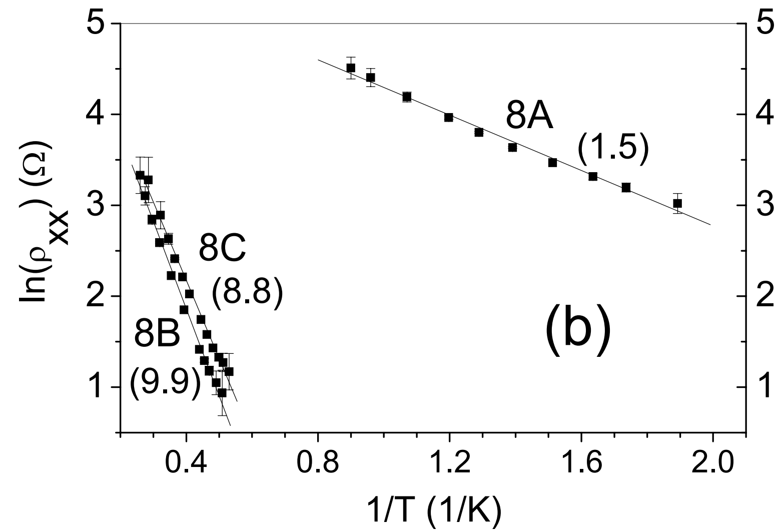




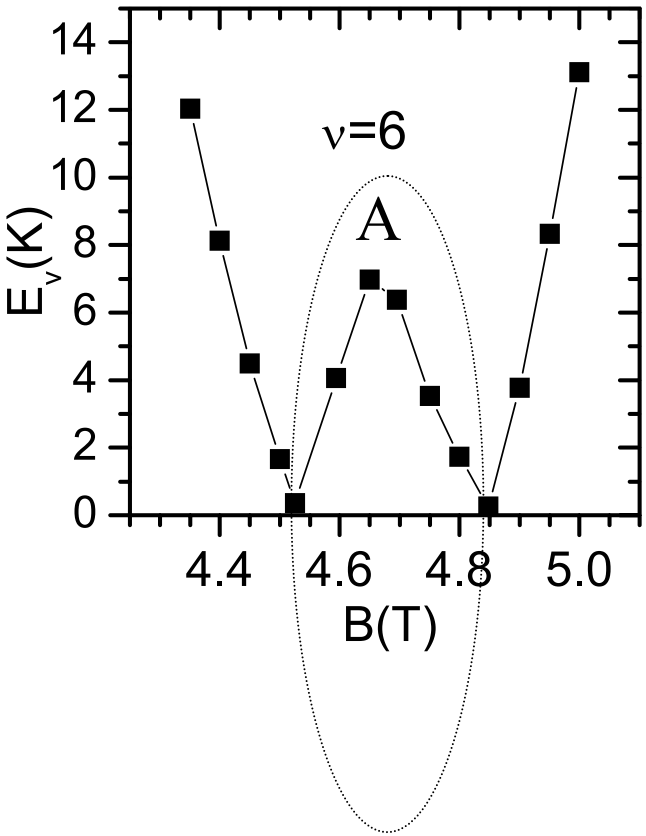
Two series of ring structures at $\sigma_{xy}=6e^2/h$ and $\sigma_{xy}=8e^2/h$



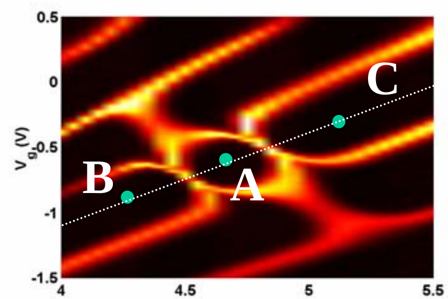




While the energies in the region B, and C are almost identical, the energy in the ring region is significantly smaller by a factor of 3 for the states with $6e^2/h$, and a factor of 5 for the states with $8e^2/h$.

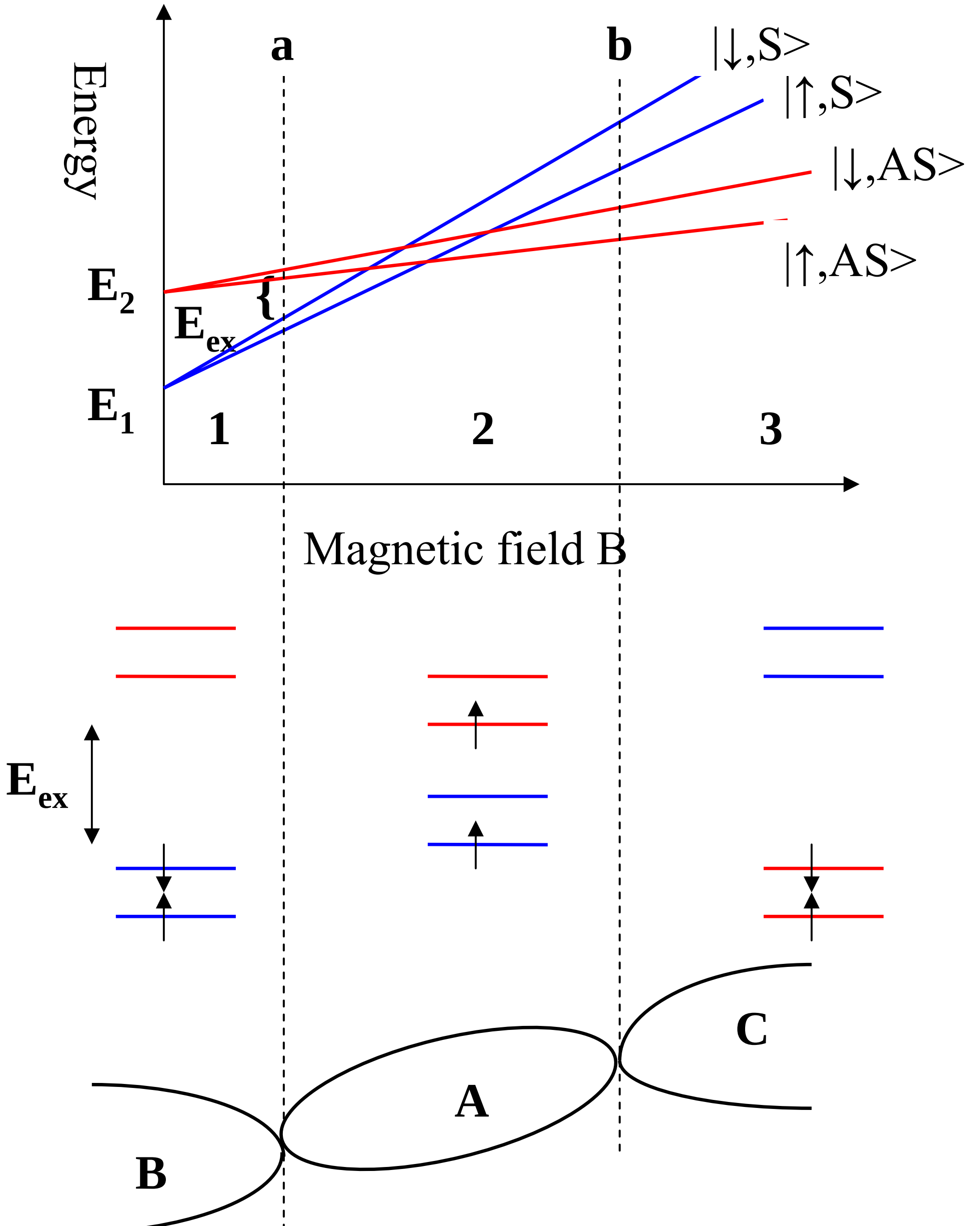


E_ν(K)
B(T)
ν=6
A



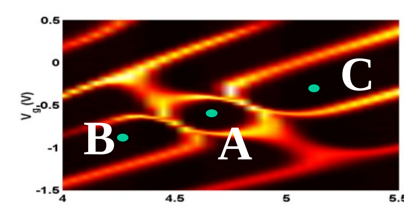
V_g (V)
B
A
C

What is inside the ring?



When two LL's with opposite spin and different subband indices approach each other, there is now an opportunity for the electrons in the first subband to occupy the up-spin state of the second subband. By spin-flipping to the second subband, the electrons can actually save exchange energy.

Ferromagnetic phase of real-spins (not S, AS of pseudospins)



