YKIS2007 (Interaction and Nanostructural Effects in Low-Dimensional Systems)

November 16th, Kyoto, Japan

Nuclear spin spectroscopy for semiconductor hetero and nano structures

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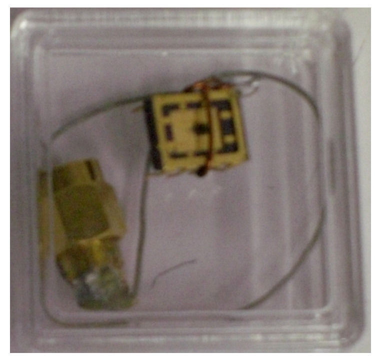

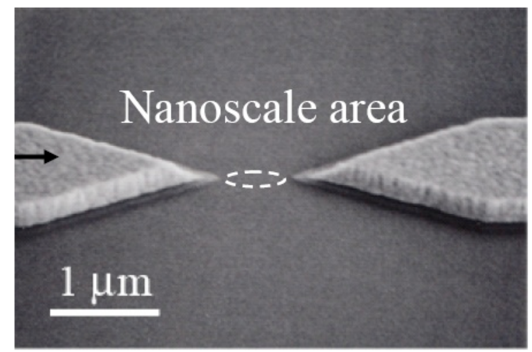

cm^3, mm^3 | μm^2 x nm | nm^3

- Introduction
- Electron and nuclear spin interactions and resistively detected NMR
- Possibility of nuclear spin control in nanoscale
- Nuclear-spin-based measurements as a powerful tool to study electron spin physics in 2DEG

- Novel NMR: Electric field induced NMR
- Summary

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- Electron and nuclear spin interactions and resistively detected NMR
- Possibility of nuclear spin control in nanoscale
- Nuclear-spin-based measurements as a powerful tool to study electron spin physics in 2DEG
  - Skyrmion
  - Spin degree of freedom
  - Canted spin states
  - Spin orbit interaction
- Novel NMR: Electric field induced NMR
- Summary

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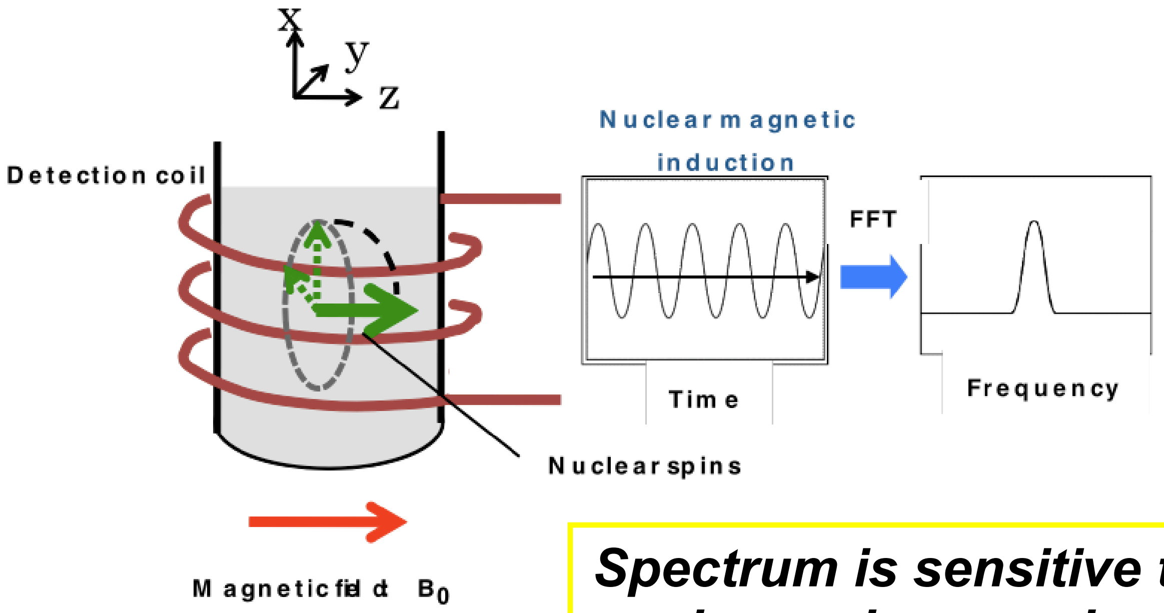
Standard NMR



NMR

MRI

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

Effect of surrounding nuclei ---- structure analysis

Knight shift ---- electron spin information

Quadrupolar splitting ---- strain around the nucleus

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

Standard NMR : view from semiconductor physicist

Disadvantages:

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

Not suitable for *I*>=3/2 like Ga, As , -----

NMR studies for semiconductor systems

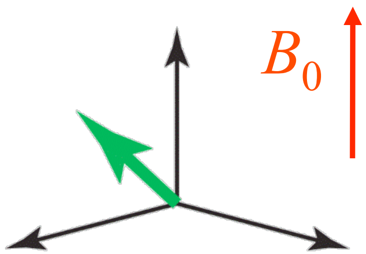
Bell, CNRS (1995-)

100 layers of quantum wells

Standard NMR is not suitable for semiconductor single-layer-systems and nanosystems, where characteristics are controlled by gate bias.

Resistively detected NMR

Magnetization M of nuclear spins

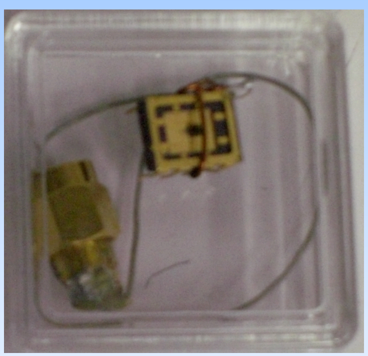


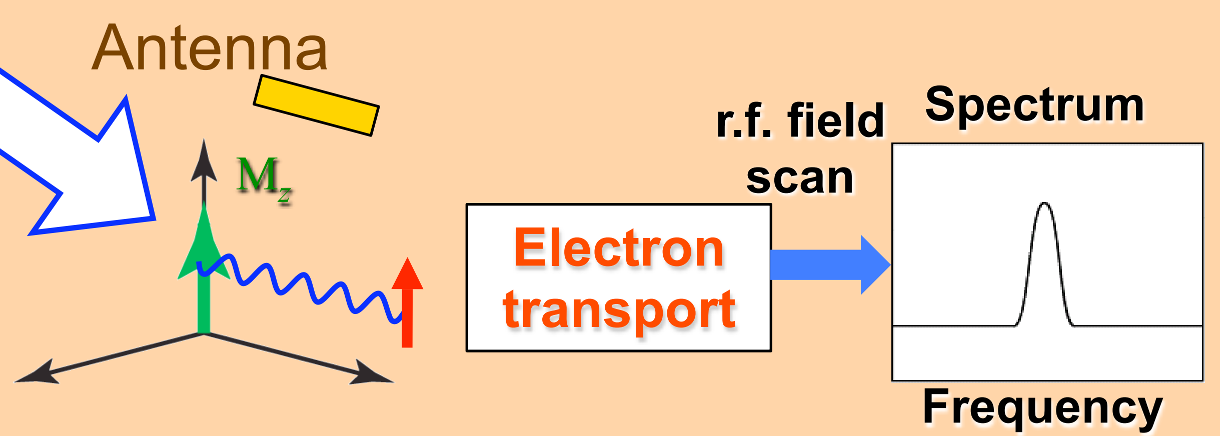
To overcome limitations of the standard NMR, a novel NMR technique has been developed.

The technique is based on direct detection of *Mz* by using conductive electron and nuclear spin interactions.

Novel NMR: Resistively detected NMR

z-component: M_z



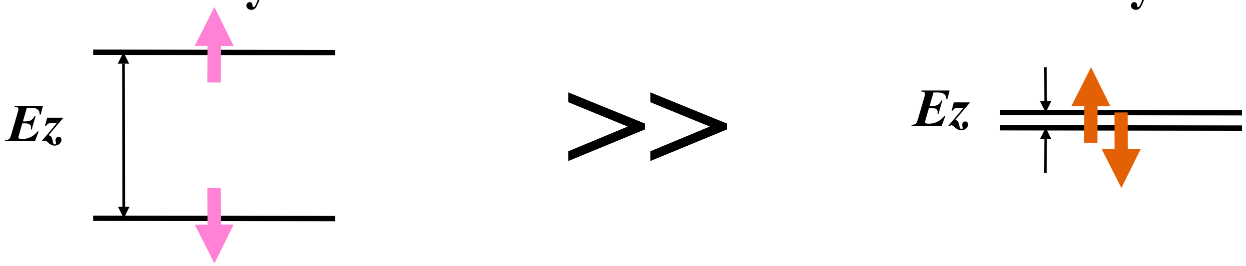


NMR on a chip: NMR suitable for thin layer and nanostructure

- Electron and nuclear spin interactions and resistively detected NMR
  - Nuclear spin / electron spin interactions
  - Nuclear spin polarization
  - Detection of nuclear spin polarization

Conventional situation

electron system **nuclear system**

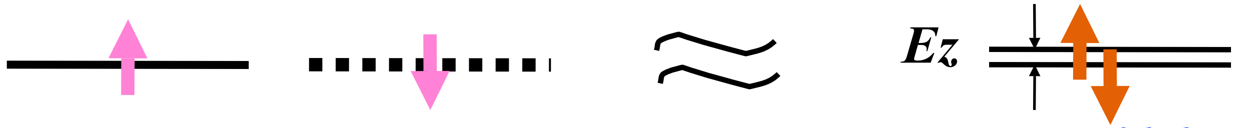


Energy and angular momentum transfers are ***not possible*** **.**

→ ***negligible interaction between electron and nuclear spins***

Degeneration of different electron-spin states

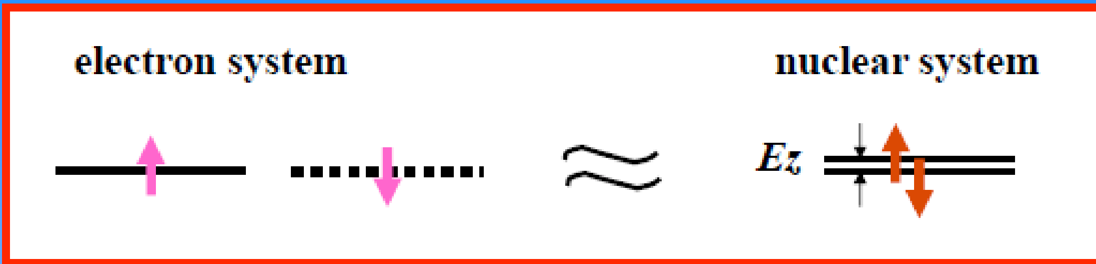
electron system **nuclear system**

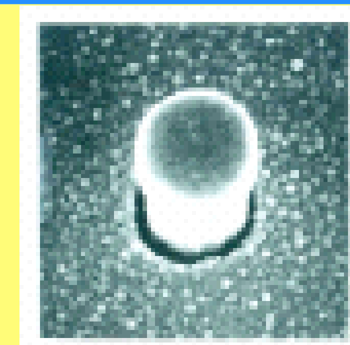


Energy and angular momentum transfers are now ***possible*** **.**

→ ***interesting interactions between electron and nuclear spins***

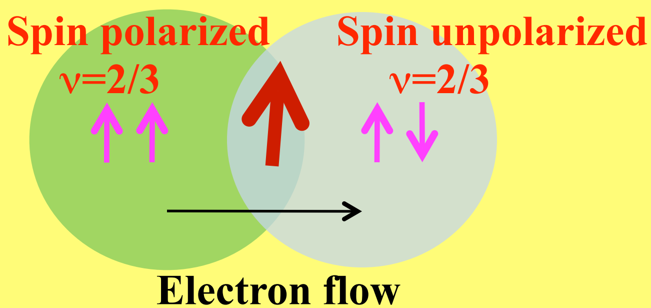
Nuclear-spin polarization and detection





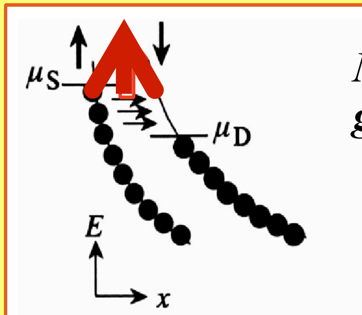
Coupled quantum dot
Tarucha group

ν=2/3 Fractional QHE regime



von Klitzing group
Hirayama group

Edge channel or breakdown in integer QHE regime



Machida group

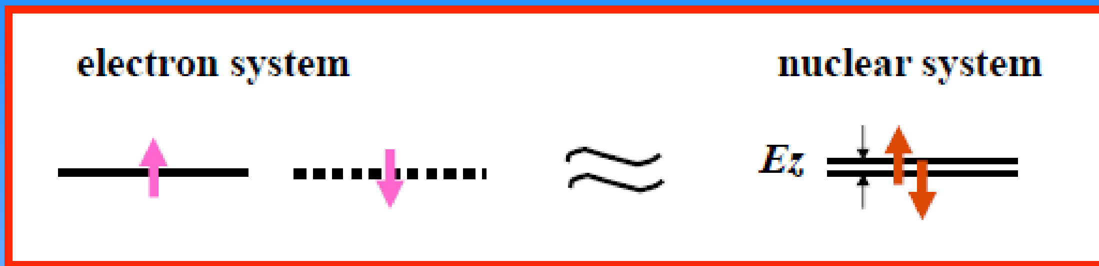
Nuclear spin polarization induces resistance change if resistance is sensitive to the effective Zeeman energy

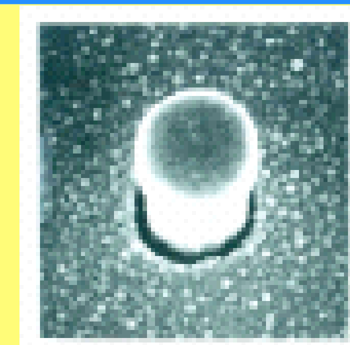
- **Transition region in the FQHE**
- **Transition between localized and extended states in QHE**

Circularly polarized light illumination

e.g., Awschalom group

Nuclear-spin polarization and detection





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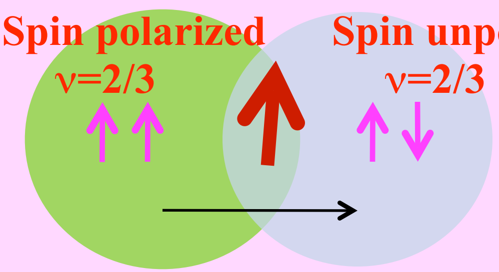

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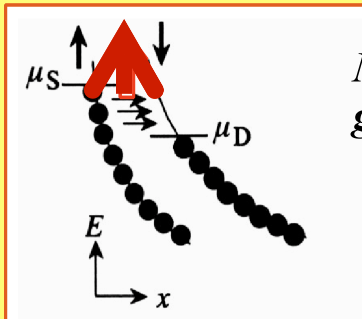

