NGC 2017

NGC (Tomsk, September 18, 2017)

Nuclear Spin Related Measurements for Semiconductor Quantum Systems

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Tohoku University

GP Spin

MULTI DIMENSION

TOHOKU UNIVERSITY

Today's Topics

1. Resistively-detected nuclear magnetic resonance (RDNMR)
   - Introduction
   - Dynamic nuclear polarization and RDNMR (GaAs)
     - ▪Domain structure ▪Quantum Hall breakdown ▪Optical irradiation
   - InSb ν=2 quantum Hall ferromagnet (QHF) and RDNMR
2. Physics unveiled by RDNMR
   - Electron spin polarization measured from Knight-shift
   - Electron spin fluctuation measured from T_1 time
   - Application to nanostructures
3. Microscopic nuclear resonance imaging by using nanoprobe
4. Future possible extension

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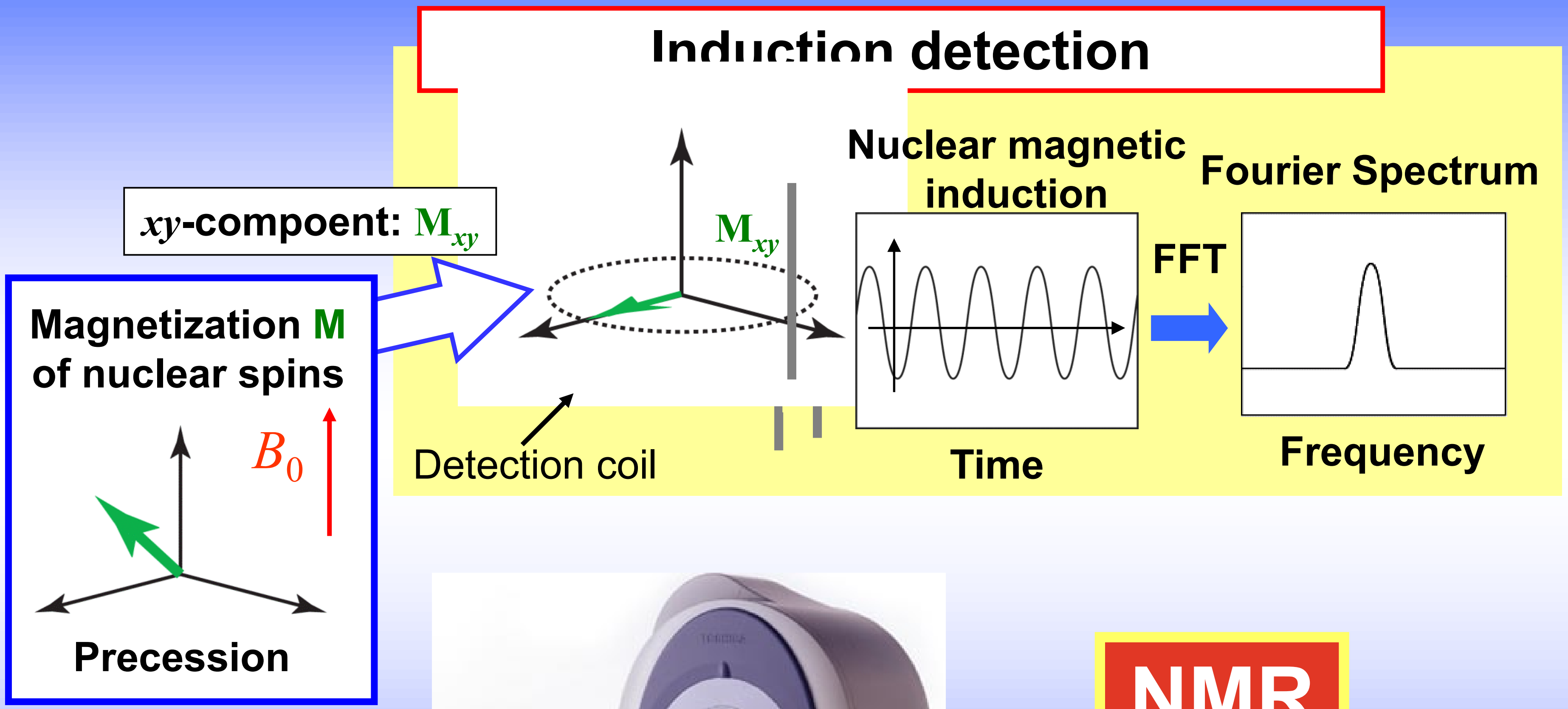
Standard NMR



NMR

MRI

Standard NMR: Advantage and Disadvantage

Spectrum is sensitive to the conditions where nuclear spins are placed.

Effect of surrounding nuclei

$\longrightarrow$ structure analysis

Knight shift

$\longrightarrow$ electron spin information

Quadrupolar splitting

$\longrightarrow$ strain around the nucleus

Disadvantages:

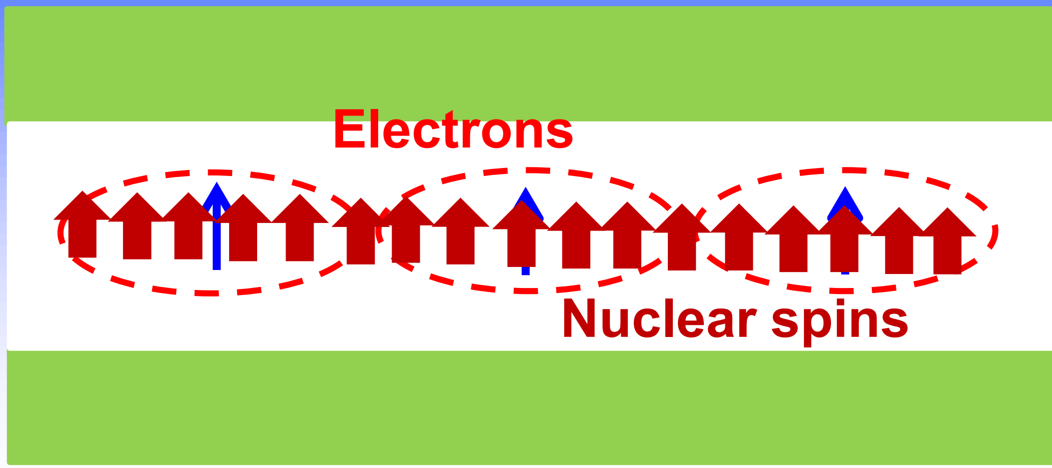
Weak signal

Necessity of a large volume sample (more than 10^{11} nuclei)

NMR is widely used in the physical, chemical and biological science.

Standard NMR is not suitable for layer and nanosystems.

NMR based on Hyperfine Interaction



AlGaAs(AlnSb)

GaAs(InSb) QW

AlGaAs(AlInSb)

$$H_{HF} = A_{HF}\mathbf{I}\cdot\mathbf{S} = A_{HF}\left[\underbrace{\frac{1}{2}(I_+\cdot S_- + I_-\cdot S_+)}_{\textit{Flip-flop term}} + \underbrace{I_z\cdot S_z}_{\textit{Zeeman term}}\right]$$

Zeeman term → Detection of nuclear polarization
(If some parameter is sensitive to Zeeman energy)
Flip-flop term → Dynamic nuclear polarization

[Overview]

Y. Hirayama et al., Semicond. Sci. Technol. 24, 023001 (2009) [Topical Review]

Y. Hirayama, Chapter 38, Quantum Hall Effects (3rd Edition) (World Scientific, 2013)

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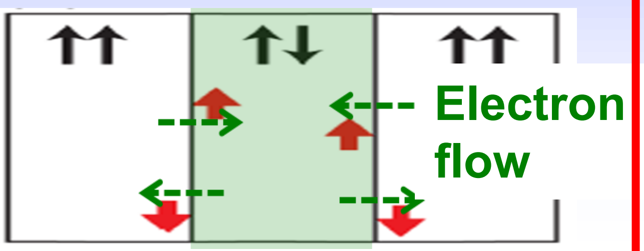
DNP in GaAs Quantum Systems

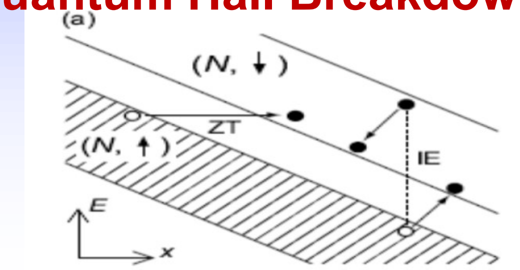
Basic concept: Nuclear spins are dynamically polarized via flip-flop process when electron spins are inverted.

Domain Structure



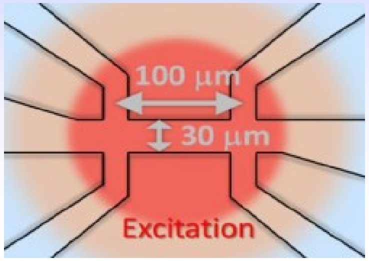
*At the spin phase transition, different spin states form a domain structure.
*Electron travel between domains results in DNP via flip-flop process.

Quantum Hall Breakdown



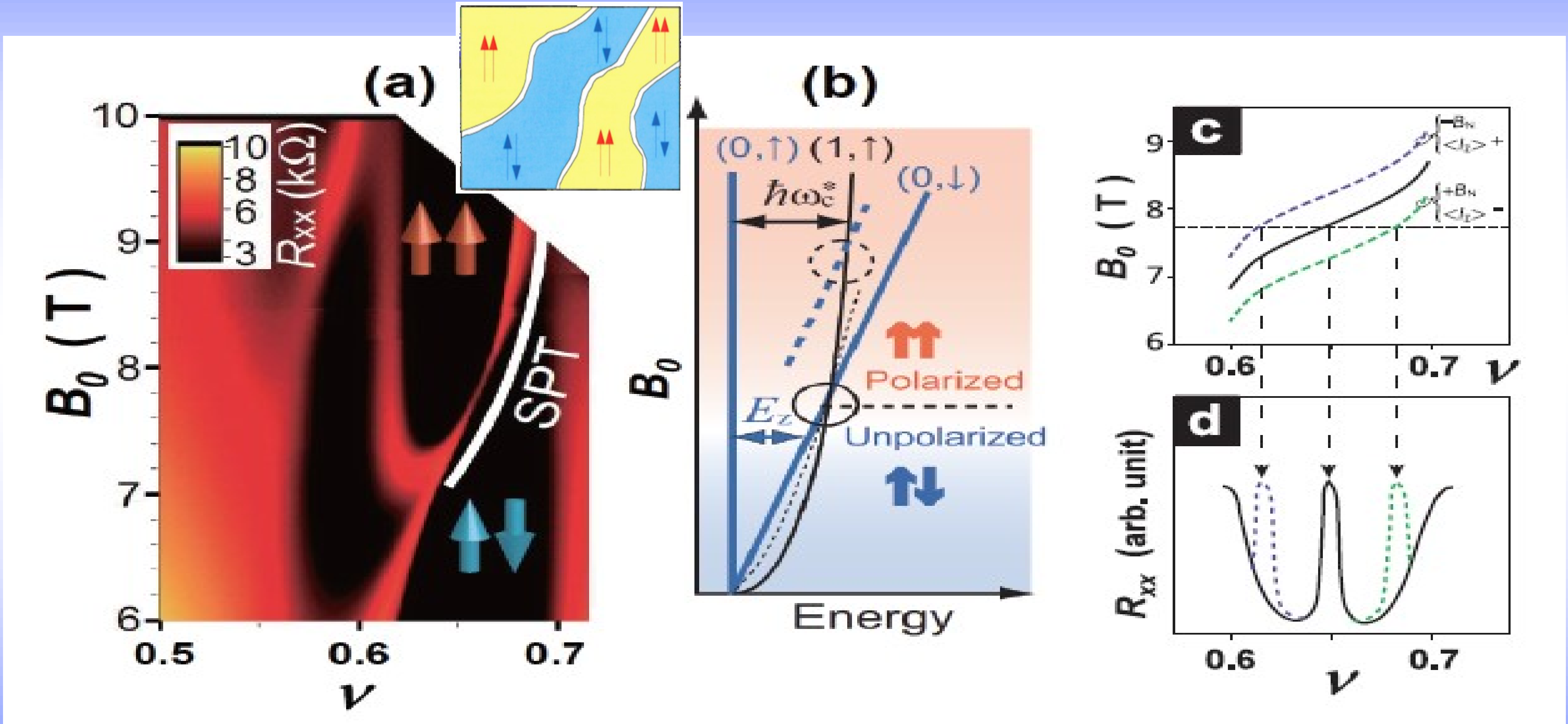
*Landau-level (LL) formation in the quantum Hall effect (QHE) regime.
*Large current results in breakdown of the QHE.
*Jump of electrons to opposite spin LL results in DNP.

Optical Excitation



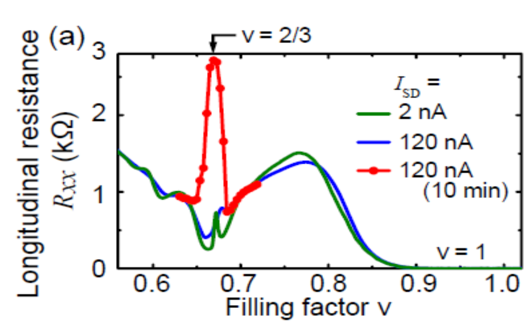
*Absorption of circularly-polarized light accumulate certain spin electrons in the QW.
*Accumulated electron spins are transferred to nuclear spins.

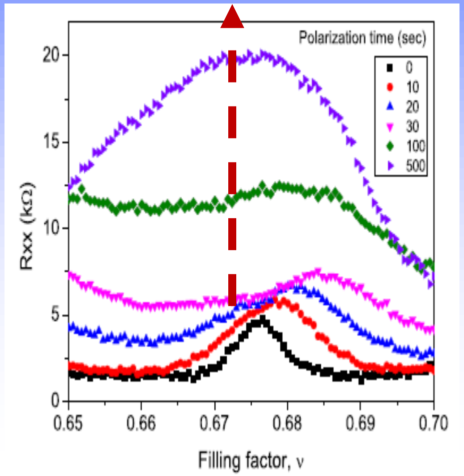
The ν = 2/3 Spin Phase Transition (SPT)
Sensitive Detector of B_N

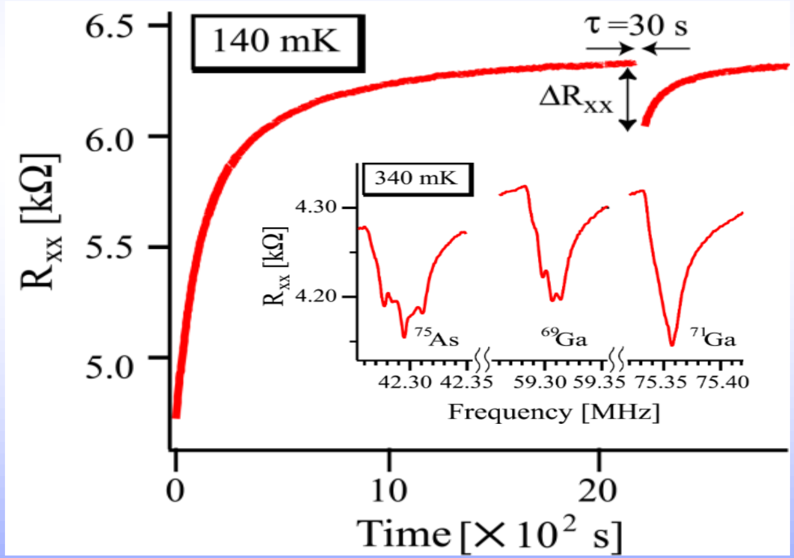


The spin phase transition (SPT) appears for ν = 2/3 fractional quantum Hall state, which is ν = 2 of the composite fermion. The SPT becomes a sensitive detector of Zeeman field, which is modified by nuclear polarization.

Current Induced Dynamic Nuclear Polarization at ν = 2/3







The large current results in developments both amplitude and width of SPT peak, reflecting dynamic nuclear polarization. Nuclear polarization becomes spatially inhomogeneous in the case of DNP based on domain structures.

S. Kronmüller et al., Phys. Rev. Lett. 81, 2526 (1998); S. Kronmüller et al., Phys. Rev. Lett. 82, 4070 (1999); K. Hashimoto, YH et al., Phys. Rev. Lett. 88, 176601 (2002); M. H. Fauzi, YH et al., Appl. Phys. Lett. 101, 162105 (2012); J. N. Moore et al., Phys. Rev. Lett. 118, 076802 (2017).

