SAND2015-4332C

New twist in the 5/2 fractional quantum Hall effect

Wei Pan

Sandia National Laboratories

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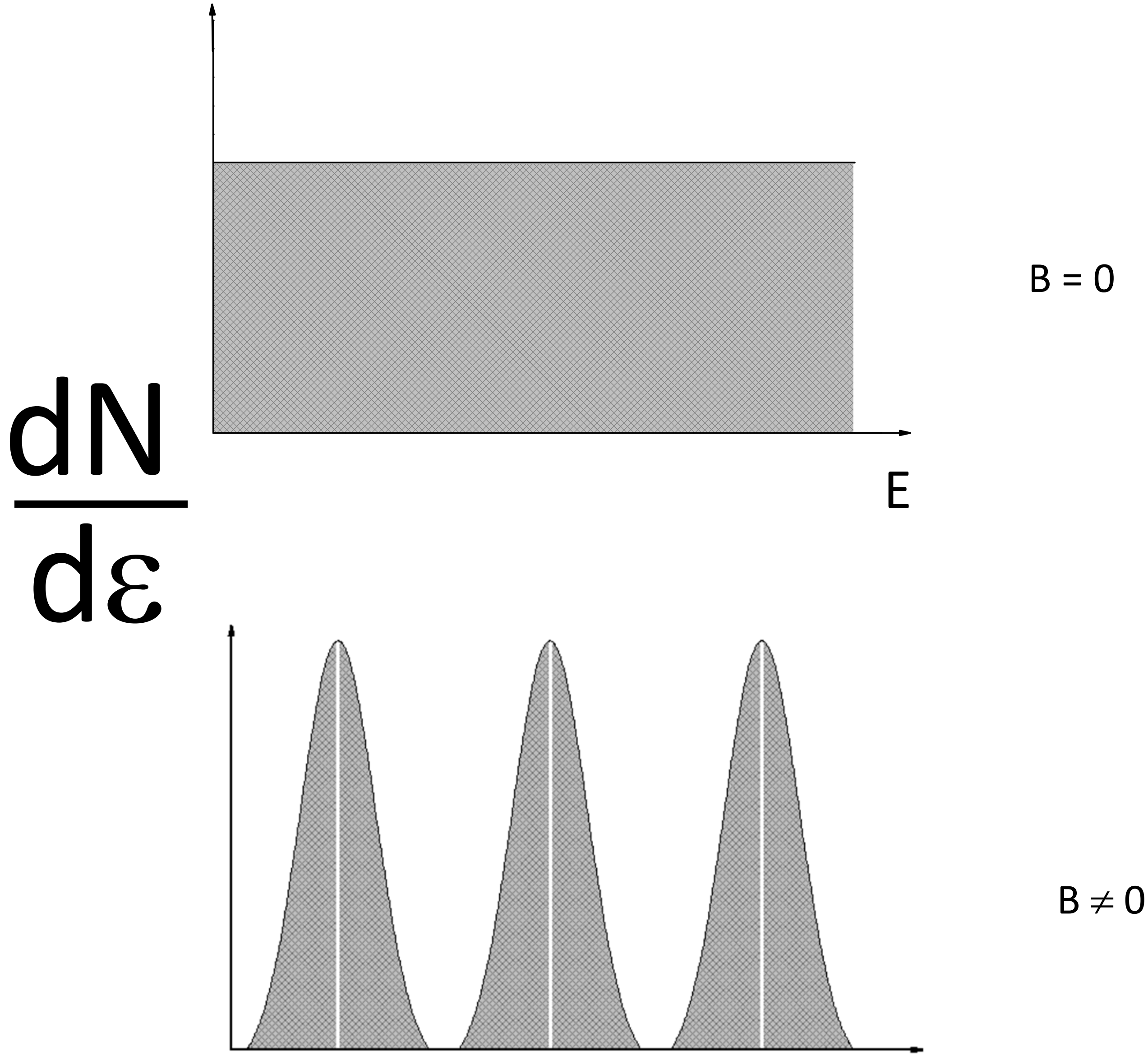
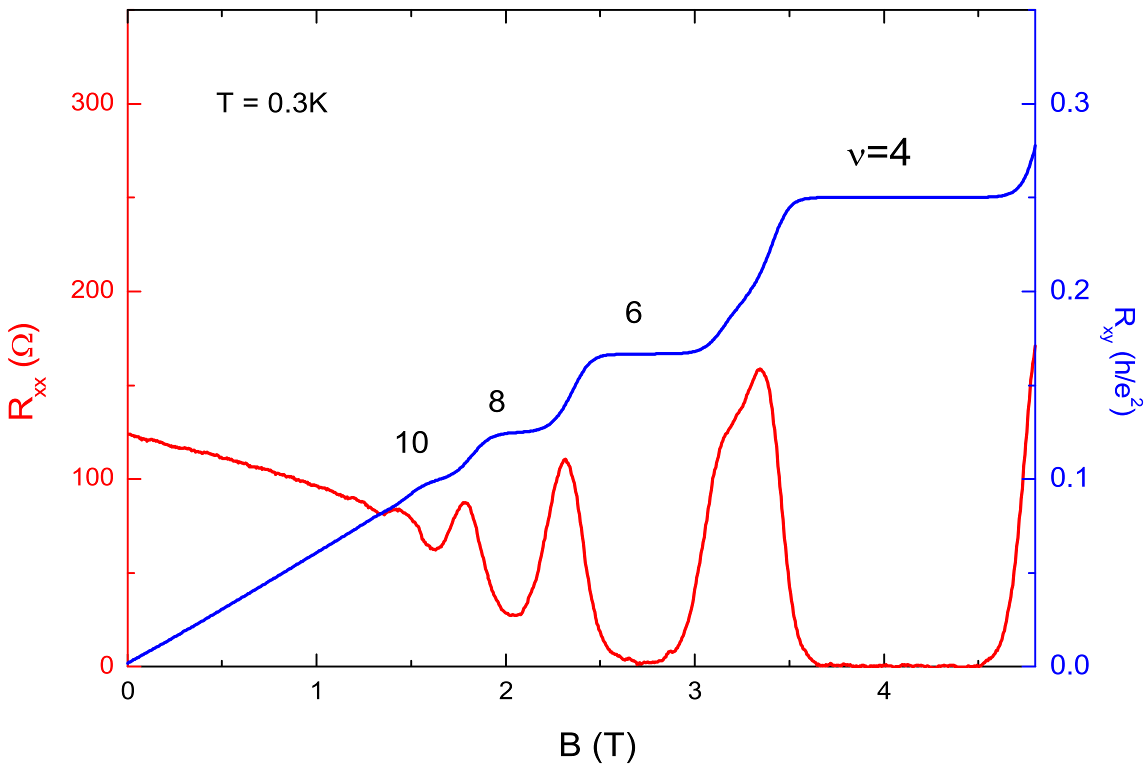
Outline:

- Introduction
- Spin transition in the 5/2 fractional quantum Hall effect
- Anisotropy in the 7/2 fractional quantum Hall effect


dN
dε
E
B = 0
B ≠ 0

Integer quantum Hall effect (IQHE)