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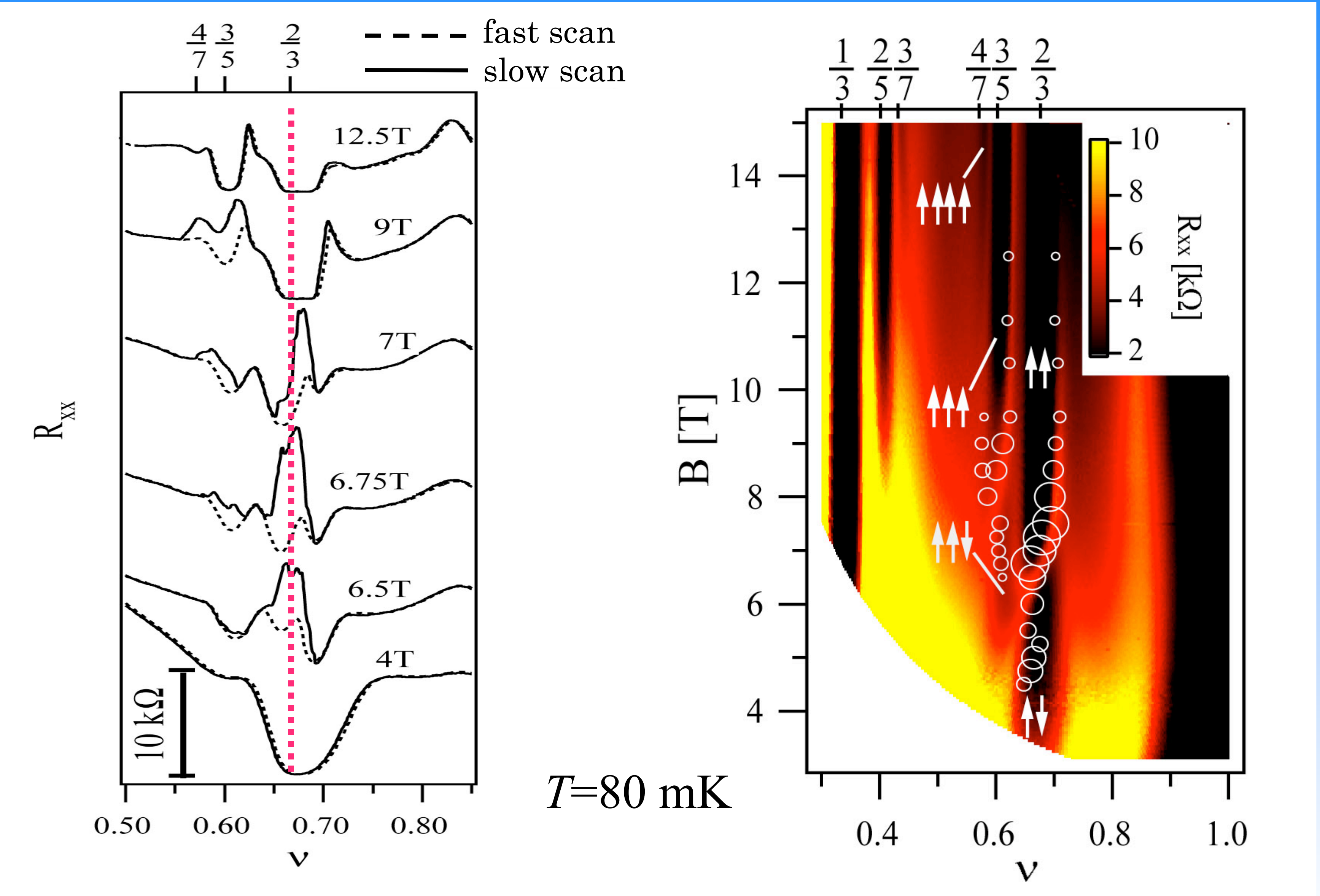
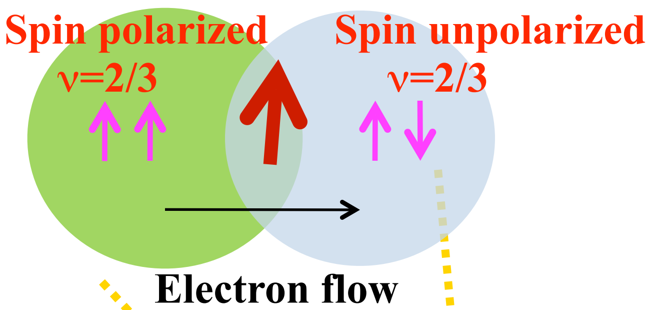
ν=2/3 transition point and nuclear spin polarization



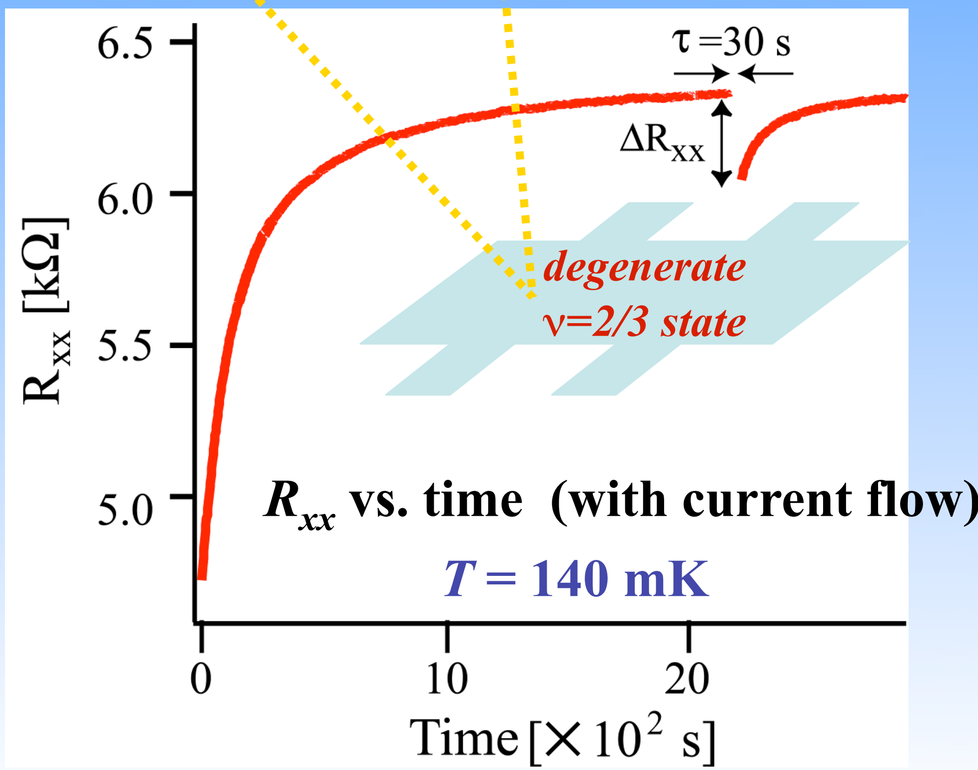
T=80 mK

Nuclear spin polarization and detection at ν=2/3



Fractional quantum Hall effect
(ν=2/3、domain？)

Kronmüller *et al*. PRL (1998)
Hashimoto *et al*. Physica B (2001)



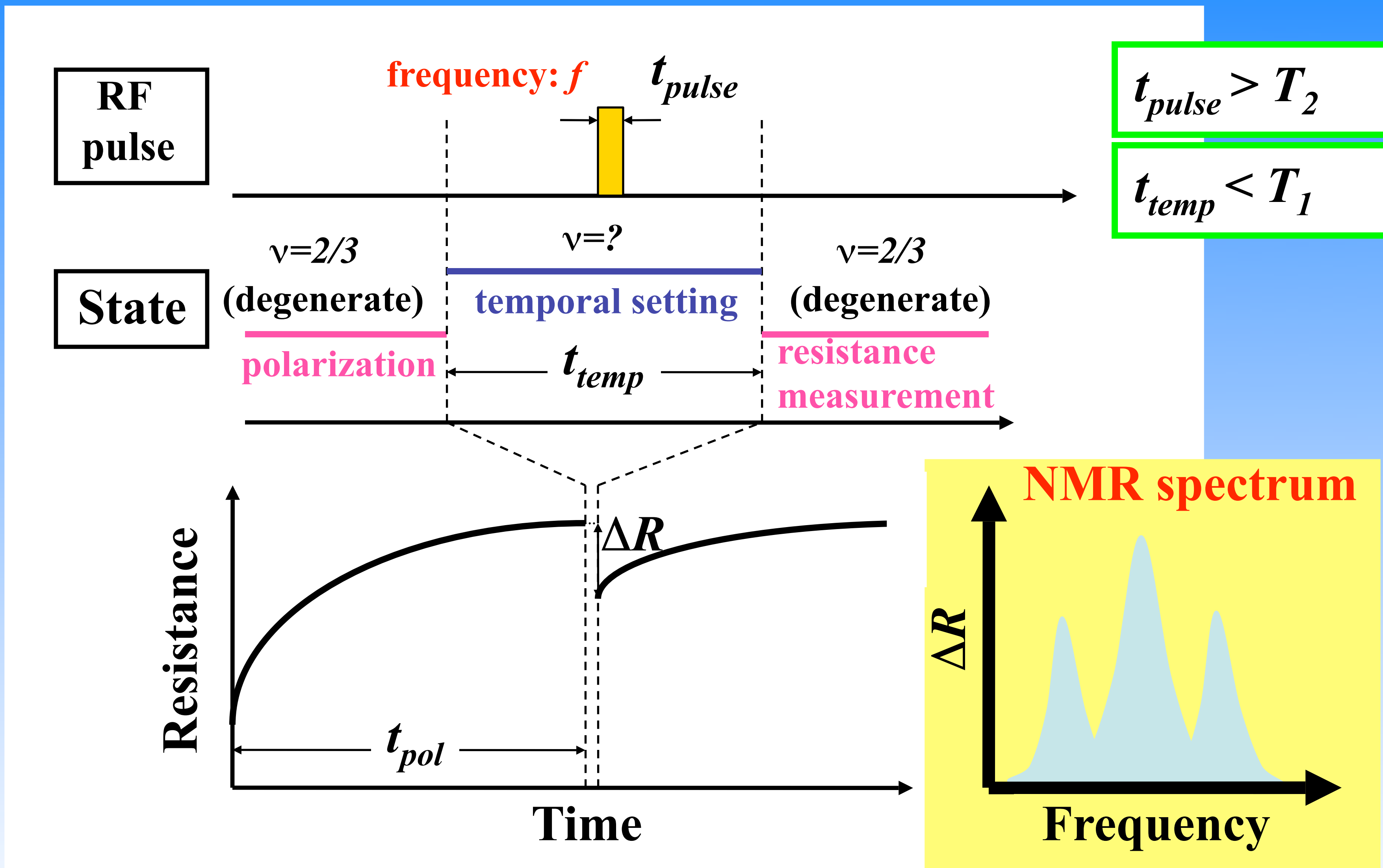
Nuclear spins can be polarized by current flow.

Vertical nuclear-spin magnetization (M_z) is directly measured by resistance value.

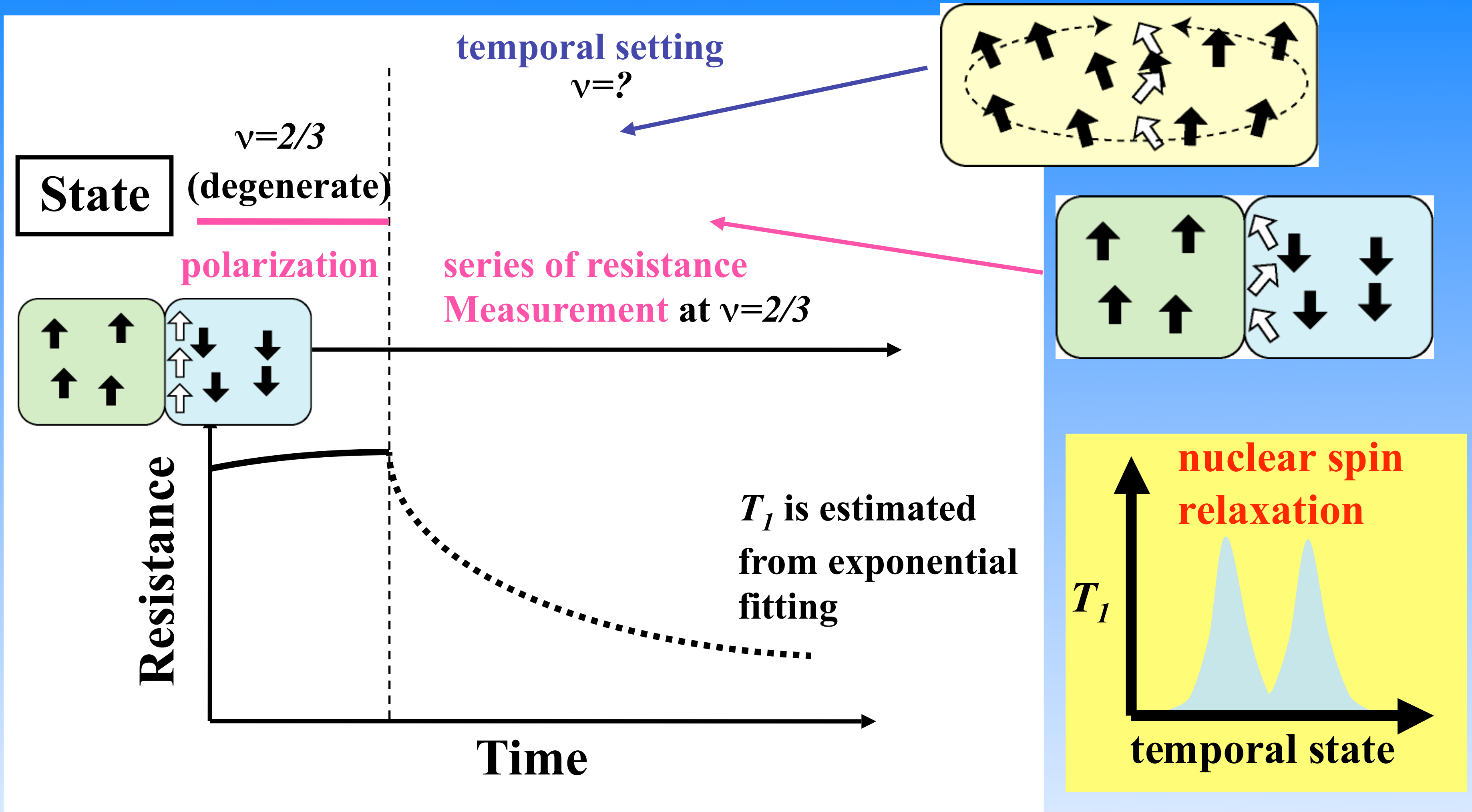
$$M_z = \alpha R_{xx}$$

Phys. Rev. Lett. 88, 176601 (2002)