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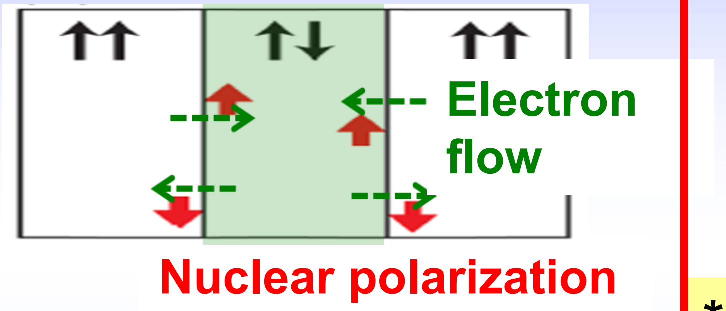

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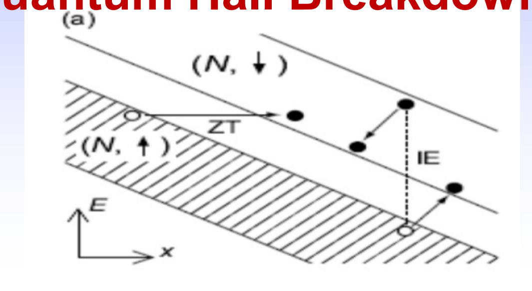
Quantum Hall Breakdown



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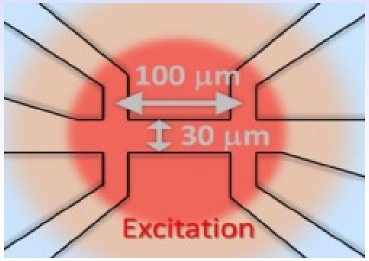

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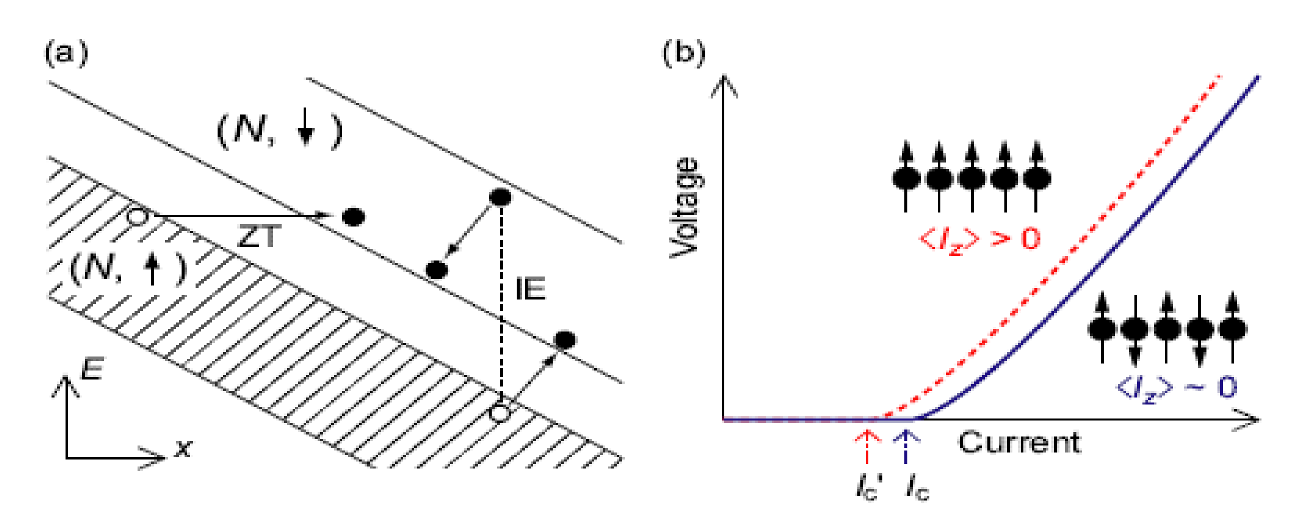
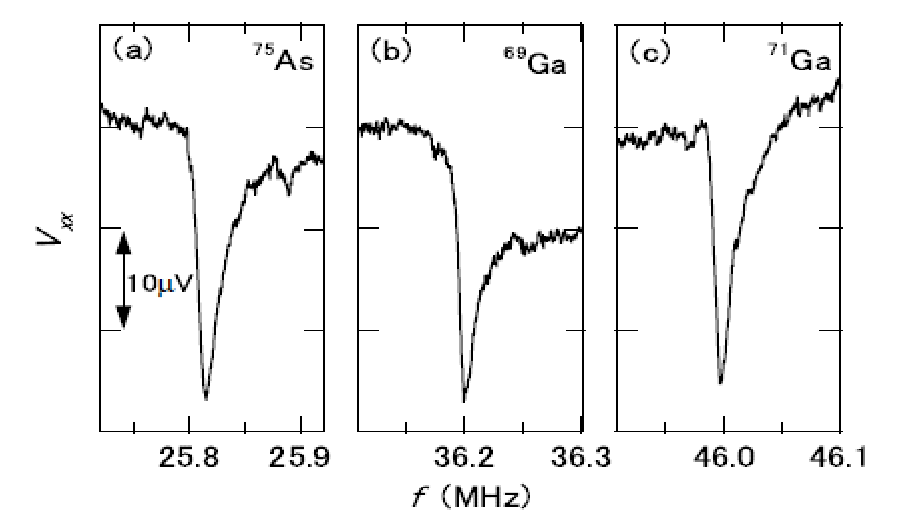


M. Kawamura et al., Appl. Phys. Lett. 90, 022102 (2007)
T. Tomimatsu, YH et al., Appl. Phys. Lett. 103, 082108 (2013).

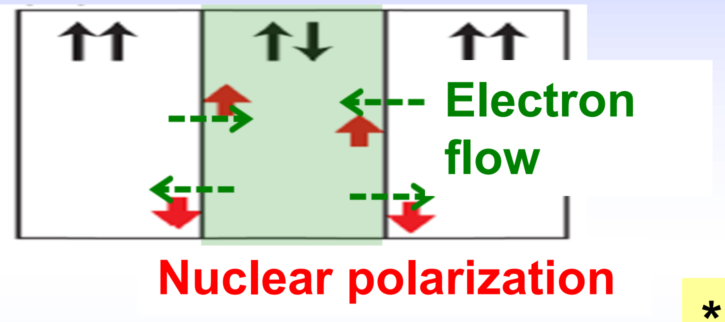


- **The breakdown characteristics are also sensitive to the Zeeman energy separation.**
- **The breakdown also induces dynamic nuclear polarization.**
- **The breakdown can be applied to the wider range, namely various magnetic field, higher temperature, and lower mobility.**

DNP in GaAs Quantum Systems

Basic concept: Nuclear spins are dynamically polarized via flip-flop process when electron spins are inverted.

Domain Structure



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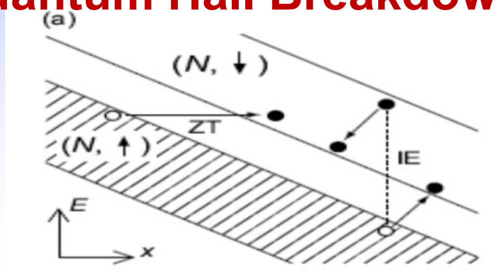

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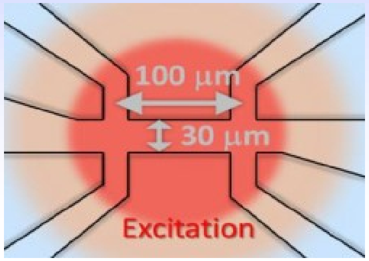

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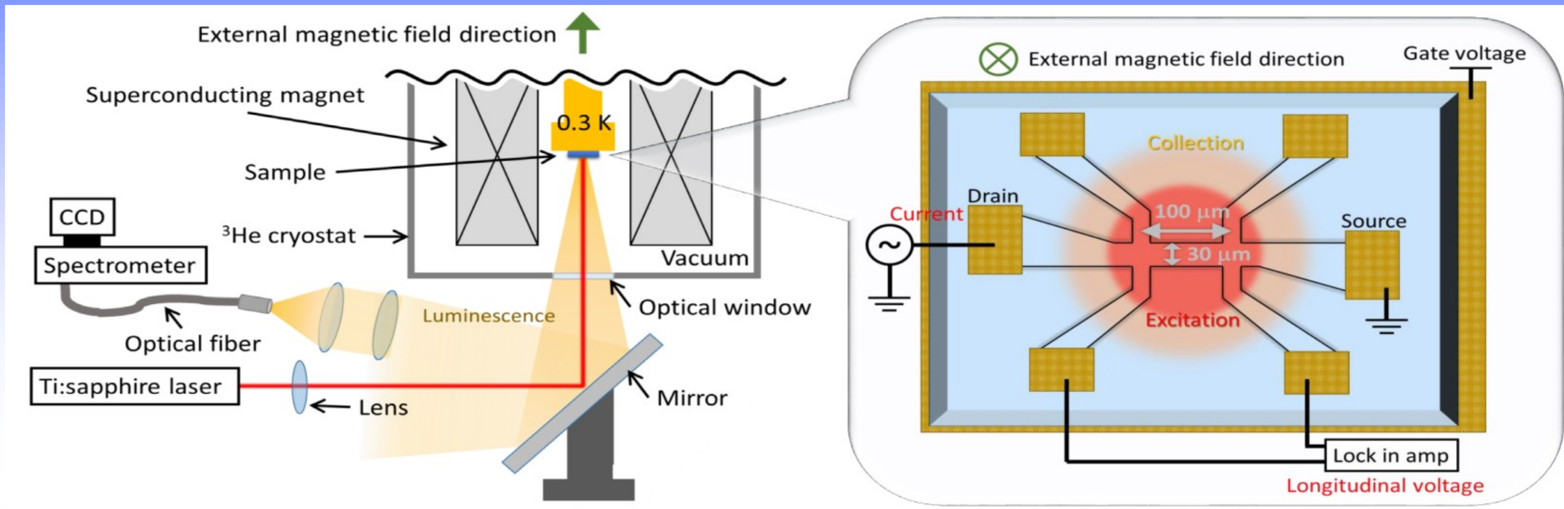
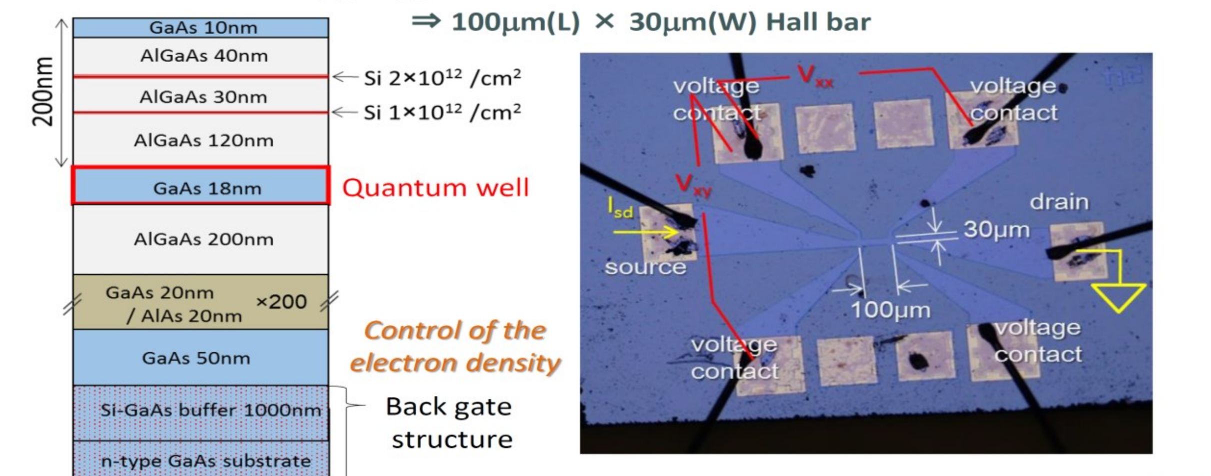
Experimental Setup for Optical Nuclear Polarization



➢External magnetic field B = 7.15T ➢Base temperature T_{base}=0.3K

➢Wafer 18nm $GaAs/Al_{0.33}Ga_{0.67}As$ quantum well supplied by Dr. Muraki, NTT-BRL

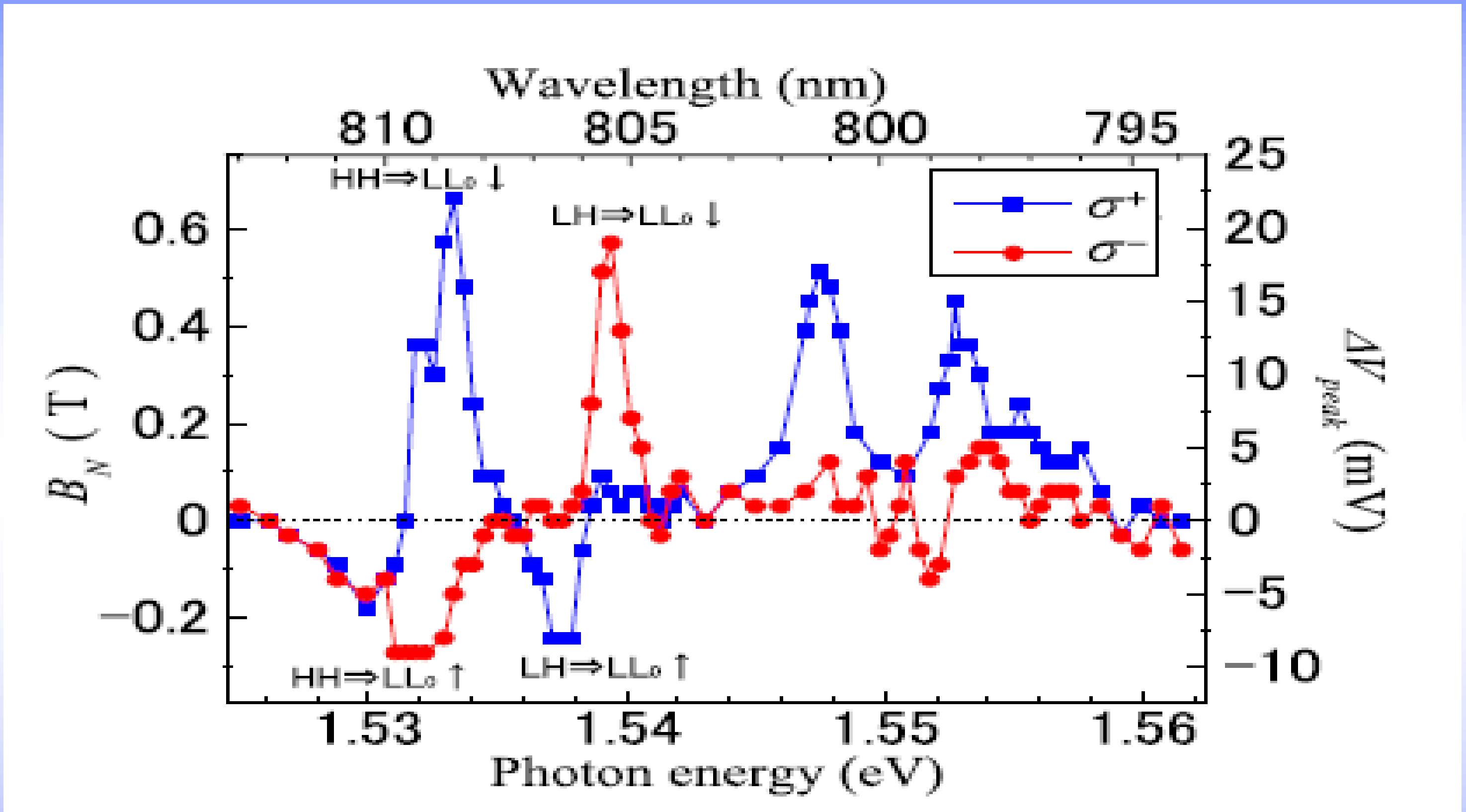
⇒ 100μm(L) × 30μm(W) Hall bar



➢Electron mobility μ=185 m^2/Vs @ 1.2×10^{15} /m^2

K. Akiba, YH et al.,
Appl. Phys. Lett. (2011) ;
Phys. Rev. B (2013) ;
Phys. Rev. Lett. (2015)
[editor's suggestion] ;
Phys. Rev. B(RC) (2016)

Irradiation Wavelength Dependence



ν = 0.3

The nuclear polarization can be controlled by irradiation wavelength.
Spectroscopy mediated by optical nuclear polarization
⟺ Novel method for electron-spin-resolved spectroscopy

K. Akiba, Y. H. et al., Phys. Rev. B87, 235309 (2013).

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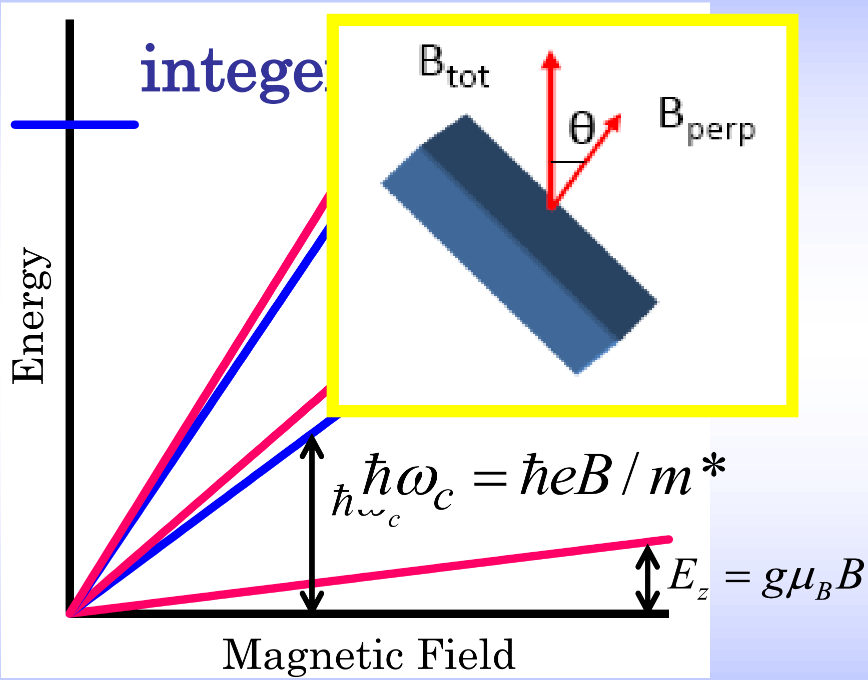
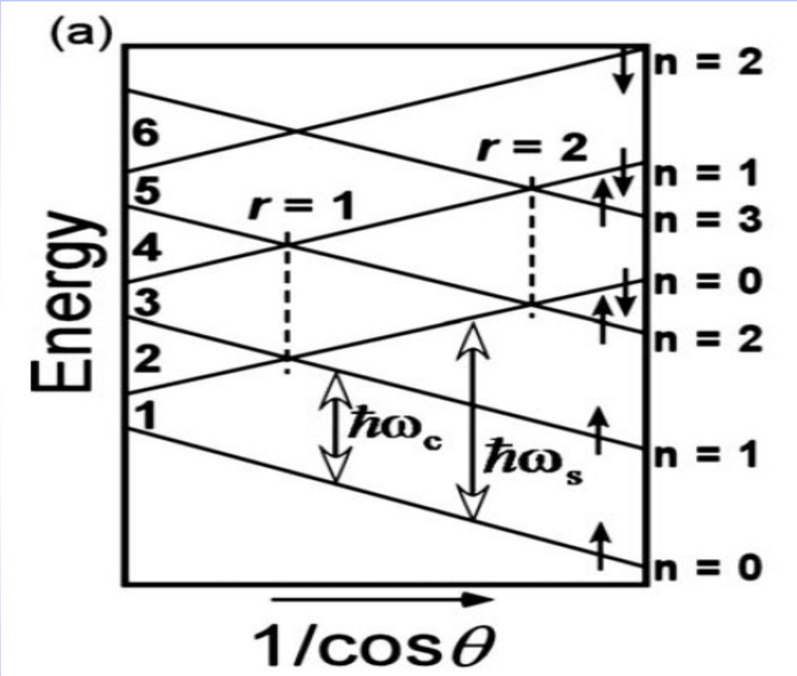
$\nu = 2$ Spin Phase Transition (SPT) under Tilted Field

Landau level crossing with different spin states





Parallel *B*-field application

This type of LL crossing is impossible for GaAs but possible for InSb with large g-factor.