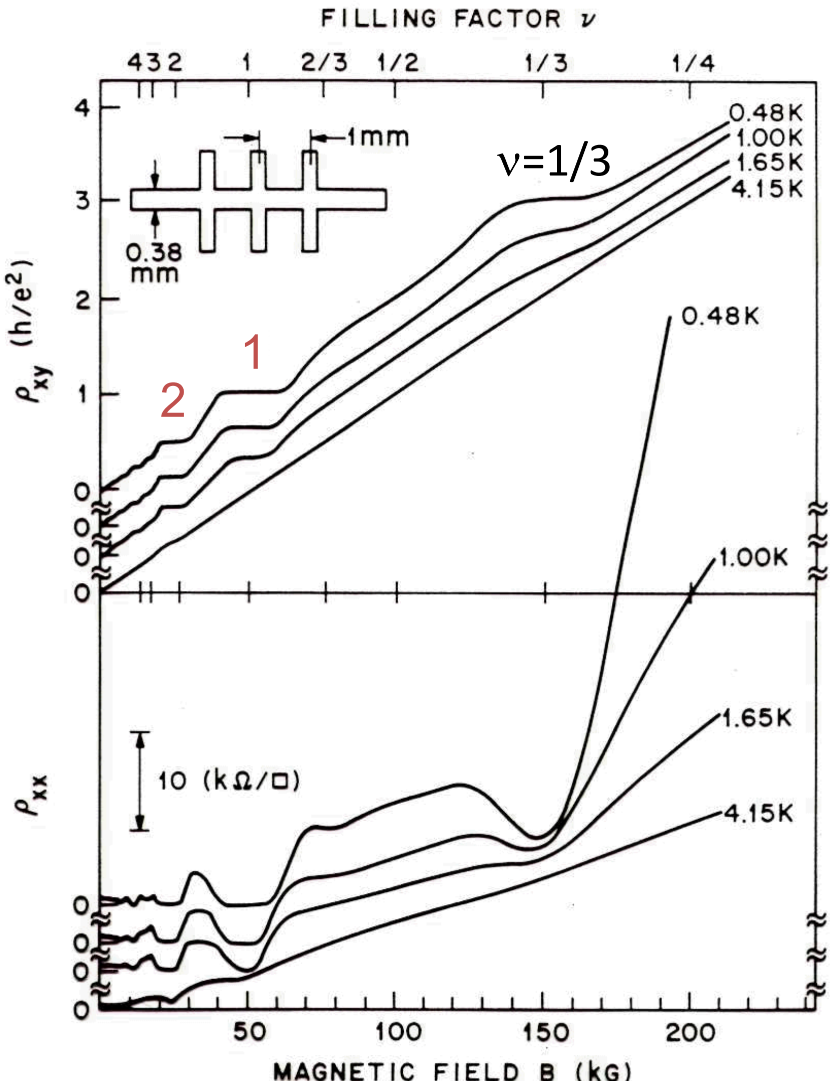
R_{xy} quantized

$$R_{xy} = \frac{h}{\nu e^2}$$

R_{xx} vanishingly small

ν – Landau level filling

fractional quantum Hall effect



Tsui, Stormer, Gossard, 1982

$$R_{xy} = \frac{h}{e^2} / \frac{1}{3}$$

$$\nu = 1/3$$

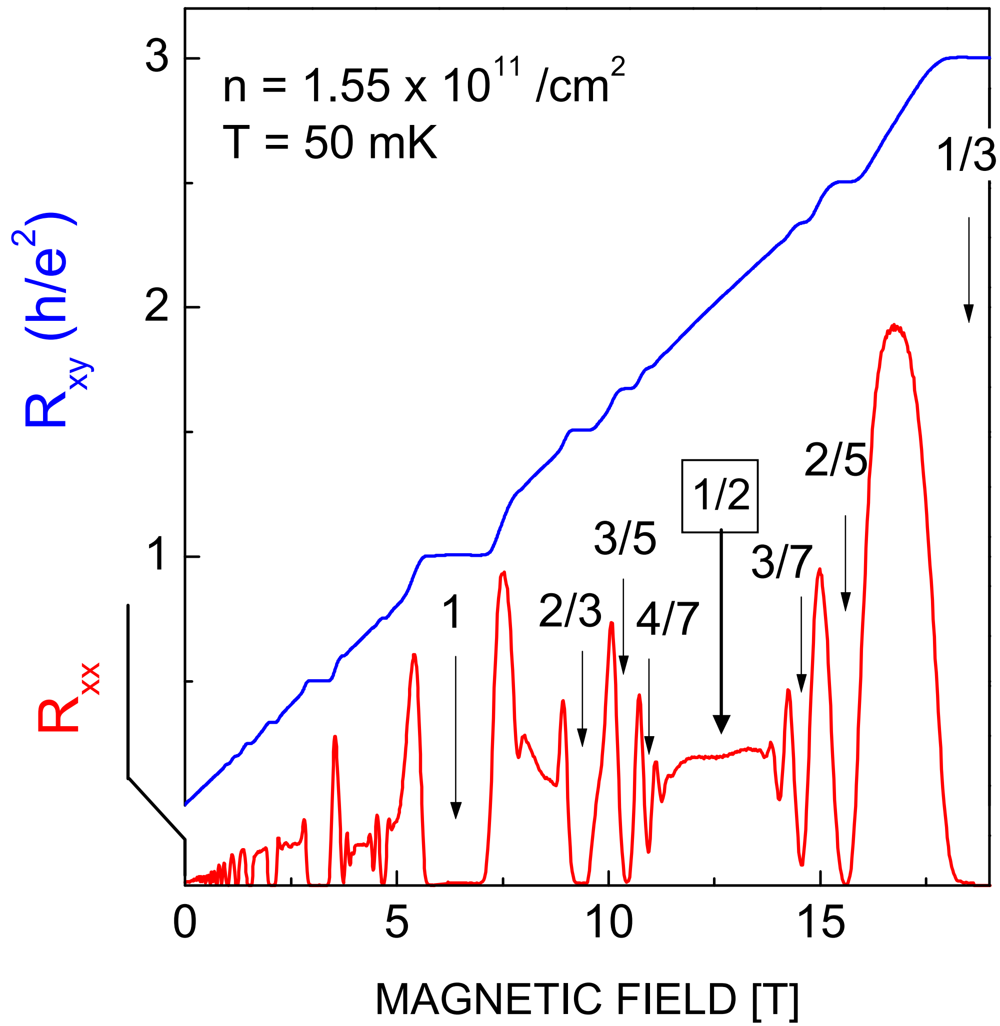
- not a single particle effect
- electron-electron correlation

Laughlin's wavefunction

$$\Psi_{1/3} = \prod_{i<j}^{n} (z_i - z_j)^3 \exp\left[-\frac{1}{4}\sum_{k}^{n} |z_k|^2\right]$$

Fractional Charge at FQHE state!