NMR spectrum measurement

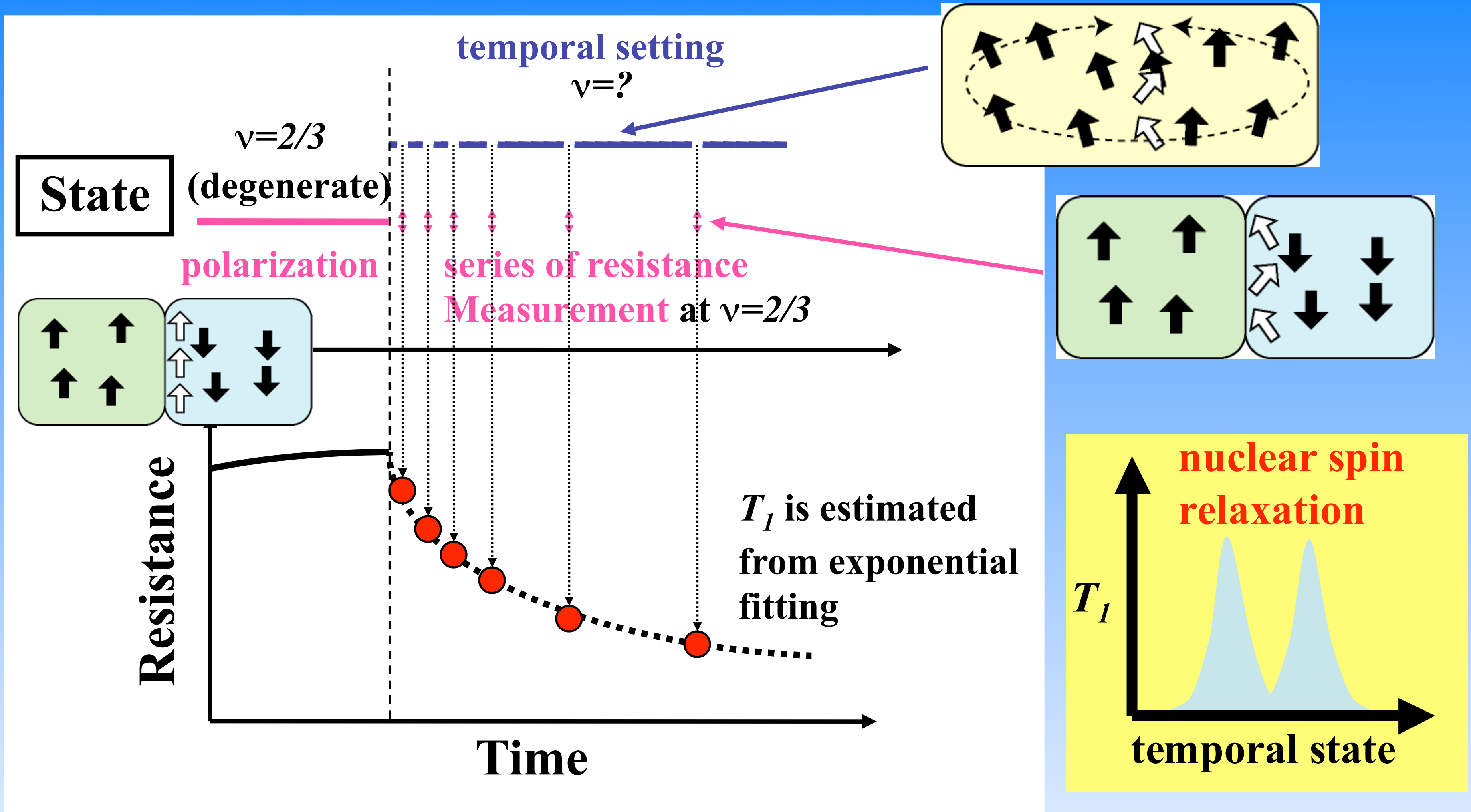


Nuclear spin relaxation measurement



- NMR spectrum and T_1 time can be measured for any states.
- We can monitor electron spin states, especially electron spin correlation, from T_1 time

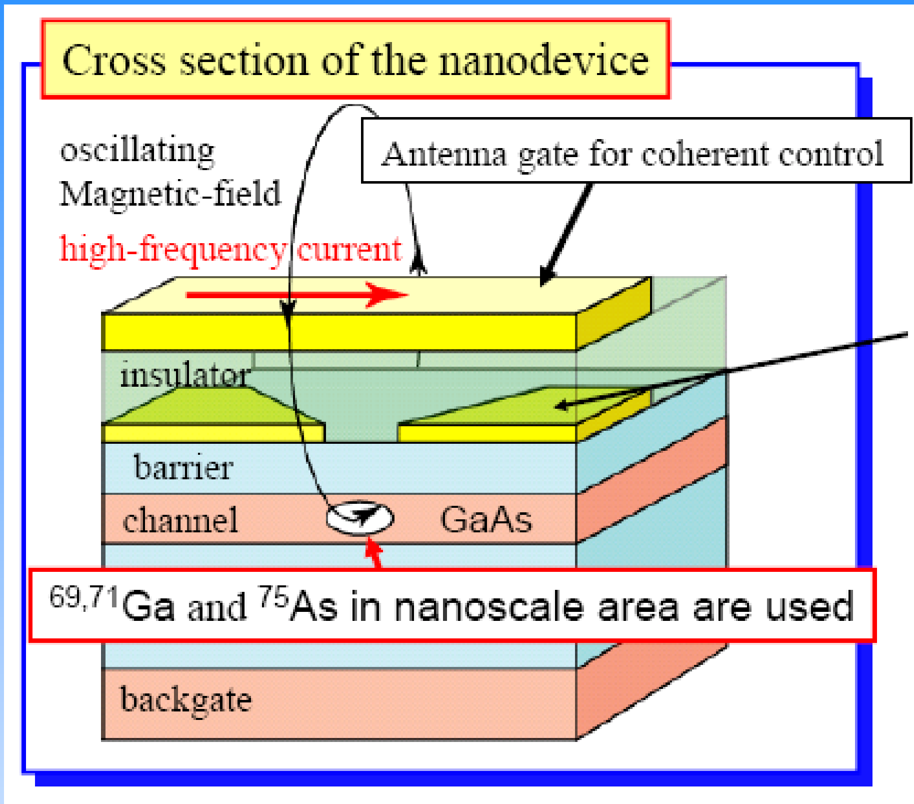
Nuclear spin relaxation measurement

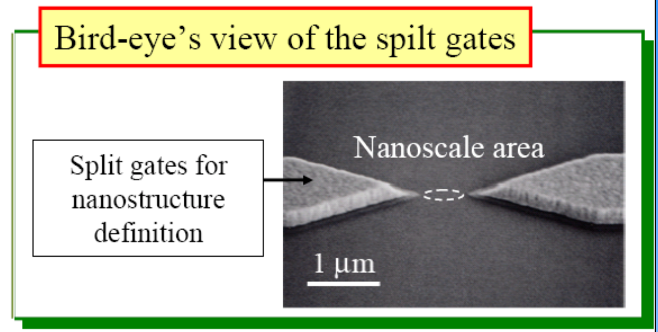


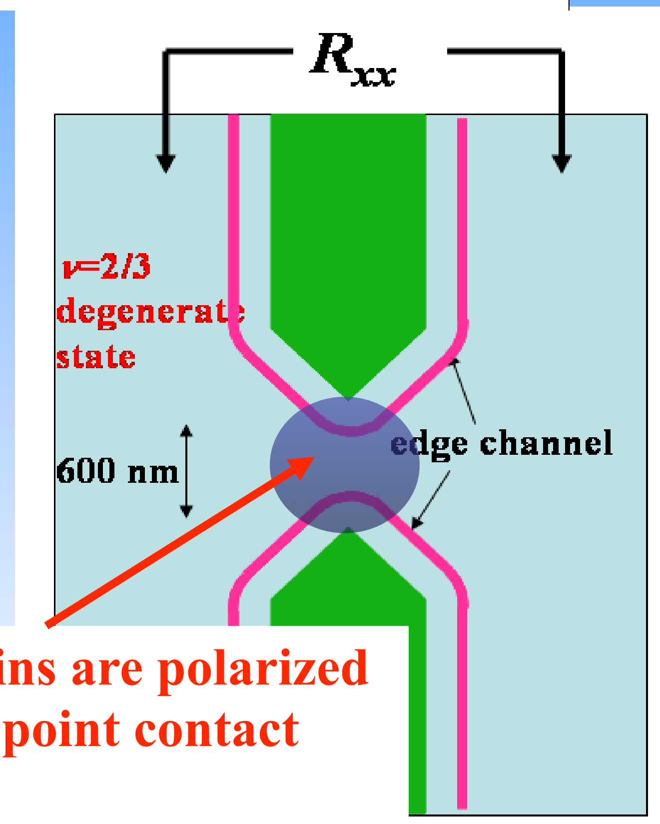
- NMR spectrum and T_1 time can be measured for any states.
- We can monitor electron spin states, especially electron spin correlation, from T_1 time

- **Possibility of nuclear spin control in nanoscale**
  - **Point-contact-device with integrated antenna gate**
  - **Full coherent control of I=3/2 quantum four level system**
  - **NMR measurements of nanoscale region**

Nanoscale GaAs NMR device



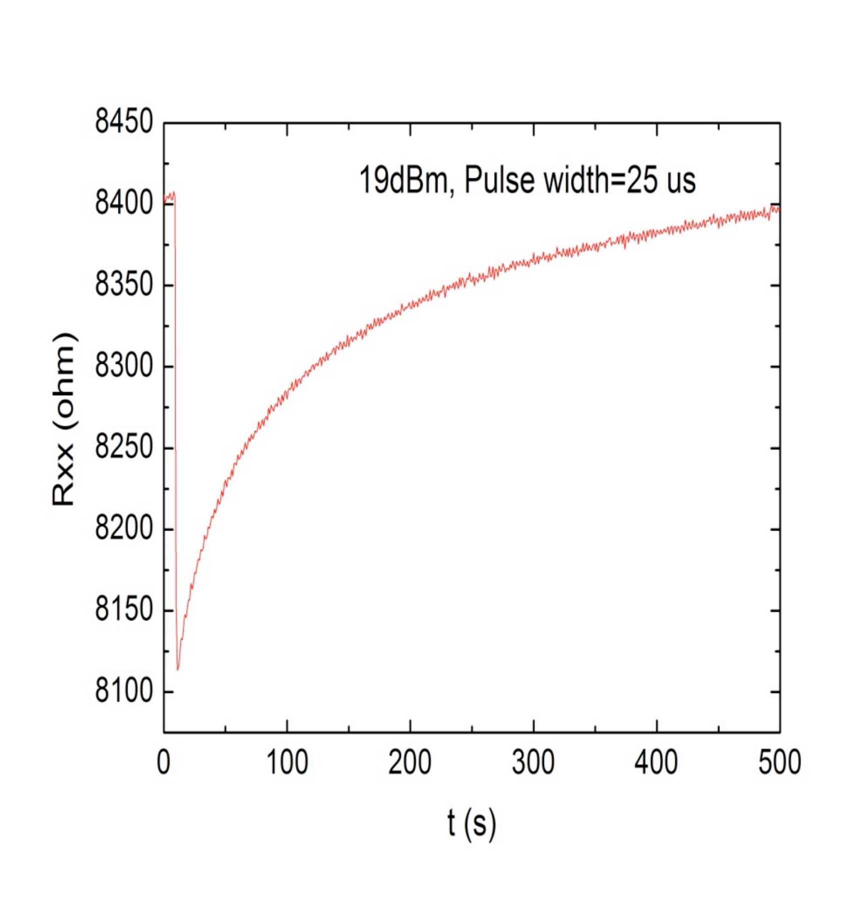




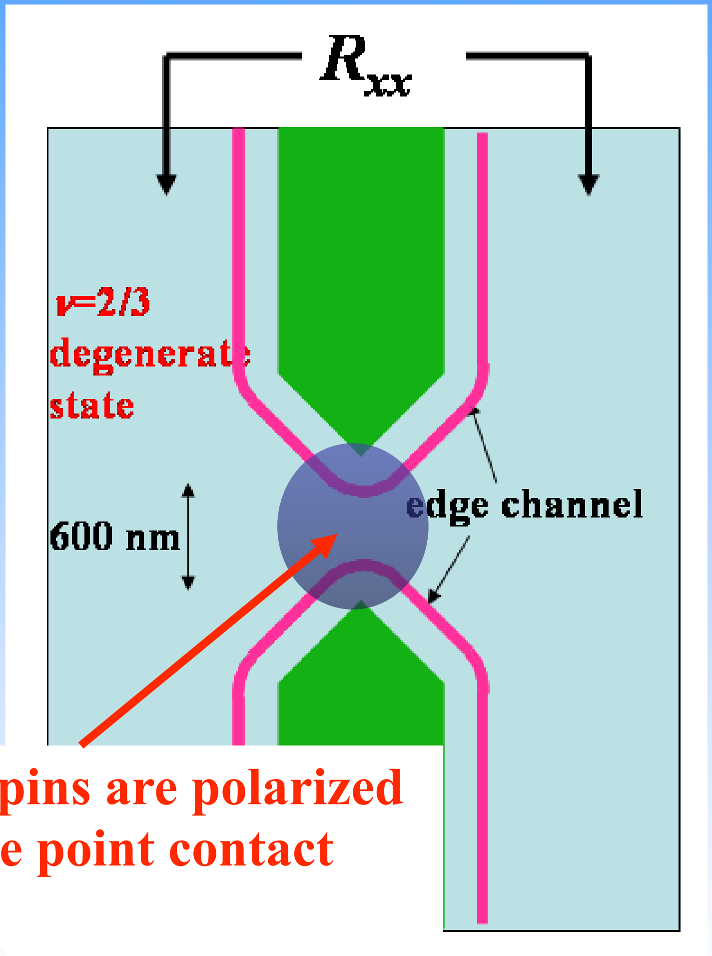
Nuclear spins are polarized only in the point contact channel.

***Nuclear spins are polarized in 200nm x 200nm x 20nm regime.**
***Coherent control and NMR have been demonstrated in nanoscale semiconductor device.**

Dynamic nuclear spin polarization in a point contact



By flowing 10nA current, nuclear spin polarization occurs only in the point contact regime.



The degree of nuclear spin polalization can be detected by R_{xx}.

Nuclear spins are polarized only in the point contact channel.

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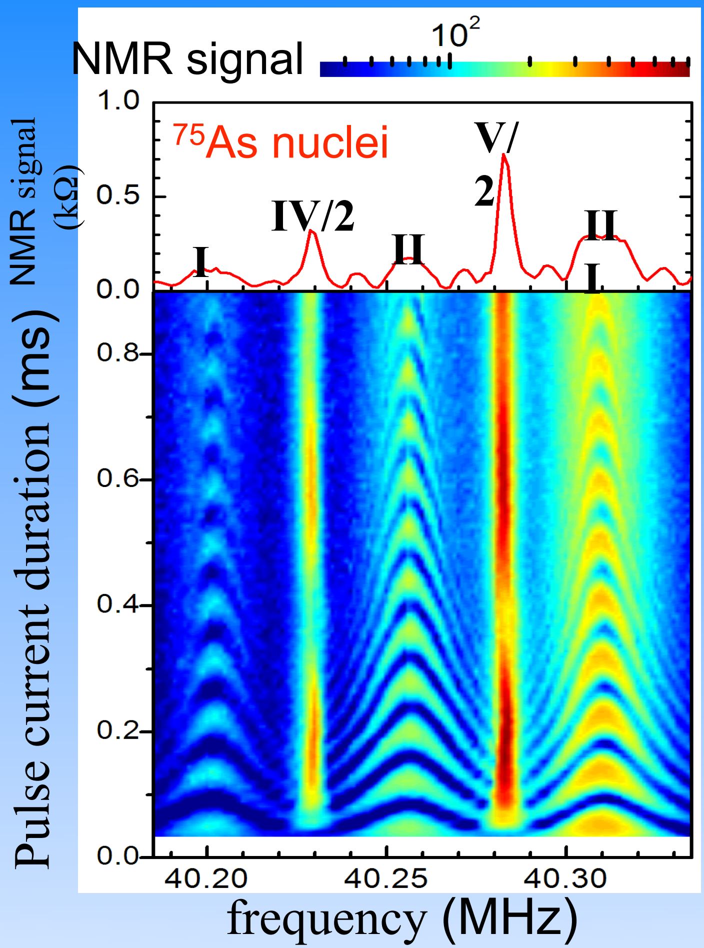
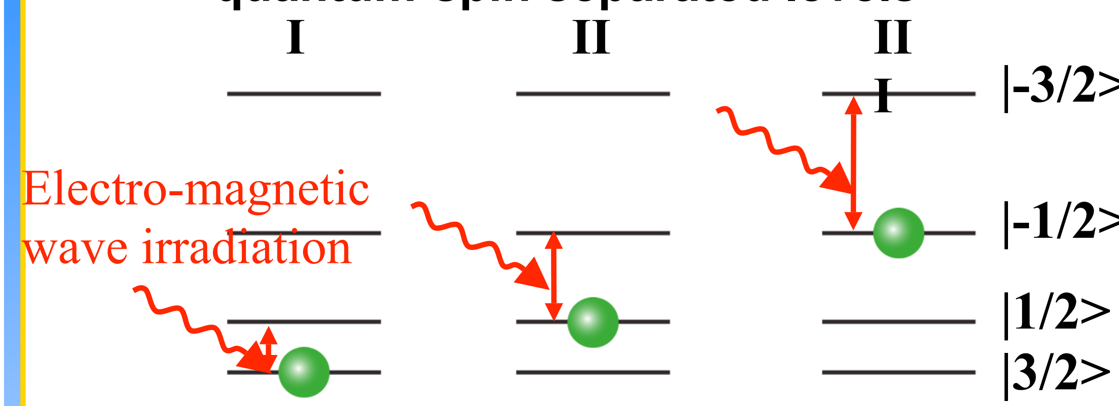
Coherent nuclear spin oscillation in point contact device