K. F. Yang, YH *et al.*, New Journal of Physics 13, 083010 (2011)

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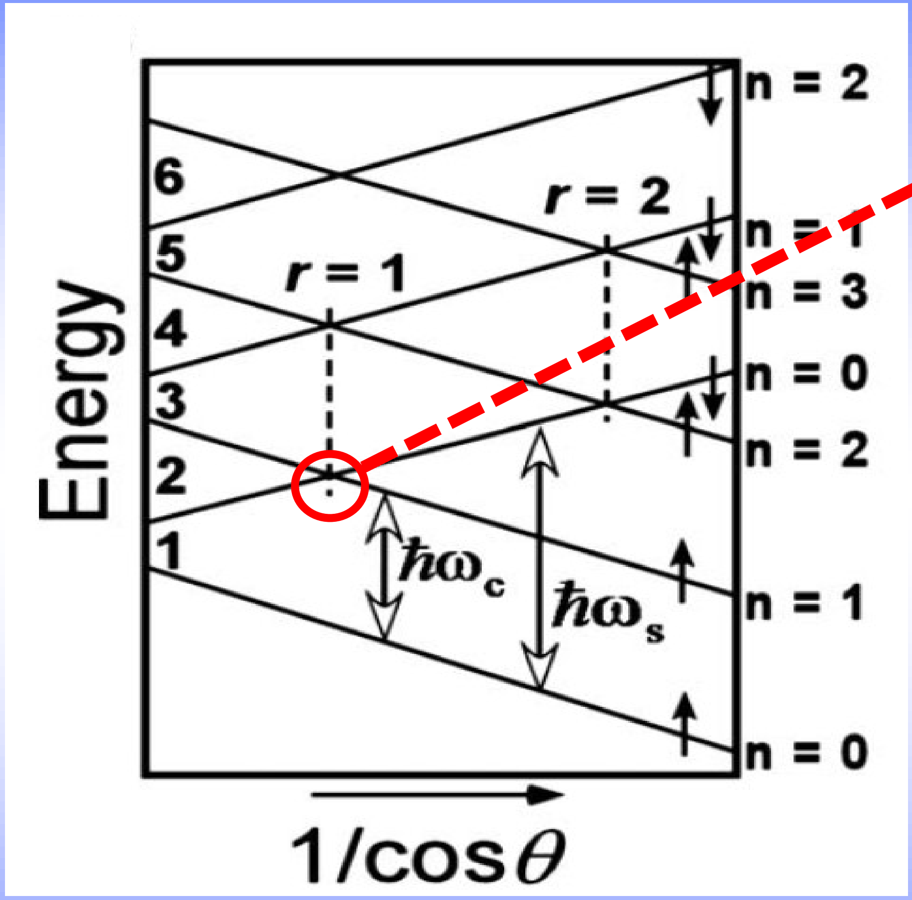
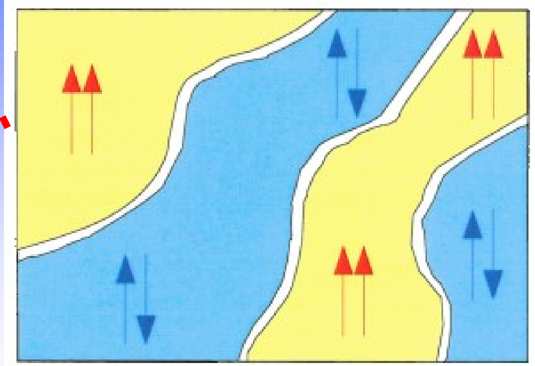
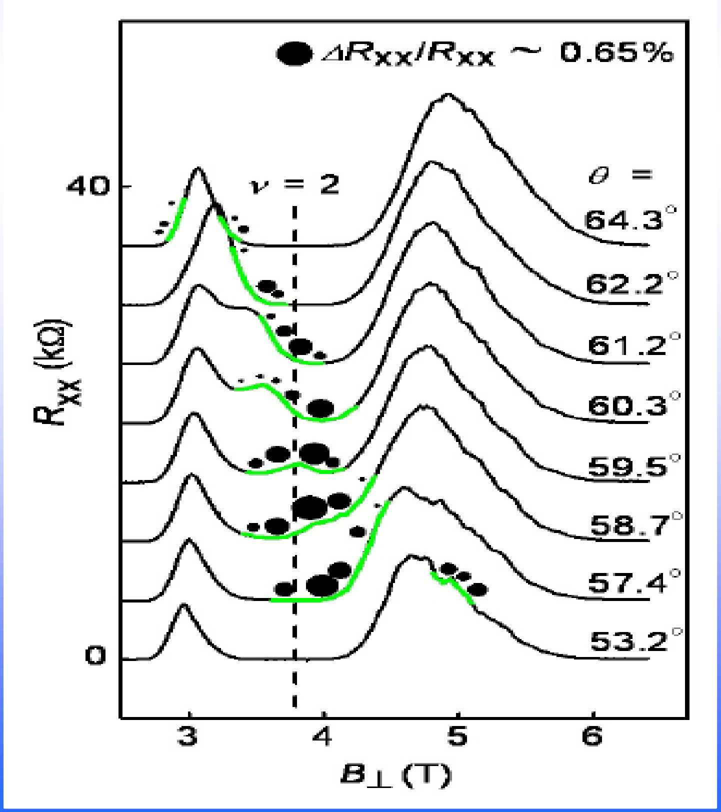
LL Crossing at $\nu = 2$ and Domain Structure Formation

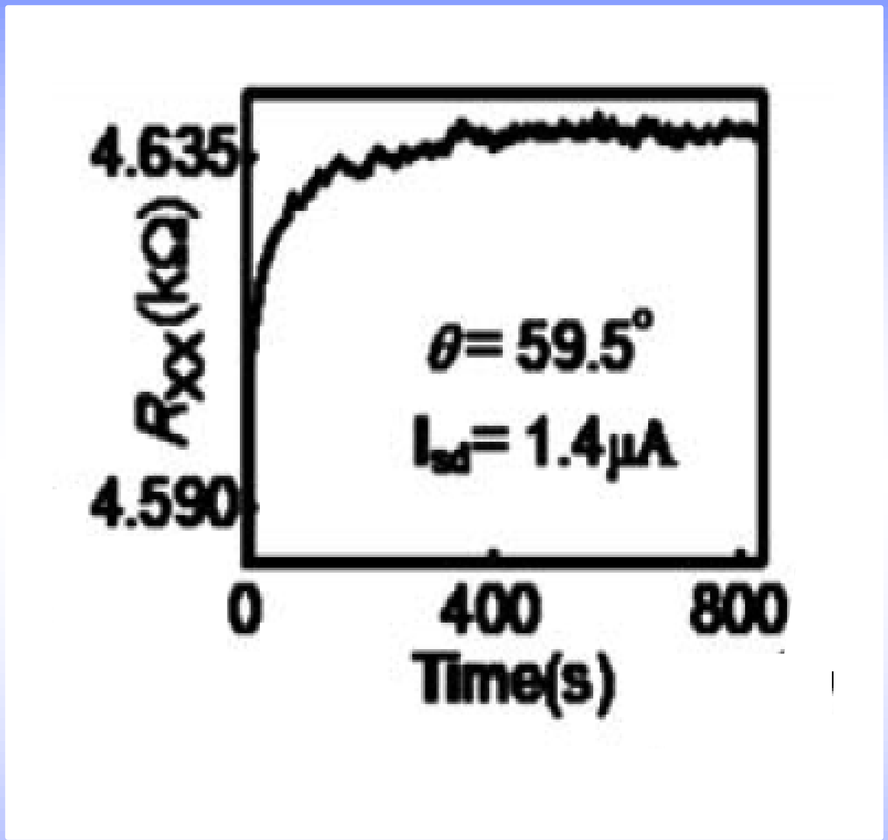


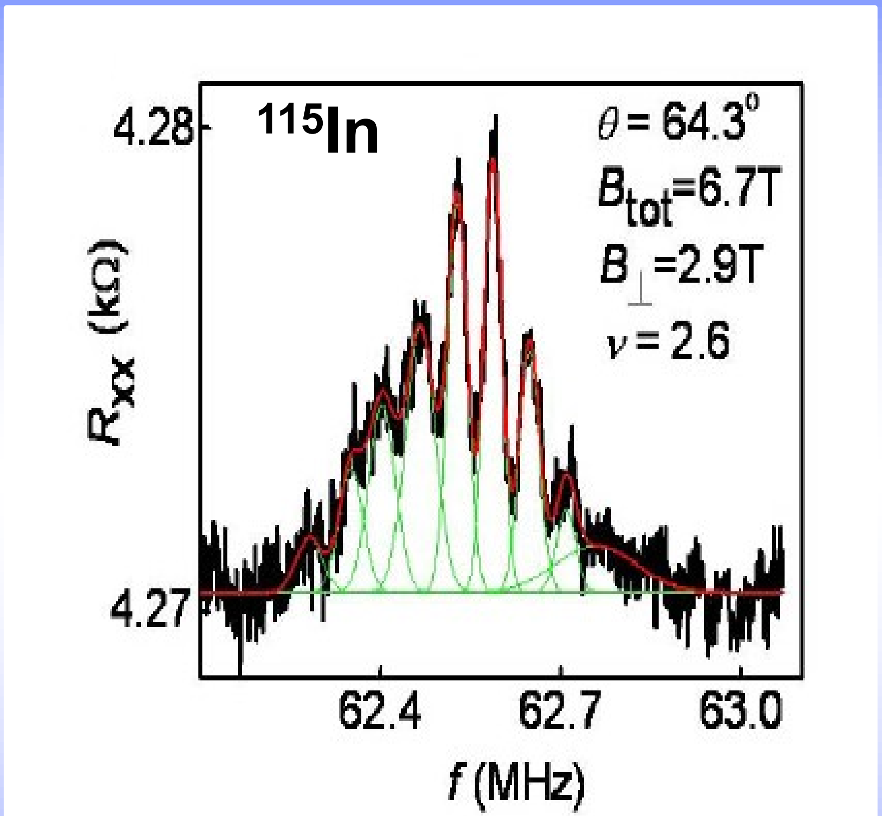




H. W. Liu, YH *et al.*, PRB 82, 241304(R) (2010) [editor's suggestion]
K. F. Yang, YH *et al.*, APL 98, 142109 (2011)

Current Driven Nuclear Polarization and NMR





AC-current

H. W. Liu, Y. H. *et al.*, Phys. Rev. B 82, 241304(R) (2010) [Editor's suggestion]
M. Korkusinski, P. Hawrylak, YH *et al.*, Scientific Reports 7, 43553 (2017)

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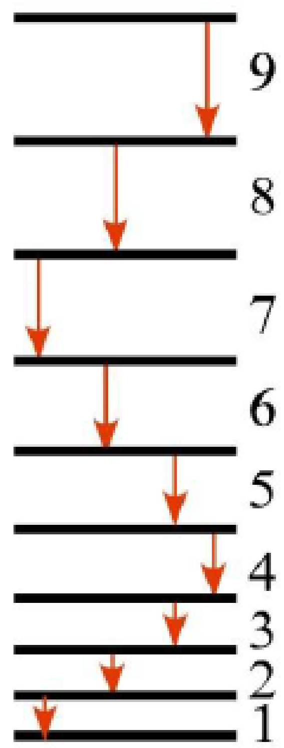
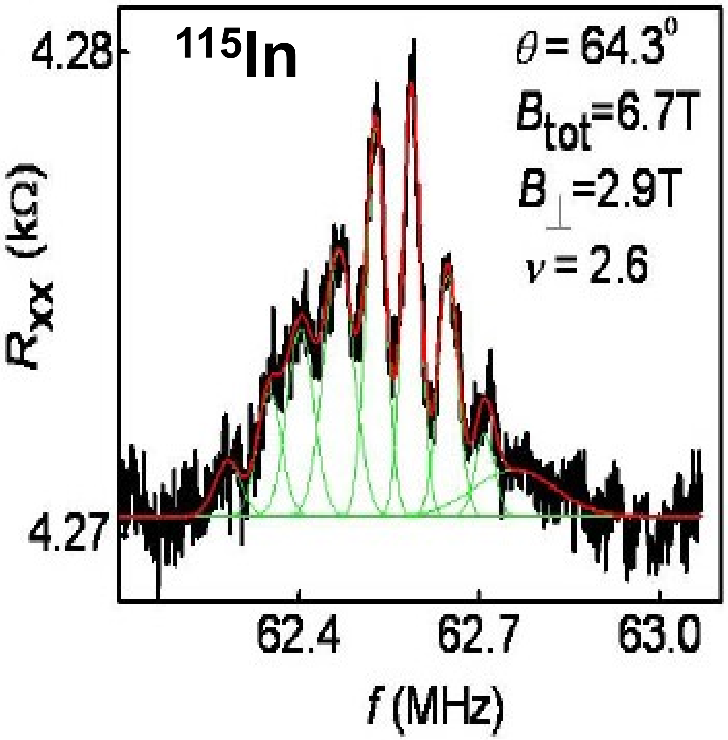