More fractions

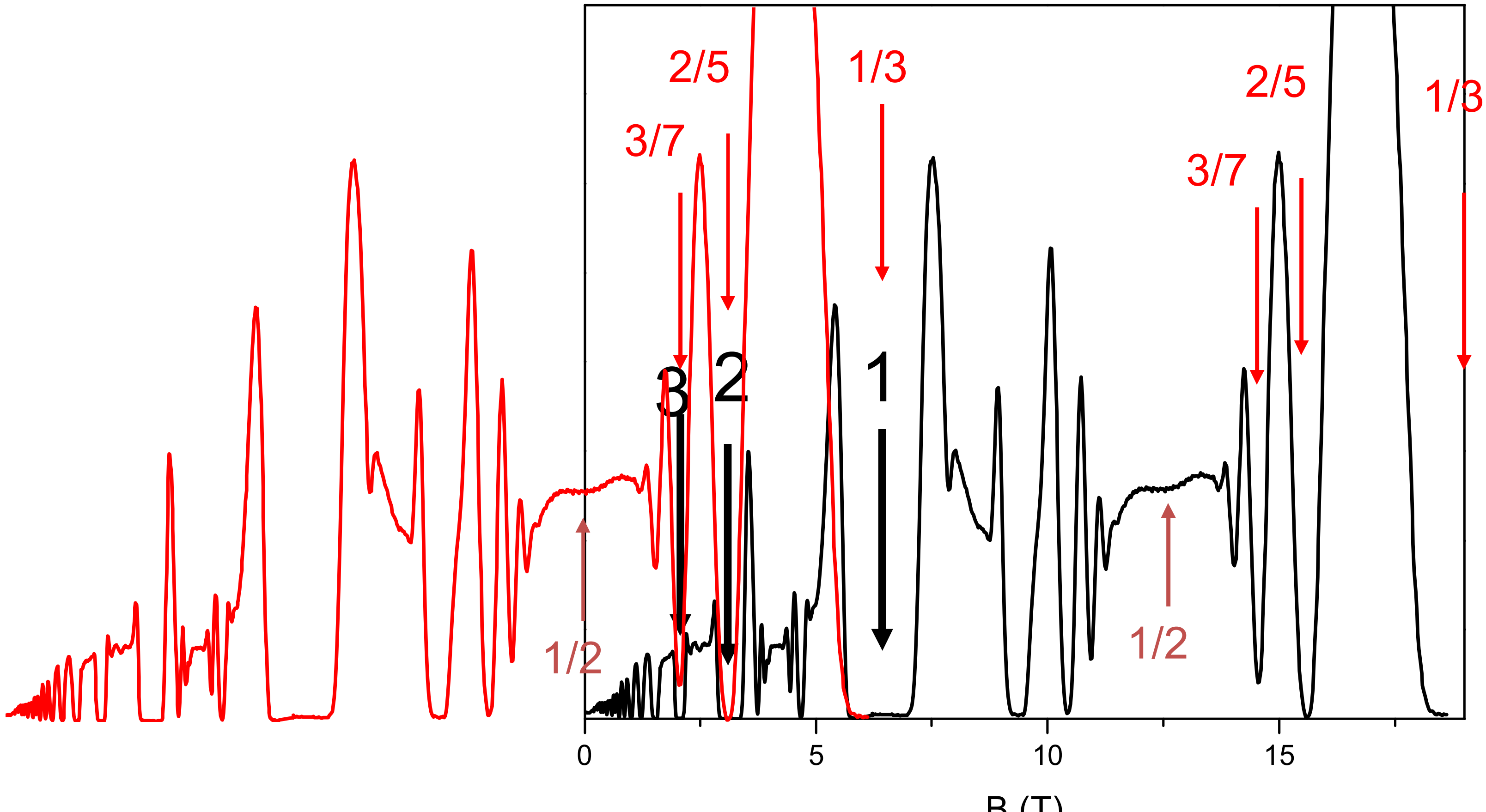


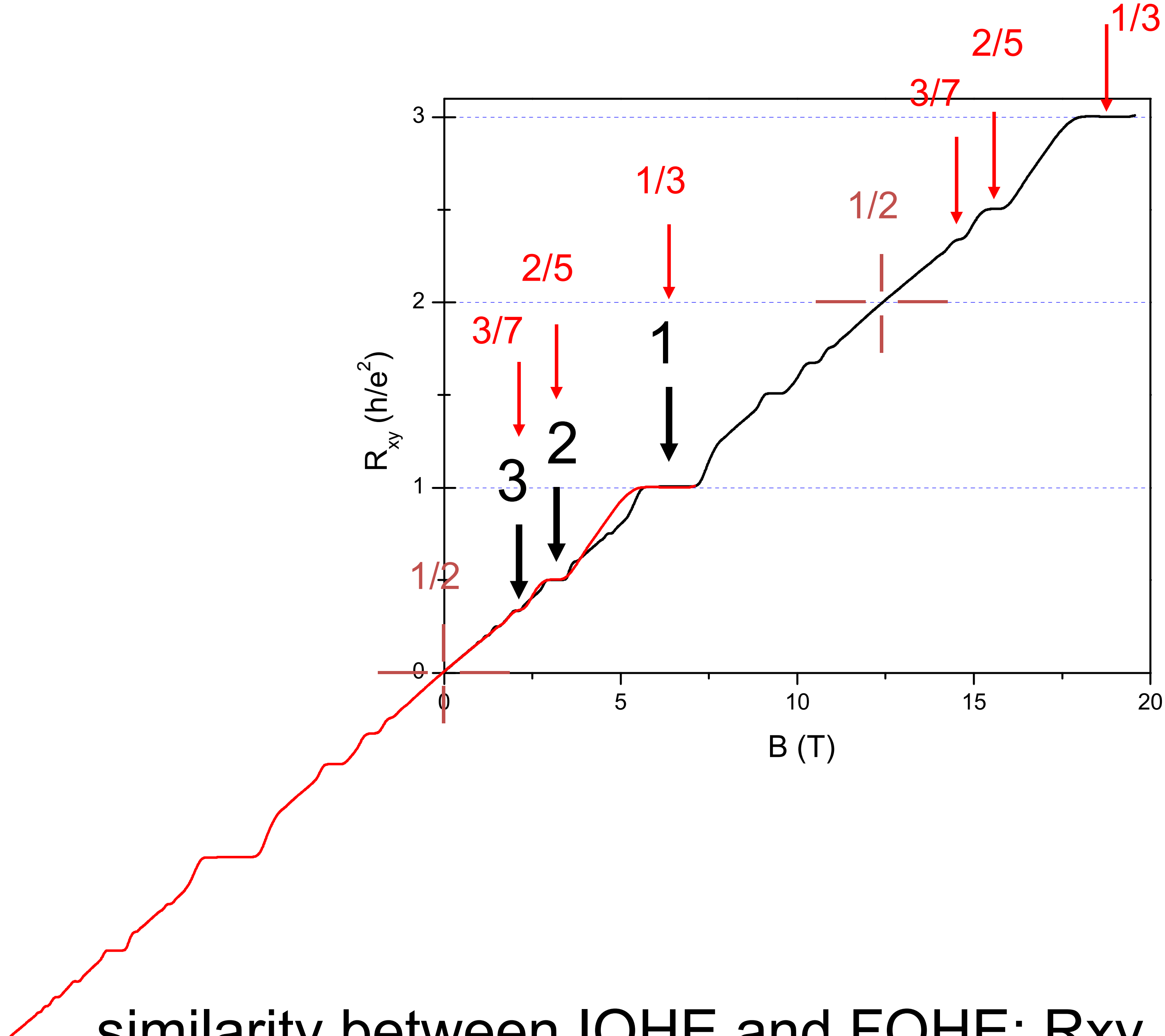
$R_{xy}=(h/e^2)/\nu$

$\nu = 1/3,\ 2/5,\ 3/7\ \ldots$

$2/3,\ 3/5,\ 4/7\ \ldots$

similarity between IQHE and FQHE: Rxx





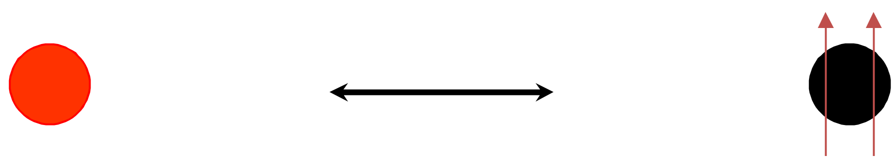
similarity between IQHE and FQHE: Rxy

J. K. Jain

Composite Fermion (CF) Model

J.K. Jain, 1989
B.I. Halperin, P.A. Lee, and N.Read,1993

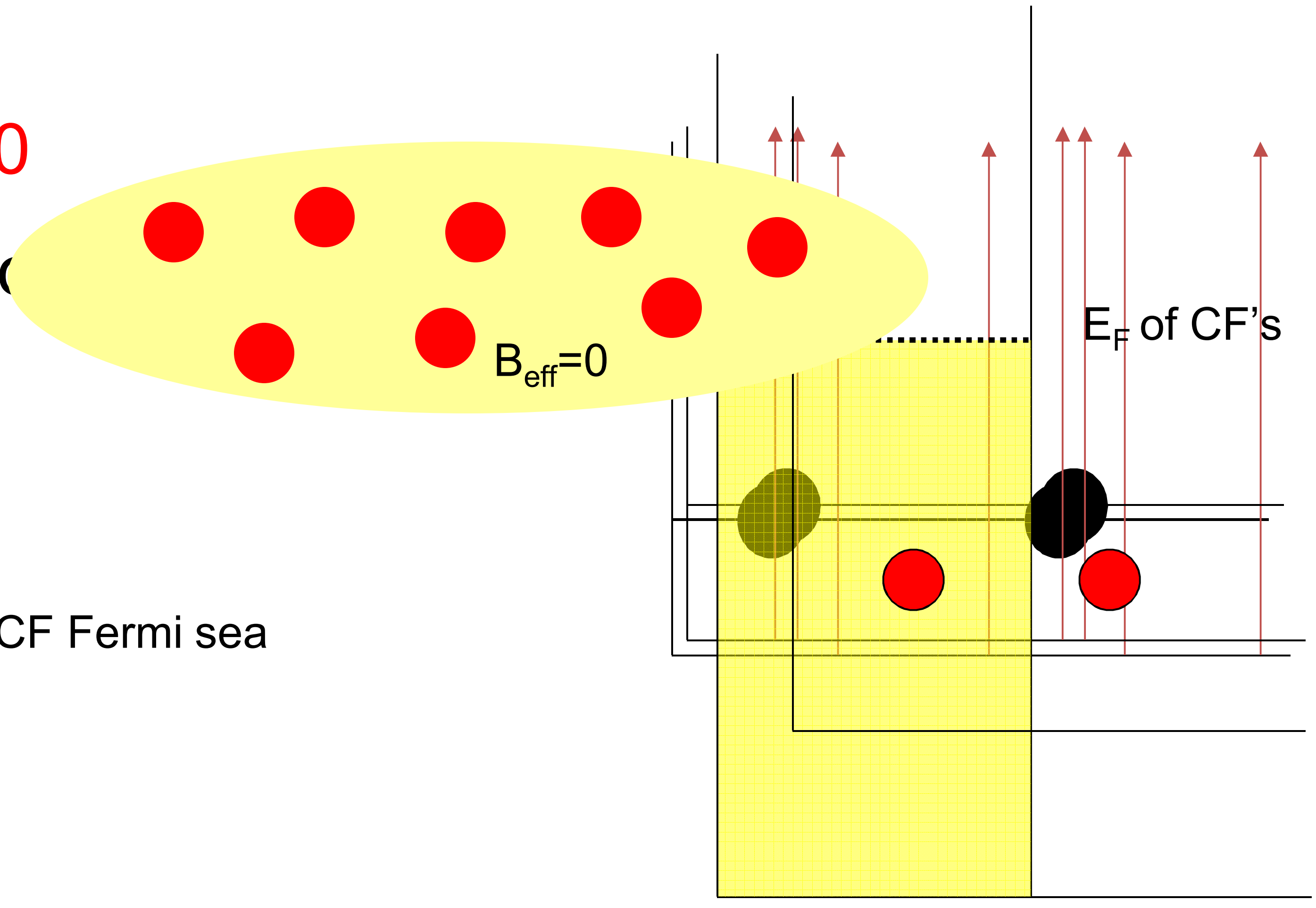
one composite fermion = one electron + 2 flux quanta