Fully coherent control of quantum four-level system = two-qubit operation

coherent oscillation between single-quantum-spin separated levels



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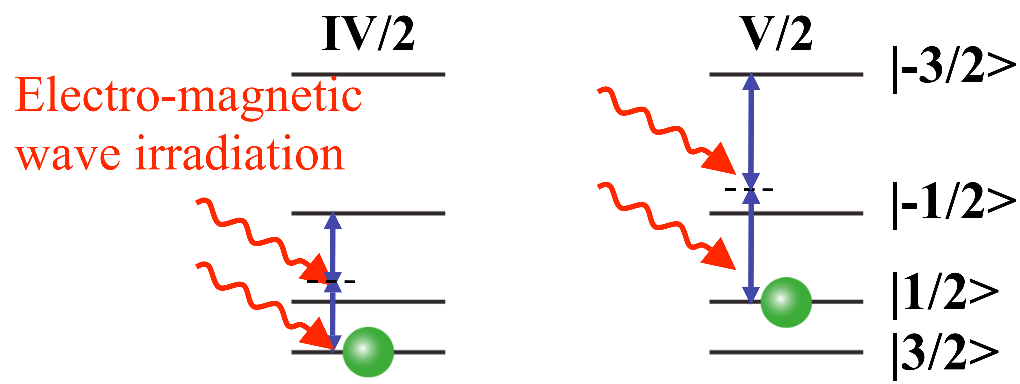

Yusa, Muraki, Takashina, Hashimoto, and Hirayama, Nature 434, 1001 (2005)

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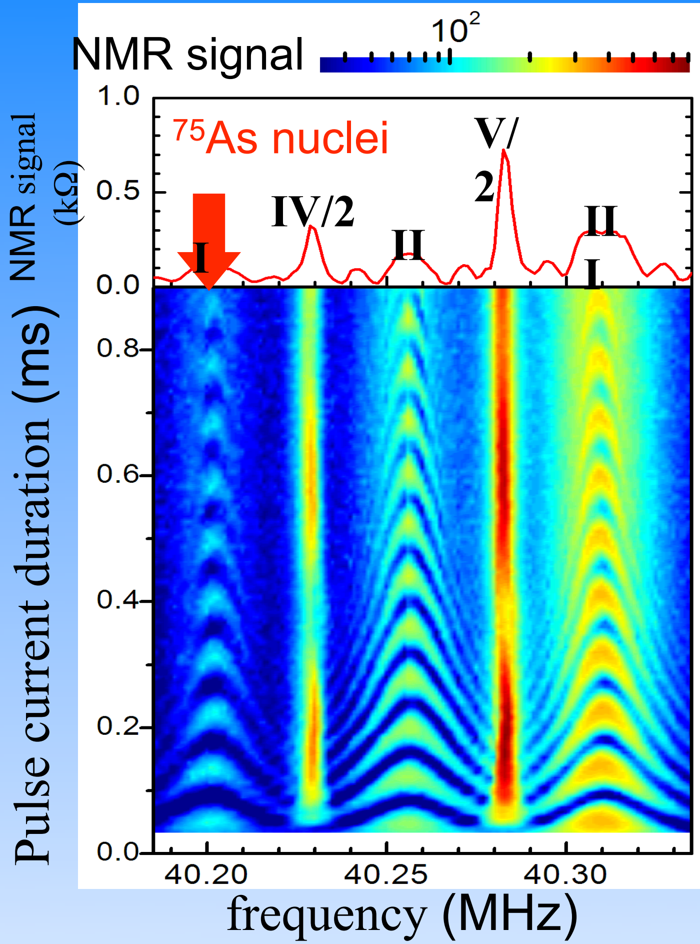

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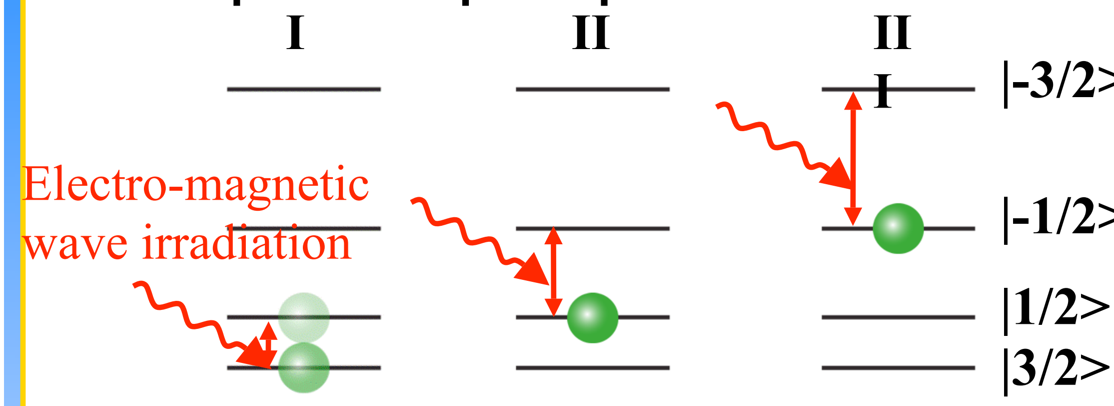

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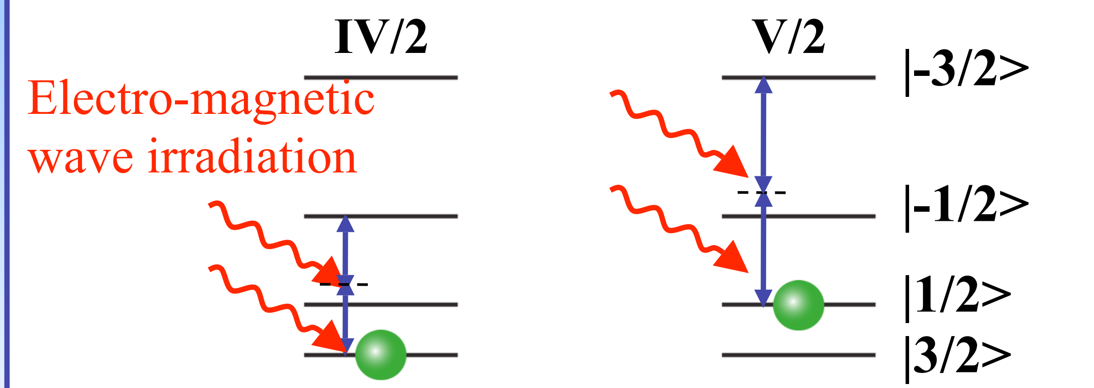

Yusa, Muraki, Takashina, Hashimoto, and Hirayama, Nature 434, 1001 (2005)

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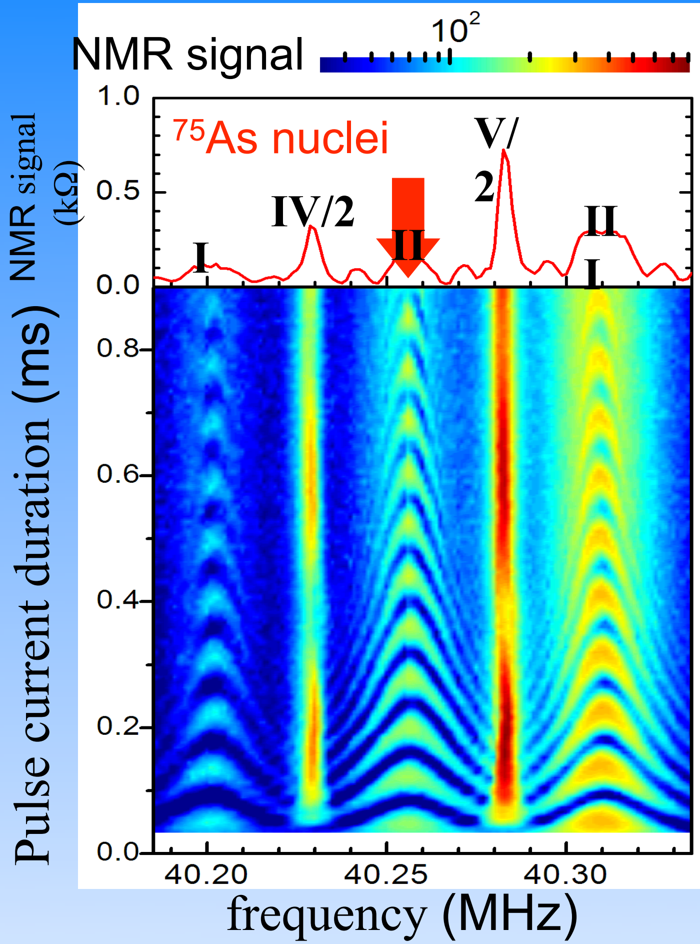

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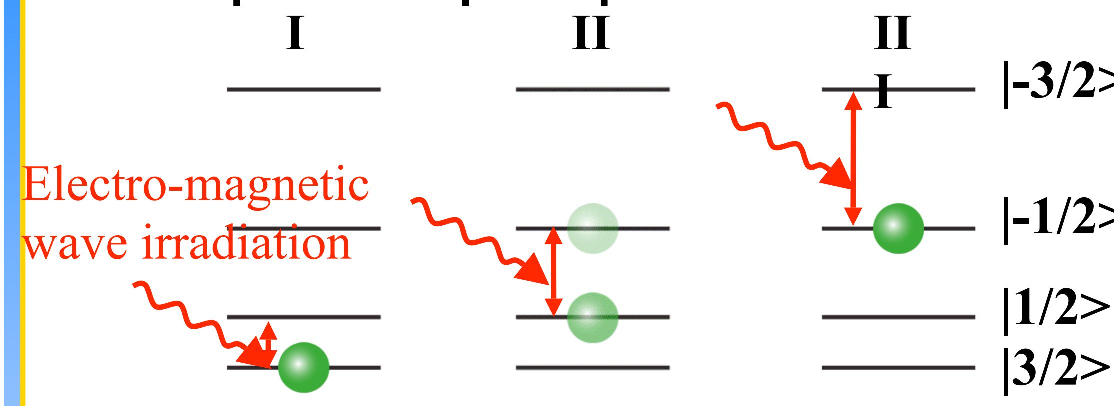

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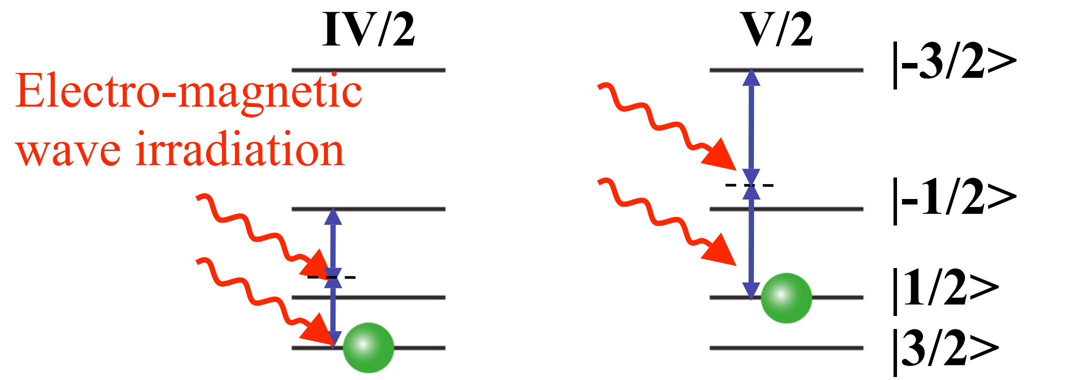

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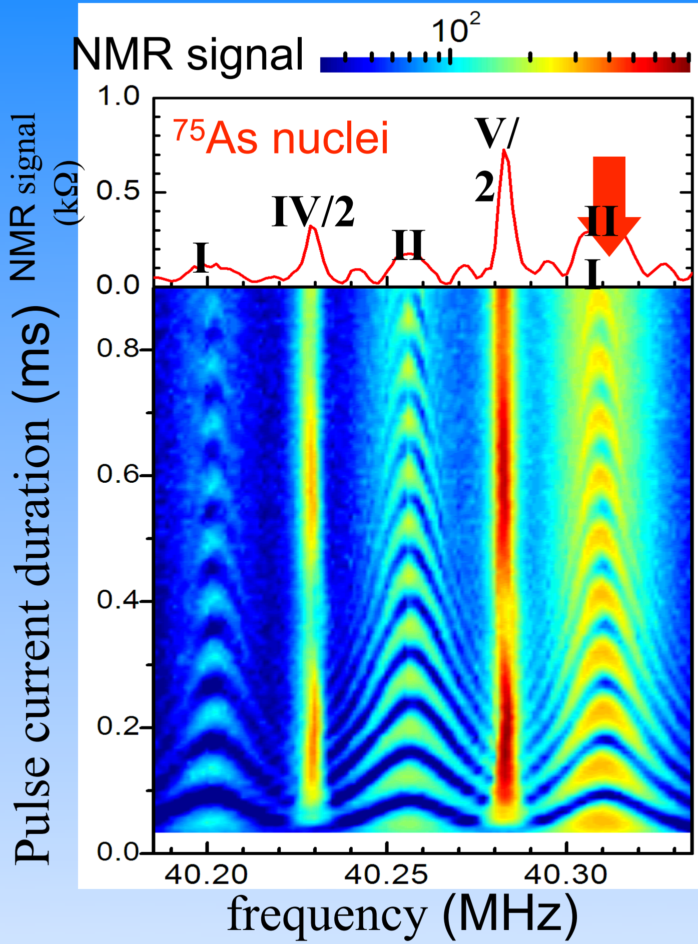

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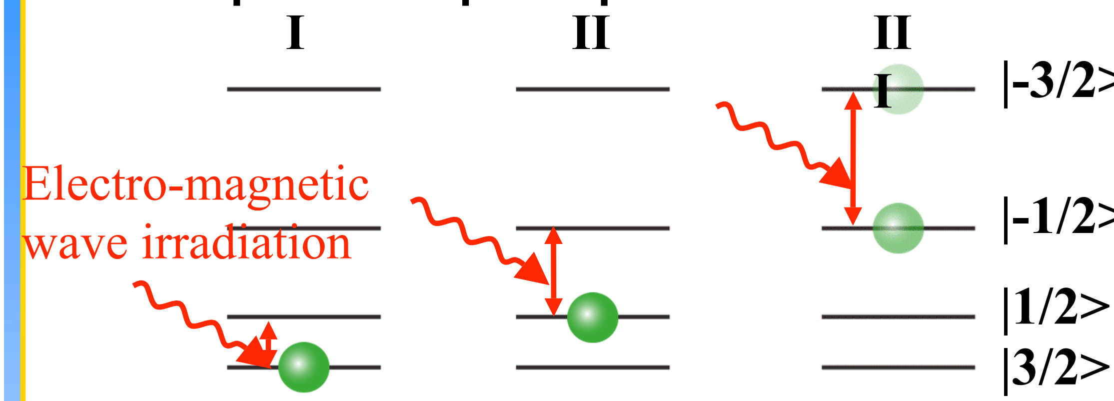
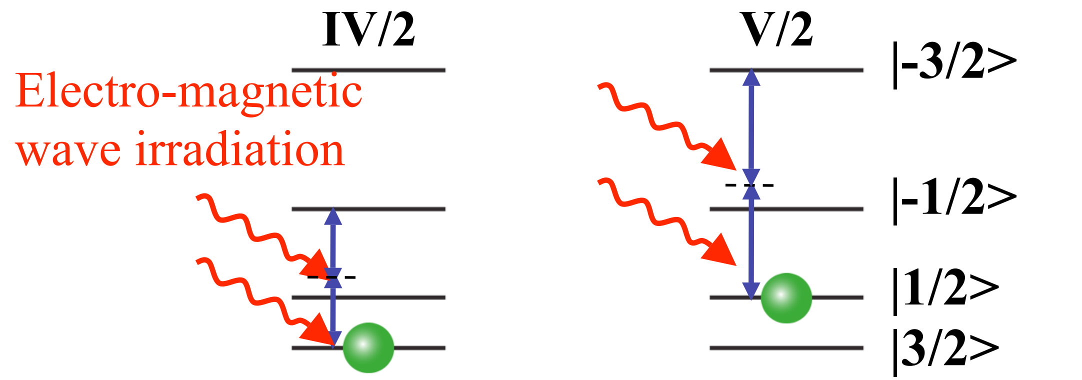


coherent oscillation between two-quantum-spin separated levels



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Yusa, Muraki, Takashina, Hashimoto, and Hirayama, Nature 434, 1001 (2005)