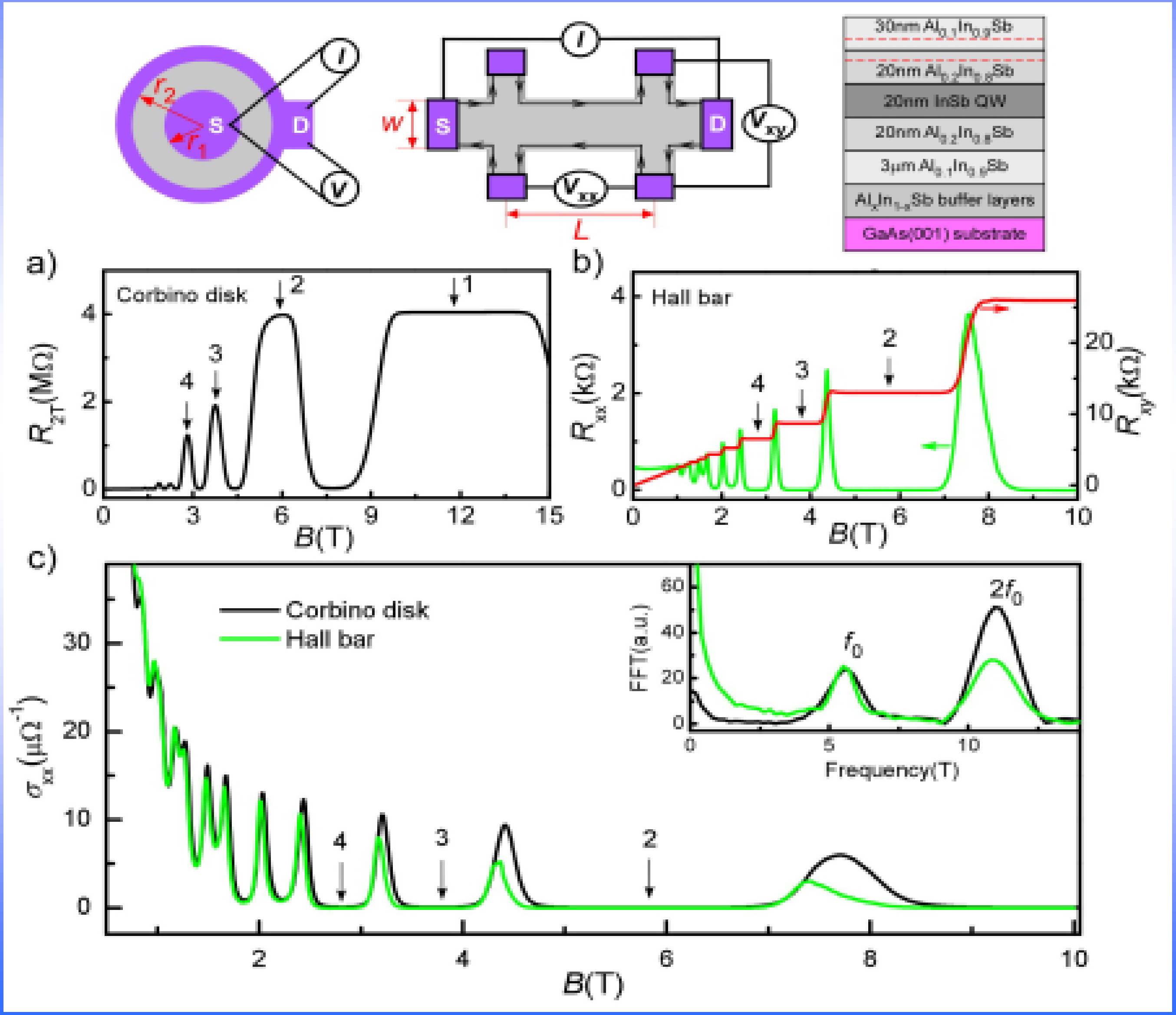


AC-current

^{115}In $I = 9/2$ → quantum 10 level system

Successful observation of quadrupolar splitted quantum 10 levels

Fabrication of Corbino and Hall-bar Structures



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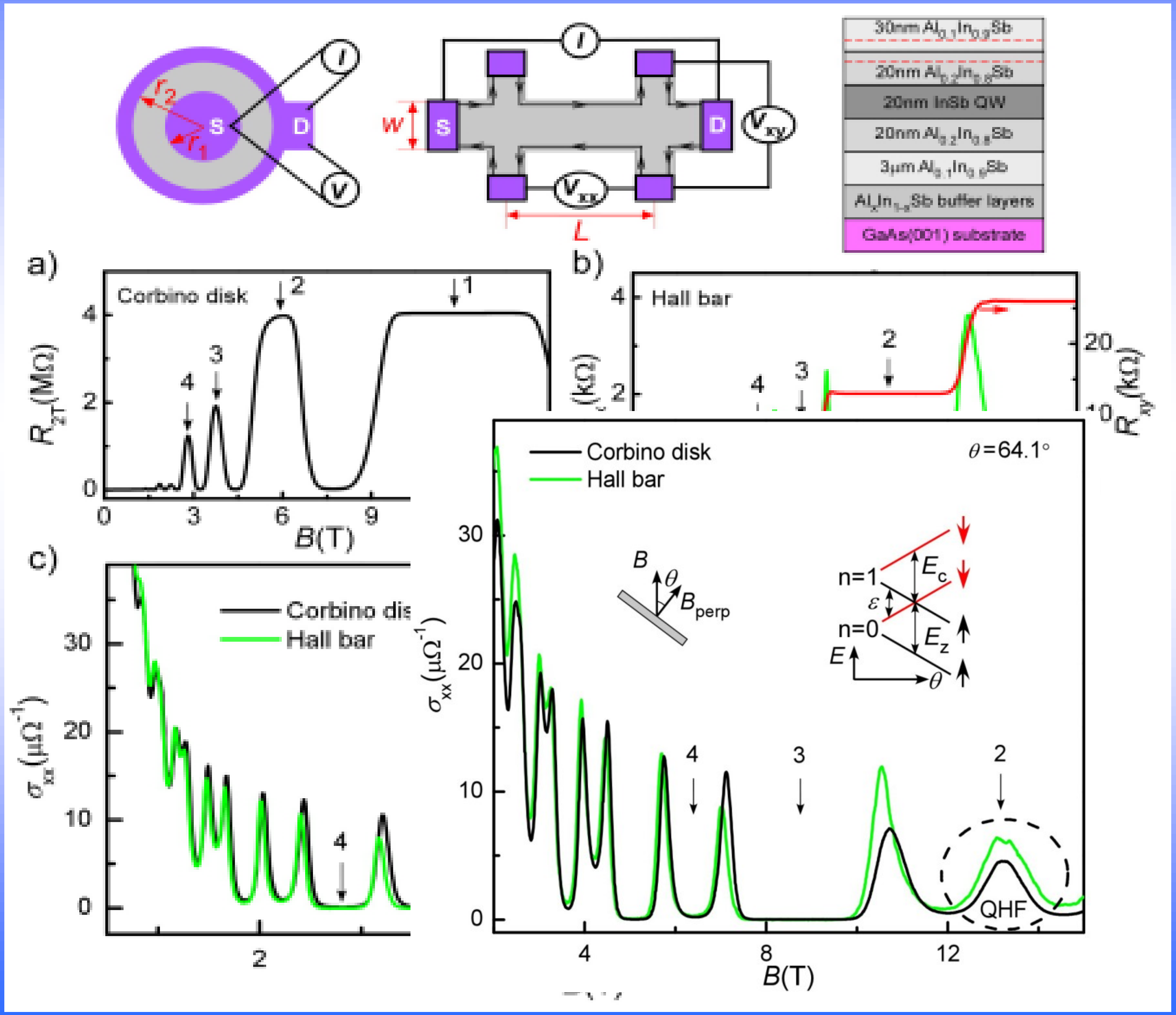
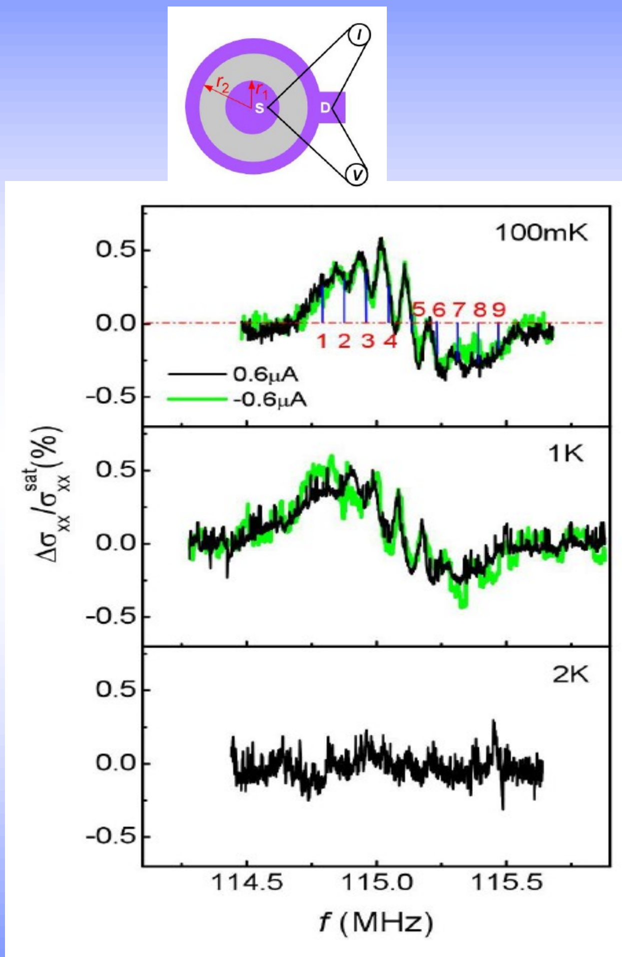
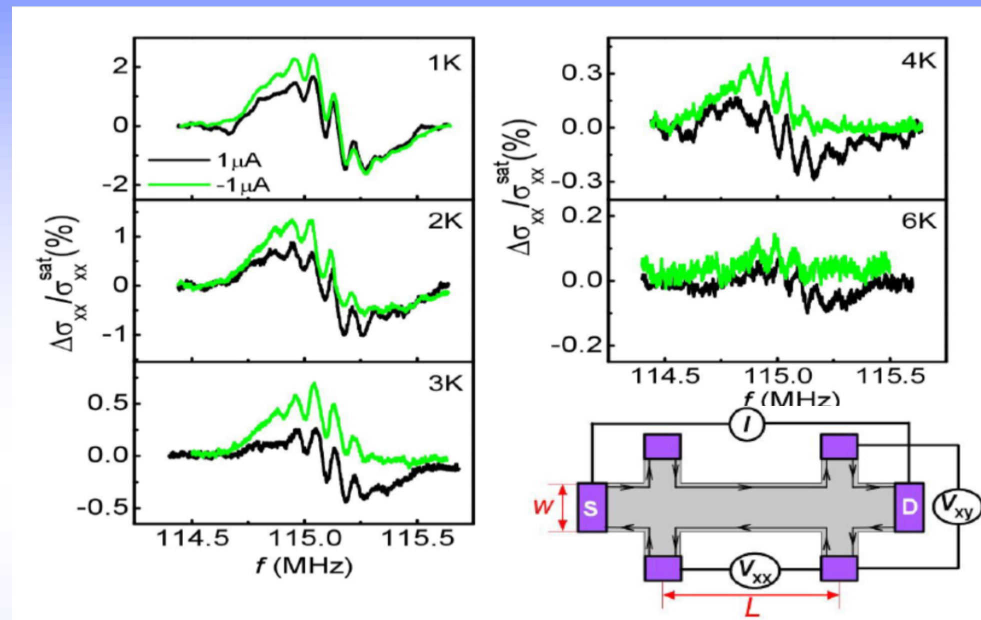


Role of Chiral Edge for Nuclear Polarization





B_t: 12 or 12.3 T, θ:64°

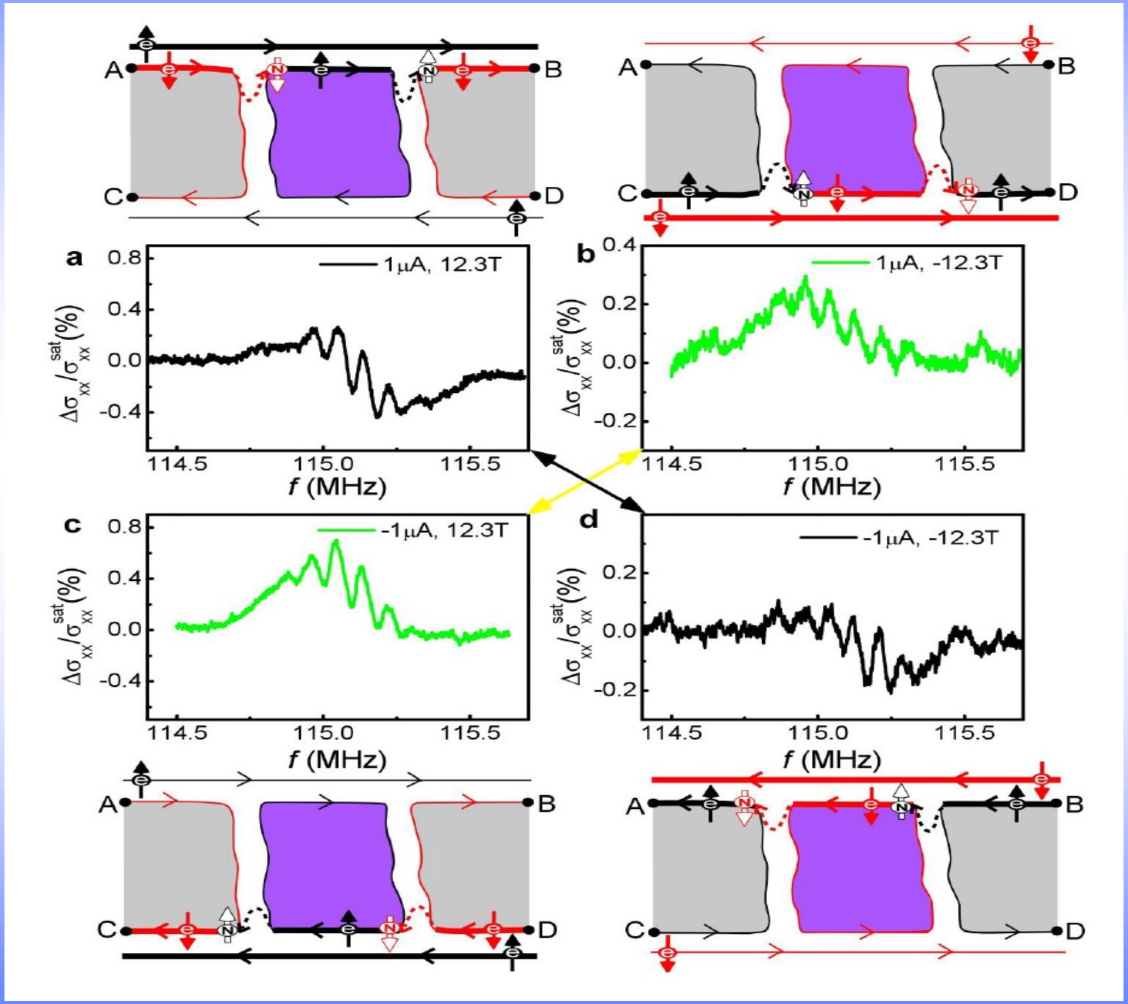
InSb 2DEG, DC measurement

Corbino (without esdge): RDNMR signal is symmetric for current flow direction and disappears at around 2 K.

Hall-bar (with edge): RDNMR signal is asymmetric for current flow direction and remains up to 6 K.

K. F. Yang, YH *et al.*, Nature Communications, DOI: 10.1038/NCOMMS15084 (2017)

Reciprocity of RDNMR Signal in QHF



At 3 K, bulk-dominated RDNM disappears and edge-dominated RDNM remains. We can see the typical characteristics arising from the edge-dominated RDNMR. The reciprocity can be confirmed for Hall-bar RDNMR reflecting fundamental feature of edge-dominated RDNMR.

***T* = 3K**

K. F. Yang, YH *et al.*, Nature Communications, DOI: 10.1038/NCOMMS15084 (2017)

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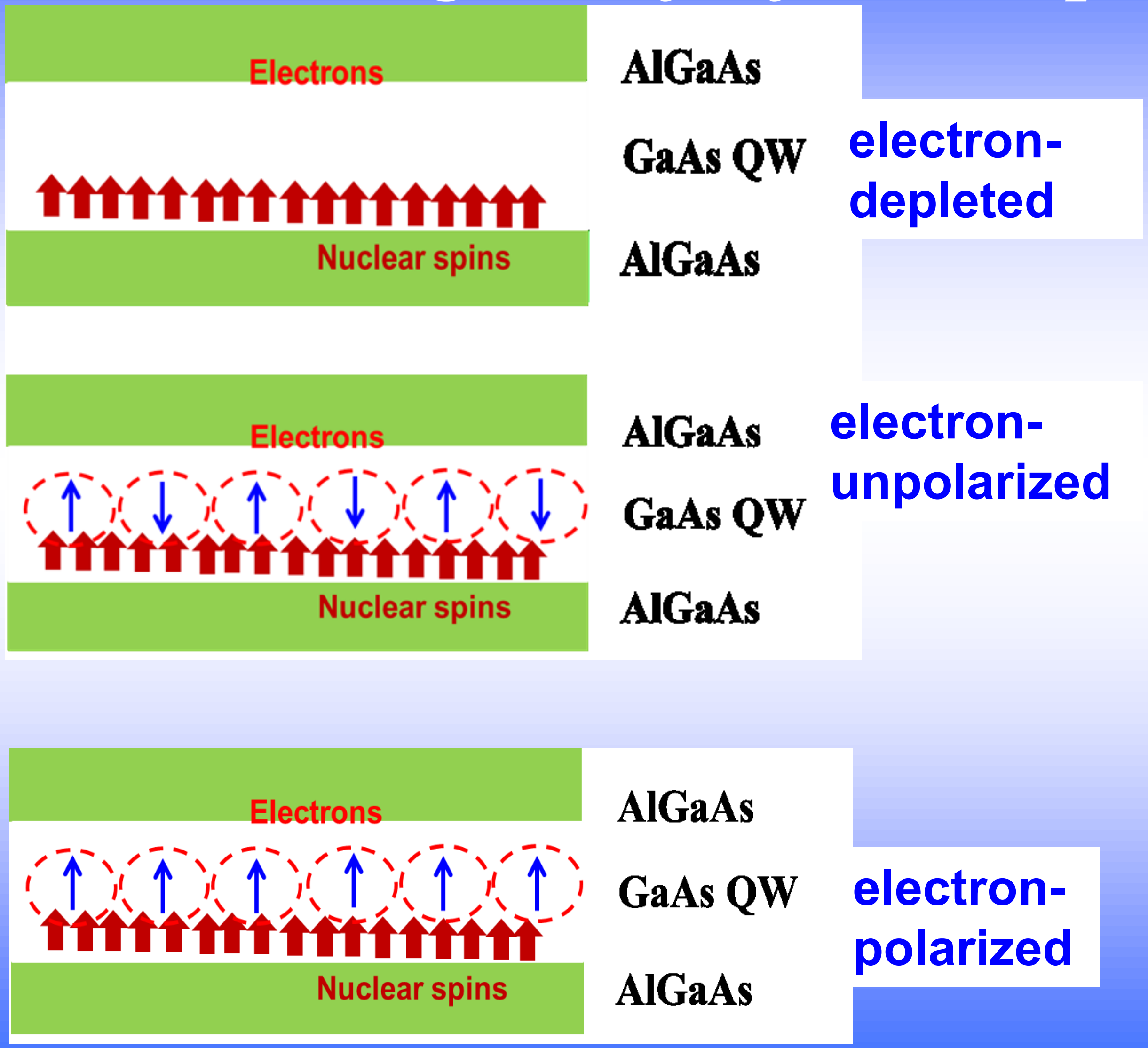
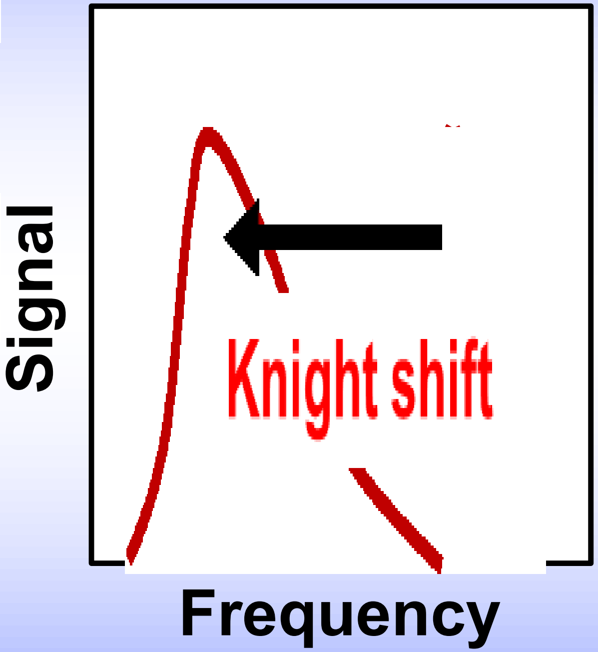
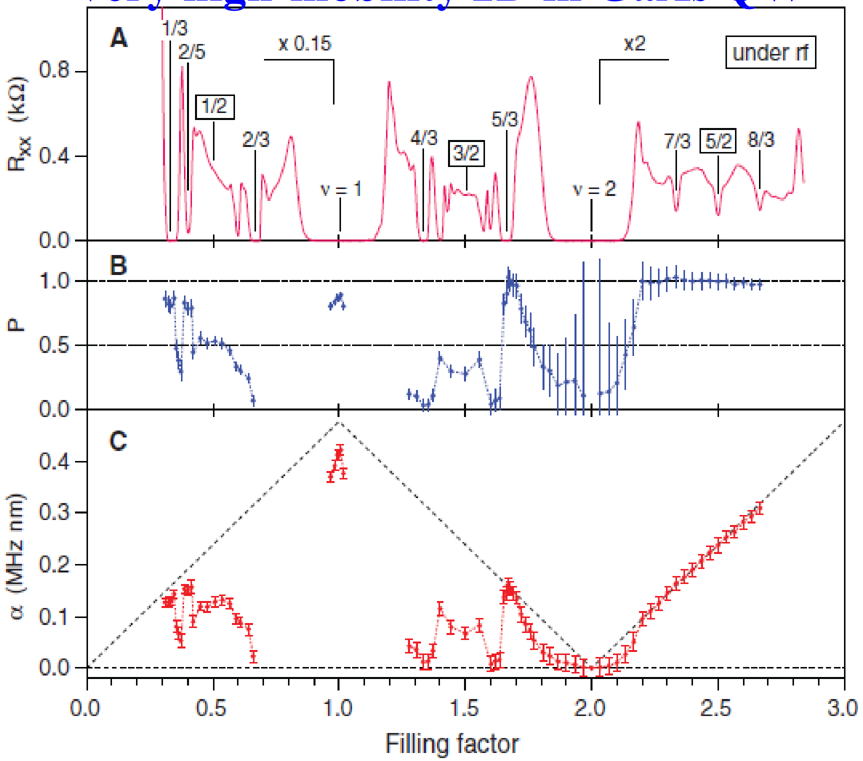
Knight Shift of NMR Spectrum