$$B_{eff} = B - 2\Phi_0 \times n = B - 2nh/e$$

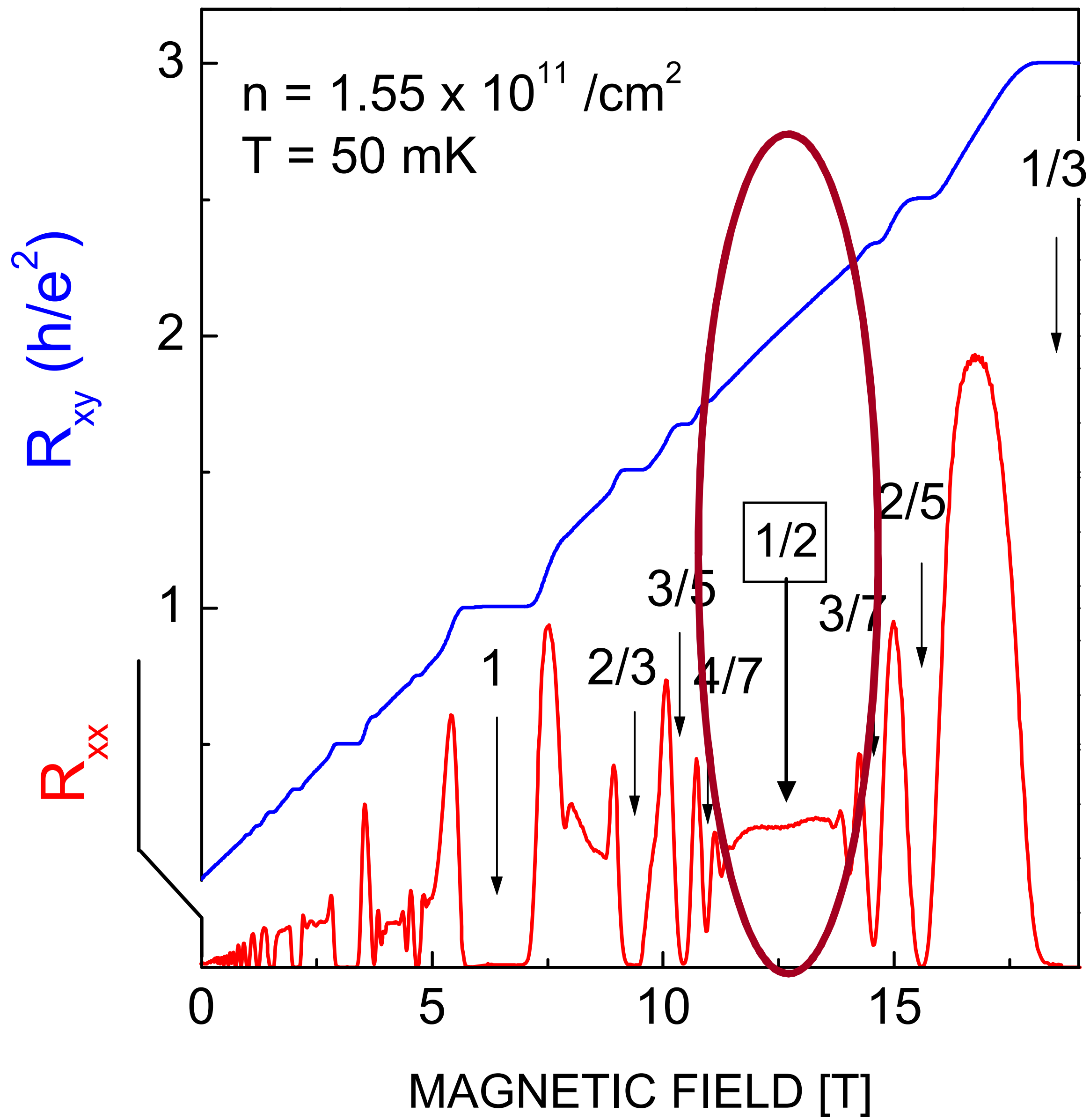
At ν = 1/2

- $B_{eff} = 0$
- CF's fo

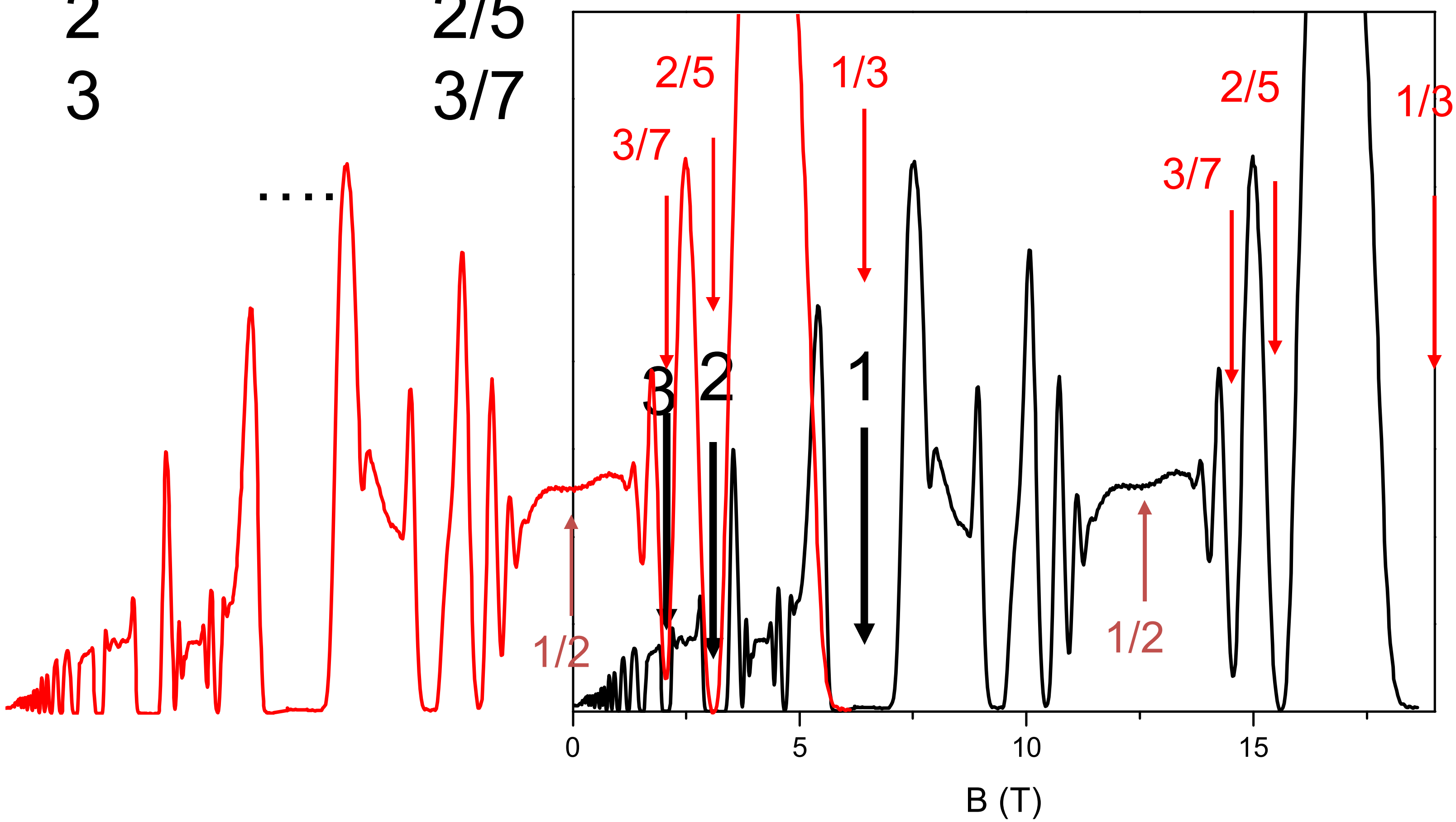


- CF Fermi sea

Featureless transport around ν=1/2 – Fermi sea state



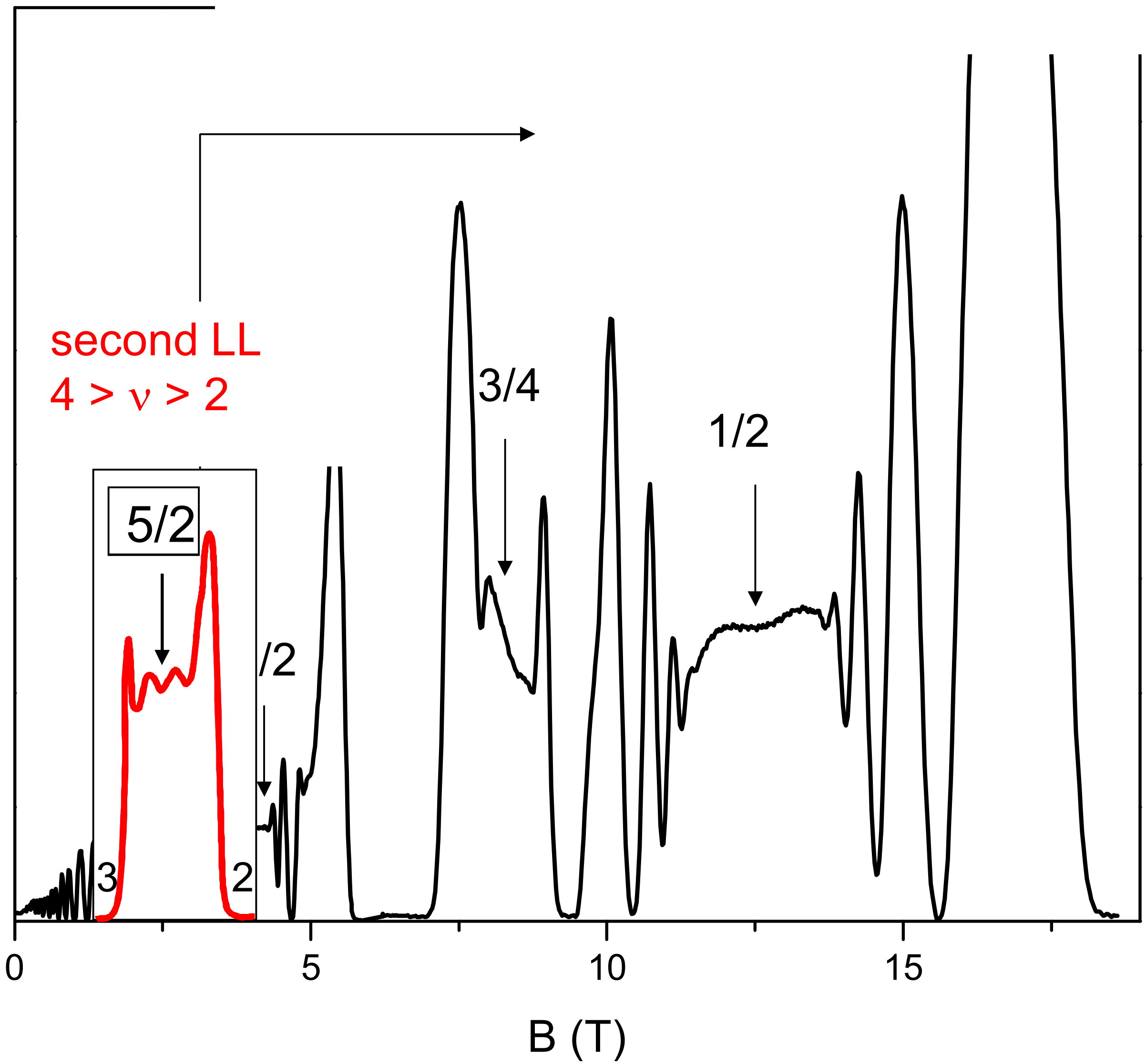
IQHE of CF	FQHE of e^-
p	$\nu = p/(2p+1)$
1	1/3
2	2/5
3	3/7



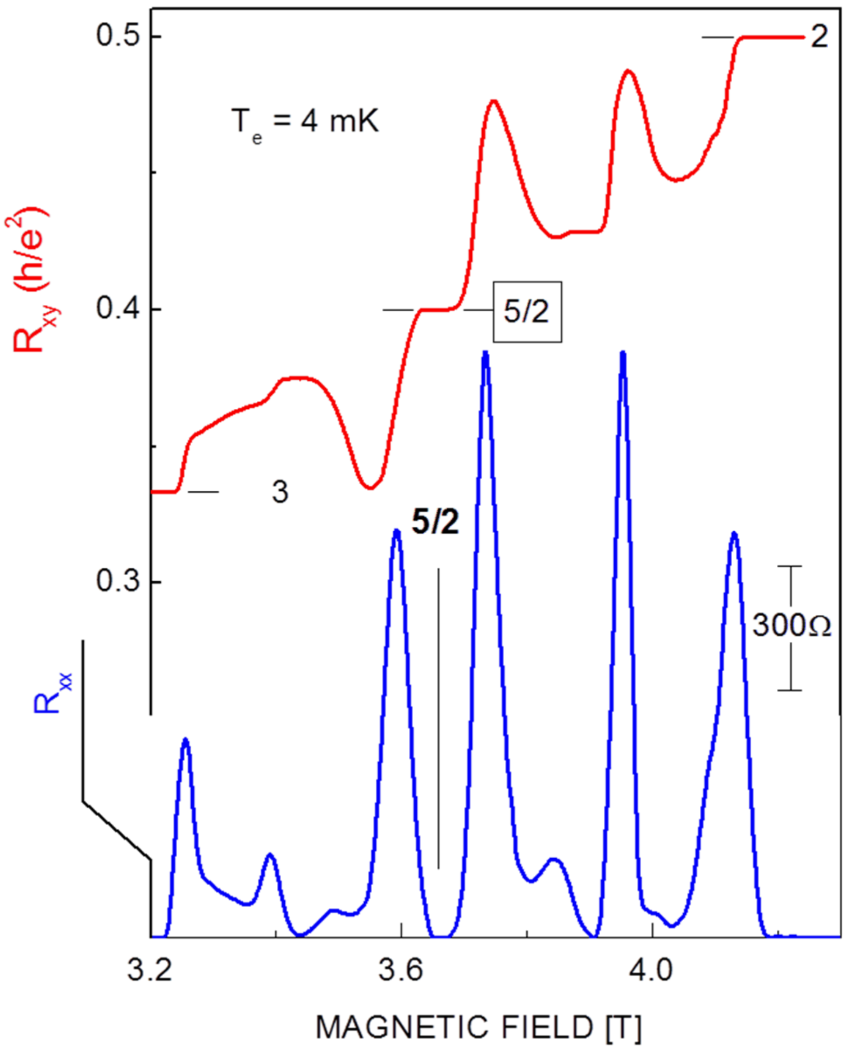
Lots of Fractions Observed

1/3	1/5	1/7	1/9	2/11	2/13	2/15	2/17	3/19	5/21	6/23
2/3	2/5	2/7	2/9	3/11	3/13	4/15	3/17	5/19	10/21	6/25
4/3	3/5	3/7	4/9	4/11	4/13	7/15	4/17	9/19		
5/3	4/5	4/7	5/9	5/11	5/13	8/15	5/17	10/19		
7/3	6/5	5/7	7/9	6/11	6/13	11/15	6/17			
8/3	7/5	9/7	11/9	7/11	7/13	22/15	8/17			
	8/5	10/7	13/9	8/11	10/13	23/15	9/17			
	9/5	11/7	14/9	16/11	19/13					
	11/5	12/7		17/11	20/13					
	12/5									
	13/5									
	14/5									

in the lowest Landau level, the
CF model applies to almost all the FQHE
states and the even-denominator fractions



True FQHE at ν=5/2



electron mobility

μ≈17×10^6 cm^2/Vs

Pan, Xia, and et al, PRL (1999)

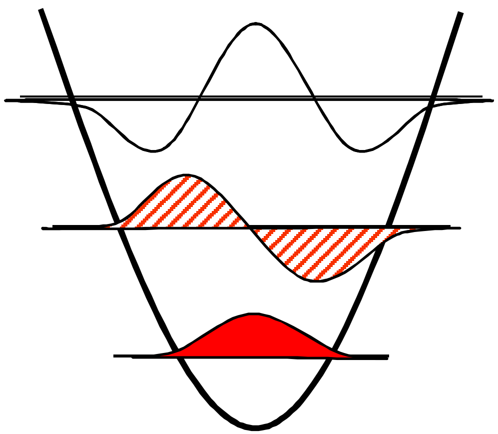
5/2-state is a true FQHE state with even-denominator

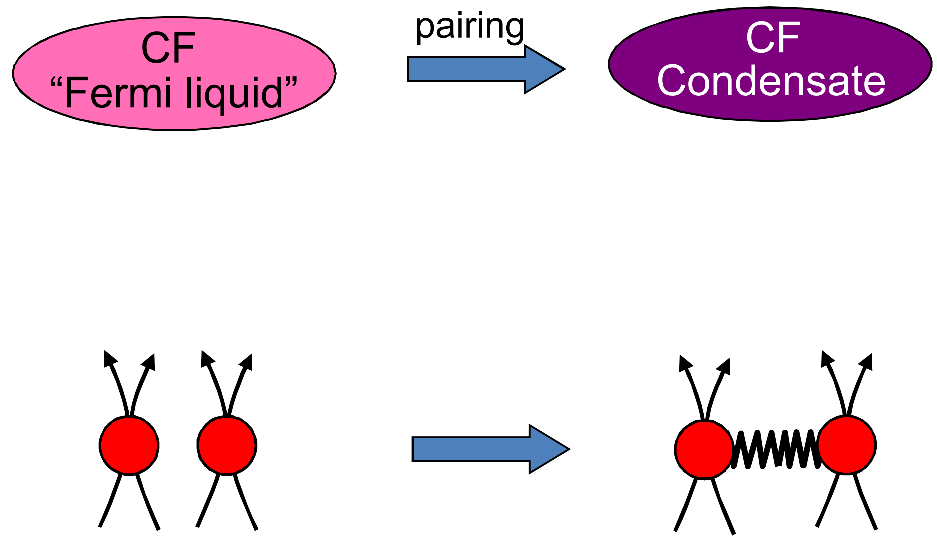
- R_{xx} is vanishingly small
- quantized Hall plateau

- Can't be explained by Laughlin's theory
- Can't be explained by hierarchical model
- Doesn't belong to any CF sequences
- Due to pairing of CF's

Origin of 5/2-state: BCS pairing of CF's

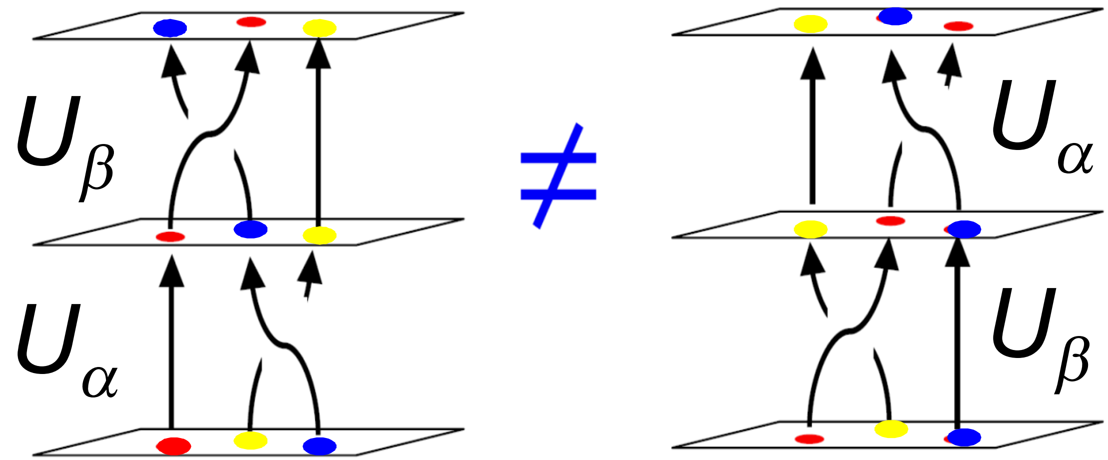
ν=5/2





Non-Abelian quantum Hall state

$U_\beta U_\alpha \neq U_\alpha U_\beta$



Topological quantum computation

error rate ~ $$\frac{T}{\Delta} e^{-\Delta/T} < 10^{-30}$$

Spin Polarization of the 5/2 Fractional Quantum Hall Effect

Non-abelian quantum Hall state

Spin polarized

Is the 5/2 non-abelian state?

www.sciencemag.org SCIENCE VOL 320 16 MAY 2008

RESEARCH ARTICLES

Quasi-Particle Properties from Tunneling in the $\nu = 5/2$ Fractional Quantum Hall State

Iuliana P. Radu,[1] J. B. Miller,[2] C. M. Marcus,[2*] M. A. Kastner,[1] L. N. Pfeiffer,[3] K. W. West[3]

Quasi-particles with fractional charge and statistics, as well as modified Coulomb intera in a two-dimensional electron system in the fractional quantum Hall (FQH) regime. T models of the FQH state at filling fraction $\nu = 5/2$ make the further prediction that tl function can encode the interchange of two quasi-particles, making this state relevan topological quantum computing. We show that bias-dependent tunneling across a na constriction at $\nu = 5/2$ exhibits temperature scaling and, from fits to the theoretical s extract values for the effective charge and the interaction parameter of the quasi-parti of values obtained are consistent with those predicted by certain models of the 5/2 st

tiple constrictions to create interference among tunneling paths (11, 22–26).