Probe spin-states by resistively detected NMR

* nuclear spins have nonzero angular momentum

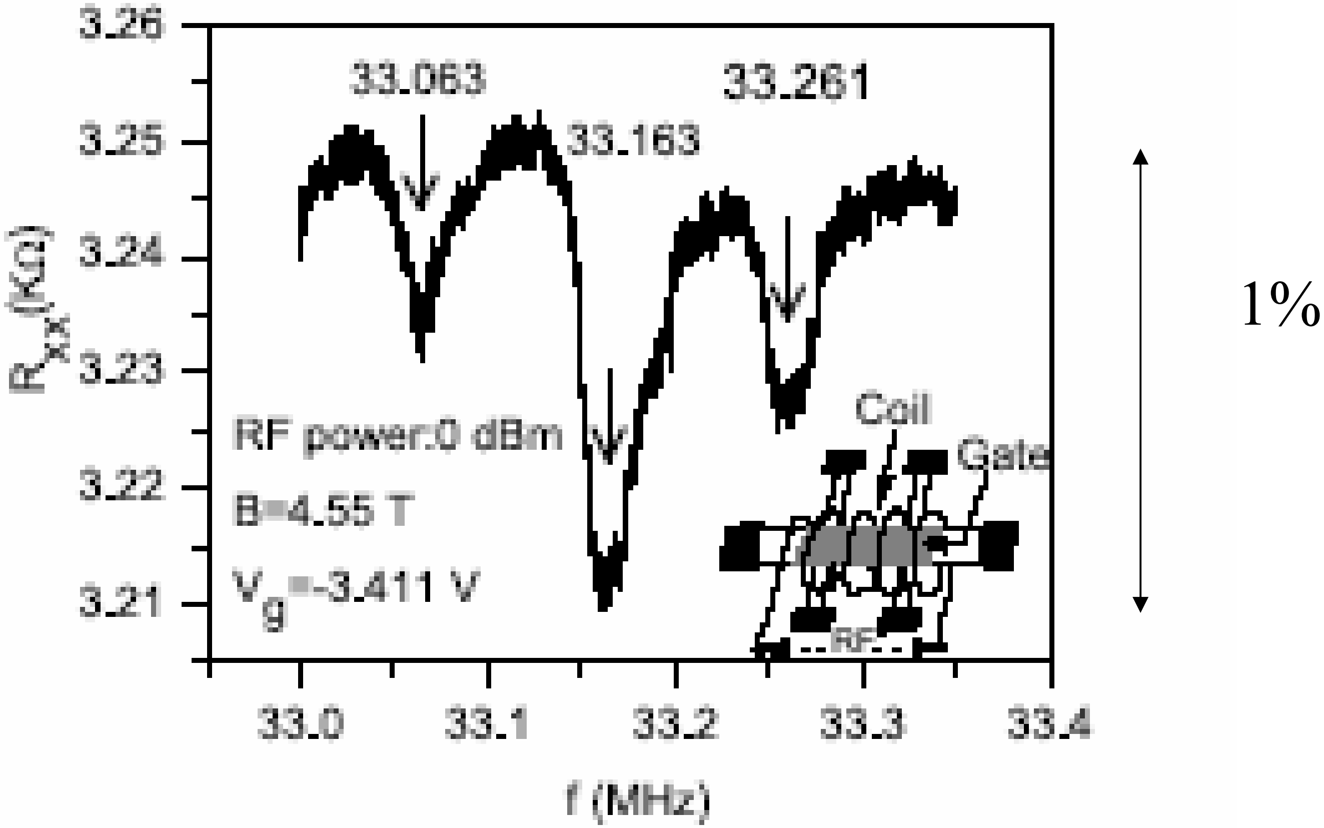
(ex. I=3/2 for Ga^{69}, Ga^{71} and As^{75} in GaAs)

* hyperfine interaction:

$$H = g\mu_B B + A\vec{I} \bullet \vec{S}$$

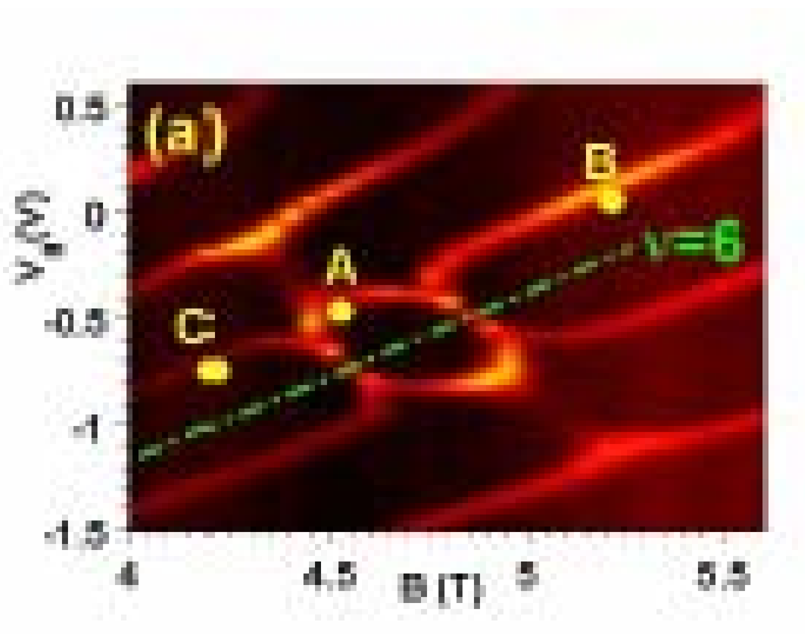
• The nuclear spins can be dynamically polarized which in turn shift the effective field on the electrons

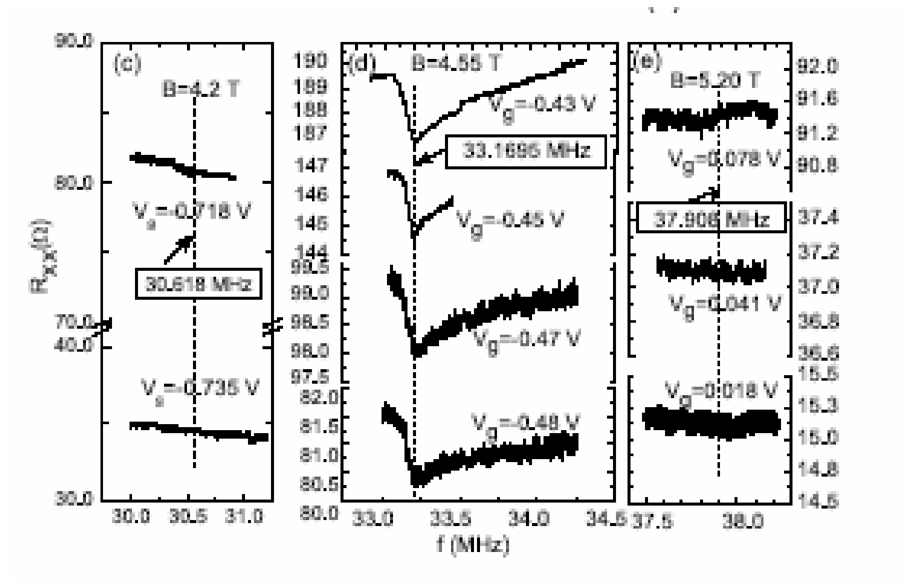
• Resistance can sense this effective field change



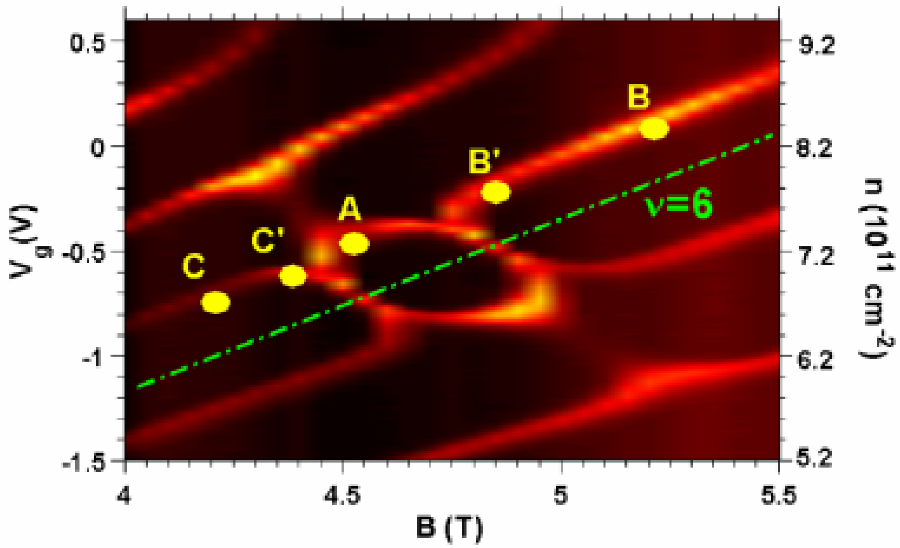
Around filling factor 1

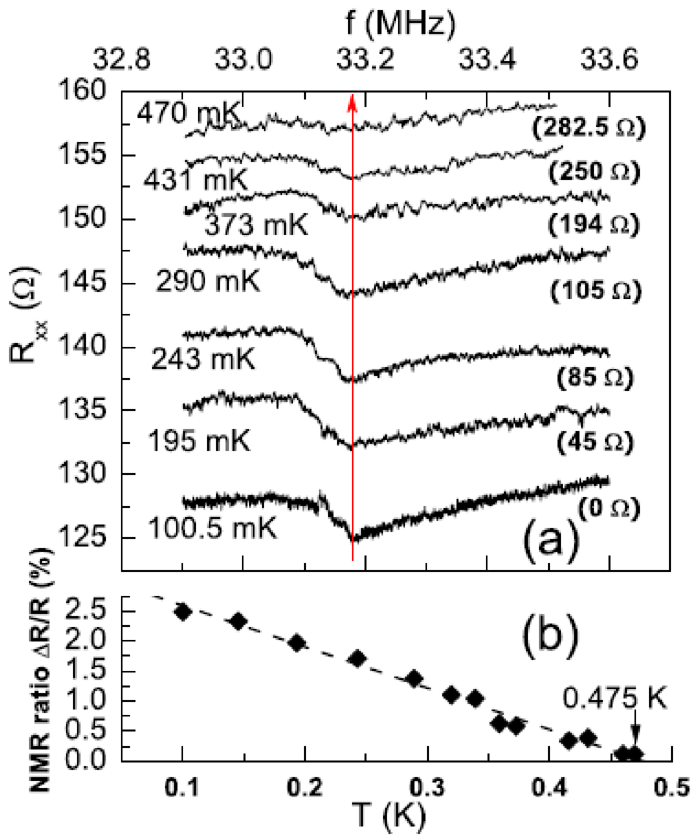
electrically detected NMR inside the ring