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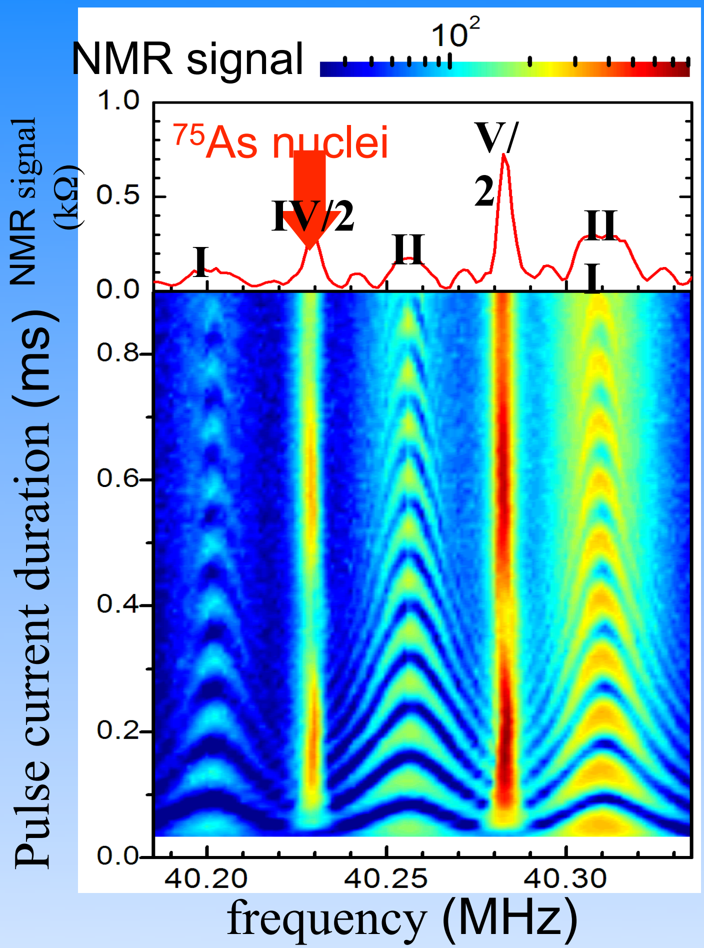

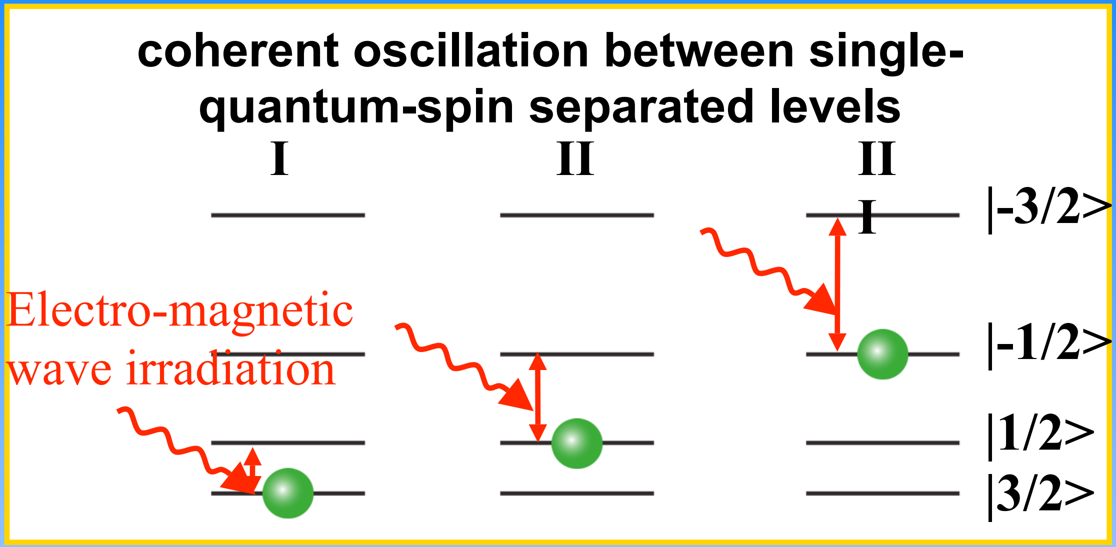

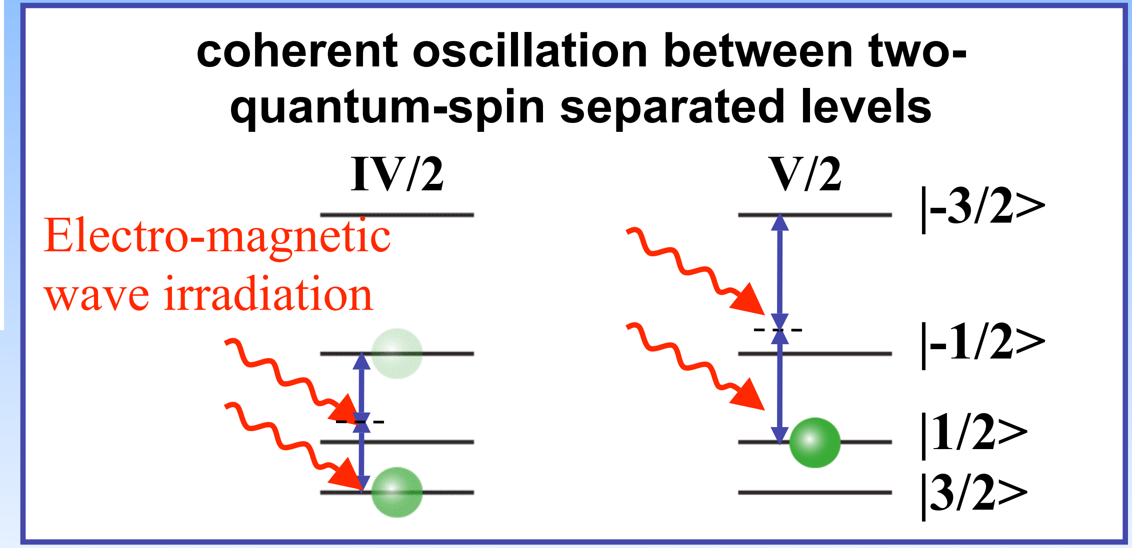

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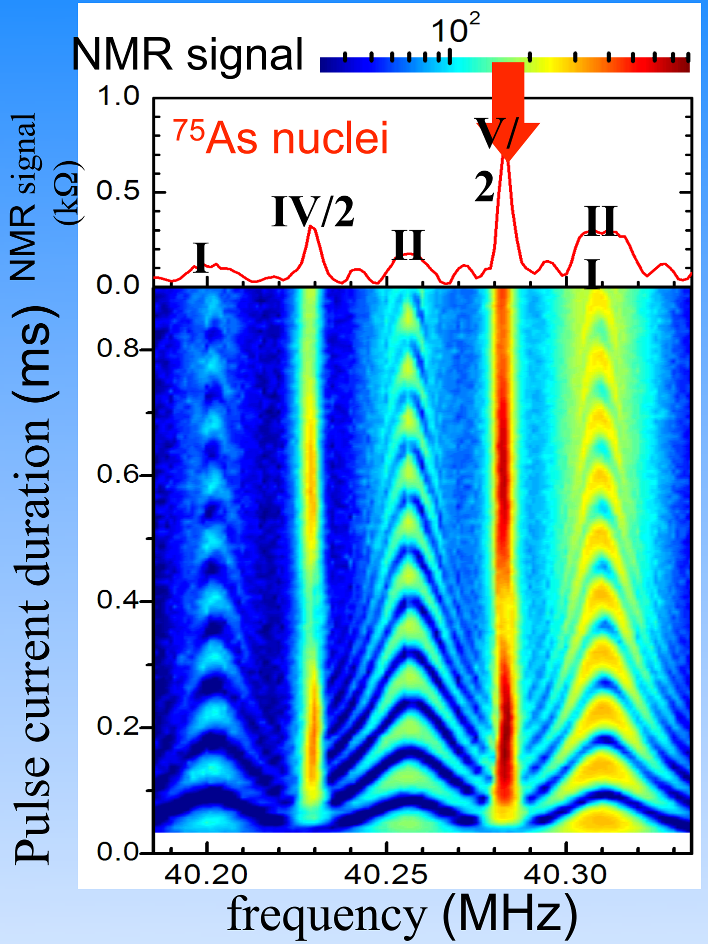

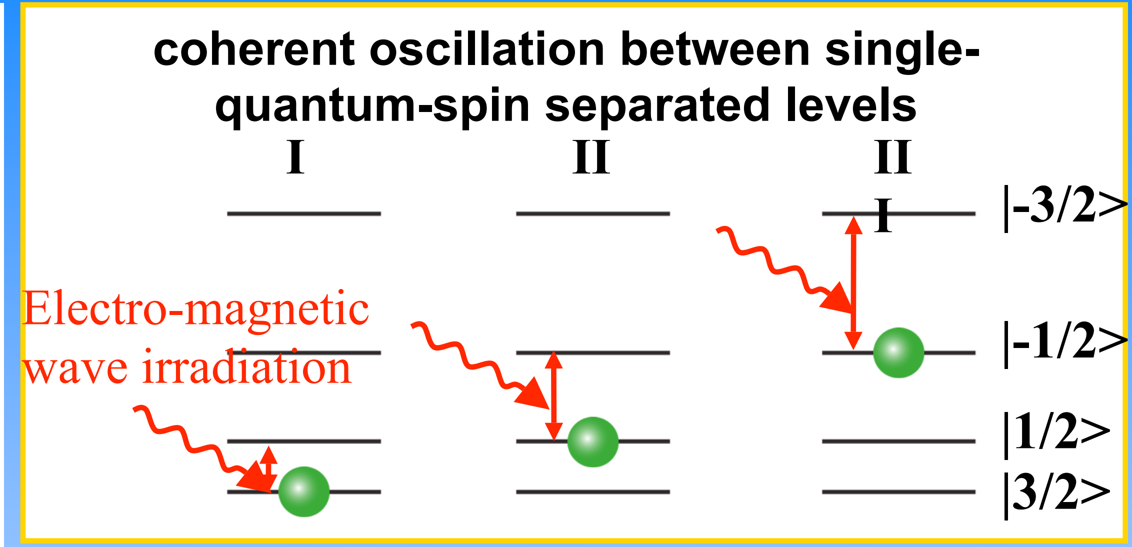

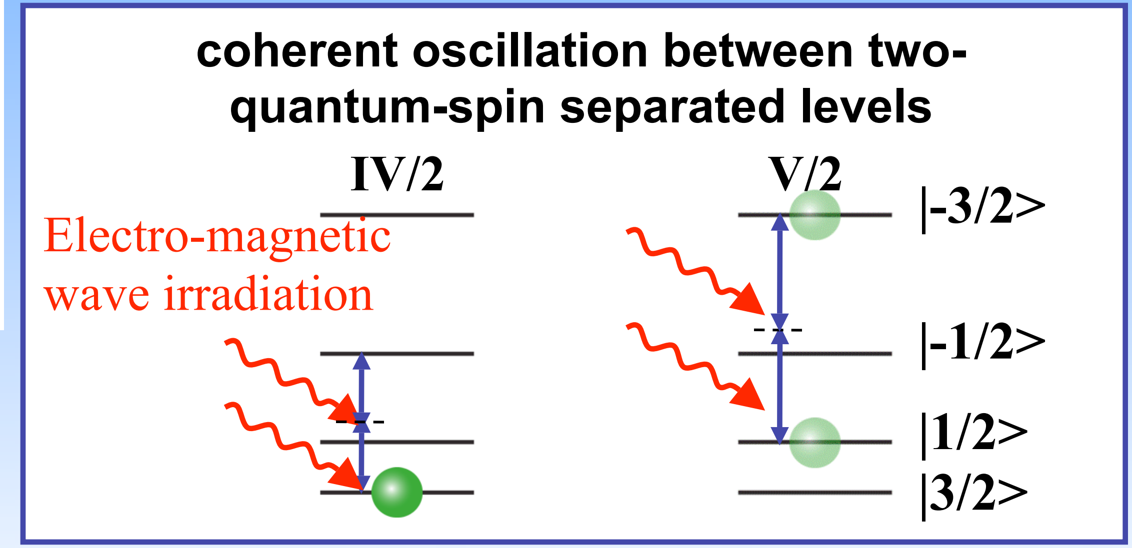

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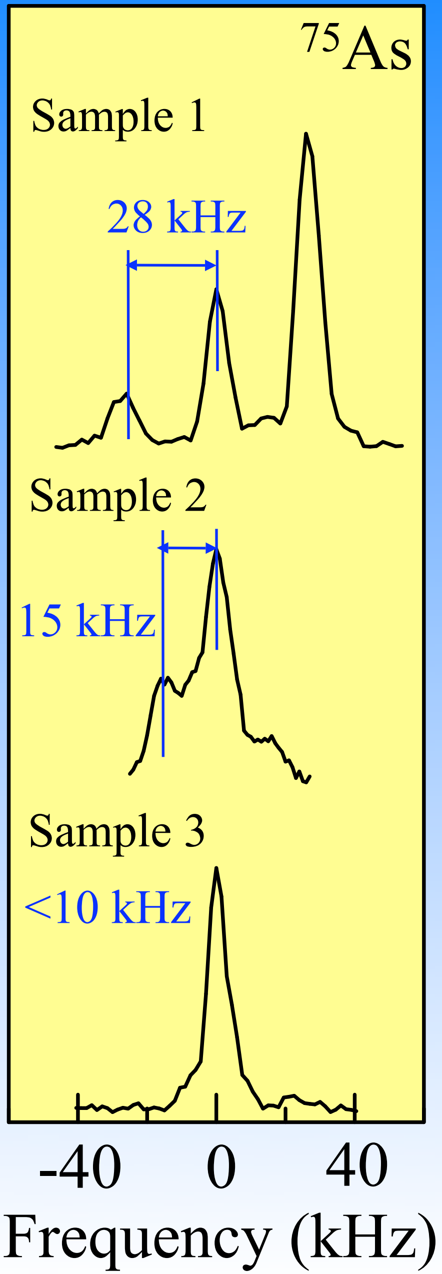
Nanoscale characteristics detected by novel NMR

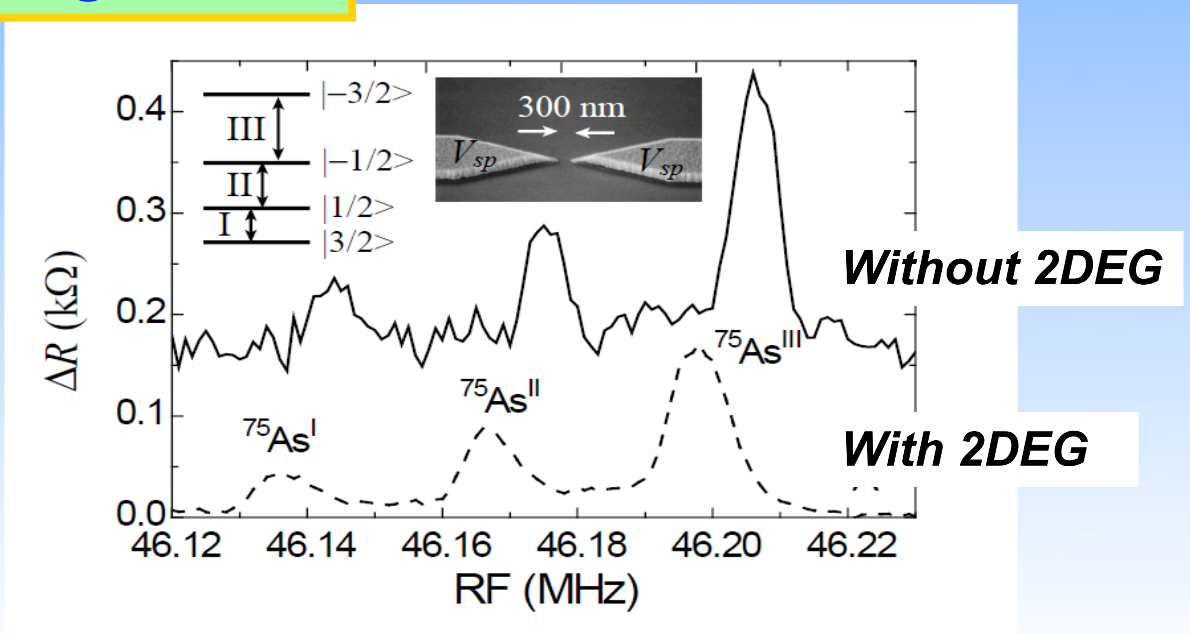


Quadrupolar splitting

- The value of the quadrupolar spilitting is different in every device though the devices are fabricated using same material.
- We speculate that this splitting probes the strain induced by sample mounting.