Experimentally, the quasi-particle charge, e^*, has been investigated for FQH states at $\nu < 1$ with use of shot noise (27, 28) and interferometry (29), yielding results generally consistent with theory. A recent measurement of quasi-particle charge for the $\nu = 5/2$ state, also using shot noise, obtained values consistent with $e^* = 1/4$ (30). Previous experiments of quasi-particle tunneling

marked in Fig. 5. Evidently the states with $e^* = 1/4$ and $g = 1/2$, both nonabelian, are most consistent with our tunneling data. The

PHYSICAL REVIEW B **85**, 165321 (2012)

Measurements of quasiparticle tunneling in the $v = \frac{5}{2}$ fractional quantum

X. Lin,[1,*] C. Dillard,[2] M. A. Kastner,[2] L. N. Pfeiffer,[3] and K. W. West[3]
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(Received 17 January 2012; published 25 April 2012)

Some models of the 5/2 fractional quantum Hall state predict that the quasiparticle have non-Abelian statistics: exchange of two quasiparticles changes the wave functi just the usual change of phase factor. Such non-Abelian statistics would make th decoherence, making it a candidate for implementation of topological quantum c quasiparticle tunneling as a function of temperature and dc bias between counterpropagating edge s to theory give e^*, the quasiparticle effective charge, close to the expected value of $e/4$ and g, the s the interaction between quasiparticles, close to 3/8. Fits corresponding to the various proposed wave along with qualitative features of the data, strongly favor the Abelian 331 state.

PHYSICAL REVIEW B **90**, 075403 (2014)

Experimental probe of topological orders and edge excitations in the second Landau level

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(Received 1 May 2014; revised manuscript received 29 June 2014; published 5 August 2014)

We measure weak quasiparticle tunneling across a constriction in the second Landau level. At $\nu = 7/3$, 8/3, and 5/2, comparison of temperature and dc bias dependence to weak tunneling theory allows extracting

the data, strongly favor the Abelian 331 state.

extracted scaling parameters. For $\nu = 7/3$, the backscattering strength strongly affects the scaling parameters, whereas quasiparticle tunneling at $\nu = 8/3$ and 5/2 appears more robust. Our results provide important additional insight about the physics in the second Landau level and contribute to the understanding of the physics underlying the fractional quantum Hall states at $\nu = 7/3$, 8/3, and 5/2.

Spin polarization of the 5/2 state ?

PRL **105**, 096801 (2010) PHYSICAL REVIEW LETTERS week ending 27 AUGUST 2010

Optical Probing of the Spin Polarization of the $\nu = 5/2$ Quantum Hall State

M. Stern,[1,*] P. Plochocka,[2] V. Umansky,[1] D. K. Maude,[2] M. Potemski,[2] and I. Bar-Joseph[1]

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(Received 17 May 2010; published 23 August 2010)

We apply polarization resolved photoluminescence spectroscopy to measure the spin polarization of a two dimensional electron gas in perpendicular magnetic field. We find that the splitting between the σ^+ and σ^- polarizations exhibits a sharp drop at $\nu = 5/2$ and is equal to the bare Zeeman energy, which resembles the behavior at even filling factors. We show that this behavior is consistent with filling factor

resembles the behavior at even filling factors. We show that this behavior is consistent with filling factor $\nu = 5/2$ being unpolarized.

PRL **108**, 066810 (2012) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2012

NMR Probing of the Spin Polarization of the $\nu = 5/2$ Quantum Hall State

M. Stern,[1,*] B. A. Piot,[2] Y. Vardi,[1] V. Umansky,[1] P. Plochocka,[2] D. K. Maude,[2] and I. Bar-Joseph[1]

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(Received 27 October 2011; published 10 February 2012)

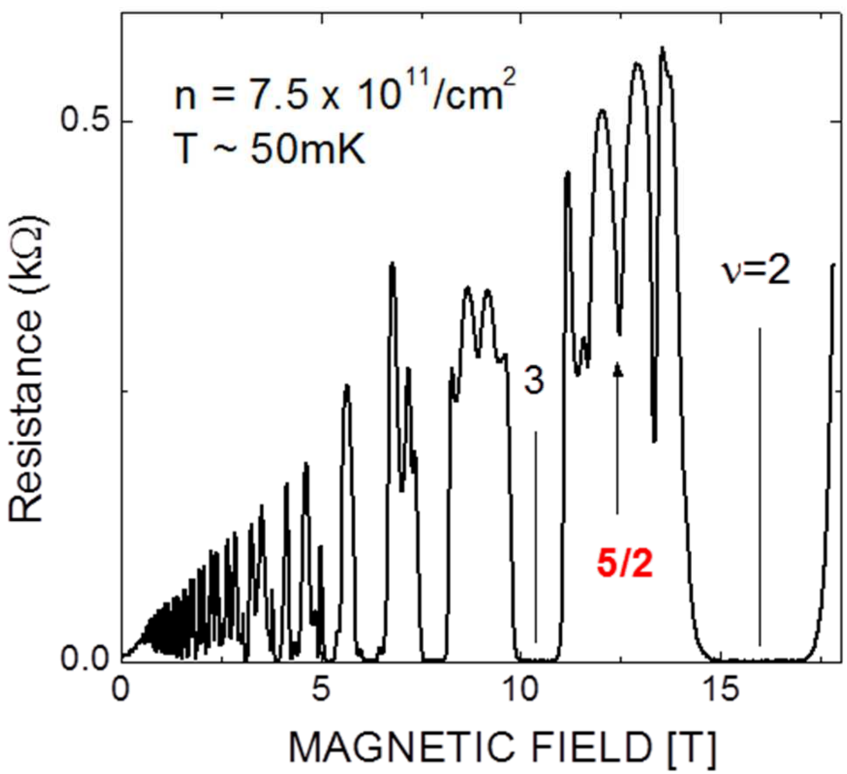
Resistively detected nuclear magnetic resonance is used to measure the Knight shift of the ^{75}As nuclei and determine the electron spin polarization of the fractional quantum Hall states of the second Landau level. We show that the 5/2 state is fully polarized within experimental error, thus confirming a fundamental assumption of the Moore-Read theory. We measure the electron heating under radio frequency excitation and show that we are able to detect NMR at electron temperatures down to 30 mK

level. We show that the 5/2 state is fully polarized within experimental error,

SPIN POLARIZATION OF THE 5/2 FQHE

– DENSITY DEPENDENCE OF THE 5/2 ENERGY GAP

5/2 state at very high magnetic field



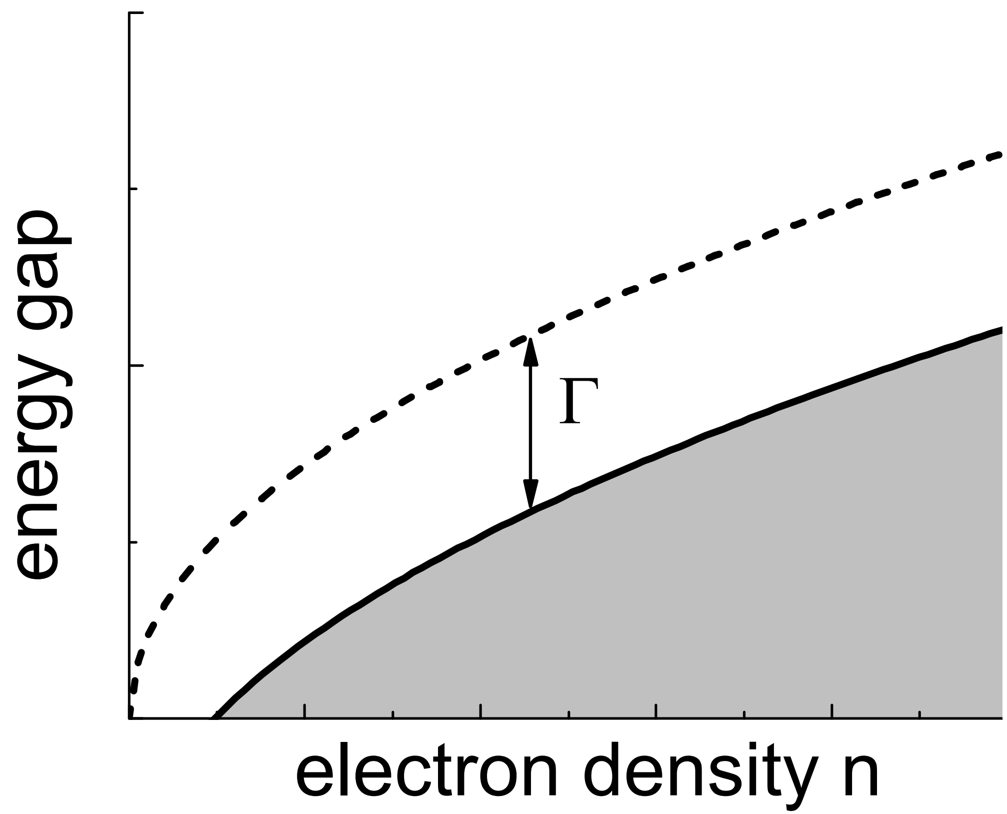
At high B,
$E_z = g\mu_B B \sim 4K >> \Delta_{5/2}$