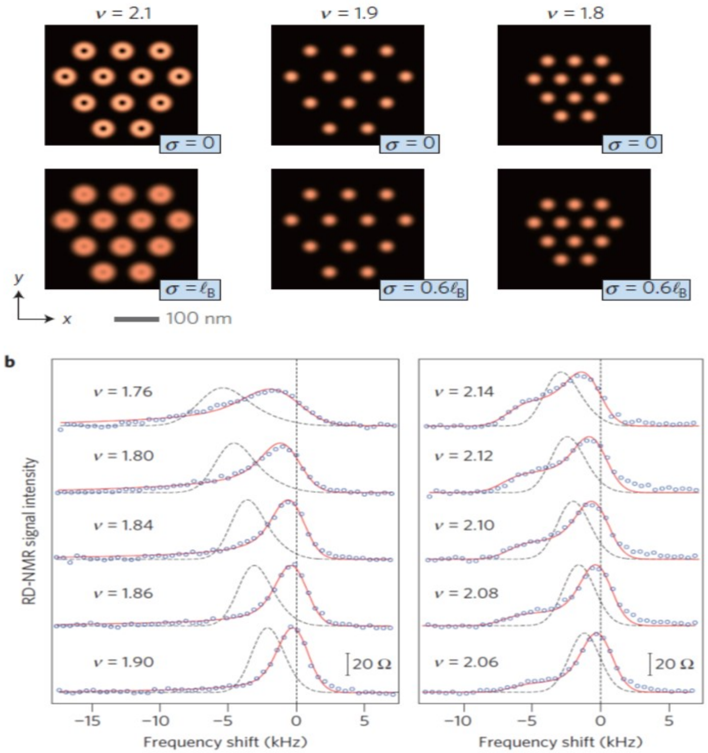




Knight Shift Measurements

Very high-mobility 2D in GaAs QW





L. Tiemann et al., Science 335, 828 (2012)

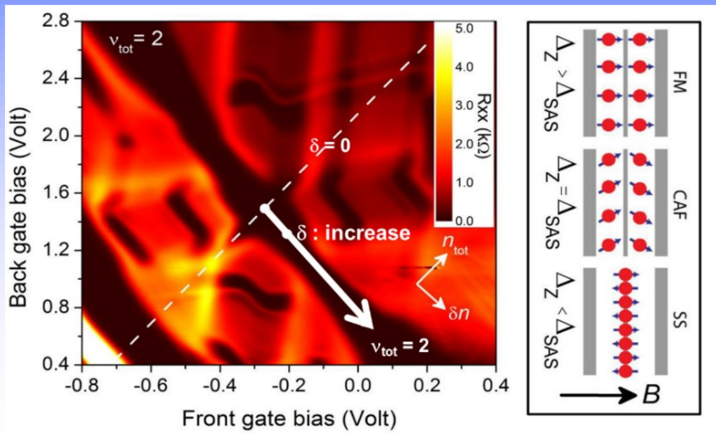
The Knight shift measurements clarify electron spin polarization, charge/spin ordering, and inhomogeneity in quantum Hall systems.

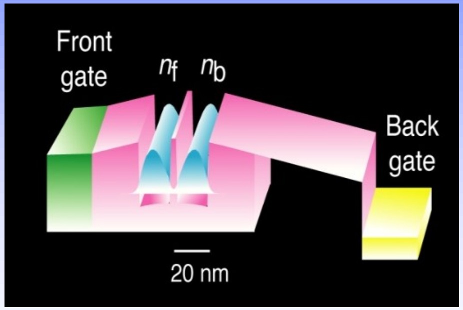
L. Tiemann et al., Nature Physics 10, 648 (2014)

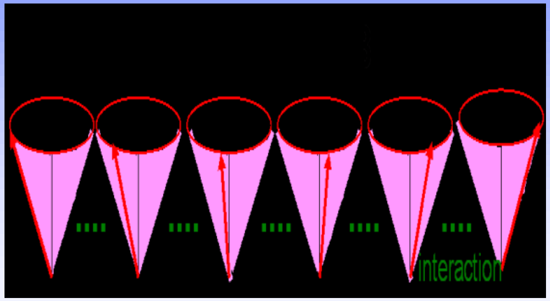
B. Friess et al., Phys. Rev. Lett. 113, 076803 (2014)

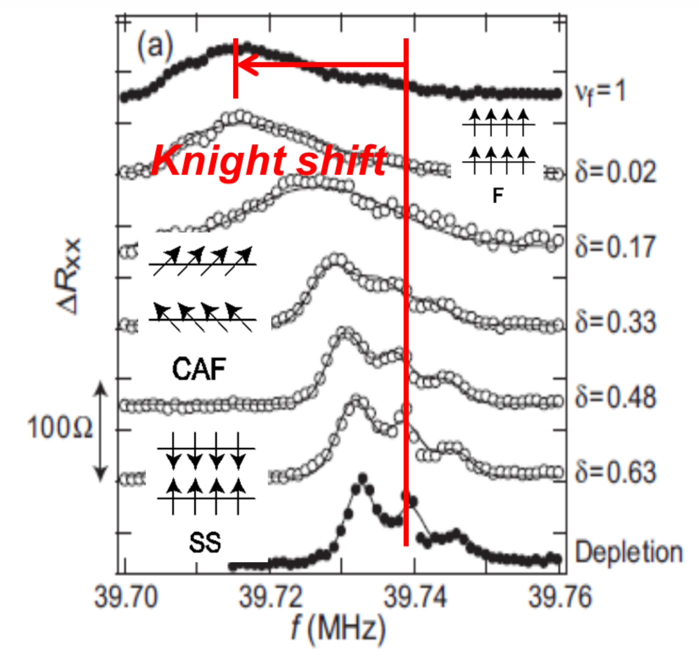
T. D. Rhone et al., Phys. Rev. B 92, 041301 (2015)

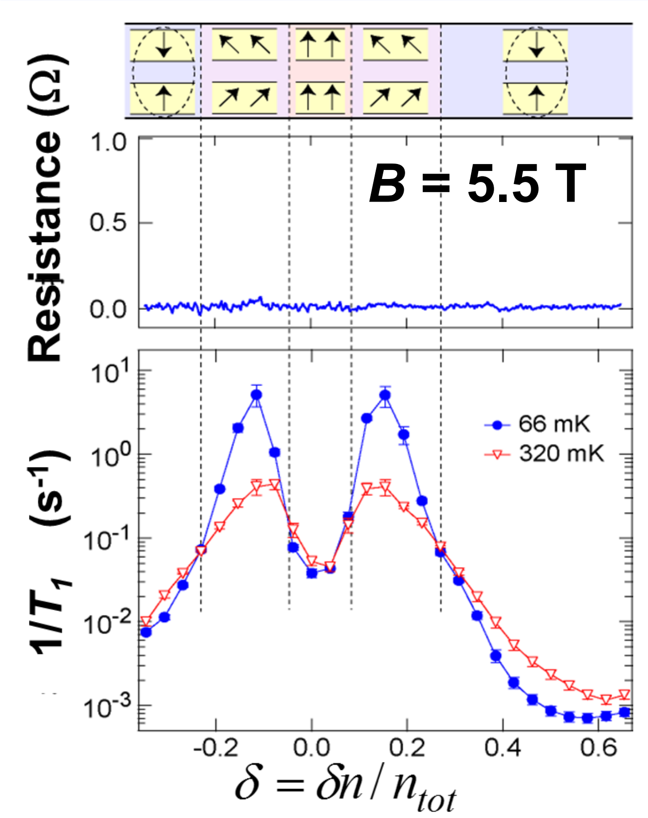
Bilayer ν = 2 : Canted Spin State and Goldstone mode









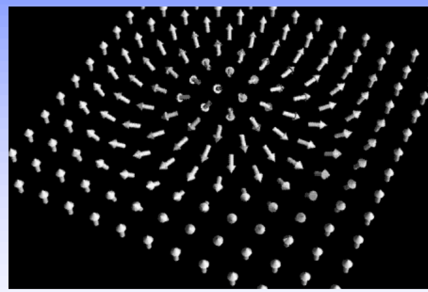


Knight shift and $1/T_1$ measurements confirm existence of canted spin state and related spin Goldstone mode.

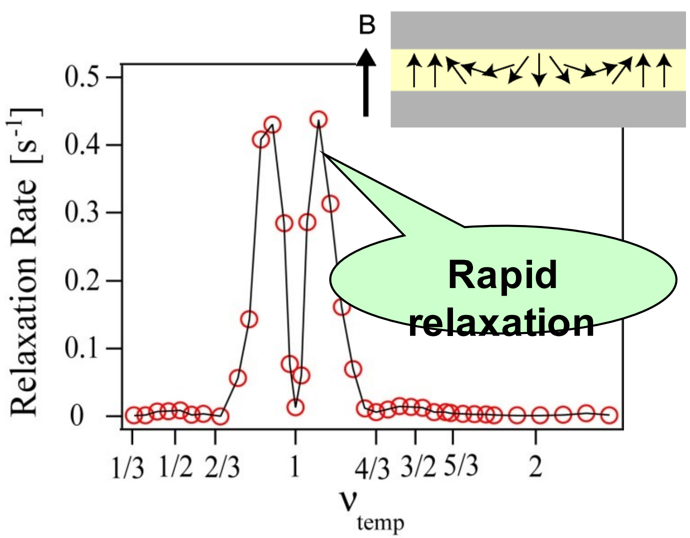
N. Kumada, Y. H. et al, Science 313, 329 (2006)
Phys. Rev. Lett. 99, 076805 (2007)

Skyrmion at around $\nu = 1$

film

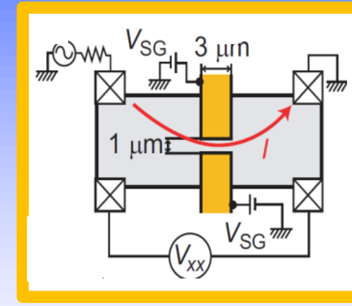


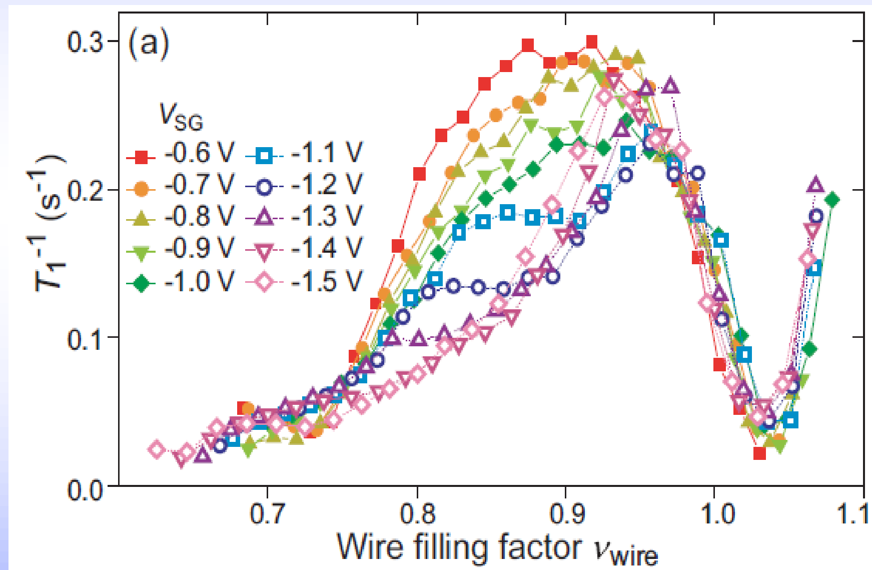
Skyrmion



K. Hashimoto, Y. H. et al., Phys. Rev. Lett. 88, 176601 (2002) .
J. H. Smet et al., Nature 415, 281 (2002).

wire

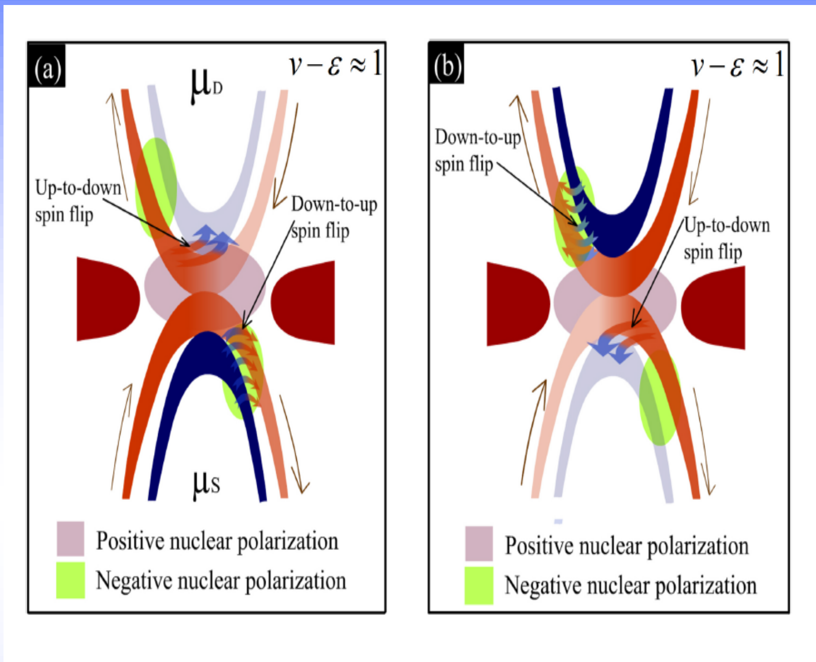


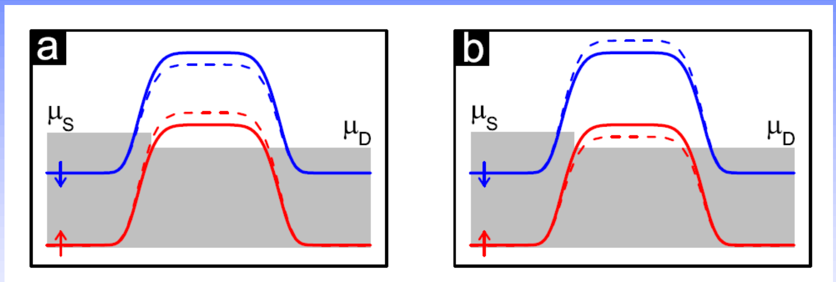


The obtained result suggests that interaction effect, Skyrmion, becomes unstable in a wire.

