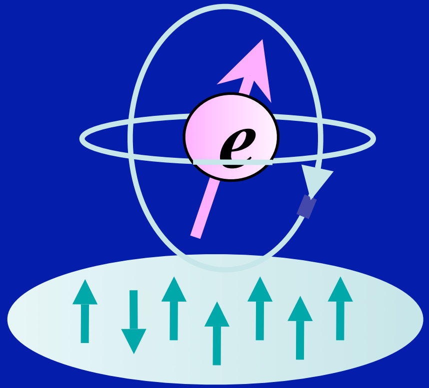


Yukawa International Seminar (YKIS) 2007
"Interaction and Nanostructural Effects in Low-Dimensional Systems”
Workshop-2 (Nov. 15: 2D systems and Nano)

Electrical Control of Electron Spin and Nuclear Spin in Quantum Dots

S. Tarucha

Dep. of Applied Physics. The University of Tokyo
ICORP-JST INQIE-MEXT

Tokyo-U A. Oiwa
M. Yamamoto
K. Hitachi
J. Baugh (Waterloo-U)

Riken/ICORP K. Ono

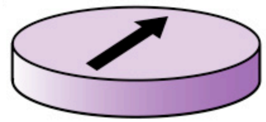
ICORP-JST **Y. Tokura NTT**
M. Pioro-Ladriere
T. Obata
Y-S Shin
S. Yoshida

INQIE T. Kodera

Spin-based QC with QDs: Loss-DiVincenzo '98

QD holding just an electron spin

Qubit = a|↑ > + b|↓ >

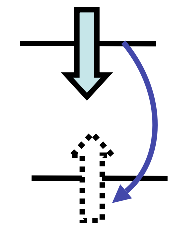


ST et al. *PRL* 96
Ciorga et al. *PRL*02

Robust spin degree of freedom

T_1 = msec to sec

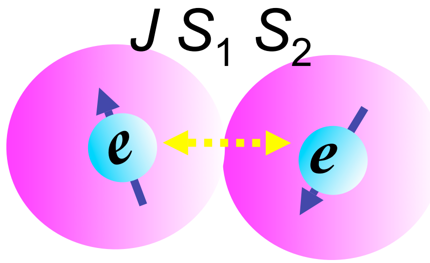
Triplet to Singlet: Fujisawa, ST et al. *Nature* 02
Zeeman states: Amasha et al. *PR* 06



Entanglement linked to Fermionic nature

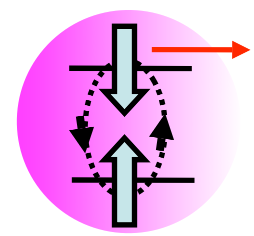
$H_{int} = J_{exch}\, S_1\, S_2$

SWAP: Petta et al. *Science* 05
Heitler-London: Hatano, ST et al. *Science* 05



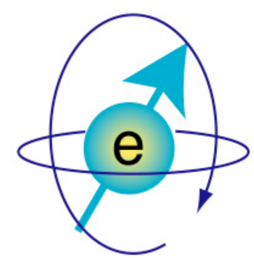
Single spin readout

Pauli spin blockade: Ono, ST et al. *Science* 02
Spin rotation using P-SB: Koppens et al. *Nature* 06
Zeeman splitting: Elzerman et al. *Nature* 05

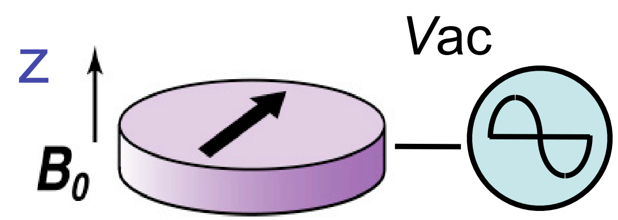


Coherent spin manipulation

SWAP-qubit: Petta et al. *Science*05
On-chip coil qubit: Koppens et al. *Nature* 06
SO-EDSR qubit: Nowack *et al.*, arXiv0707.3080



Progress Necessary for Spin Qubits with QDs



Robust, scalable qubit

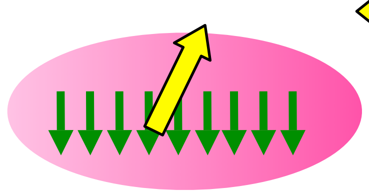
Beyond standard ESR

….Voltage-driven ESR

Decoherence problem

Spin-orbit….. $T_2 \sim T_1$ = msec to sec   Fujisawa, ST et al 02, Amasha et al. 07, Golovach, Khaetskii, Loss 04

Nuclei   ….. Short $T_2^* \sim$a few 10 ns influenced by fluctuating nuclear fields



Full polarization   Simon, Loss 07 (Thermodynamic pol.)

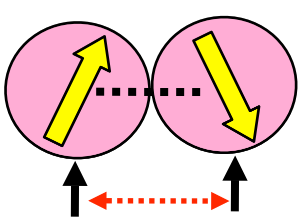
Projection measurement   Klauser, Coish, Loss 06

Other materials such as nanotubes, Si, Si/Ge with no substantial SO and nuclear spin effect

Fast, reliable readout

Single spin…10 kHz to MHz (charge) using QPC

Entanglement….Cross-correlation of shot noise



CNOT, Error correction, ….