Spin-singlet state should no longer exist

5/2-state probably is spin-polarized

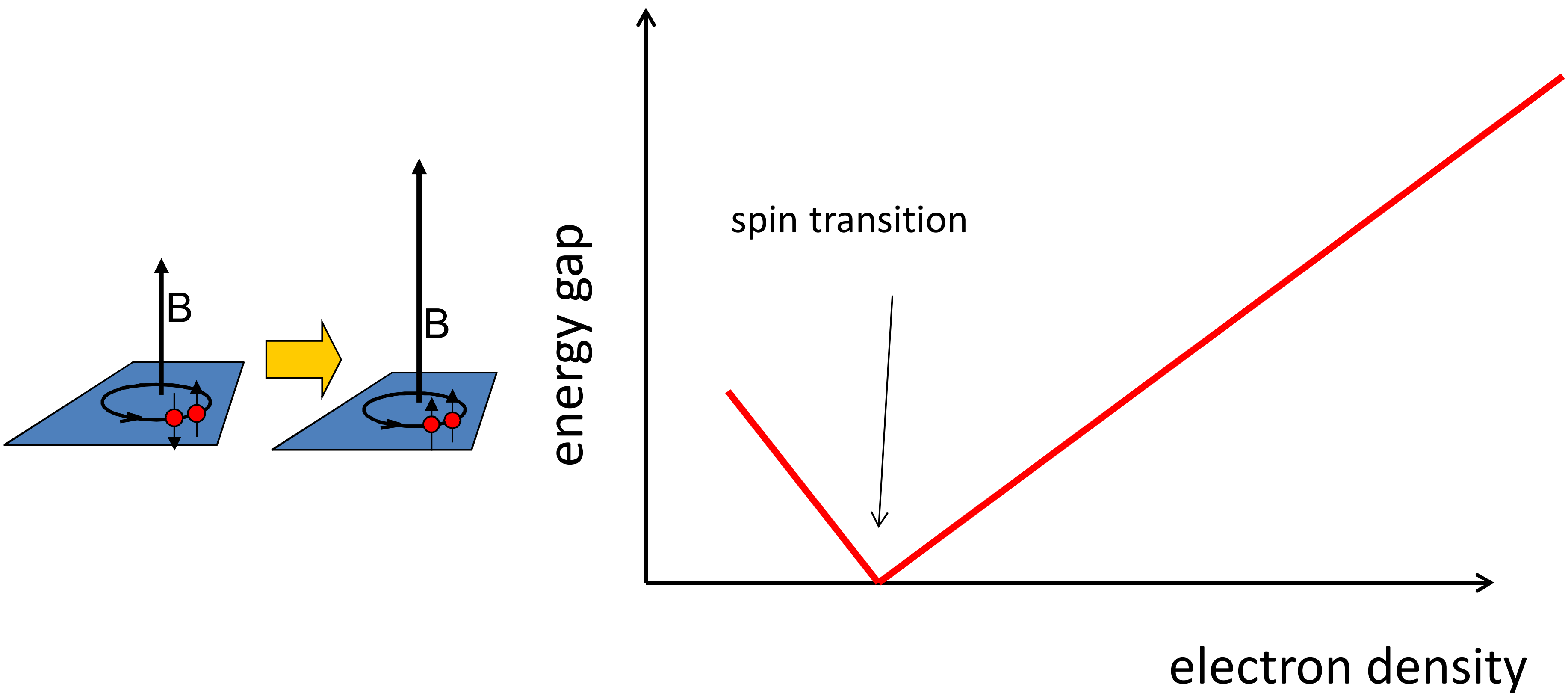
$\Delta \propto E_c$ (Coulomb energy) = $e^2/\varepsilon r \propto n^{1/2}$