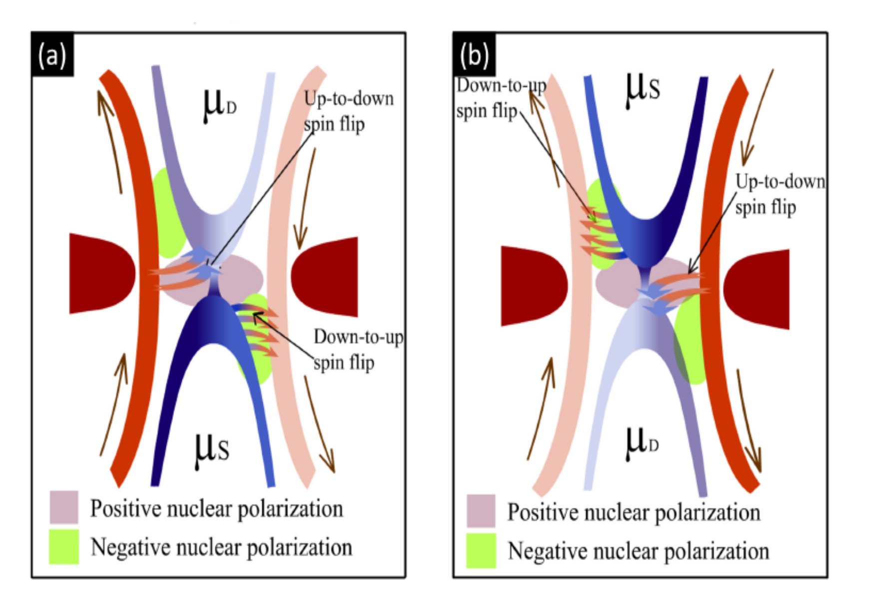
T. Kobayashi, Y. H. *et al.*, Phys. Rev. Lett. 107, 120867 (2011)

Edge Channel Scattering in Quantum Constriction





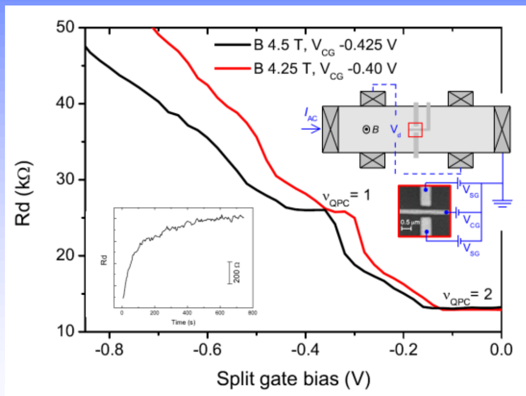
$\nu_{QPC} > 1$

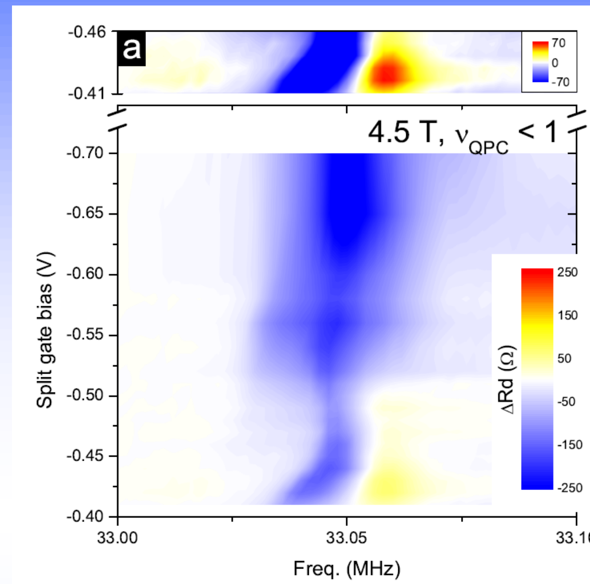


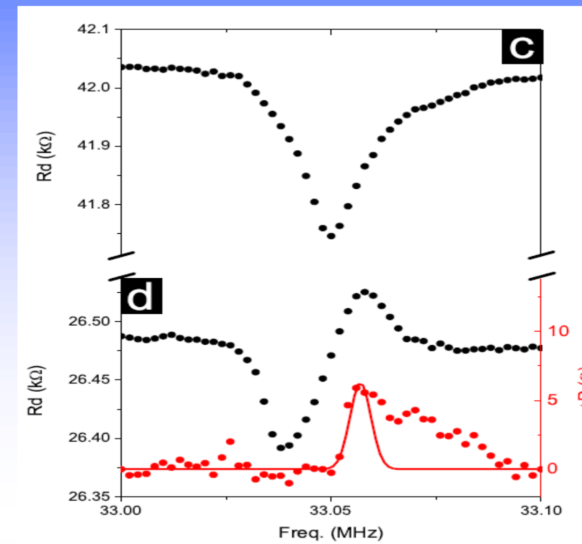
$\nu_{QPC} < 1$

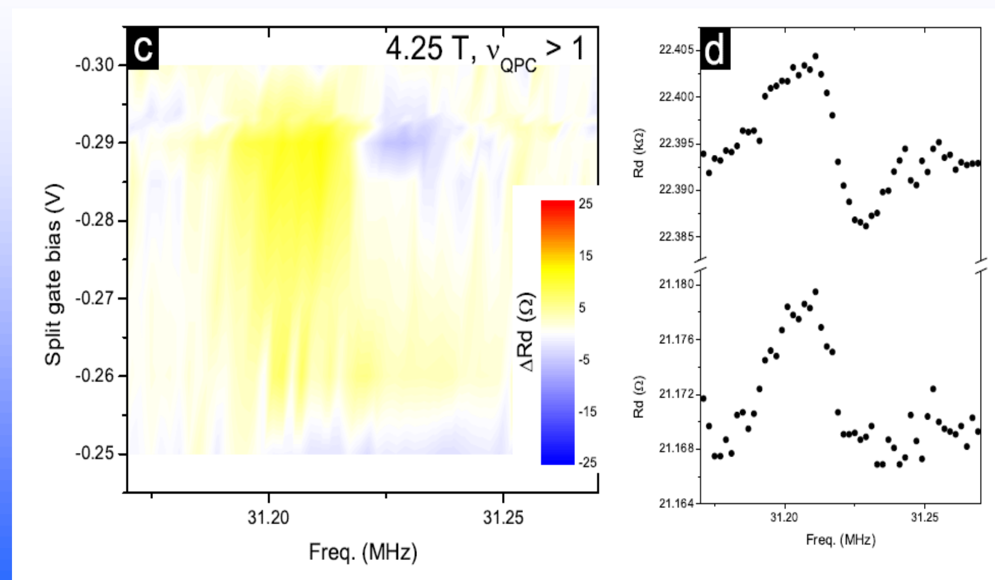
Dynamic nuclear polarization and RDNMR are possible in QPC when outside of QPC has ν=2 and inside of QPC has ν=1. Nuclear spins inside (outside) of QPC feel (don't feel) Knight shift.

RDNMR in Quantum Constriction









RDNMR line shape is complicated, reflecting nuclear polarization position and polarization polarity.

M.H. Fauzi, YH *et al.*, Phys. Rev. B95, 241404 (RC) (2017).
A. Singha, YH *et al.*, Phys. Rev. B95, 115316 (2017).

Today's Topics

1. Resistively-detected nuclear magnetic resonance (RDNMR)
   - Introduction
   - Dynamic nuclear polarization and RDNMR (GaAs)
     - ▪Domain structure ▪Quantum Hall breakdown ▪Optical irradiation
   - InSb ν=2 quantum Hall ferromagnet (QHF) and RDNMR
2. Physics unveiled by RDNMR
   - Electron spin polarization measured from Knight-shift
   - Electron spin fluctuation measured from T_1 time
   - Application to nanostructures
3. Microscopic nuclear resonance imaging by using nanoprobe
4. Future possible extension

MULTI DIMENSION

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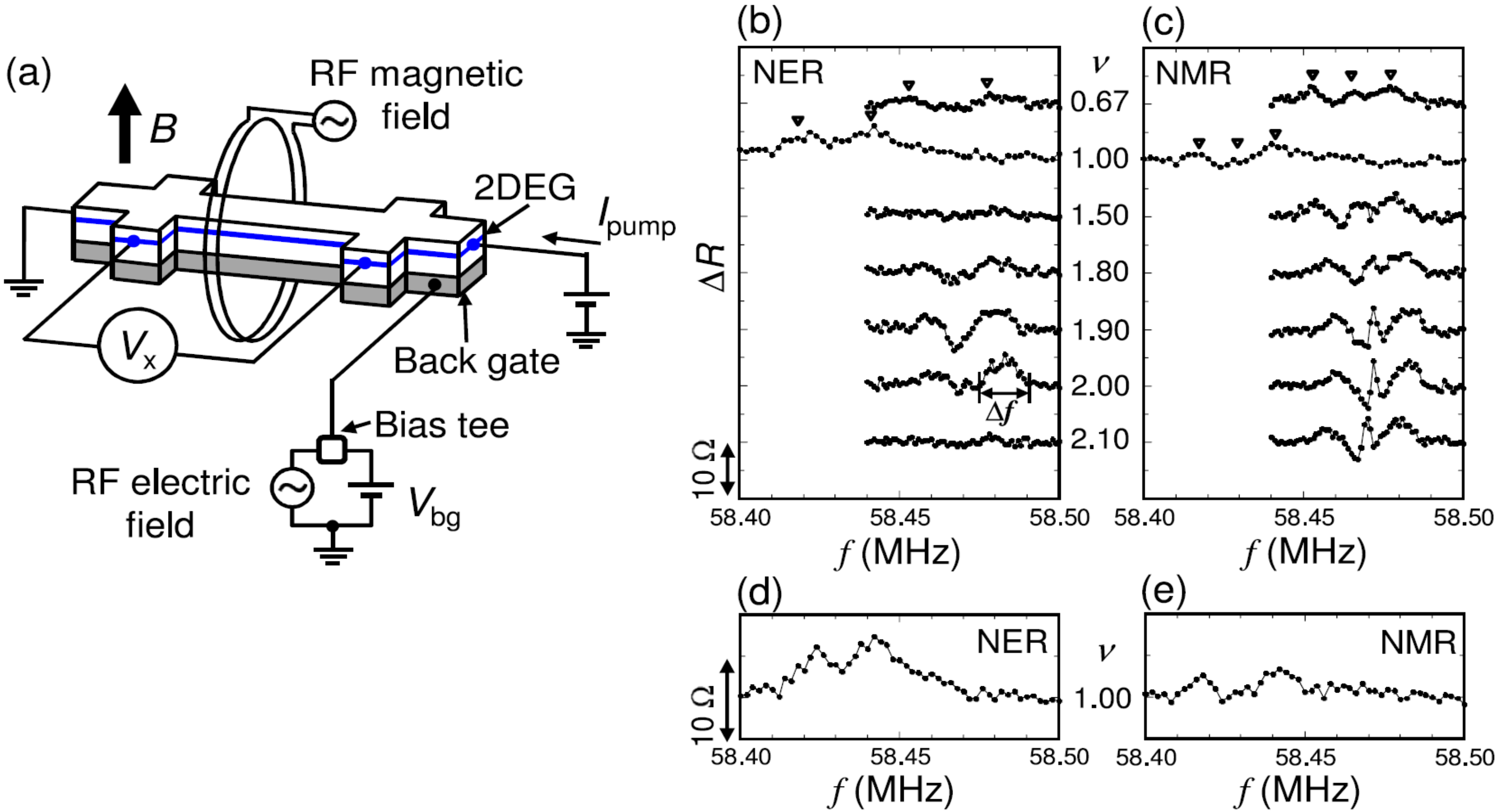
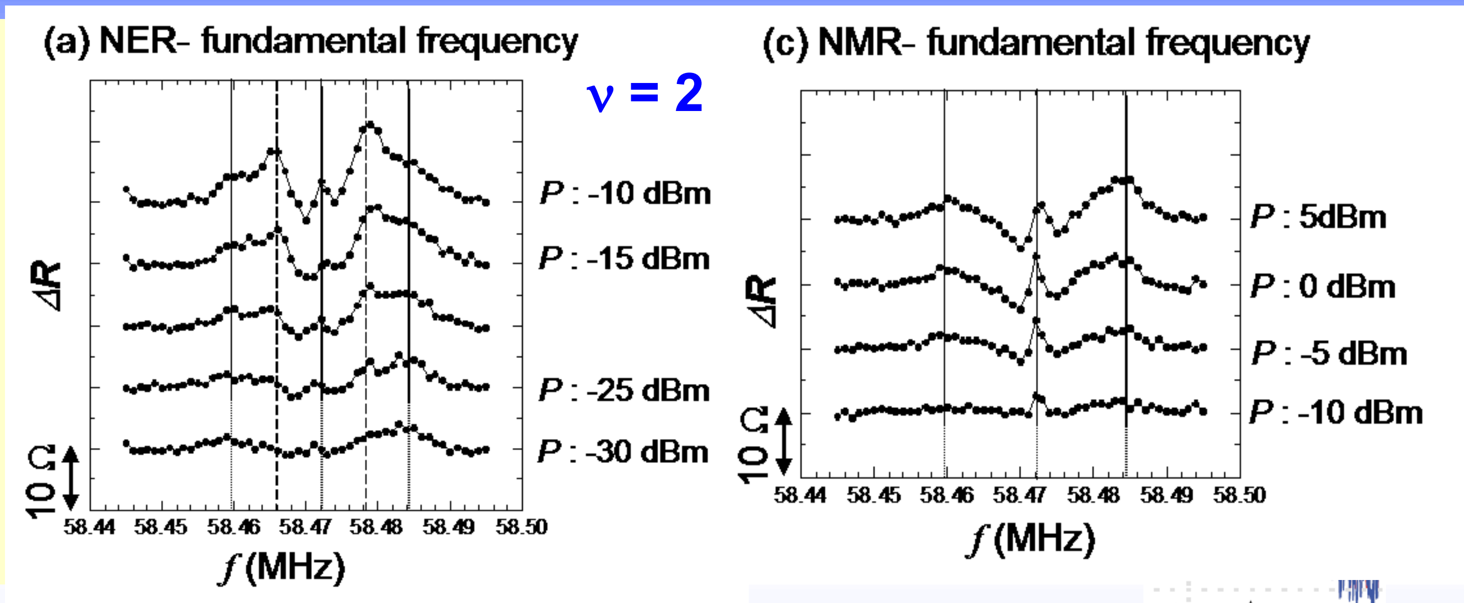
NER: Nuclear Electric Resonance

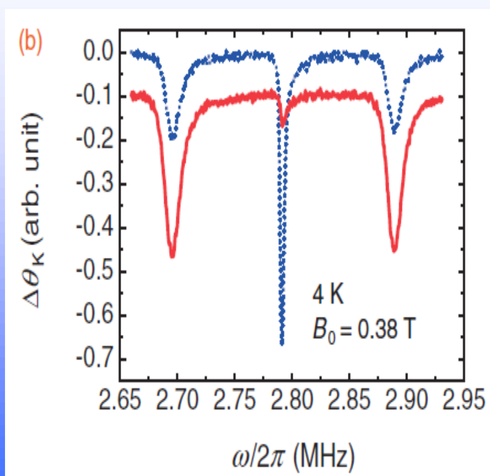


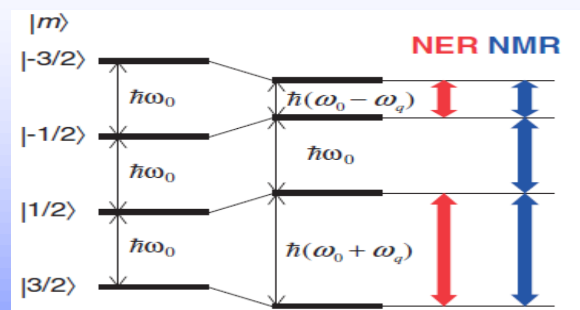
T. Tomimatsu, YH et al., AIP Advance 5, 087156 (2015).

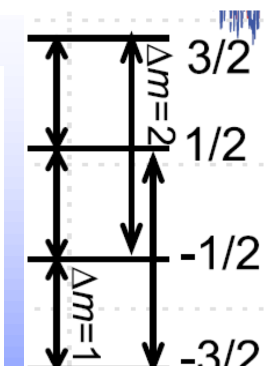
Nuclear Resonance based on Electric Quadrupolar Coupling

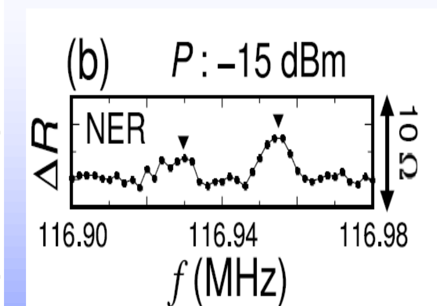


NER can be induced by electric quadrupolar coupling









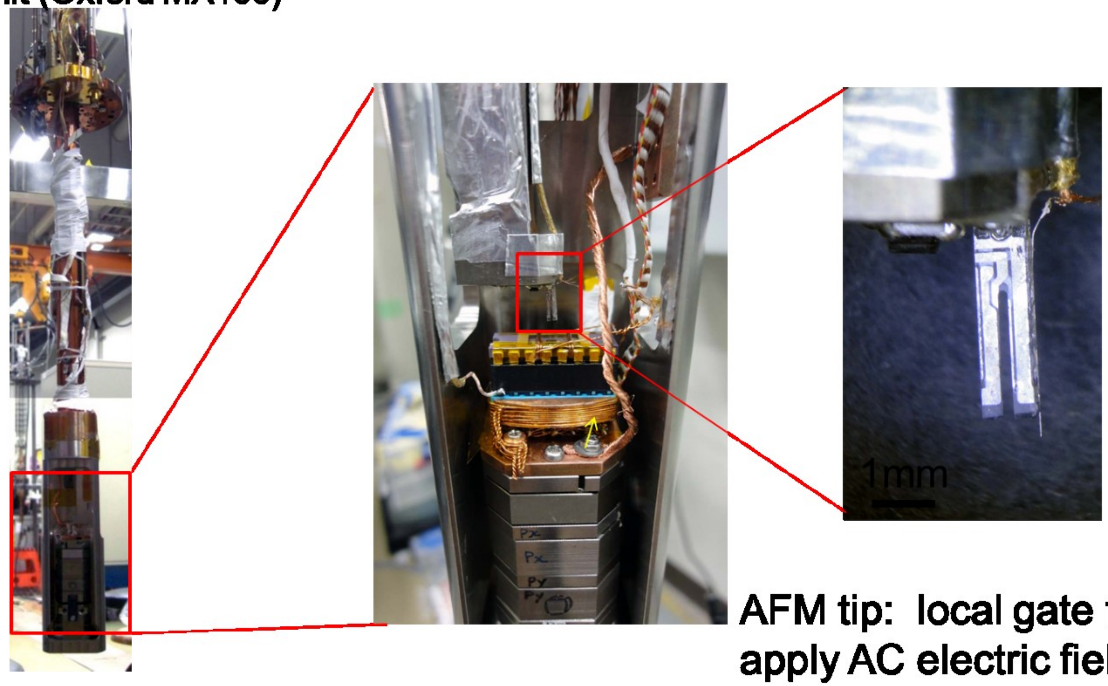
for bulk GaAs

E. Brun et al., Phys. Rev. 129, 1965 (1963).

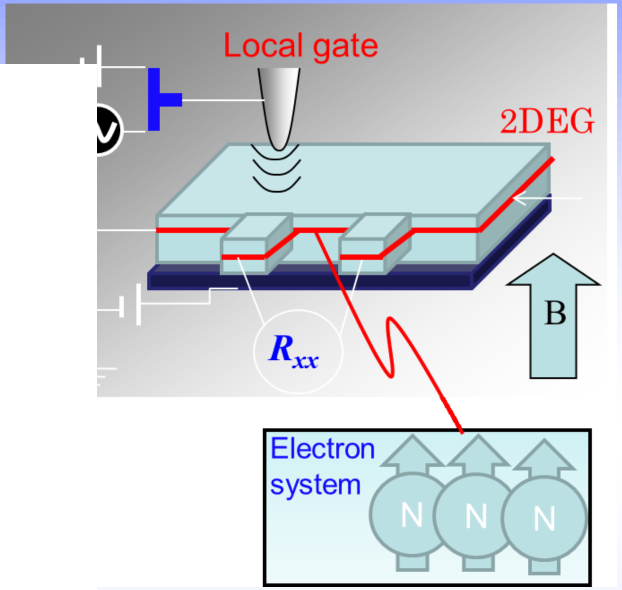
Appearance of 2*f*-signal support electric quadrupolar coupling.