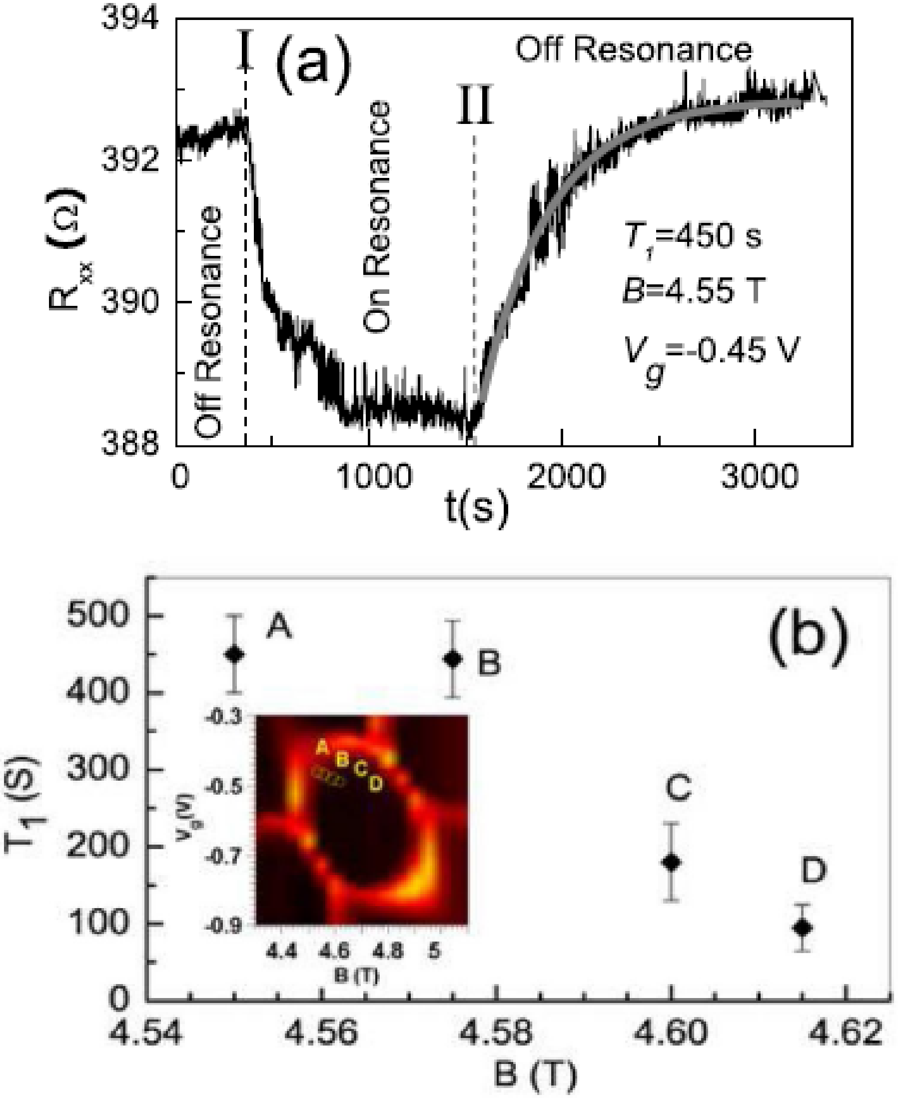


Persist to high temperatures



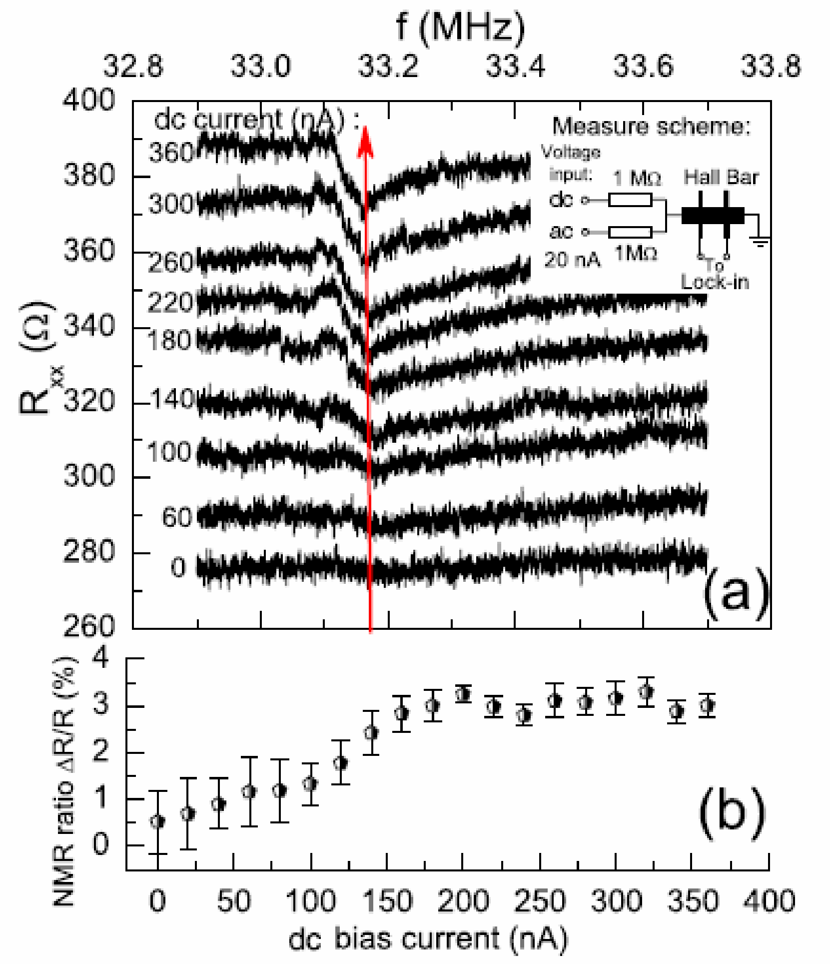


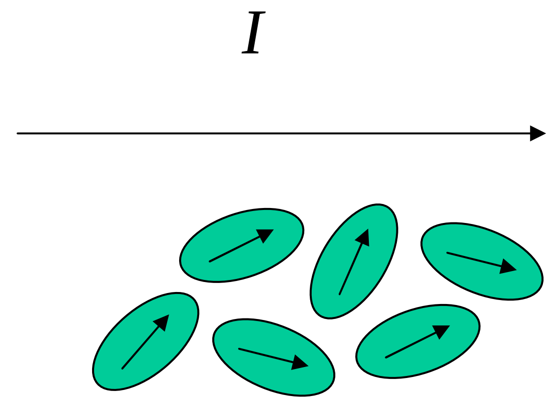
X. Zhang, G. Scott, H. W. Jiang, PRL 98, 246802 (2007)



Fast-relaxation towards center of the ring

X. Zhang, G. Scott, H. W. Jiang, PRL 98, 246802 (2007)



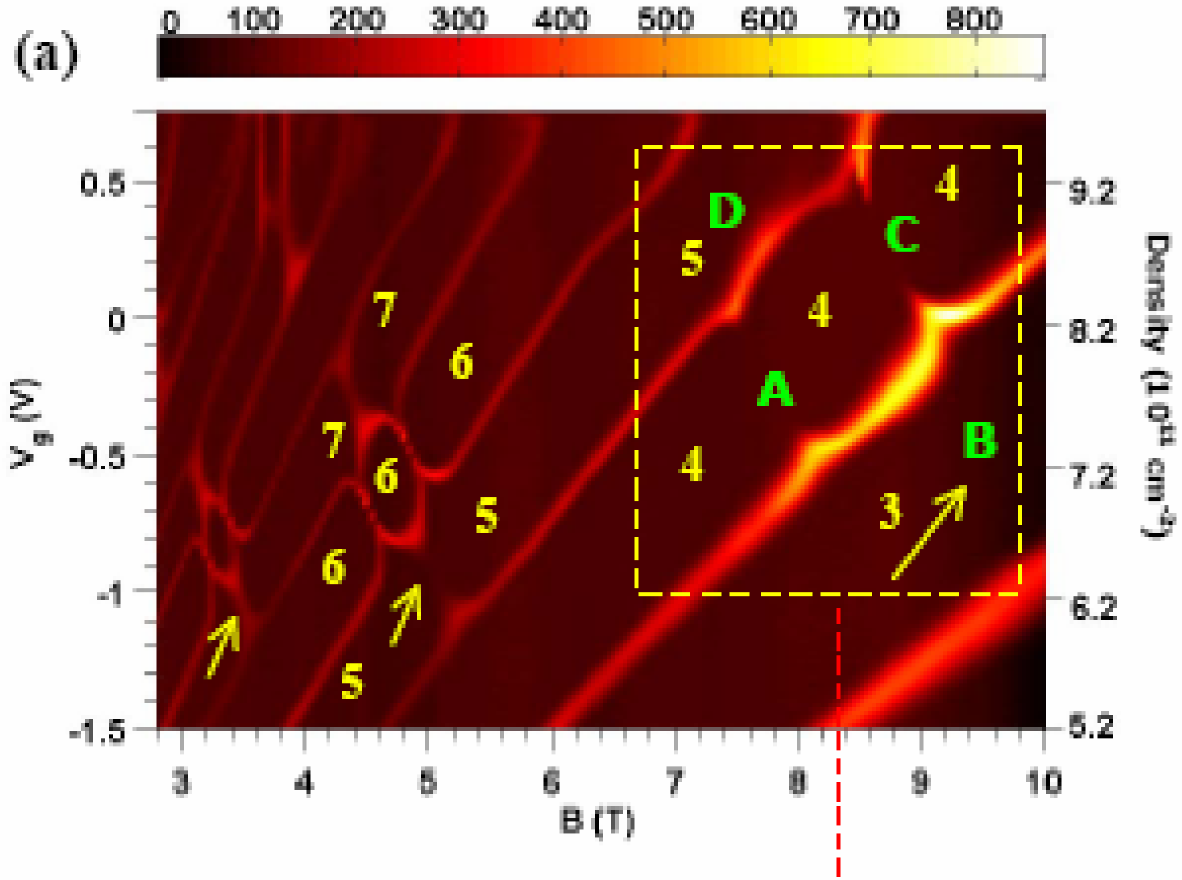


as the applied current forces electrons to scatter between adjacent domains with different spin but almost degenerate energy, the nuclei in the neighborhood can become polarized.