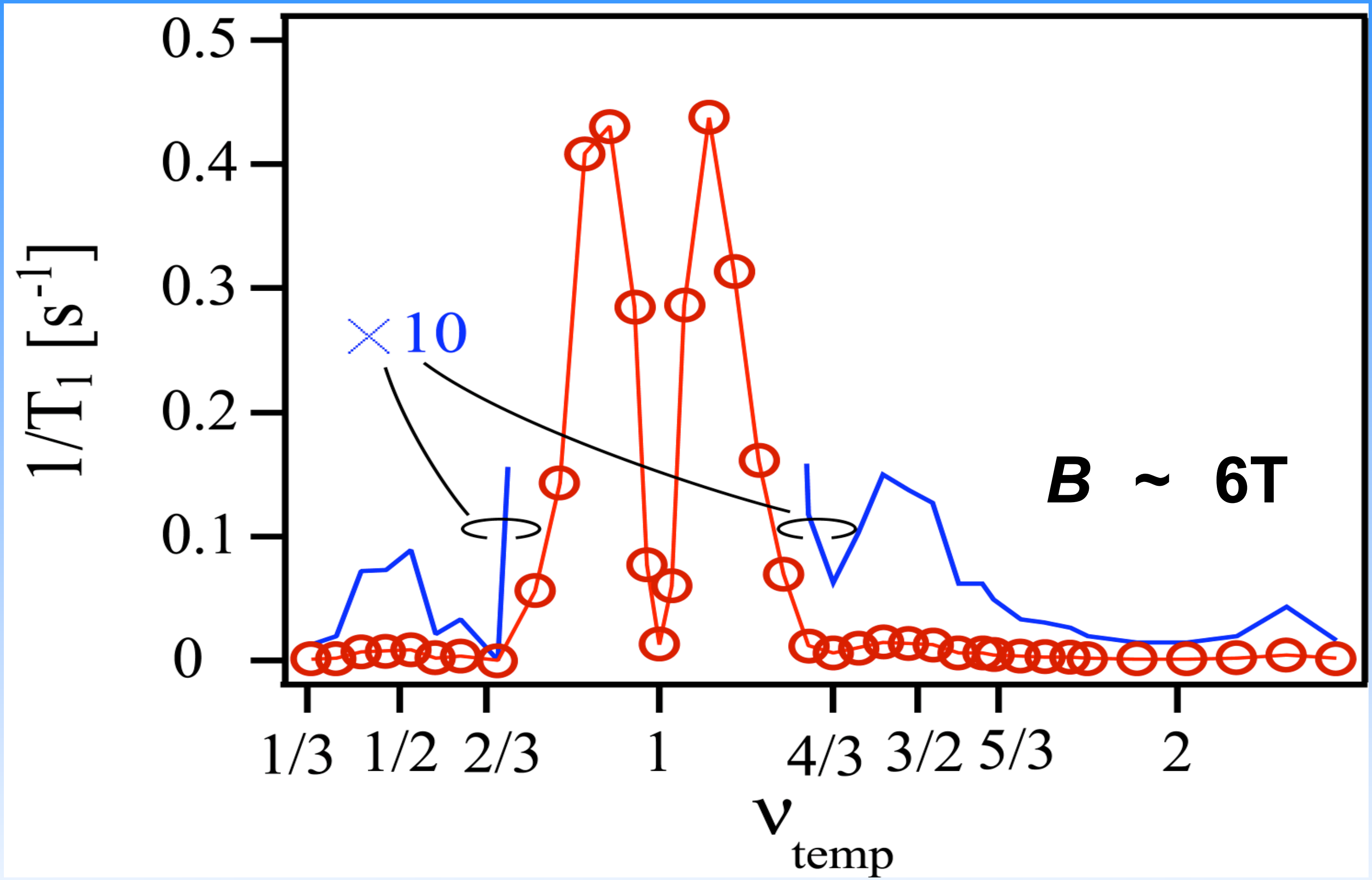
Knight shift

Electron spin polarization



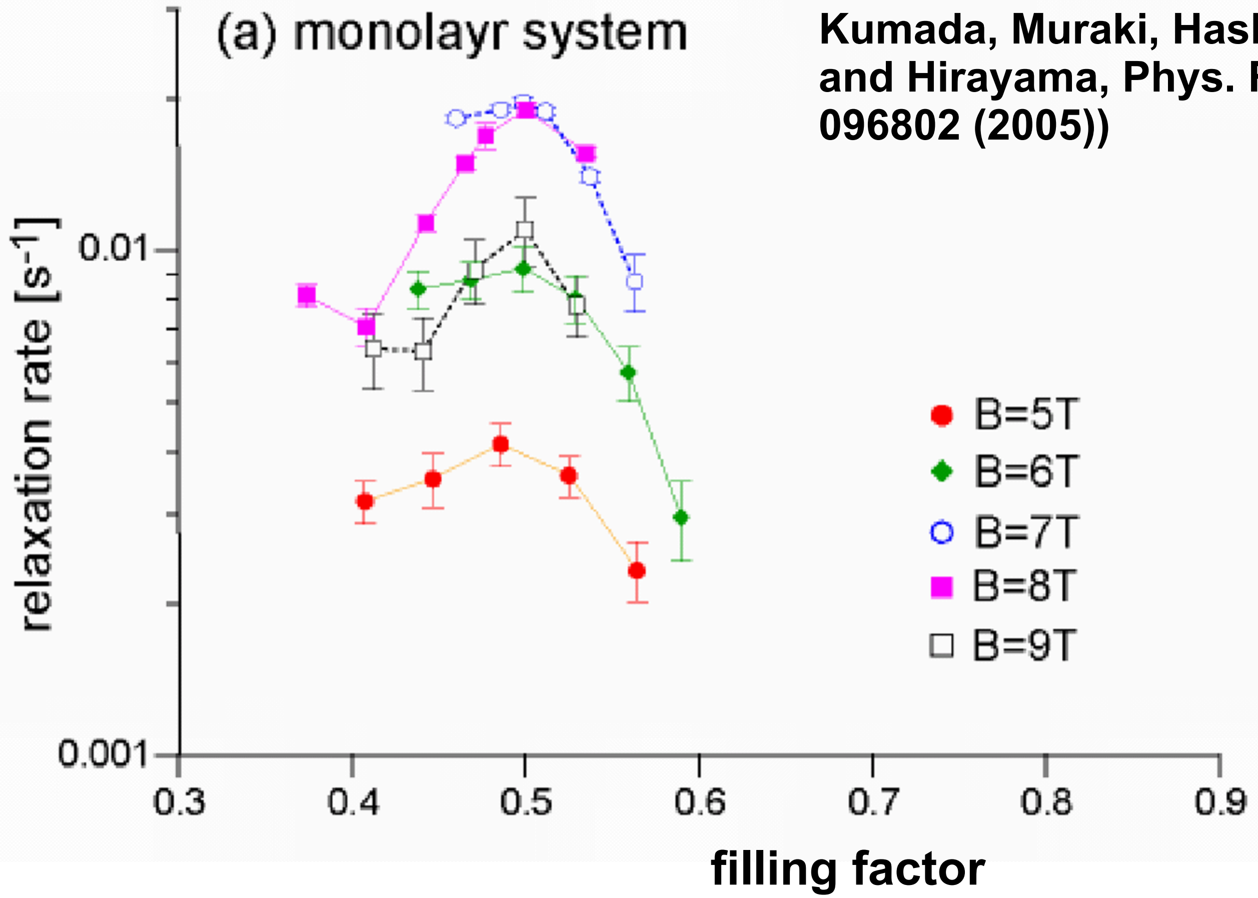
- **Nuclear-spin-based measurements as a powerful tool to study electron spin physics in 2DEG**
  - **Skyrmion**
  - **Spin degree of freedom**
  - **Canted spin states**
  - **Spin orbit interaction**

Filling factor dependence of T_1 and Skyrmion



Hashimoto, Muraki, Saku and Hirayama, Phys. Rev. Lett. 88, 176601 (2002)

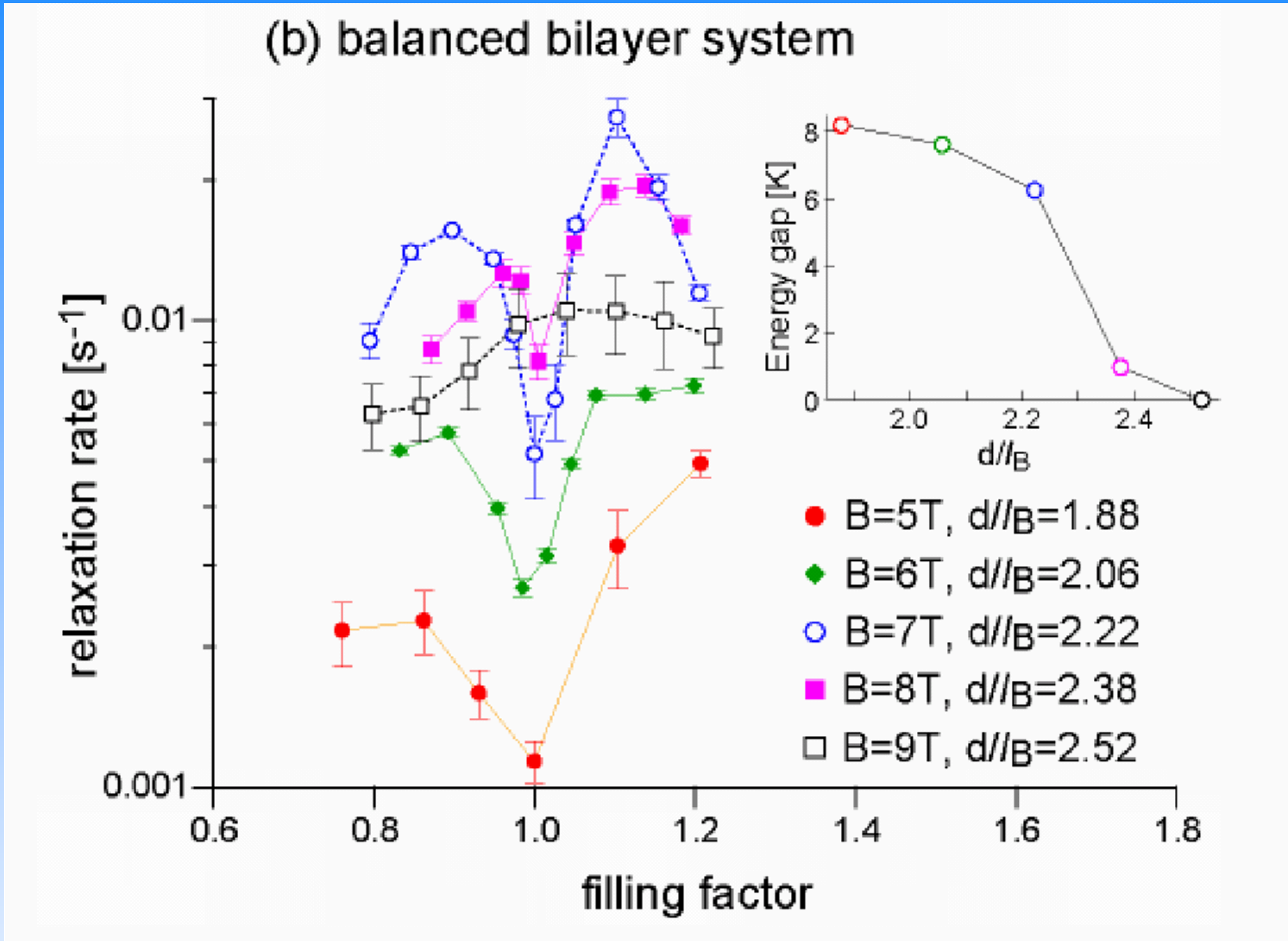
T_1 observed for single layer ν=1/2



Kumada, Muraki, Hashimoto, Saku and Hirayama, Phys. Rev. Lett. 94, 096802 (2005))

Coexistence of spin up and down CF at ν=1/2 results in a slight enhancement of nuclear spin relaxation at ν=1/2.