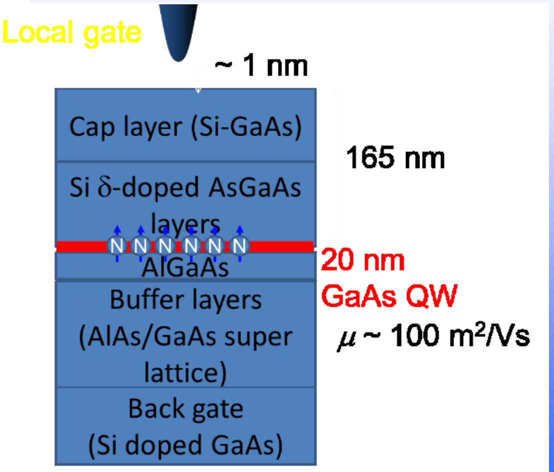
Scanning Gate Probe Operating at 100 mK

Dilution refrigerator unit (Oxford MX100)



AFM tip: local gate to apply AC electric field to 2DEG

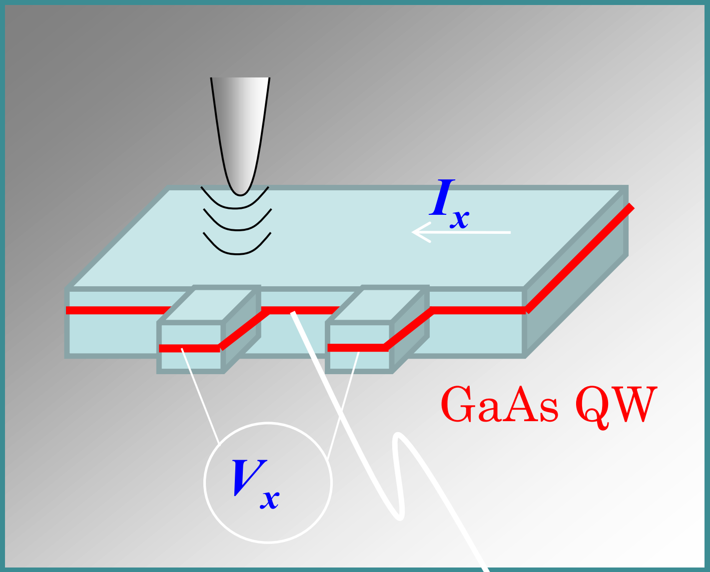


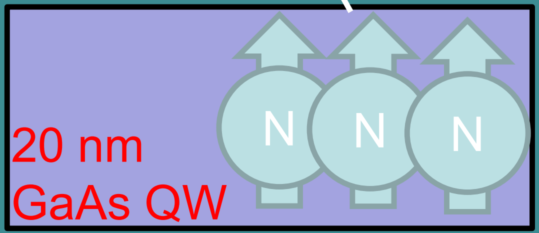


Imaging of Nuclear Related Signal in the QH Breakdown

Backgated 20 nm quantum well
(μ = 60-100 m^2/Vs)

Hall bars; 10 μm width





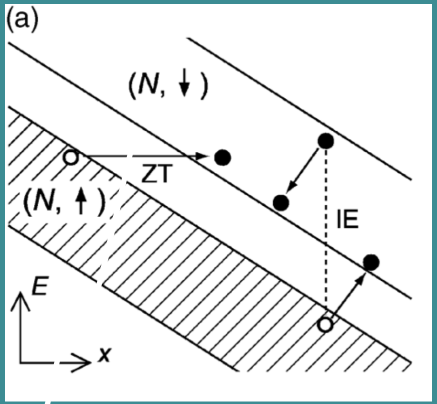
Target: ^{75}As nuclear spins

Current induced nuclear spin polarization

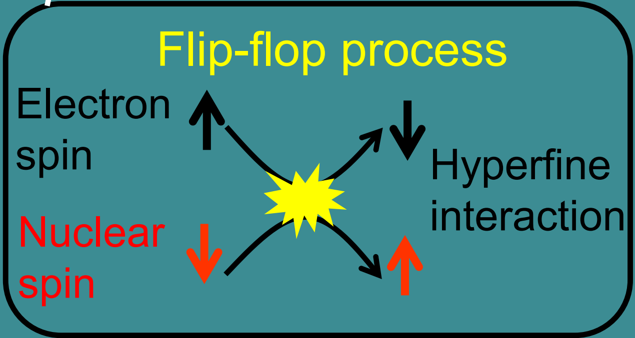
ν ~ 1 (B = 7 T－8 T)

I_{sd} = 0.6 μA－2 μA（Breakdown regime）

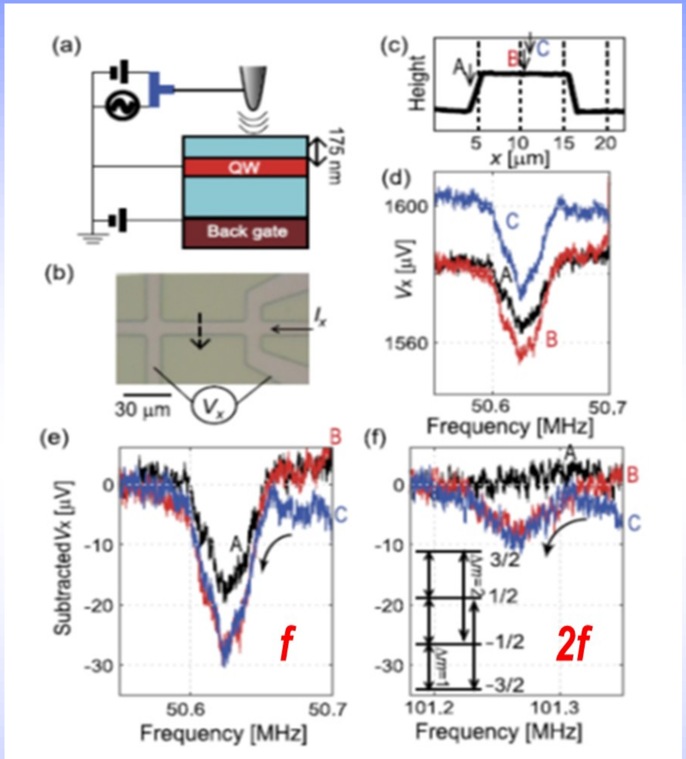
T = 200 mK－300 mK



Kawamura *et al*. APL **90**, 022102 (2007).



Microscopic Imaging of NER Signal



Successful imaging of the quantum Hall breakdown will be published soon.

Unintentional background can be suppressed by 2*f*-NER.

The 2D mapping of the breakdown characteristics is now possible by using the NER imaging.

K. Hashimto , YH *et al.*, AIP Advances 6, 075024 (2016).

K. Hashimoto, YH *et al.*, (submitted).

Conclusions

1. Resistively-detected nuclear magnetic resonance (RDNMR) is possible for GaAs, InSb, and ???? quantum systems.
2. The RDNMR becomes powerful tool to study electron spin polarization (Knight-shift), electron spin fluctuation (T_1 time), and strain felt by carriers (quadrupolar splitting).
3. Microscopic nuclear resonance imaging is possible by using nanoprobe. As one example, we have demonstrated imaging of quantum Hall breakdown.
4. Interesting possible extension; novel cooperative physics, RDNMR of topological insulator, and more.

GP Spin

MULTI DIMENSION

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(～March 2015)
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M. Korkusinski

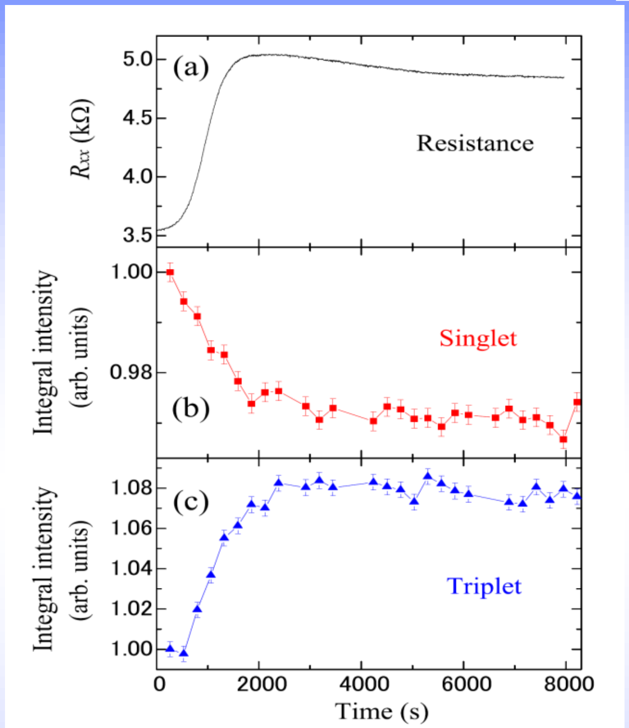
IIT bombay
B. Muralidharan
A. Singha

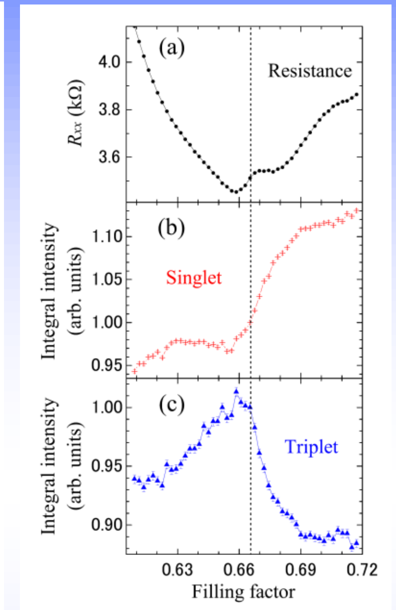
NII
Y. Hamma
K. Nemoto

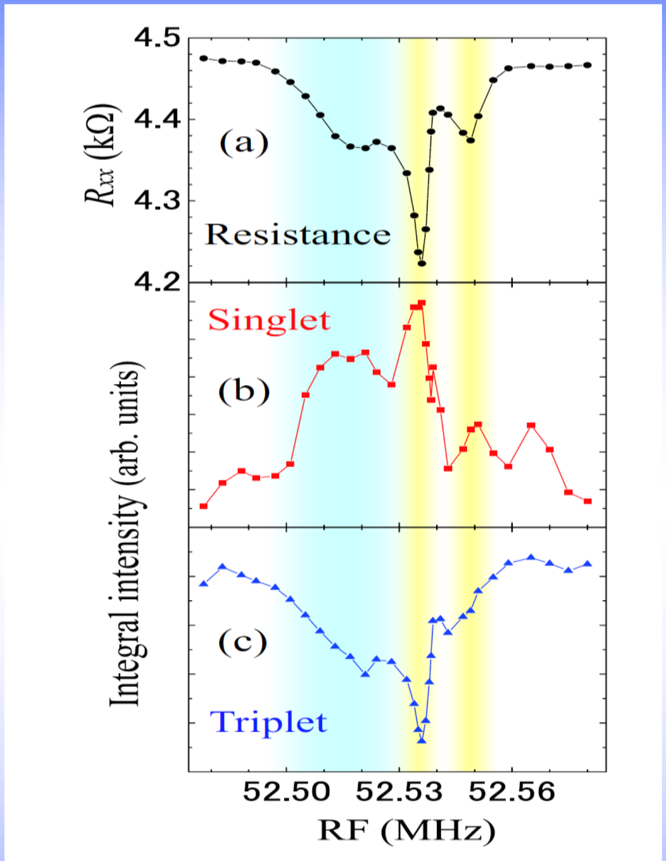
*** Former members**

Appendix:

Simultaneous Optical and Resistive Detections







Resistance and PL intensity changes with current-induced nuclear polarization

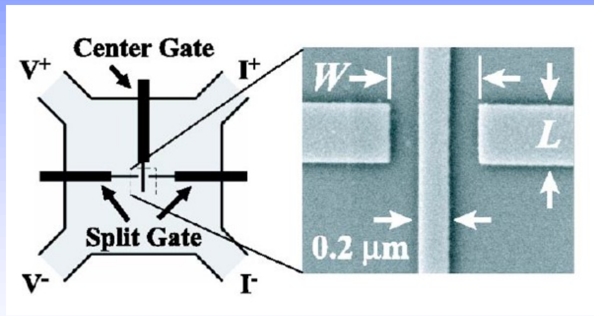
***T* = 0.3K**

NMR spectra measured by resistance and PL intensity detection

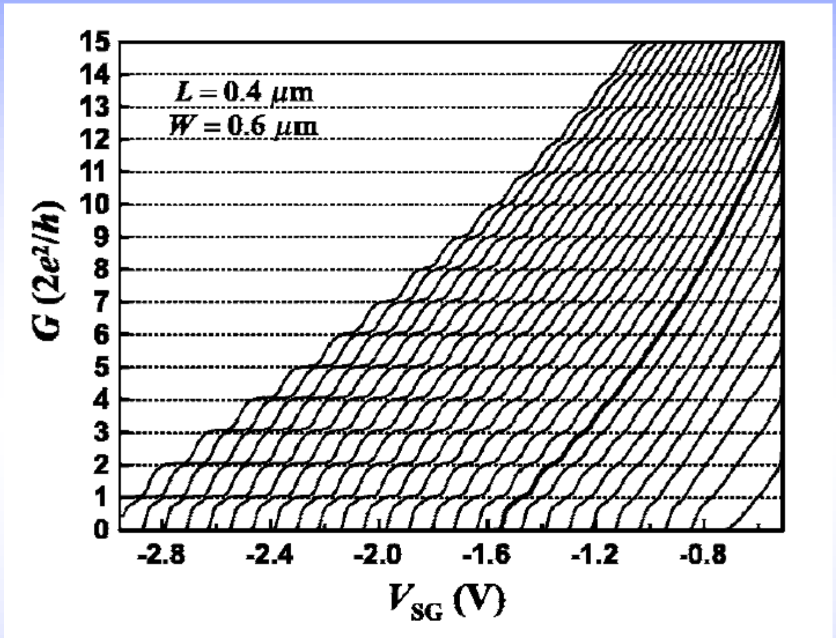
The simultaneously measured NMR spectra qualitatively showed the same feature. The optically detected signal might be originated from trion scattering induced by nuclear polarization.

K. Akiba, K. Nagase, and Y. Hirayama, Phys. Rev. B94 (RC), 081104 (2016)

Triple-Gate Quantum-Point-Contact (QPC) I

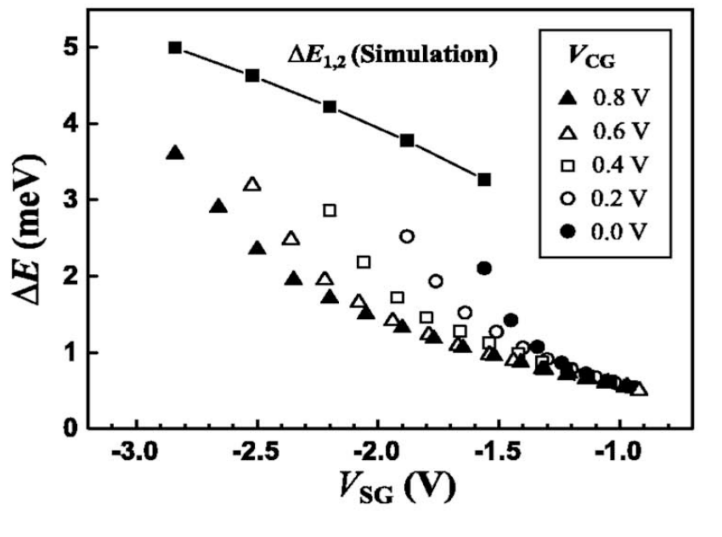


V_{cg} = 0.9 -0.45 V (0.05V interval)



High mobility wafer

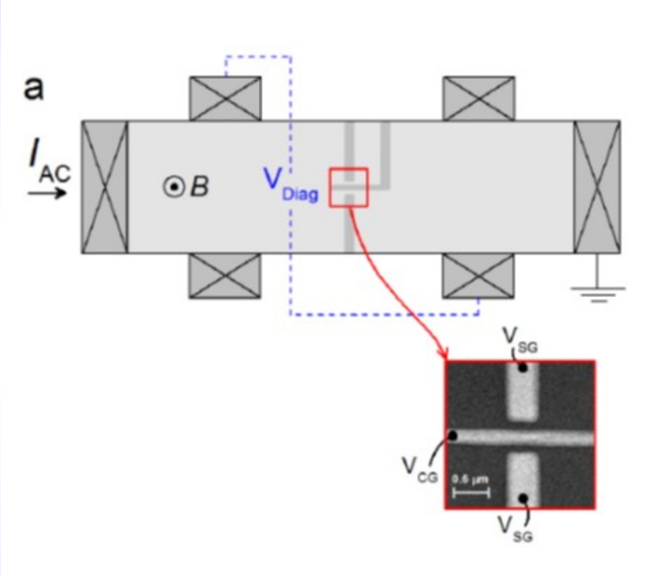
μ = $3 \times 10^6 cm^2/Vs$ at $1.5 \times 10^{11} cm^{-2}$ (1.5 K)

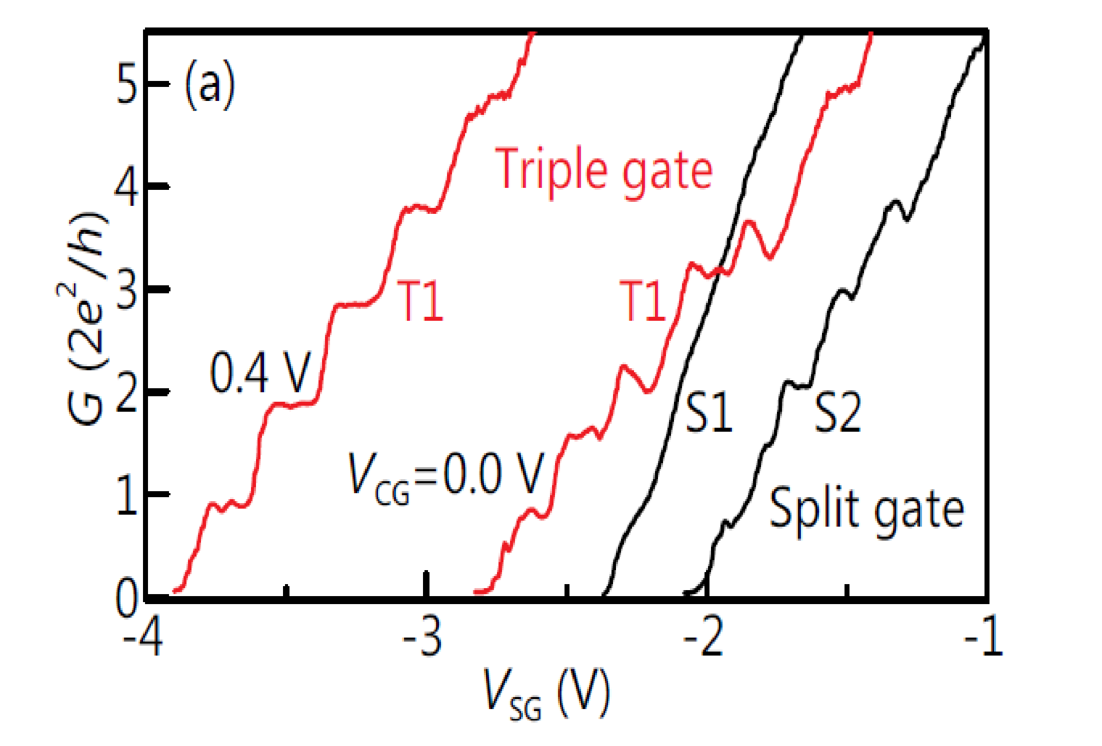


Positive center gate bias in the triple-gate structure results in a strong confinement with large 1D subband energy separation. We can expect pronounced quantization in the triple-gate QPC.