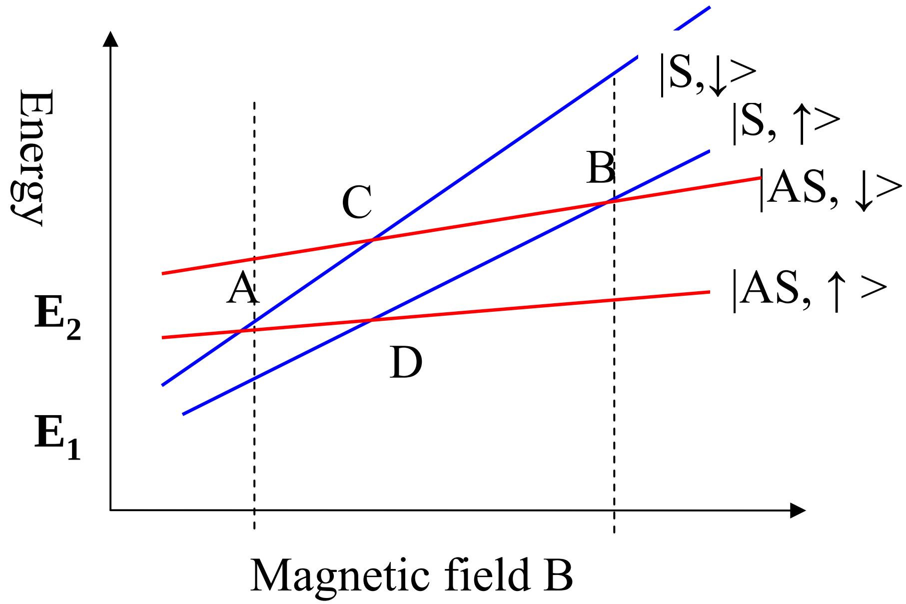
Dynamic nuclear polarization by DC current

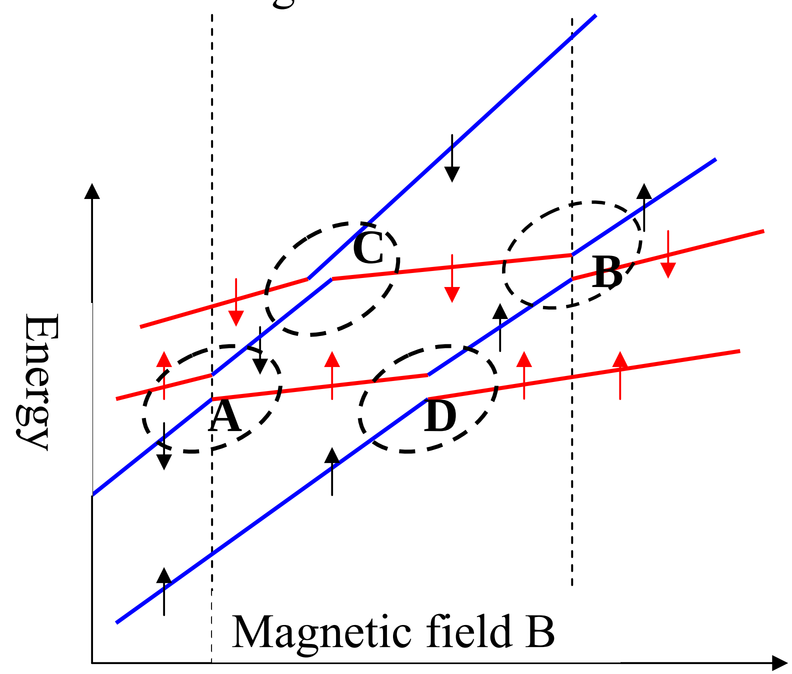
X. Zhang, G. Scott, H. W. Jiang, PRL 98, 246802 (2007)

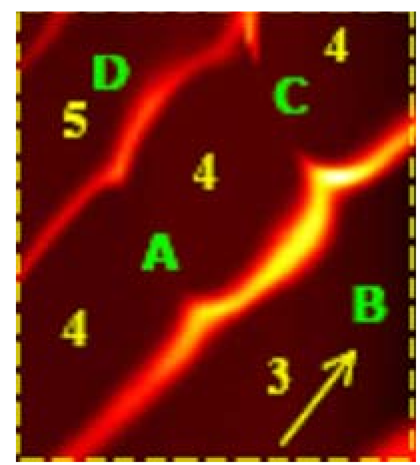
Different topology at high-magnetic fields



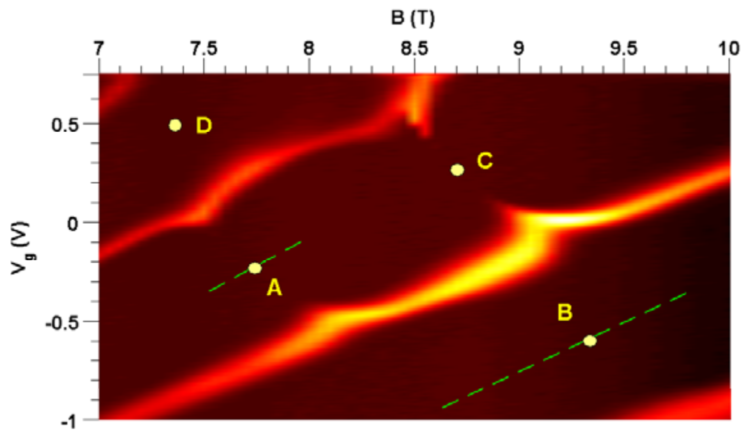
X.C. Zhang, I. Martin, and H.W. Jiang, PRB 74, 073301 (2006)

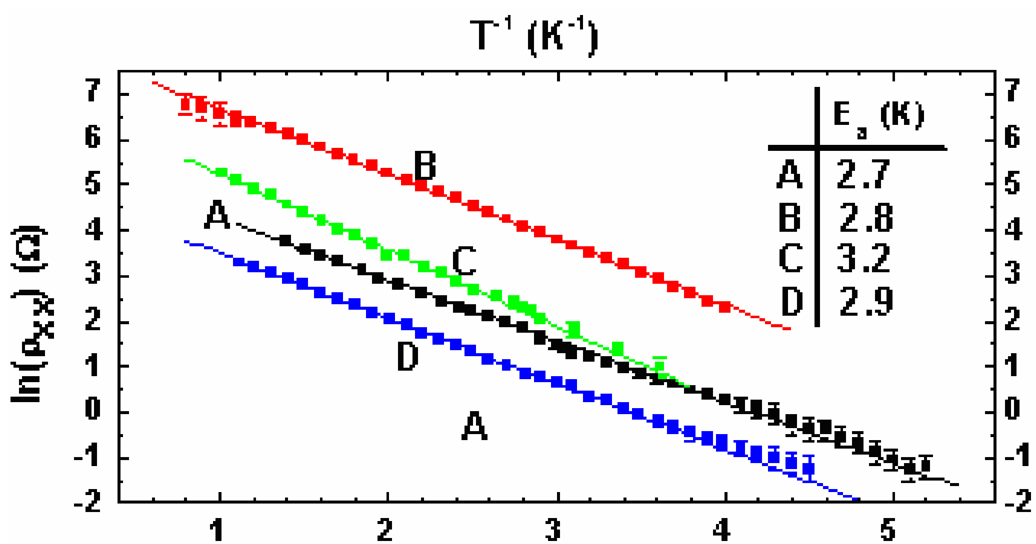

Energy
E2
E1
|S,↓>
|S, ↑>
|AS, ↓>
|AS, ↑ >
A
B
C
D
Magnetic field B


Energy
A
B
C
D
Magnetic field B


D
C
A
B
5
4
4
4
3

activation energy measurement



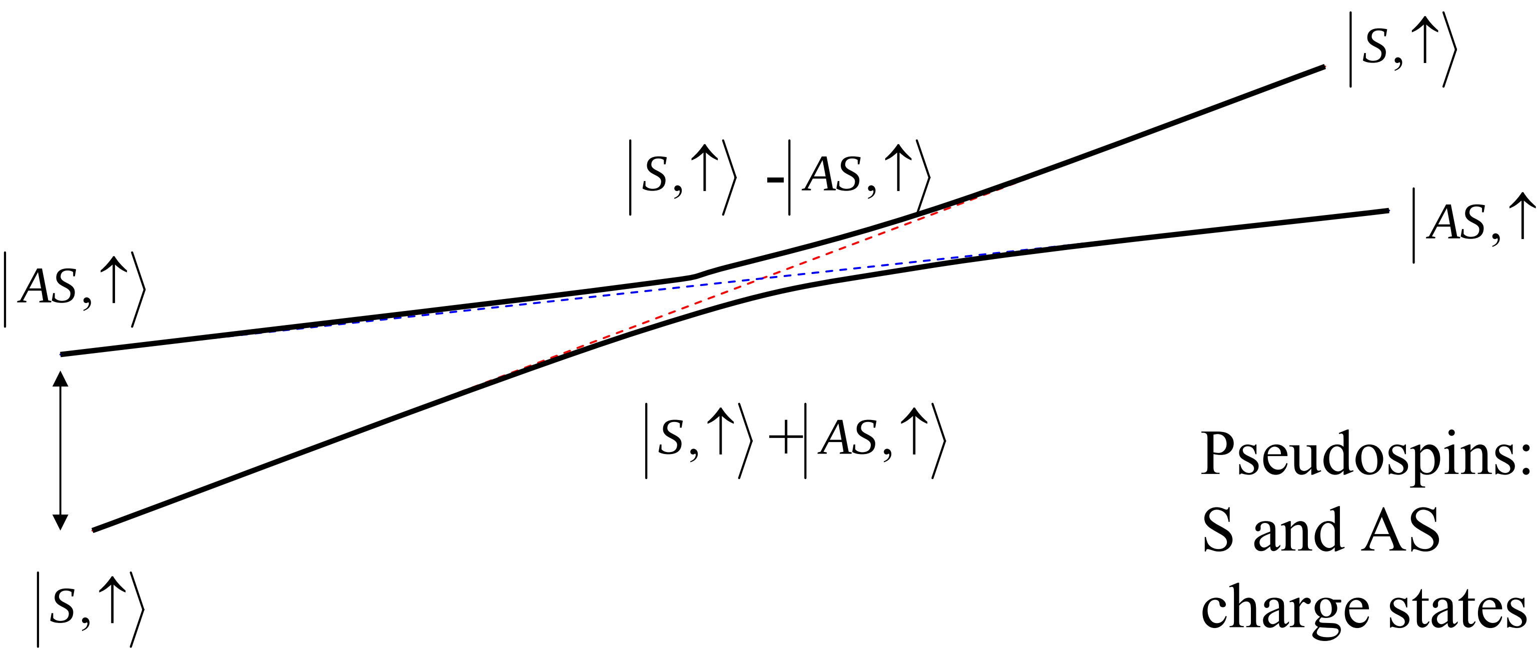


Clear evidence of energy gap at degeneracy points A, B, C, and D

Jungwirth and MacDonald 2000: quantum Hall ferromagnetism

Easy-plane magnet of pseudospins at ν=3: X-Y ferromagnet

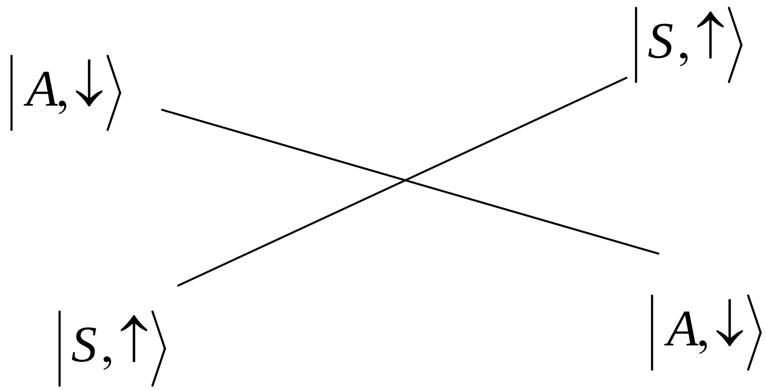
gap is due to the superposition of S and AS pseudospins which causes an exchange energy penalty for a pseudospin flip.