spin polarized ground state: $\Delta = \alpha\sqrt{n} - \Gamma$

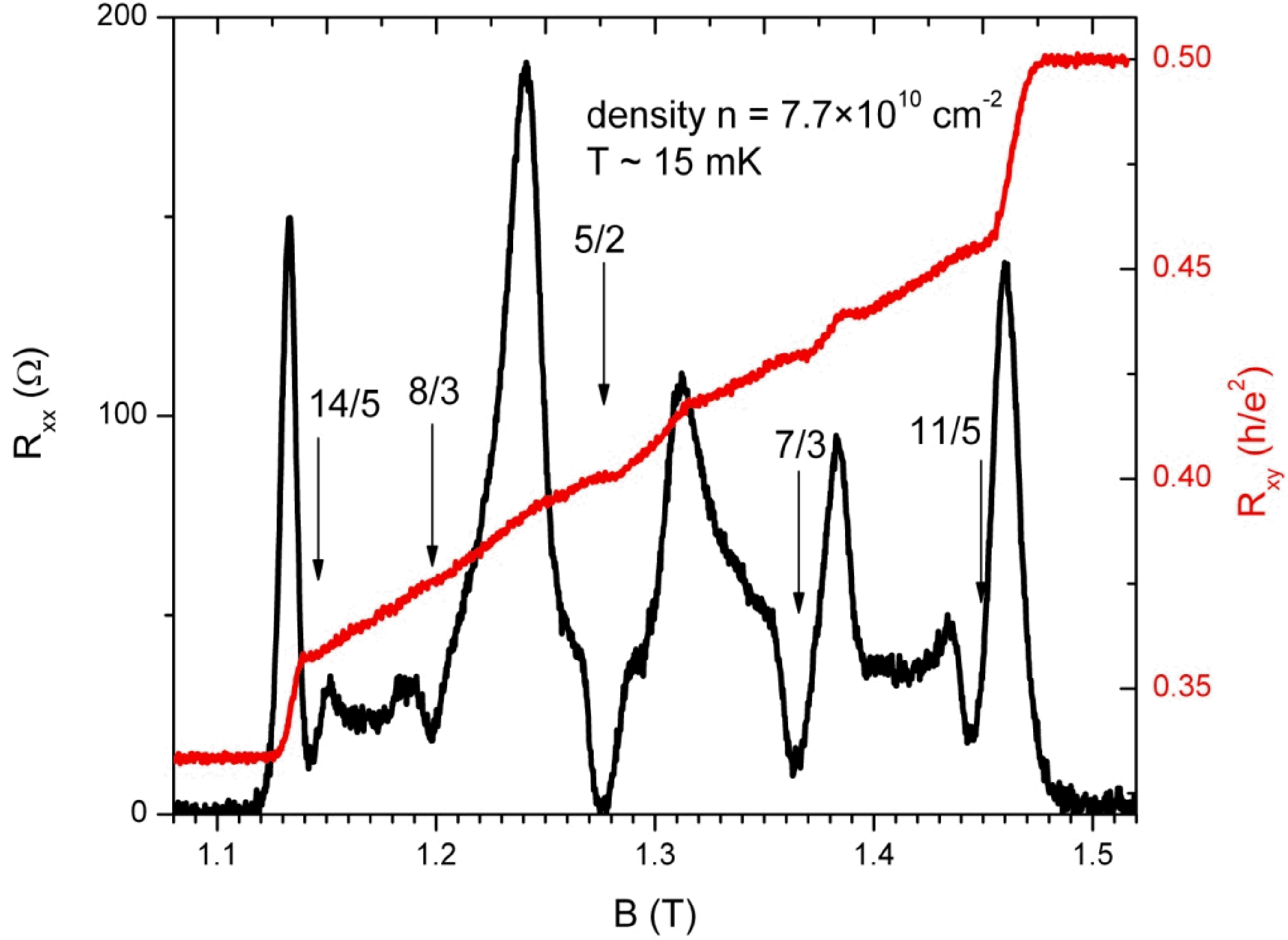


$E_c \propto n^{1/2}$, E_z(Zeeman energy) $\propto n$

spin unpolarized ground state: $\Delta = \alpha\sqrt{n} - \beta n - \Gamma$

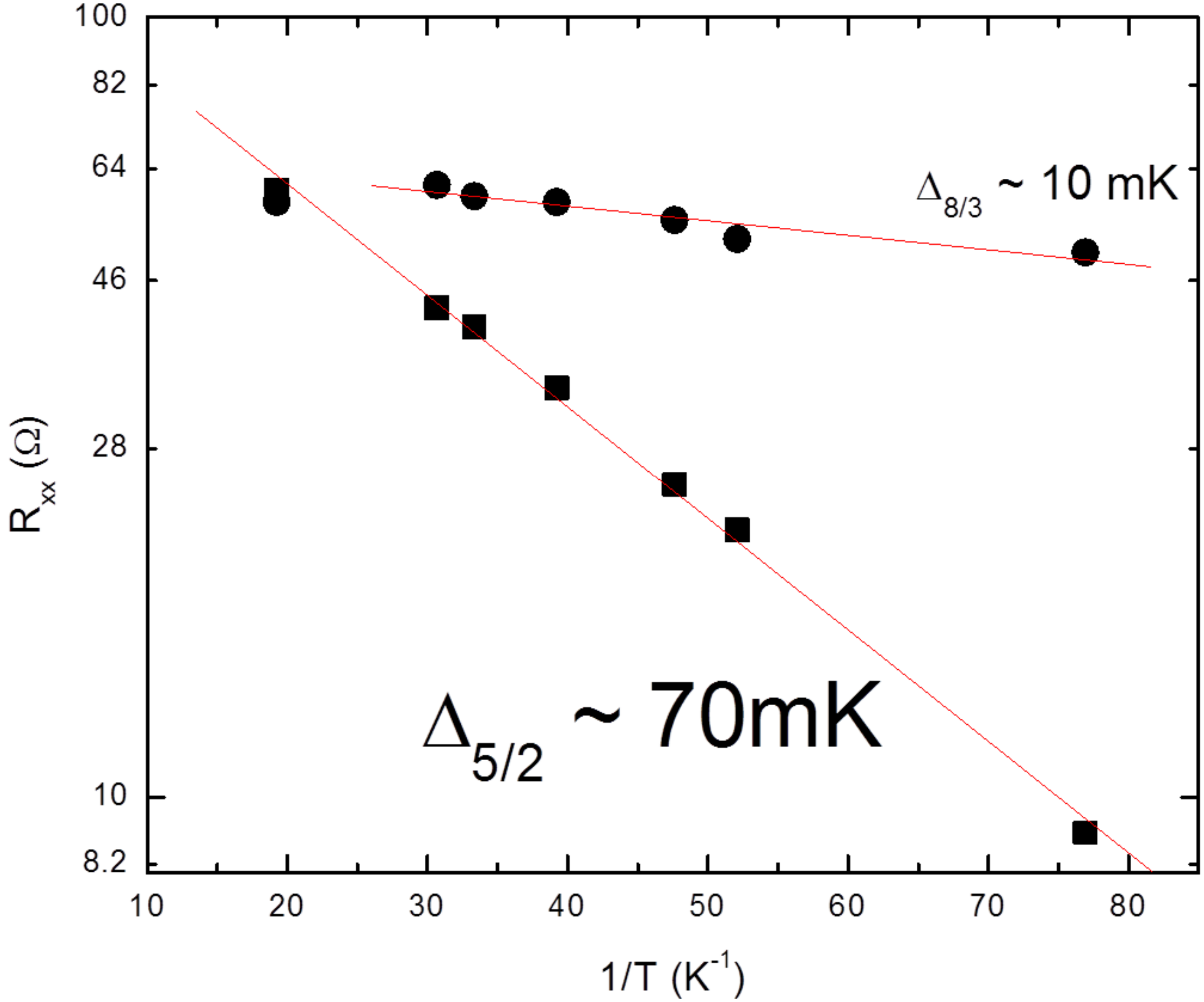


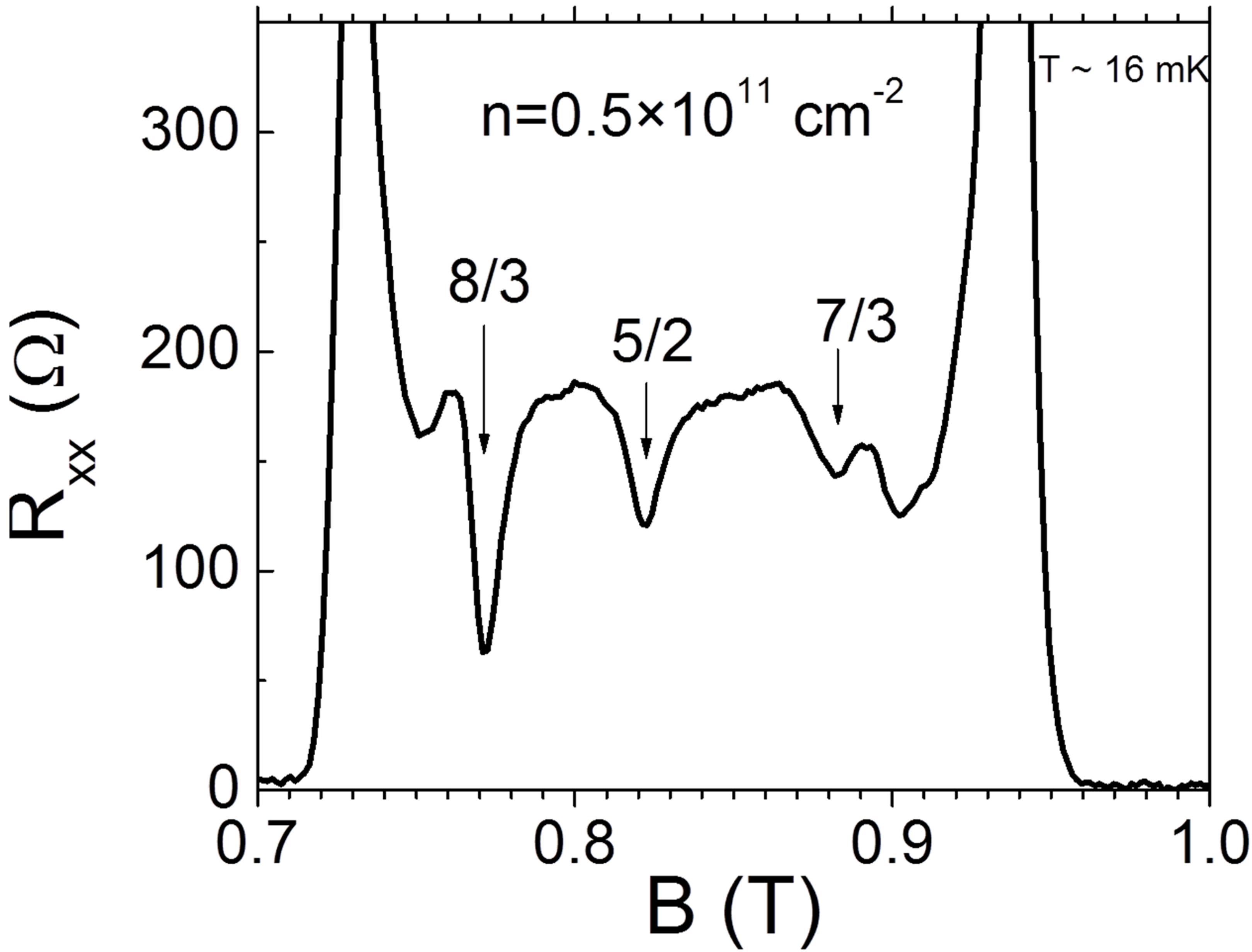
samples	well width (nm)	density (10^{11} cm^{-2})	mobility (10^6/V s)	l_B at ν=5/2 (nm)	W/l_B
A	65	0.41	10	31.1	2.1
B	60	0.5	10	28.2	2.1
C	56	0.77	13	22.7	2.4
D	45	1.15	13.8	18.6	2.4
E	33	2.1	23	13.8	2.4
F	30	2.6	24	12.4	2.4
G	30	3.1	31	11.3	2.6



density n = 7.7×10^10 cm^-2
T ~ 15 mK
14/5
8/3
5/2
7/3
11/5
200
100
0
0.50
0.45
0.40
0.35
1.1
1.2
1.3
1.4
1.5
Rxx (Ω)
Rxy (h/e^2)
B (T)

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

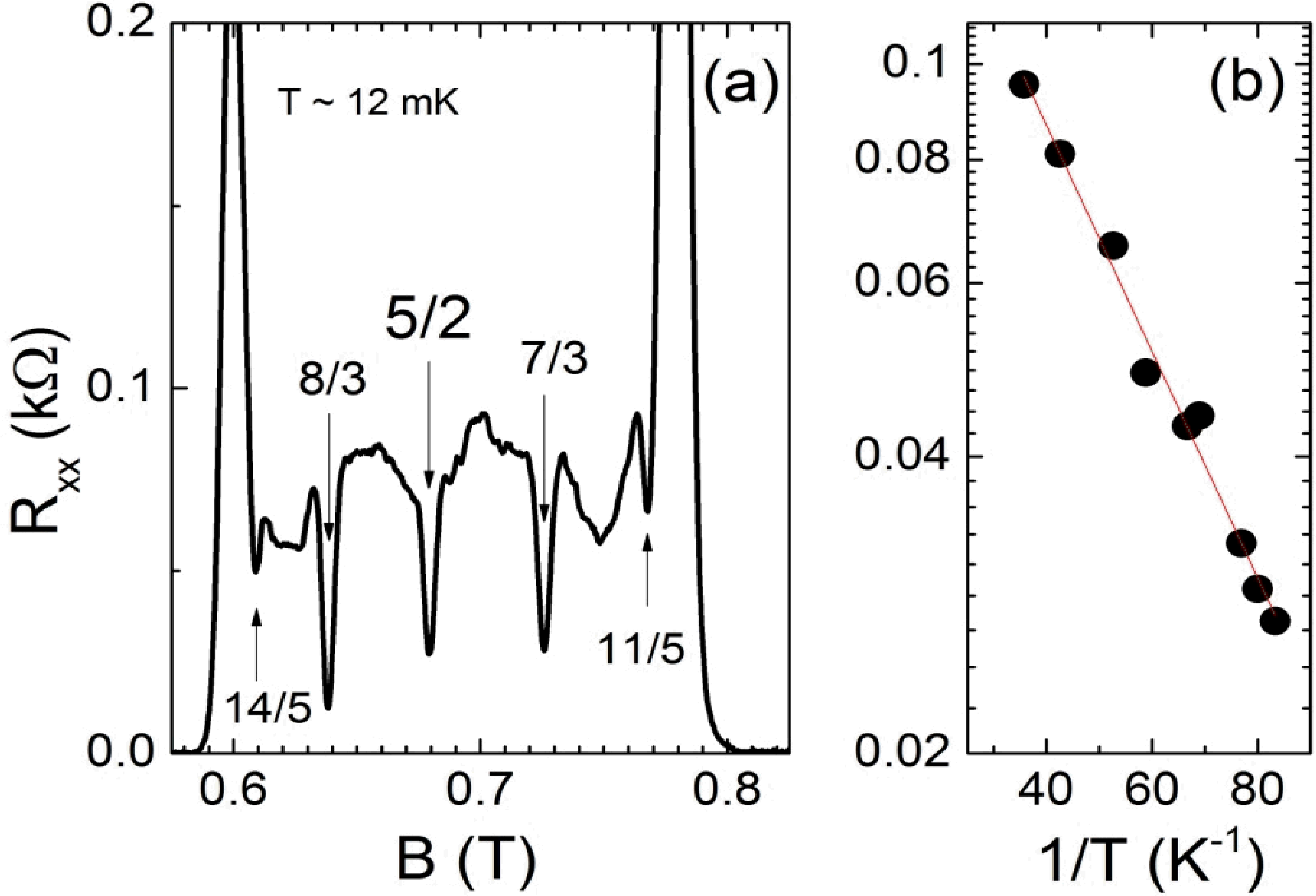




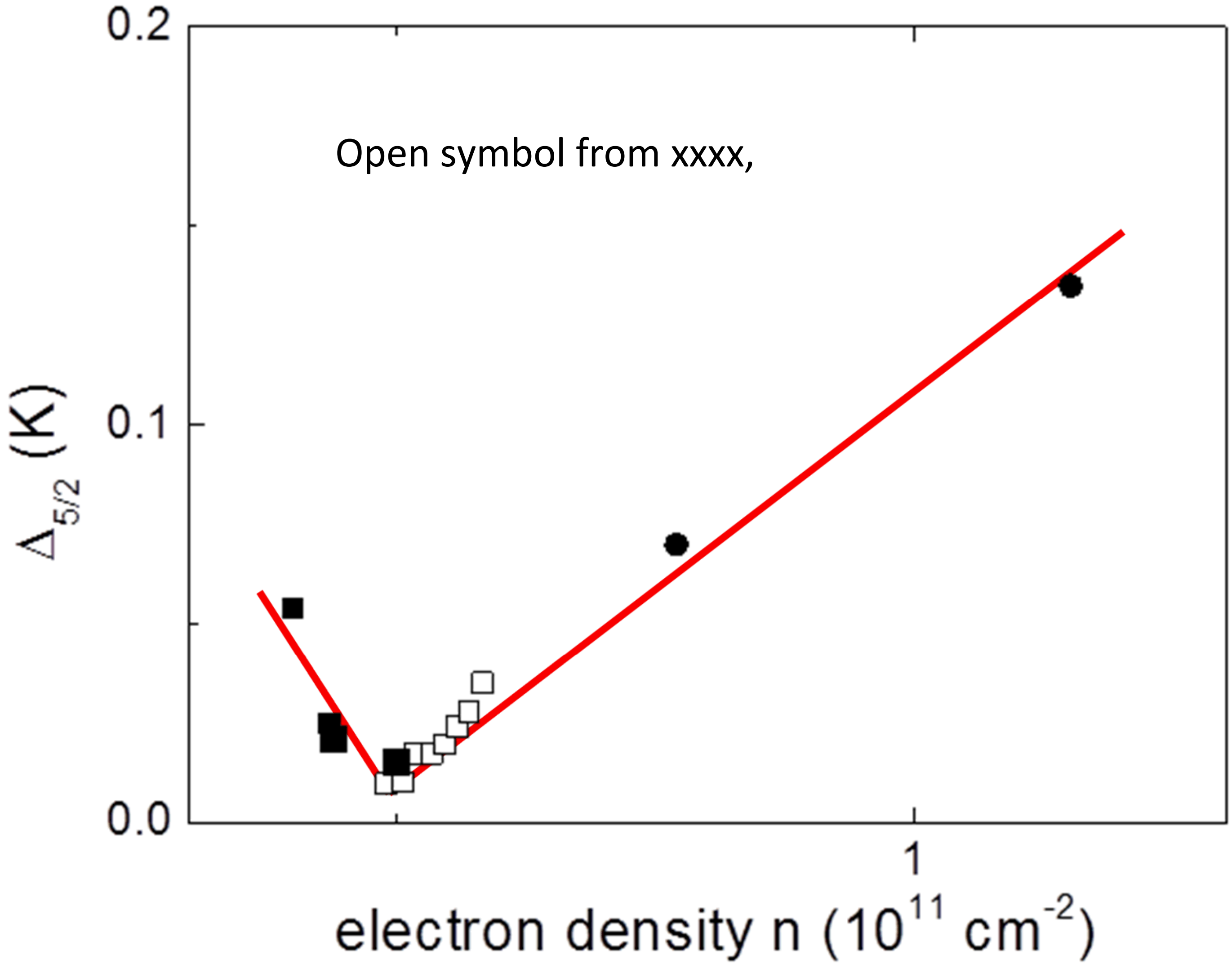
T ~ 16 mK
n=0.5×10^11 cm^-2
8/3
5/2
7/3
300
200
100
0
R_{xx} (Ω)
0.7
0.8
0.9
1.0
B (T)

$n = 0.41\times10^{11}$ cm^{-2}

$\Delta_{5/2} \sim 55$ mK



Spin transition in the 5/2 state



The transition is

• a spin transition from a spin singlet state (an Abelian state) to a spin-polarized state (a non-Abelian state)?

- ➢ wide quantum well, thicker 2DES, Coulomb repulsion weakened – favor spin-singlet state, or formation of Skyrmions. [Wojs et al, PRL (2010)].

OR

• a spin transition from a non-Abelian spin-singlet state to a non-Abelian spin-polarized state

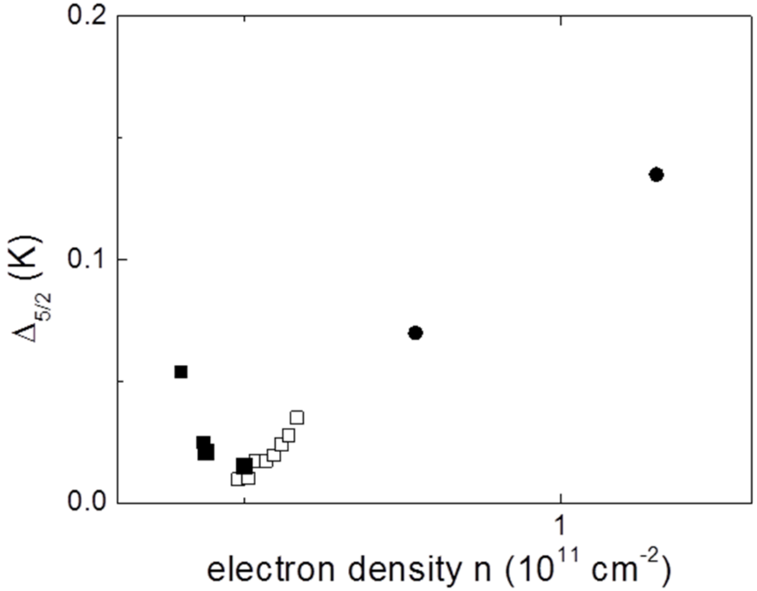
Or due to rotation of spin polarization?