T_1 observed for bilayer $\nu=1$



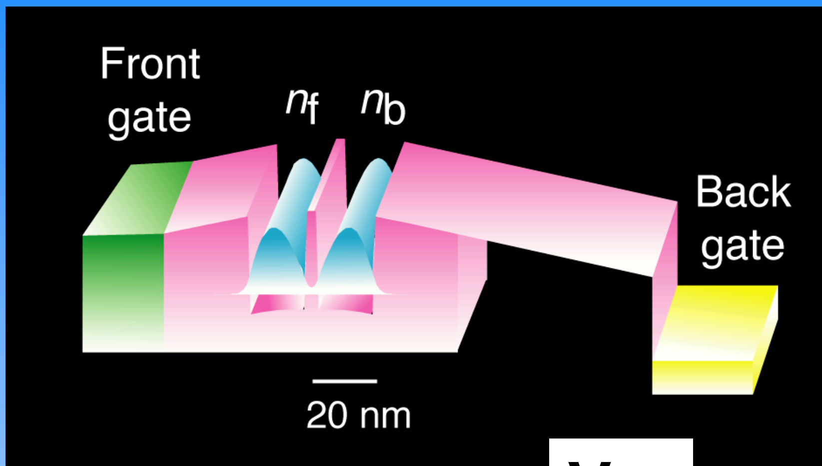
balanced bilayer at $\nu=1$

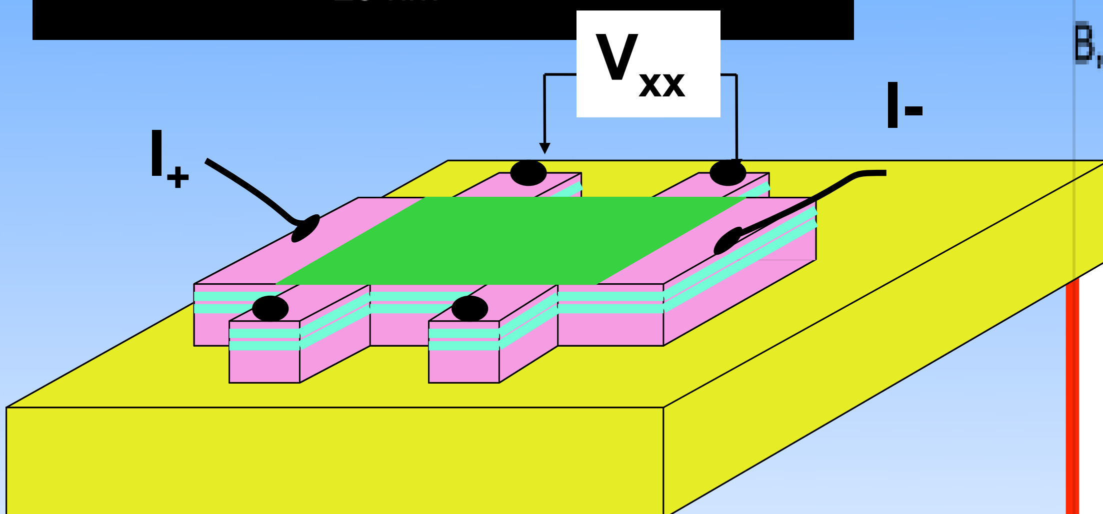
(each layer has $\nu=1/2$ filling)

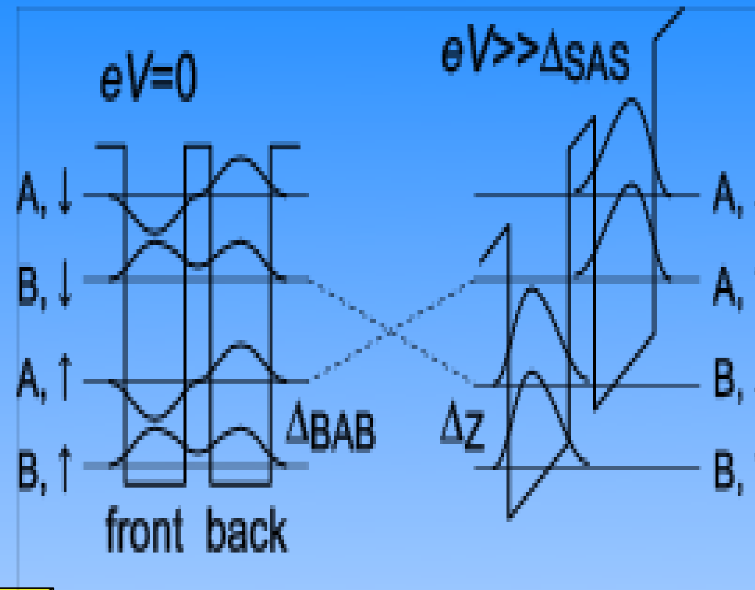
The bilayer $\nu=1$ state has a small, but finite, spin fluctuation.

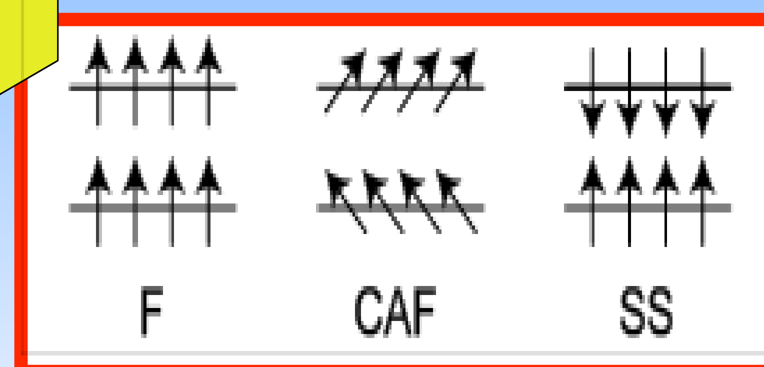
Kumada, Muraki, Hashimoto, Saku and Hirayama, Phys. Rev. Lett. 94, 096802 (2005))

Bilayer system with ν=2







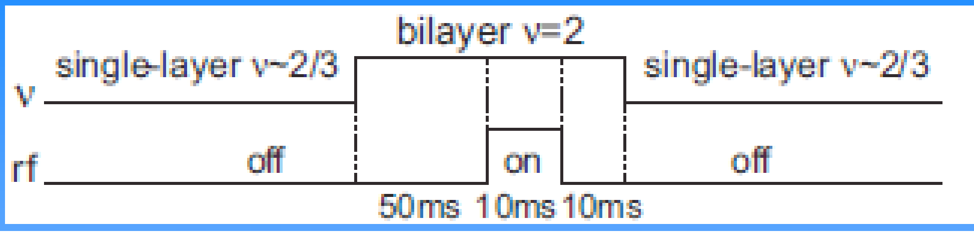


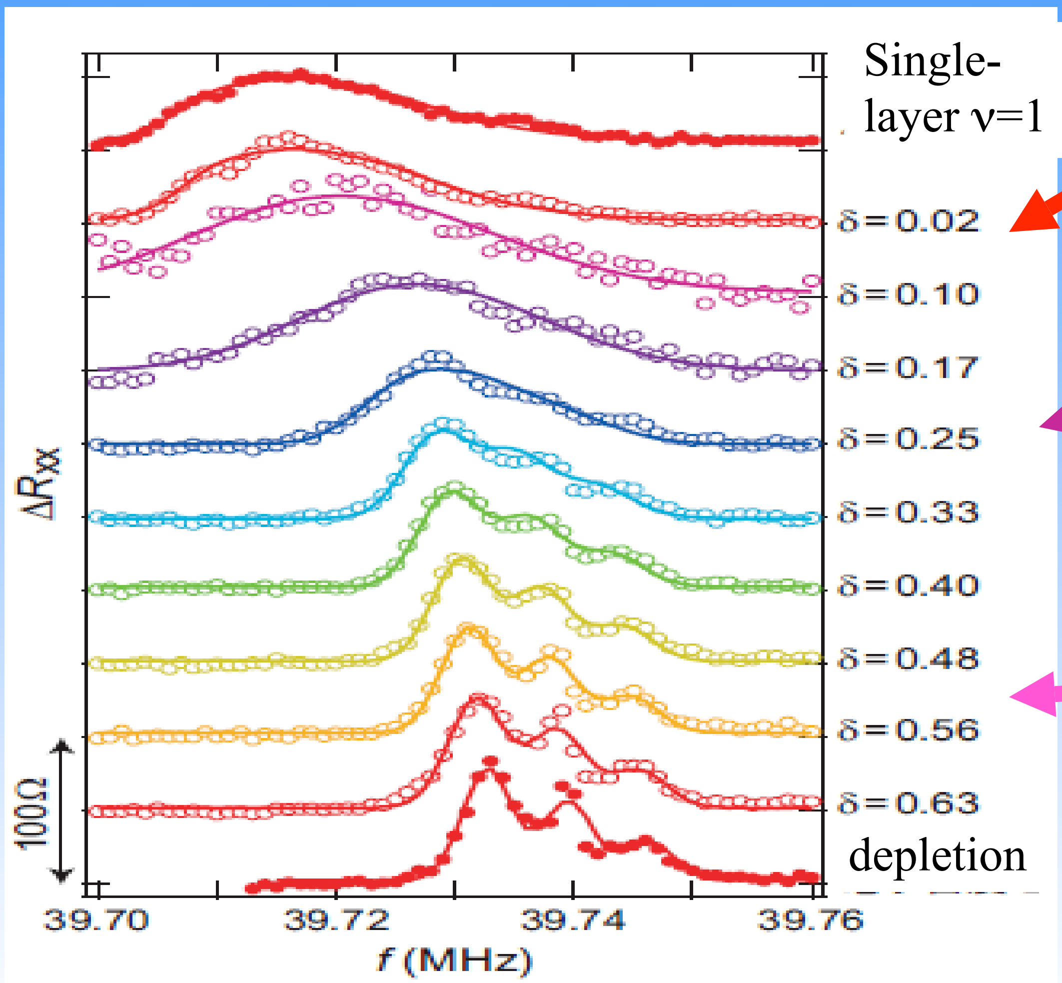
Width : 50 μm
Length between voltage probes: 100 μm
Quantum well thickness: 20 nm

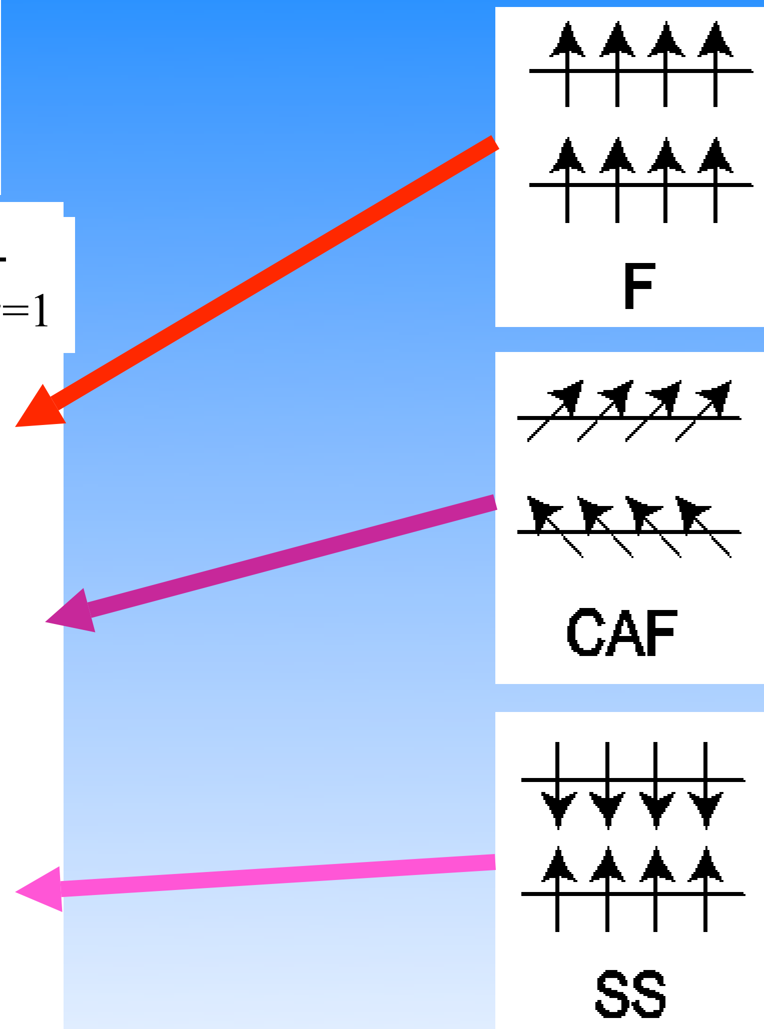
$$\delta = (n_f - n_b)/(n_f + n_b)$$

$$1+\delta = \nu_f \qquad 1-\delta = \nu_b$$

NMR spectrum observed for bilayer ν=2

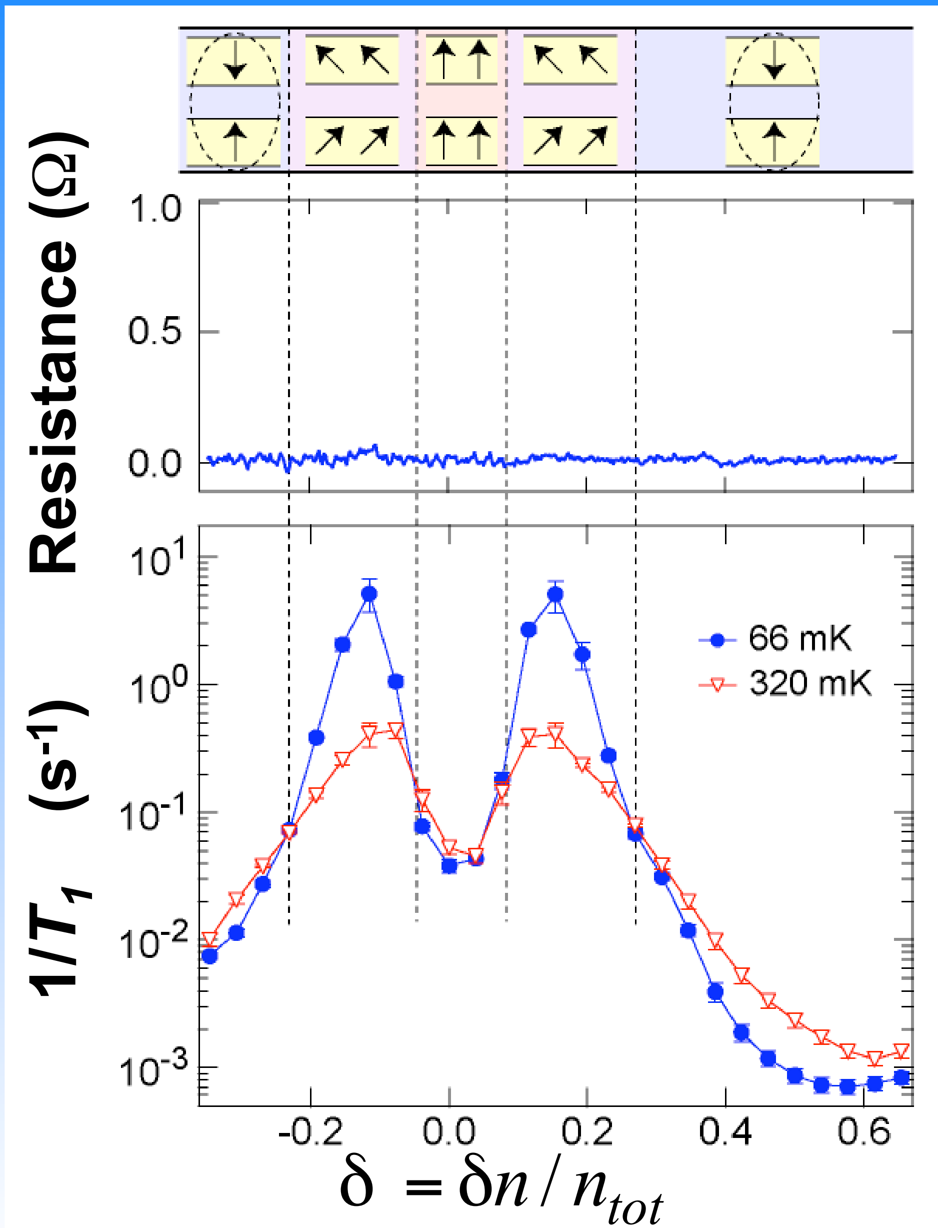






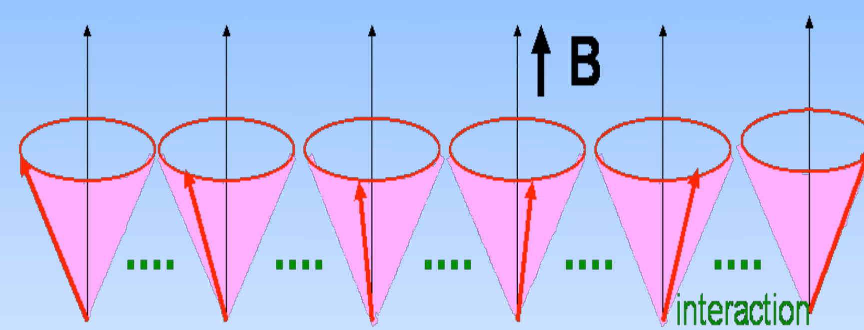
Kumada, Muraki and Hirayama,
Phys. Rev. Lett. 99, 076805 (2007)

Nuclear spin relaxation observed for bilayer ν=2



A. Sawada, Z. F. Ezawa, H. Ohno, Y. Horikoshi, Y. Ohno, S. Kishimoto, F. Matsukura, M. Yasumoto, and A. Urayama, Phys. Rev. Lett. **80** (1998) 4534; A. Fukuda, S. Kozumi, D. Terasawa, Y. Shimoda, N. Kumada, Y. Hirayama, Z. F. Ezawa, and A. Sawada, Phys. Rev. B **73** (2006) 165304.