same electron spins

Pseudospins:
S and AS
charge states

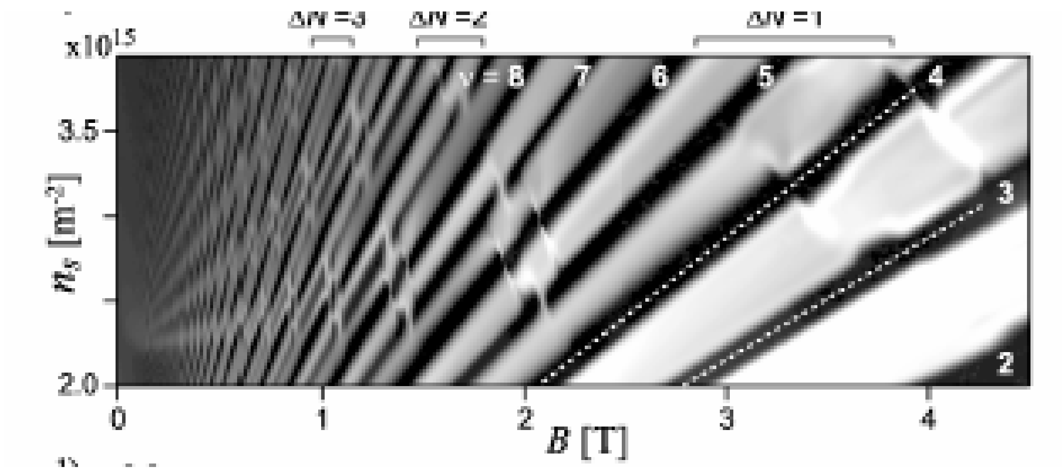
Easy-axis magnet of pseudospins at ν=4: Ising ferromagnet

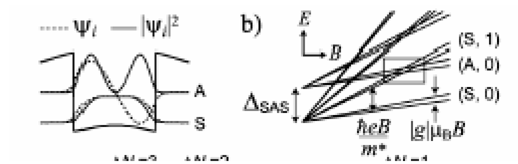


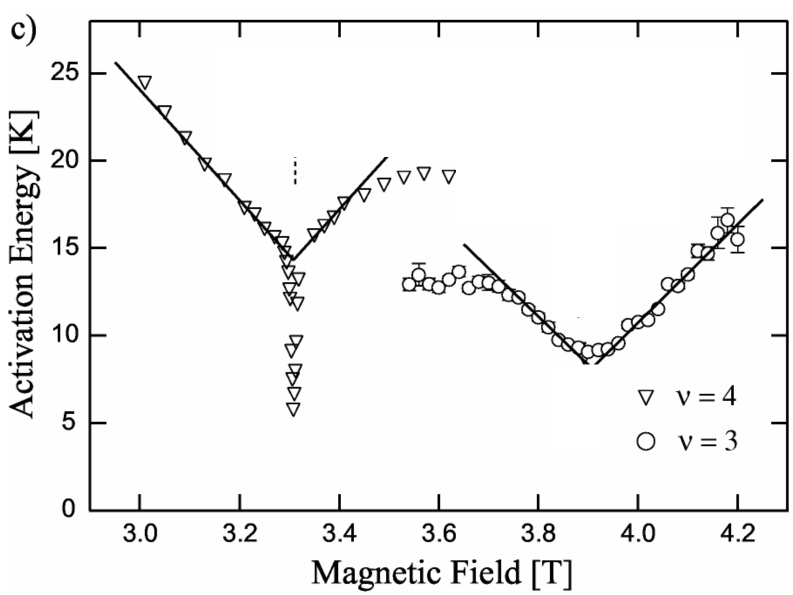
opposite electron spins
break spontaneously into domains

Pseudospins magnetism in a two-subband system

400 A QW



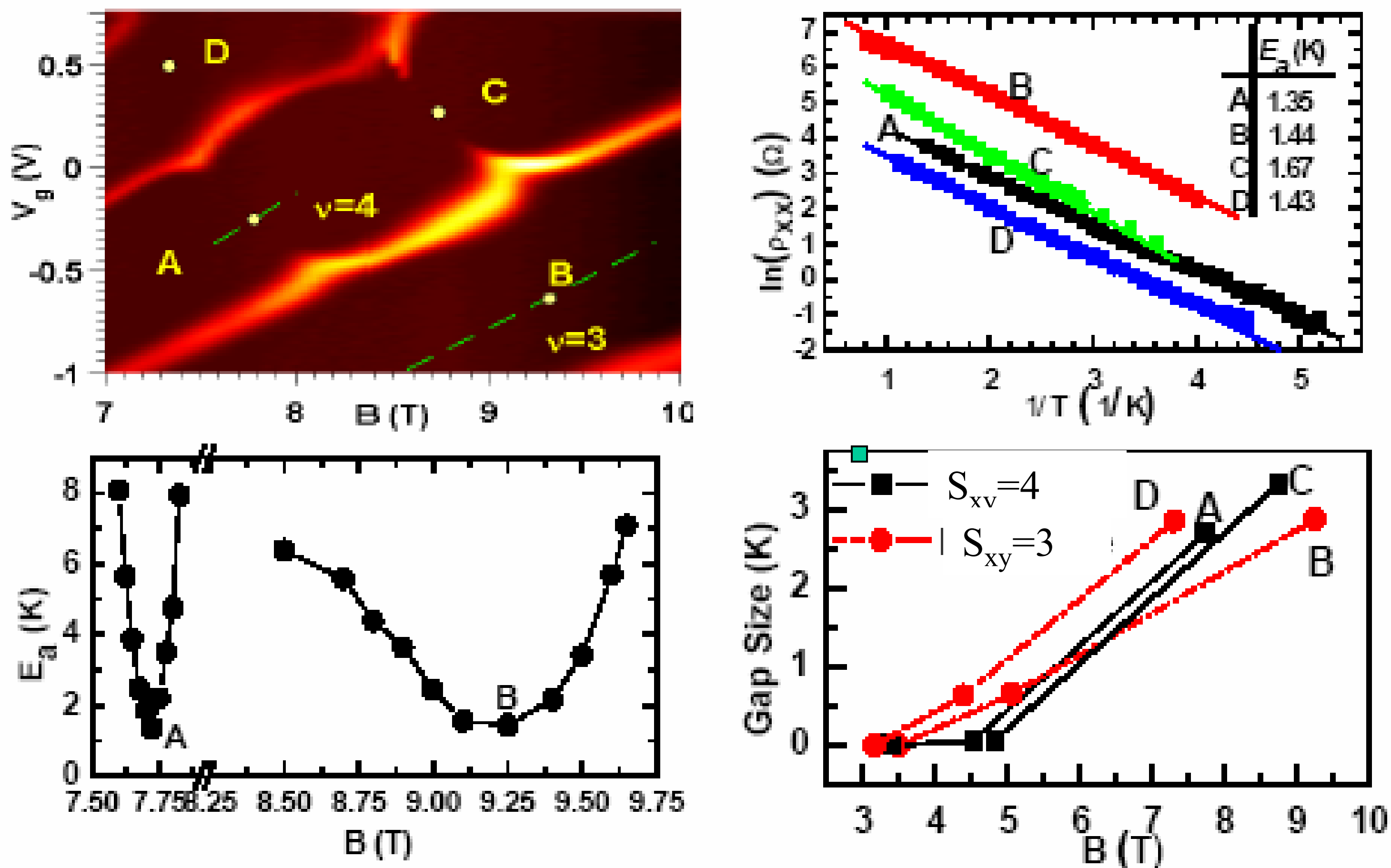




Spike: domain well scattering

Muraki, Saku, and Hirayama PRL 02

In our system



$S_{xy}=4$
cusp like

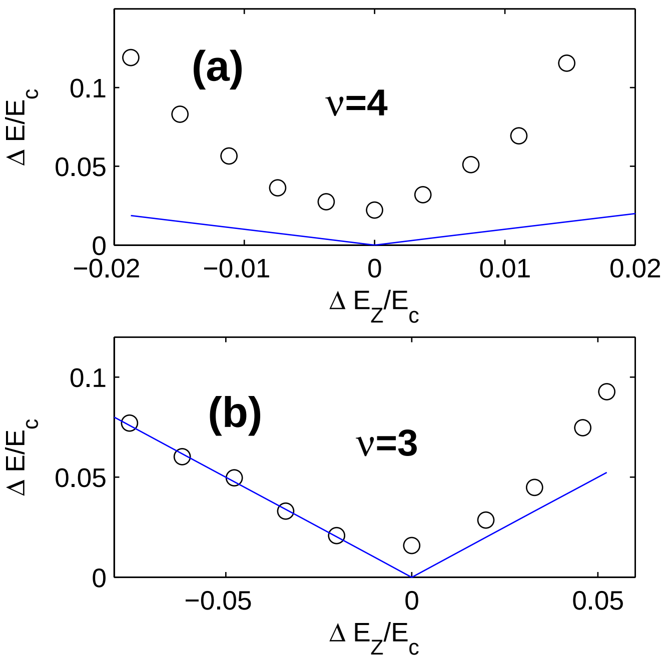
$S_{xy}=3$
smooth transition

X.C. Zhang, I. Martin, and H.W. Jiang, PRB 74, 073301 (2006)