Quantum Hall ferrom ... in the fractional regime

(PRL,2008)

Depar ... itzerland

The competitio ... haus spin-orbit cou-
plings is studied f ... fects. A transition of
the direction of th ... ian energy. We show
that these values ... d thus provide infor-
mation about the ... iples of the Laughlin
wavefunctions and ... r bath.



low-density

P=1

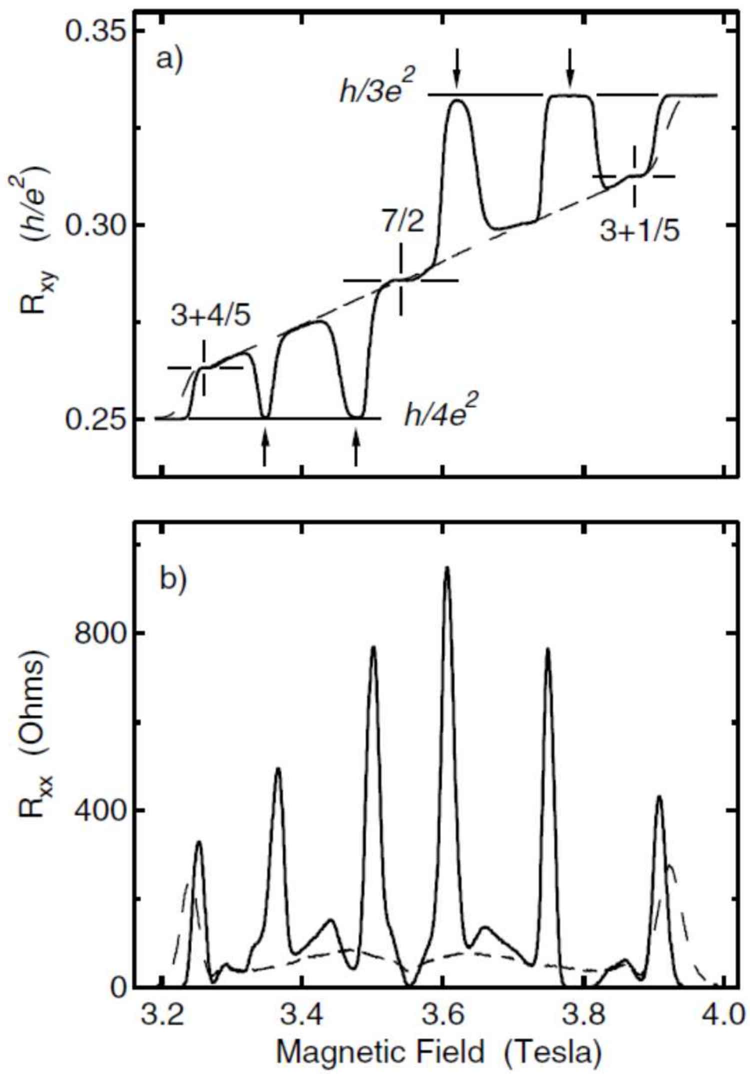
high-density

P=1

Anisotropic 7/2 state

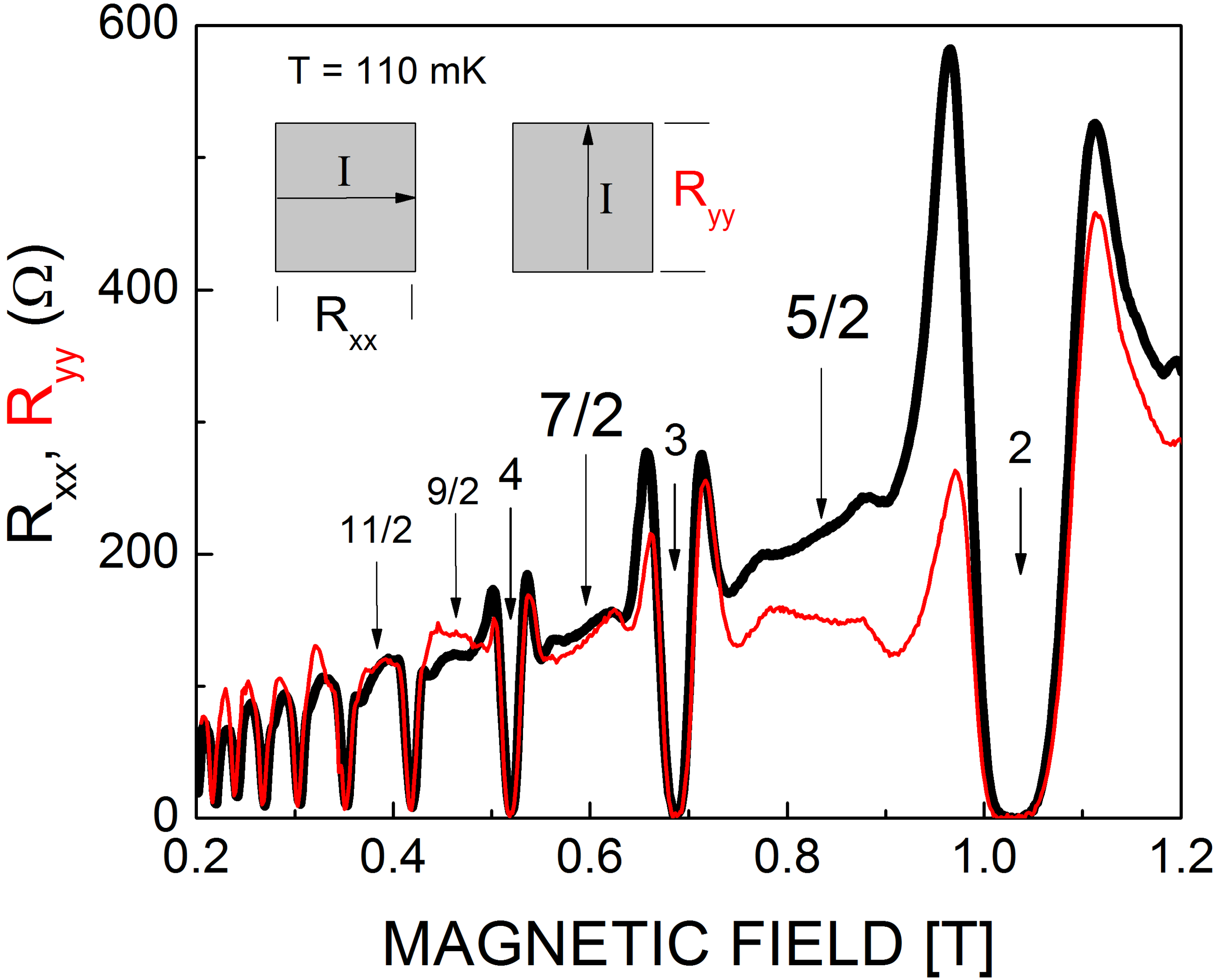
7/2 is a quantum Hall state at high densities

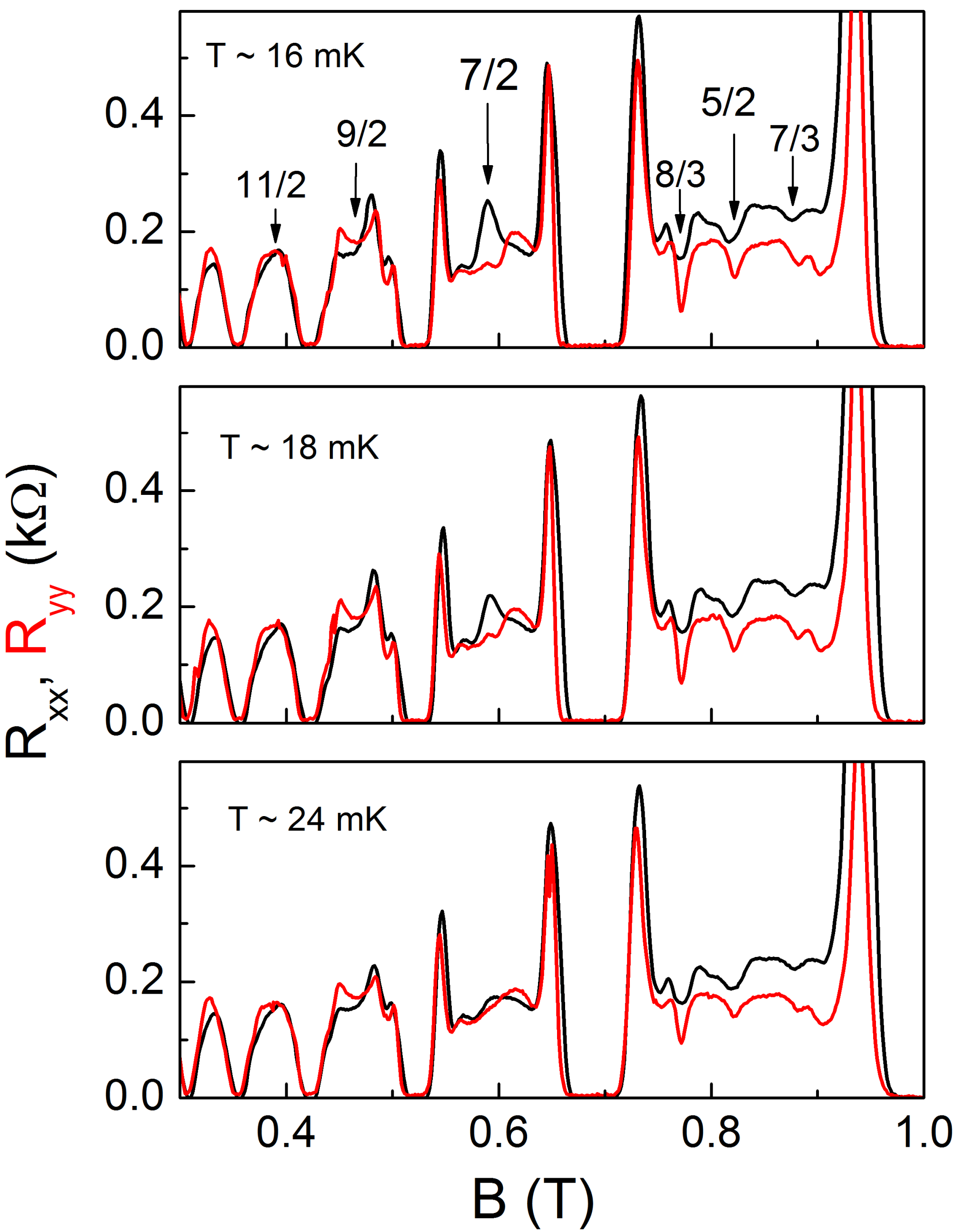
Particle hole conjugate state of the 5/2 state



Eisenstein et al, PRL 2002

In our low density sample, isotropic 7/2 state at high temperatures





7/2 is anisotropic at lower temperatures.

It becomes isotropic at 24mK!

More or less isotropic at 9/2, 11/2, 13/2, etc. in this sample

Landau level mixing effect?

Thank you for your attention!