Although transitions between different phases are detected by transport experiments, nuclear spin based measurements give us a very clear evidence.

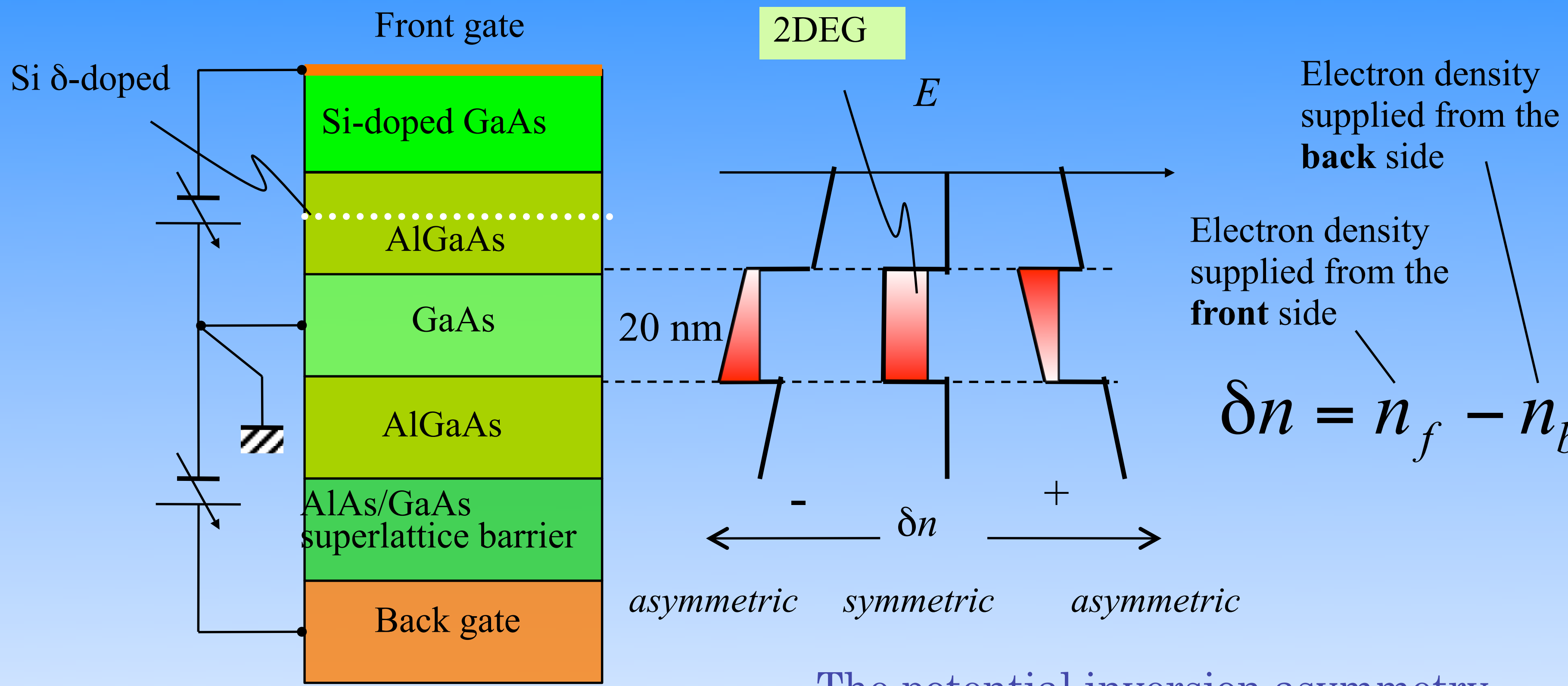


Experimental confirmation of low-energy collective excitation mode

Kumada, Muraki and Hirayama, Science 313, 329 (2006)

Single quantum well: confinement potential modulation

Effect of confinement potential

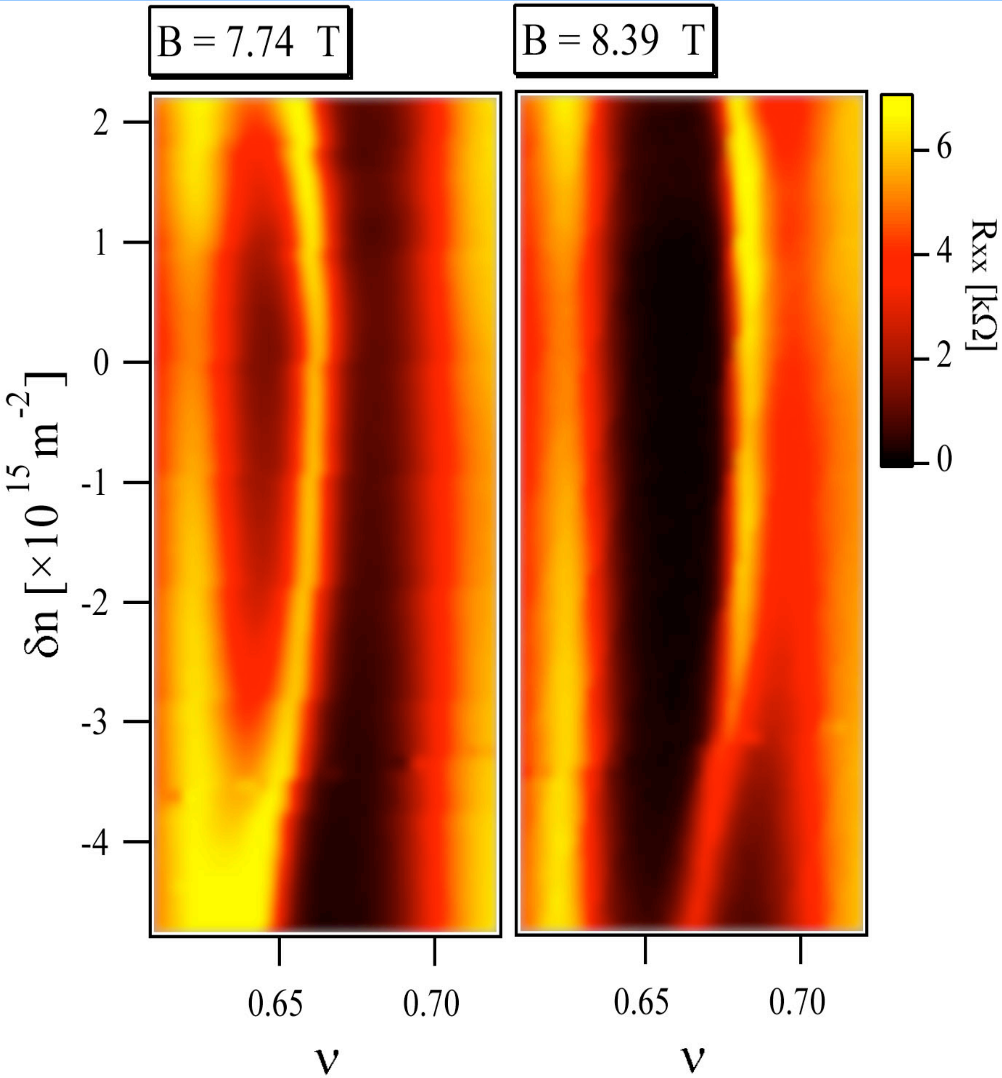


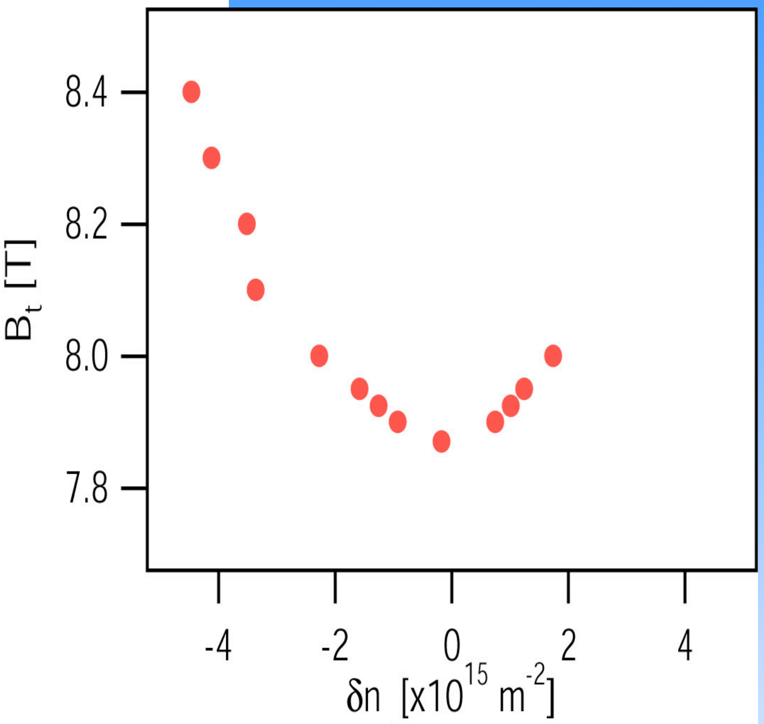
$$\delta n = n_f - n_b$$

Symmetry of electronic confinement potential can be controlled keeping the electron density constant.

The potential inversion asymmetry enhances spin-orbit interaction. However, the effects are tiny in a conventional GaAs 2DEG system.

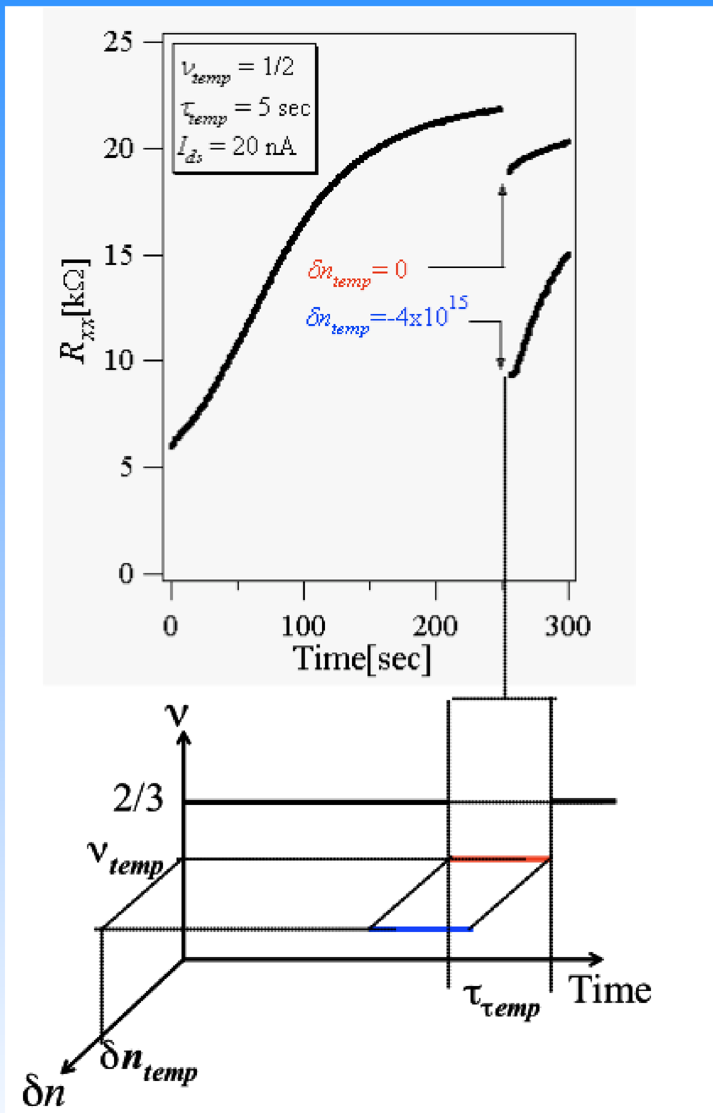
Control of confinement-potential-symmetry and ν =2/3 electronic-spin transition

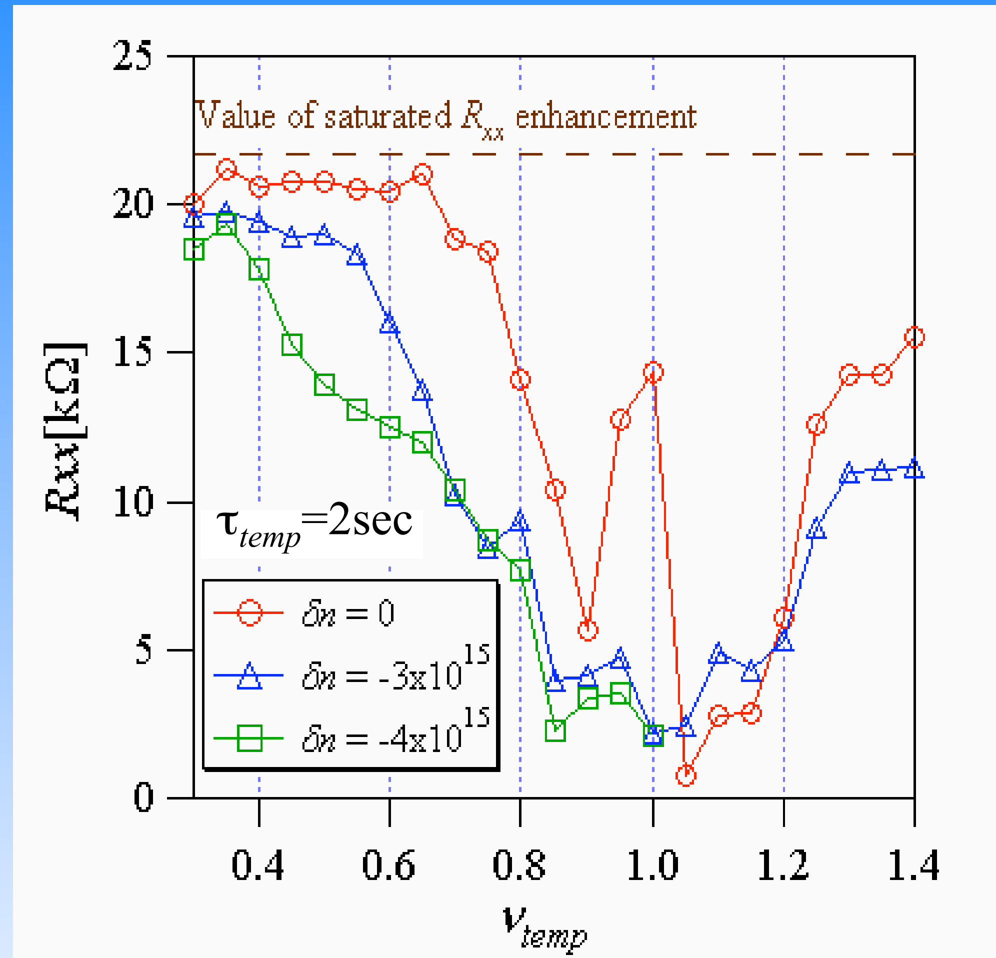




B_t as a function of δ n

Effect of confinement potential symmetry on T_1





Nuclear spin relaxation is enhanced under asymmetric confinement.

Hashimoto, Muraki, Kumada, Saku and Hirayama, Phys. Rev. Lett. 94, 146601 (2005)

Summary

- We have developed novel and highly sensitive NMR based on direct detection of nuclear spin magnetization by the resistance measurements.
- This NMR provides us powerful tool to study coherent control of nuclear spins in semiconductors and to characterize quantum wells and nanosystems.
- Some electron spin features, which was difficult to detect by other methods, were already clearly detected.
- We have developed fully-electrical NMR based on the domain motion.

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