Plot against ΔE_Z

Easy-axis

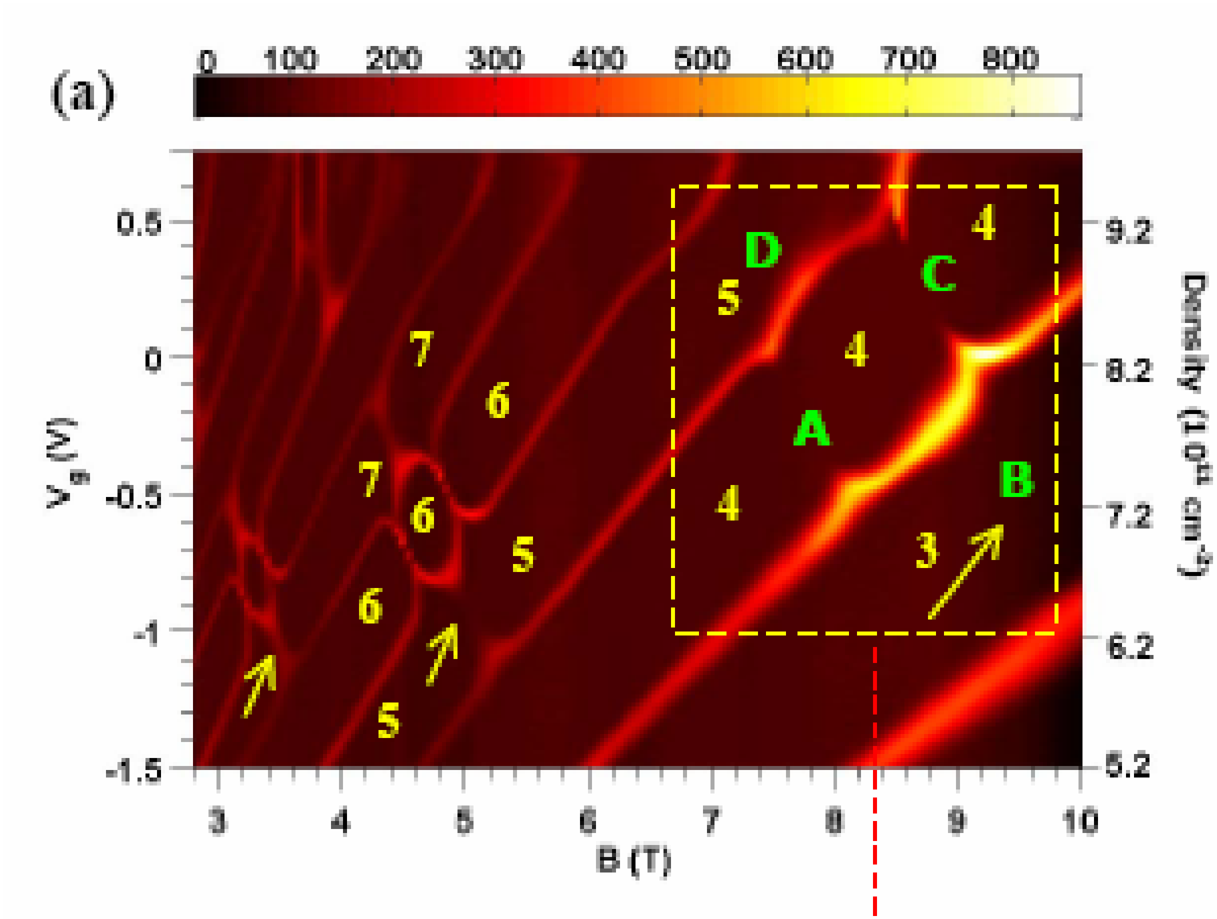
Easy-plane

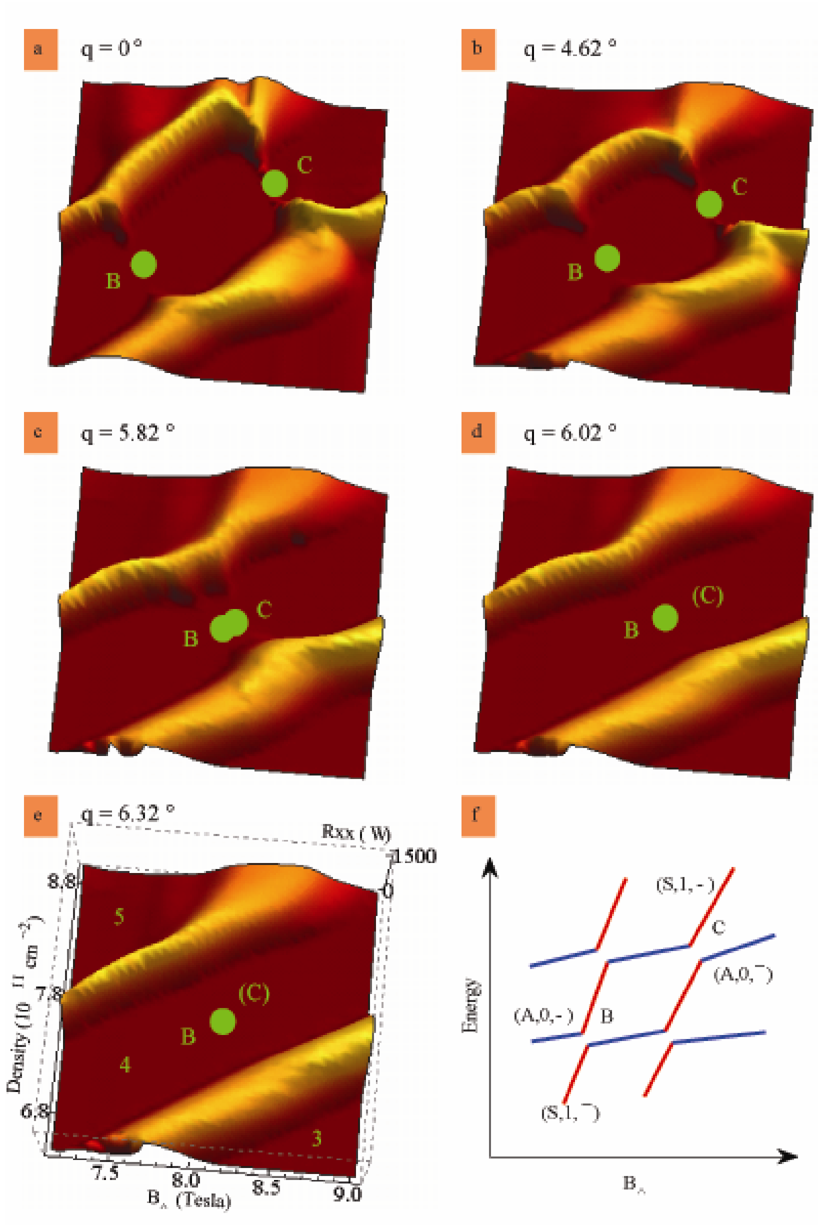


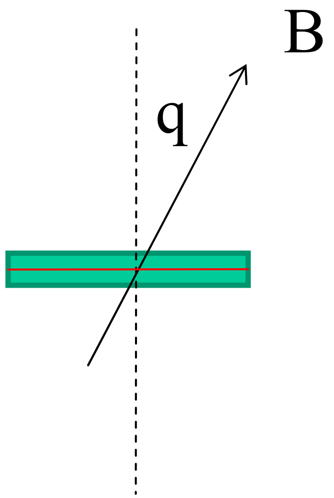
5 pseudospin flips (estimated from the slope)
method of A. Schmeller, J. P. Eisenstein 1995 for flipping of Skyrmion quasiparticle

the quasiparticle becomes a simple electron-hole excitation between the single-particle levels ("pseudospins aligned")