H. –M. Lee, YH et a. J. Appl. Phys. 100, 043701 (2006)

Triple-Gate Quantum-Point-Contact (QPC) II



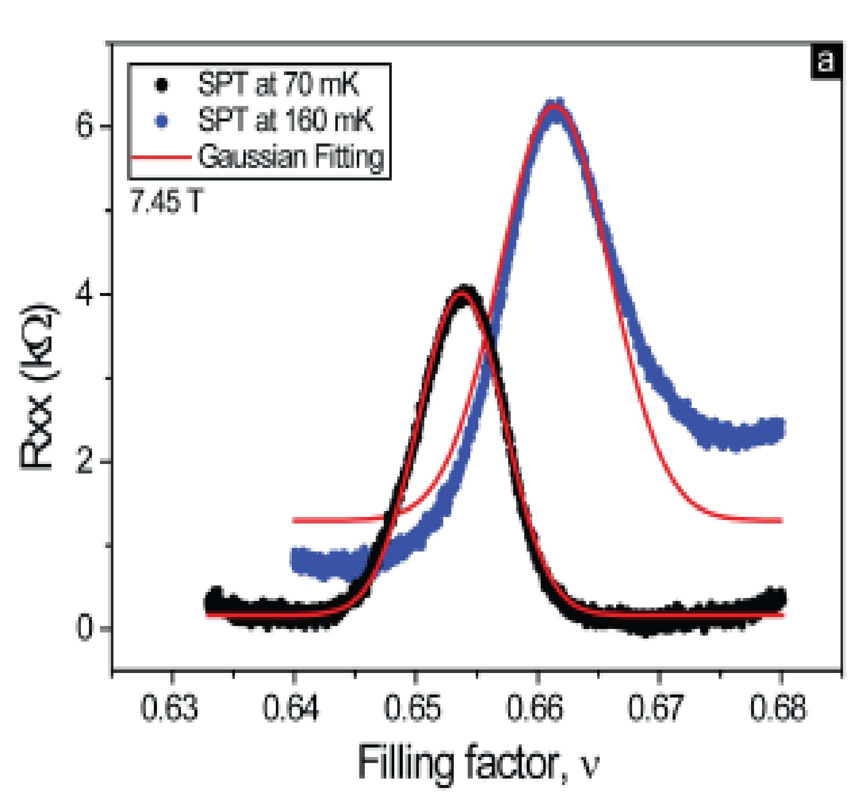


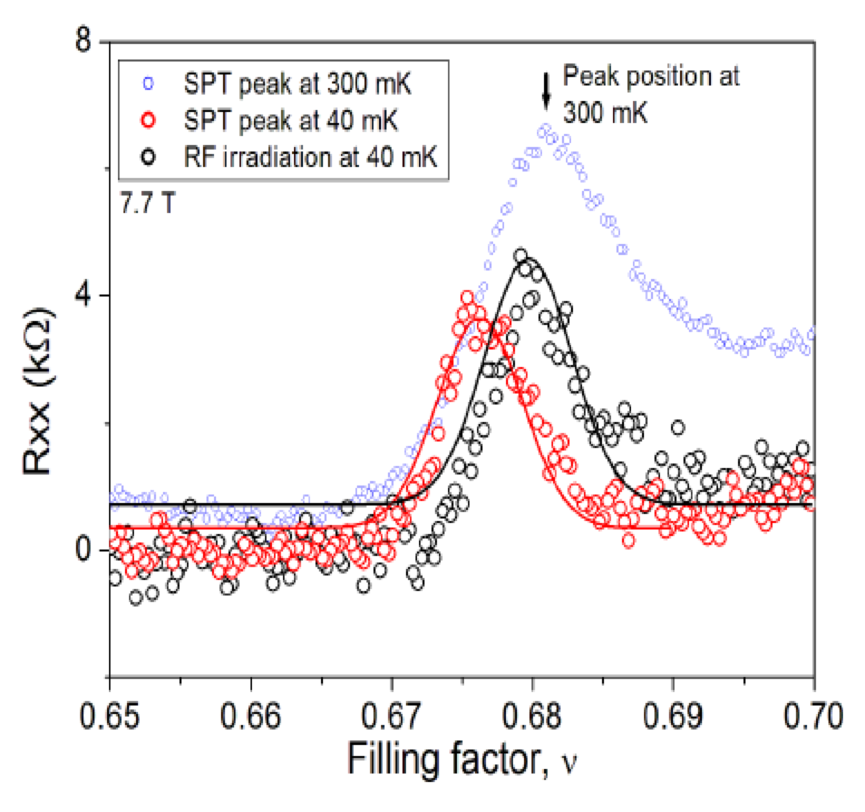
Not high mobility wafer
μ **= 28cm²/Vs (1.8x10¹¹cm⁻², 1.5K)**

Triple-gate structure enhances quantized conductance even for a relatively low-mobility wafer.

S. Maeda, YH *et al*., Appl. Phys. Lett. 109, 143509 (2016).

Detection of Low-T Nuclear Polarization





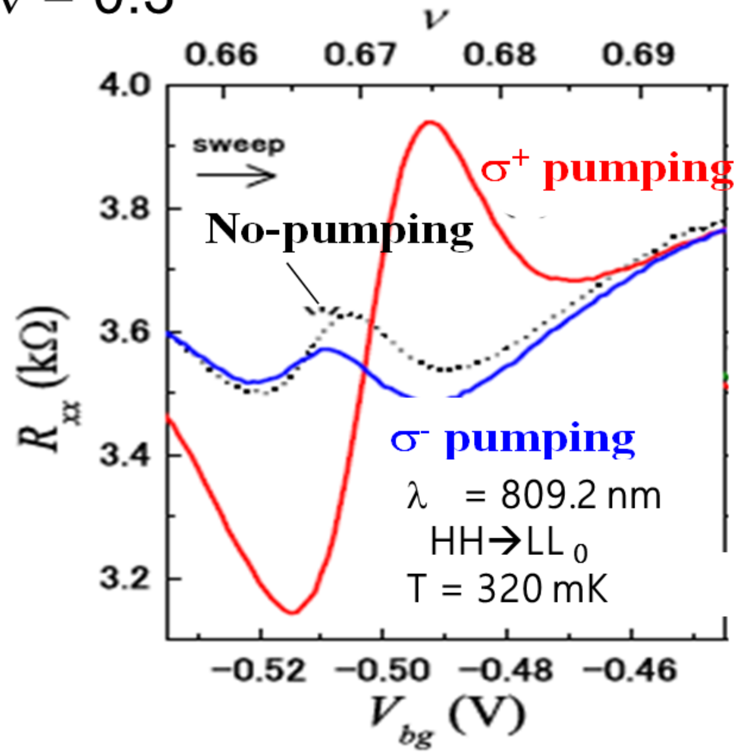
The shift of SPT peak by low-temperature nuclear polarization suggests a possibility to detect nuclear polarization down to 1% of the total nuclear spins.
The sharp SPT peak confirms spatially uniform nuclear polarization at low temperatures.

M. H. Fauzi, Y. H. et al., J. Korean Phys. Soc., 60, 1676 (2012).

Optical Nuclear Polarization and ν = 2/3 SPT Detection

$$\boxed{B_N = -A\left(\langle S_Z\rangle - \langle S_Z\rangle_{eq}\right)}$$

ν = 0.3



$\langle S_z\rangle$: Optically induced electron spin polarization

$\langle S_z\rangle_{eq}$: Background electron spin polarization

σ+ pumping → $\langle S_z\rangle = -1/2$ → $B_N > 0$

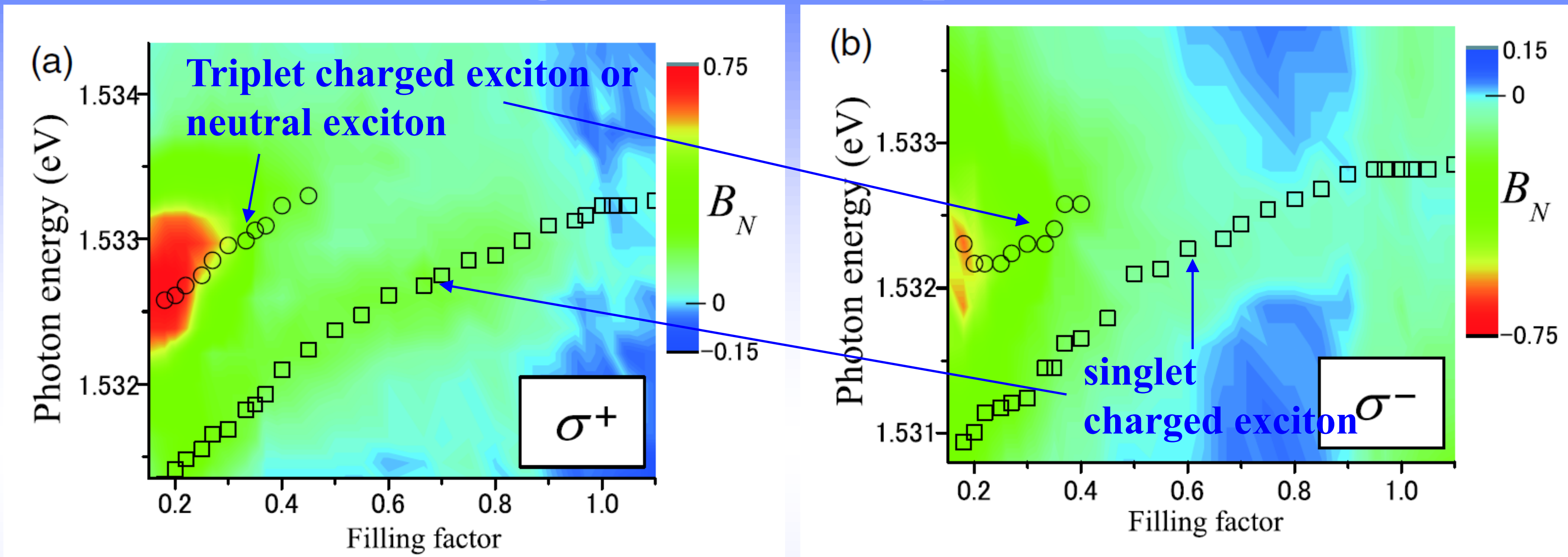
σ- pumping → $\langle S_z\rangle = 1/2$ → $B_N < 0$

Nuclear polarization can be controlled by the direction of circular polarization.

Coulomb interaction allows us $\langle S_z\rangle_{eq} \neq 1/2$ even at low temperatures, resulting $B_N < 0$ nuclear polarization.

K. Akiba, YH et al., Appl. Phys. Lett. 99, 112106 (2011)
K. Akiba, YH et al., Phys. Rev. B87, 235309 (2013)

Filling Factor Dependence

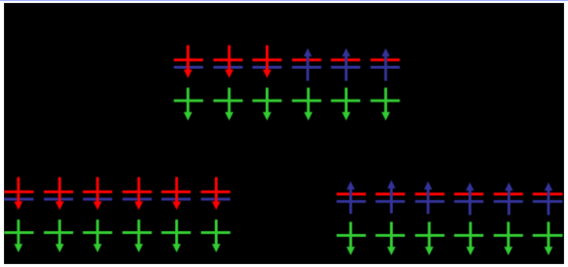


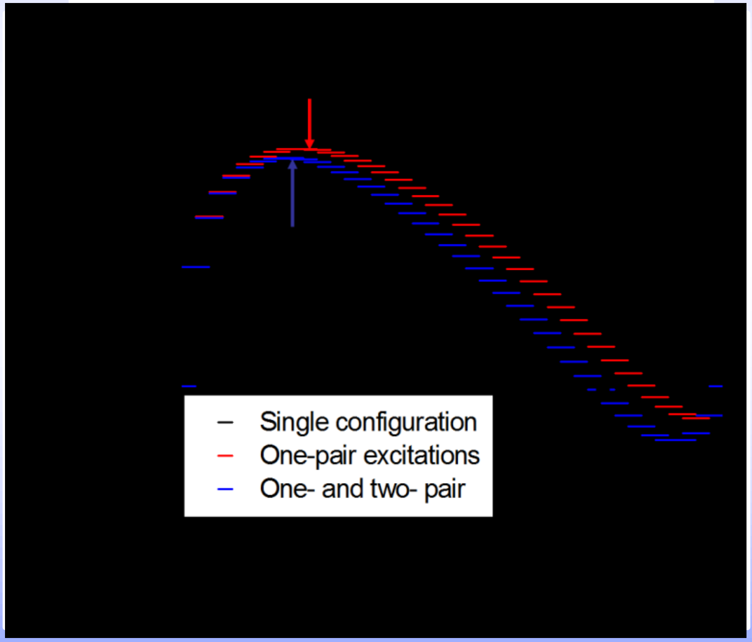
The nuclear polarization occurs at the positions where photoluminescence peak appears. That means the nuclear polarization is accompanied by the absorption. The strong nuclear polarization in the regime of $\nu < 0.3$ reflects the large <Sz> under neutral exciton absorption.

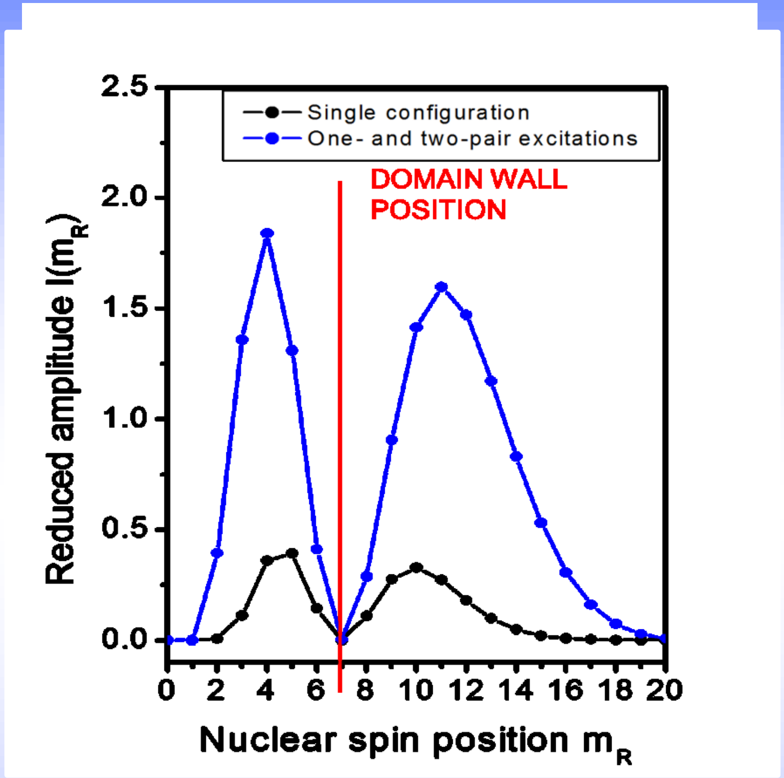
The estimated maximum B_N is about 0.6 T, suggesting 10-15% nuclear polarization.

K. Akiba, YH et al., Phys. Rev. Lett. 115, 026804 (2015) [editor's Suggestion]

DNP Based on QHF Domains: Theoretical Approach







M. Korkusinski, P. Hawrylak, YH *et al.*, Scientific Reports **7**, 43553 (2017).

Energy needed to flip one electron spin in a domain wall becomes comparable to the energy needed to flip the nuclear spin. The movement of the domain wall relative to the position of the nuclear spin enables the manipulation of the nuclear spin by electrical means.