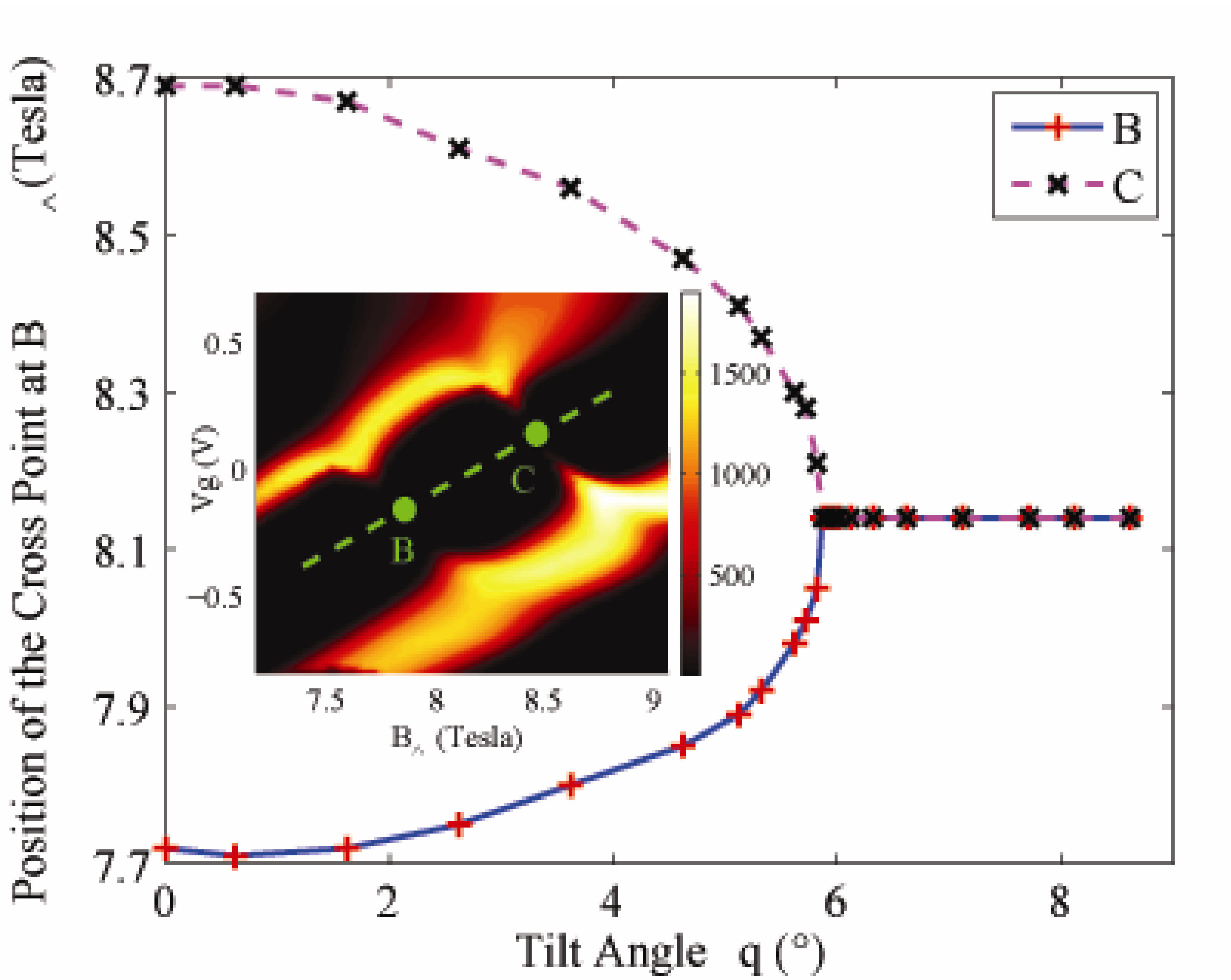
An in-plane magnetic field induced transition





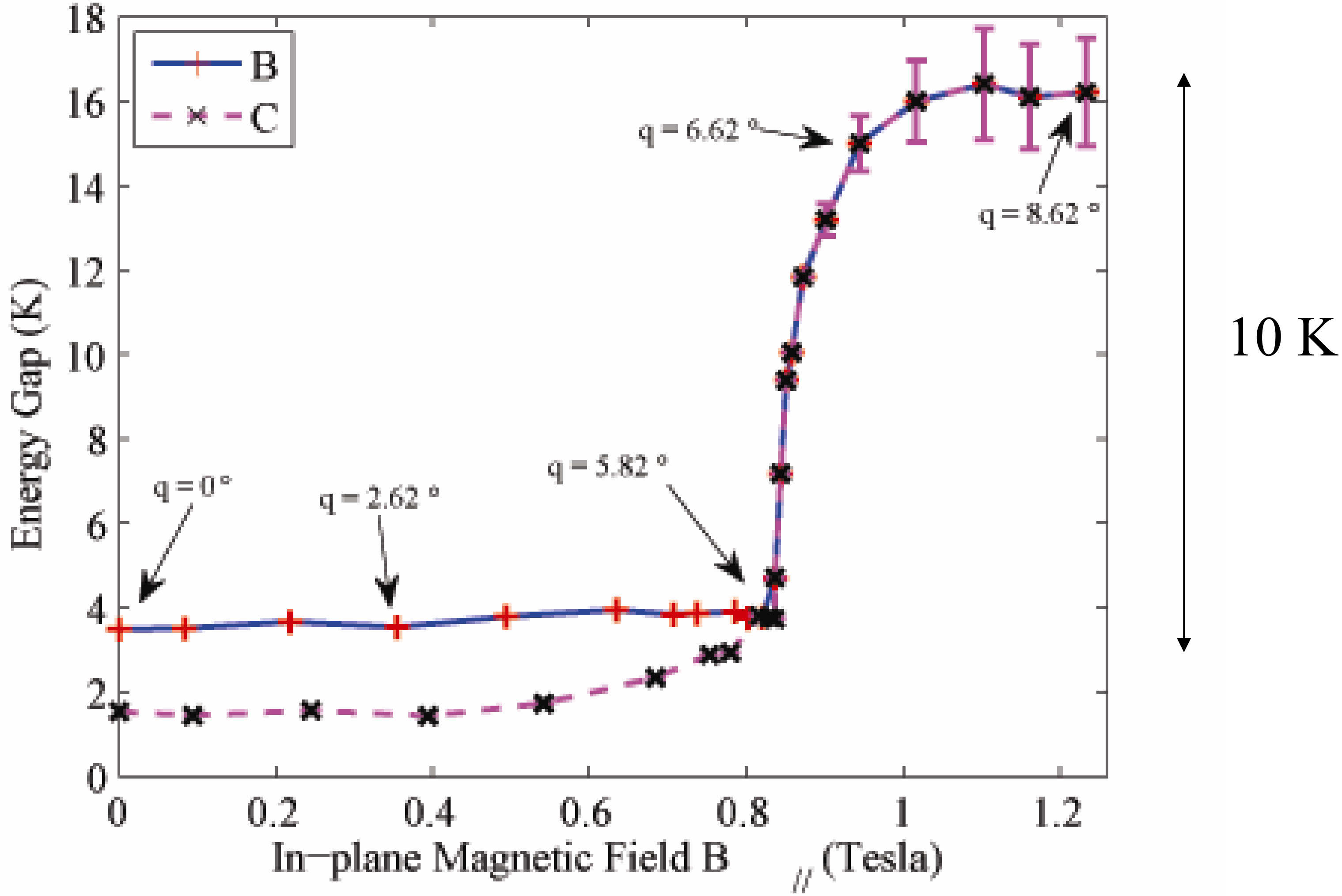


tilting magnetic field: increase the in-plane field



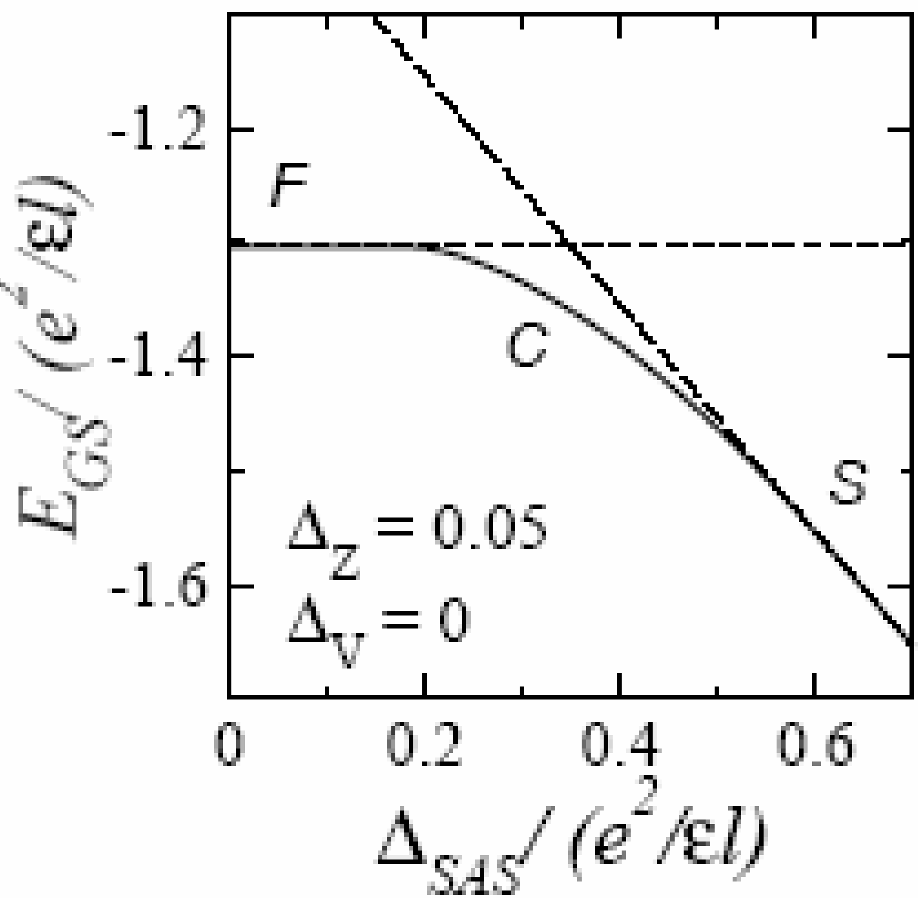
Position of the Cross Point at B (Tesla)
Tilt Angle q (°)
8.7
8.5
8.3
8.1
7.9
7.7
0
2
4
6
8
B
C
Vg (V)
B (Tesla)
0.5
0
−0.5
7.5
8
8.5
9
1500
1000
500

Activation energy measurement

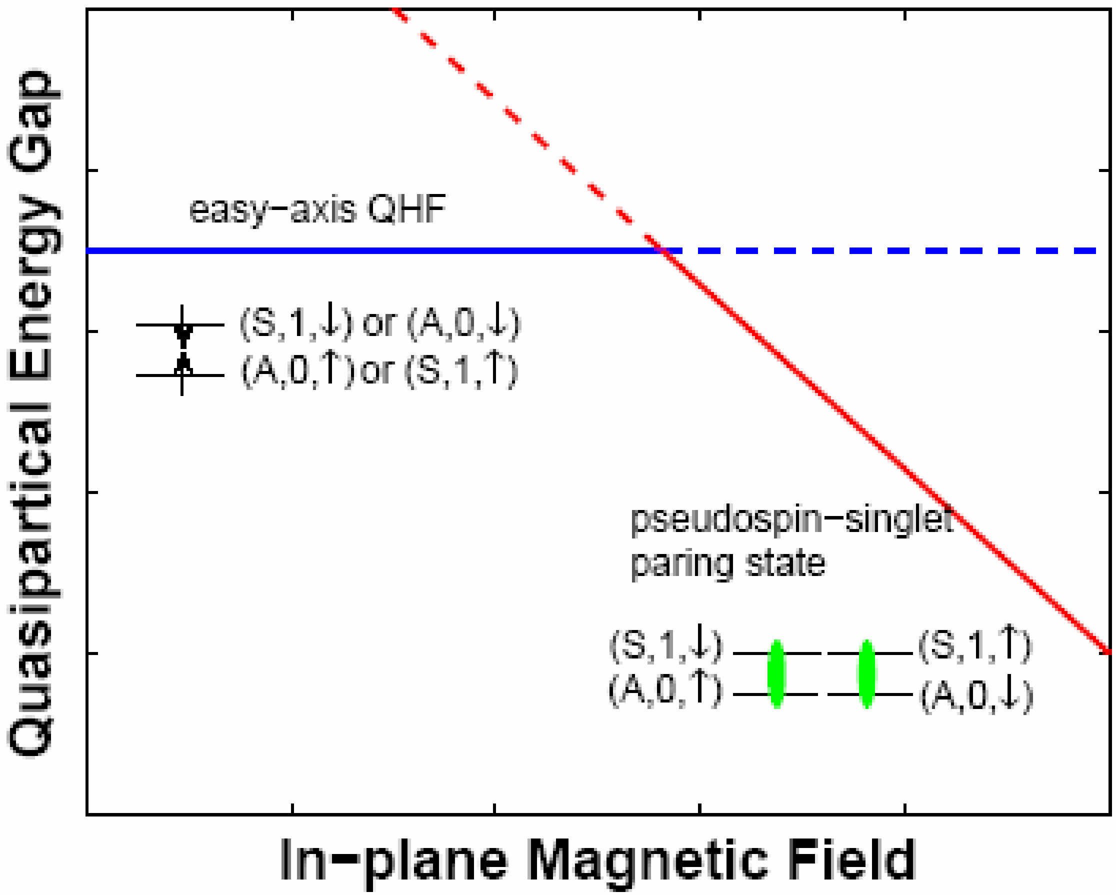


G. P. Guo, Y. J. Zhao, T. Tu, X. J. Hao, X. C. Zhang, G. C. Guo and H. W. Jiang, Phys. Rev. B78, 23305 (2008).

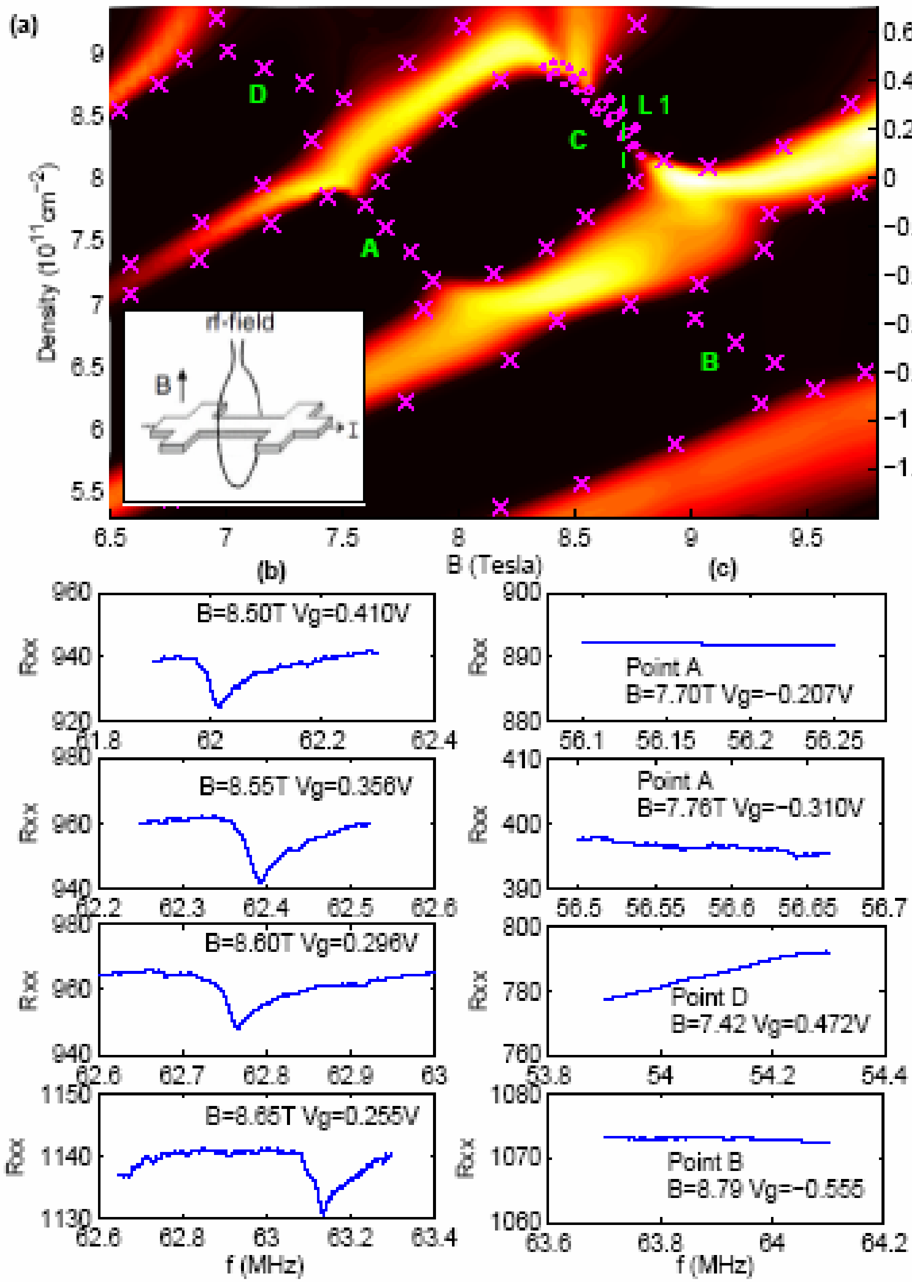
E. Demler and S. Das Sarma PRB (2000)



D. W. Wang, E. Demler, and S. Das Sarma, Phys. Rev. B **68,** 165303 (2003).



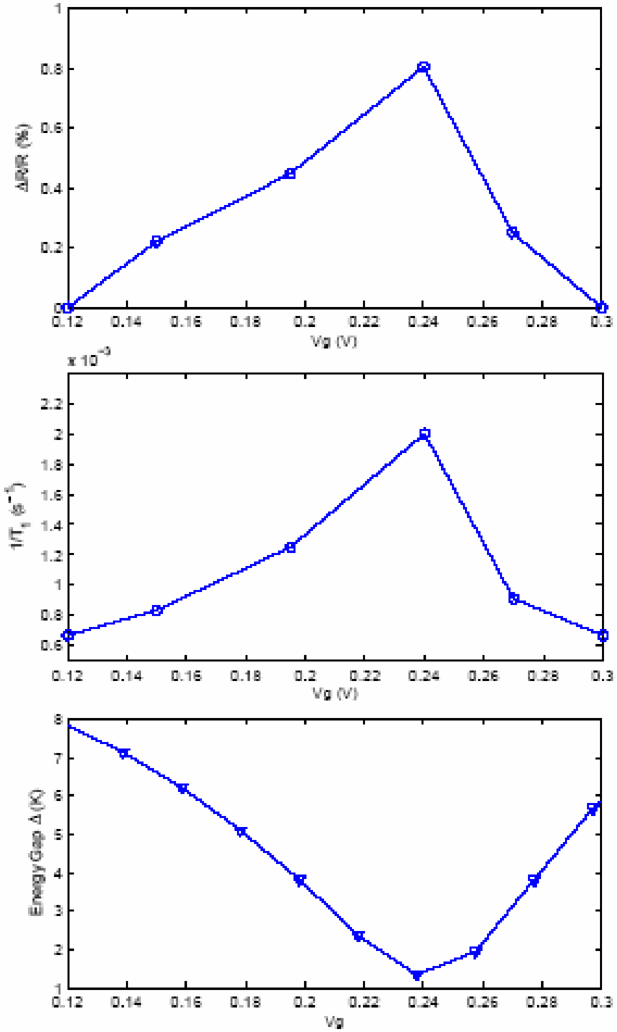
$$|S\rangle = \prod_k [C^\dagger_{(S,1,\uparrow),k} + e^{i\varphi} C^\dagger_{(A,0,\uparrow),k}][C^\dagger_{(S,1,\downarrow),k} + e^{i\varphi} C^\dagger_{(A,0,\downarrow),k}]\,|0\rangle$$

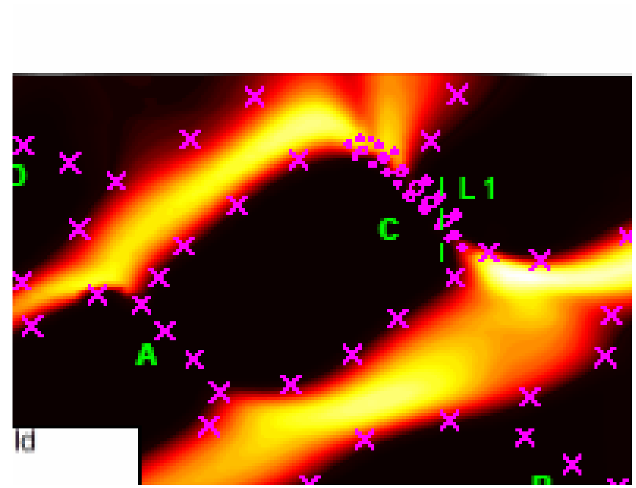


Signal can be detected near point C

D, B, easy plane QHF same real-spins

A, C easy axis QHF pseudo spins correspond to realspins





* Relaxation enhance rapidly towards “crossing point” C: low energy excitations, such as gapless Goldstone mode.
* Even shorter relaxation time at point A

Summary

- Two-subband electron system is an laboratory for study correlated electrons with tunable degenerate levels
- Levitation of extended states due to Landau level mixing
- Effect of spin exchange interaction on the topology phase diagram: ring-structures, a ferromagnetic phase
- Level anti-crossing: psuedo-spin quantum Hall ferromagnetism
- An in-plane magnetic field induced transition
- Resistively-detected NMR to probe spin collections