Outline

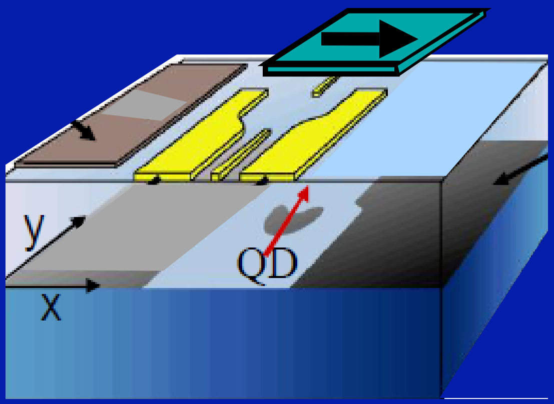
Spin control with GaAs quantum dots

Voltage driven electron spin resonance and spin qubits with quantum dots

Spin rotation using a slanting Zeeman field formed by a micro-magnet

Two-spin addressing

Micro-magnet design for scalability

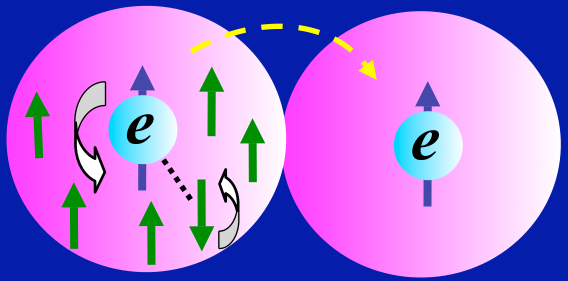


Electrical control of nuclear spin polarization

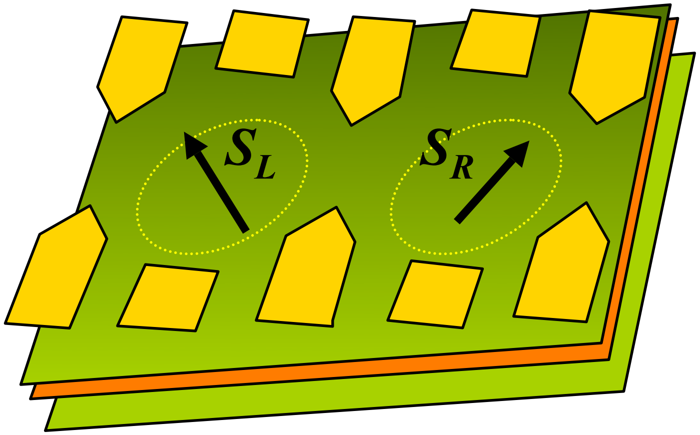
Voltage-controlled hyperfine coupling in the Pauli spin blockade

Tunable polarization up to ~50 %

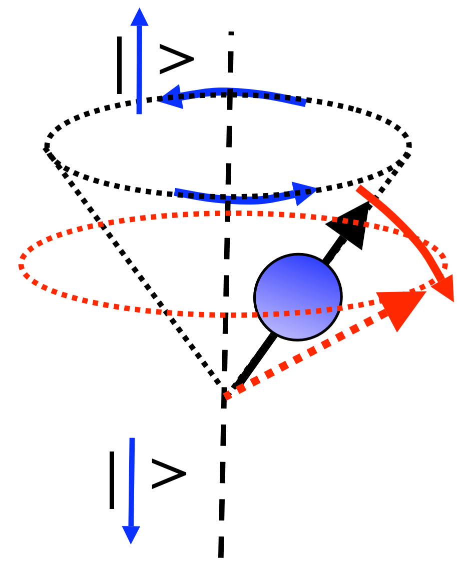
Possible approach to full polarization



Concept of Spin Qubit = ESR



Qubit: $a|\uparrow\rangle + b|\downarrow\rangle$

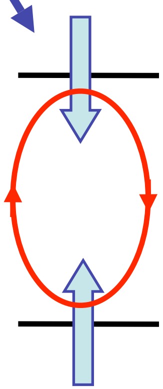


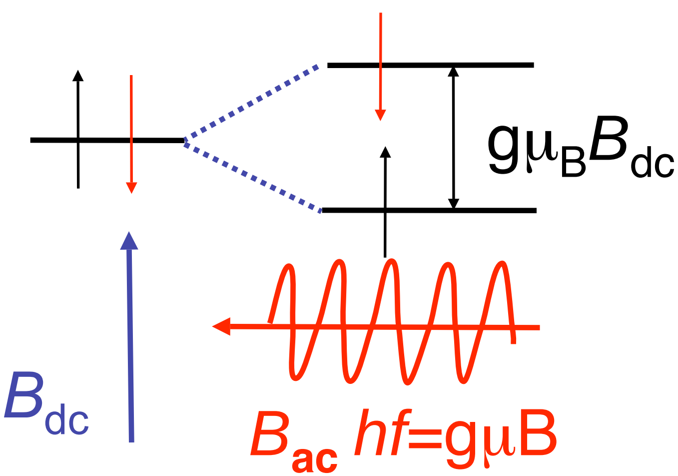
$$H_{2level} = \frac{\varepsilon_z}{2}\sigma_z + \frac{\varepsilon_x(t)}{2}\sigma_x$$

Static B_z

AC B_x

ESR Hamiltonian

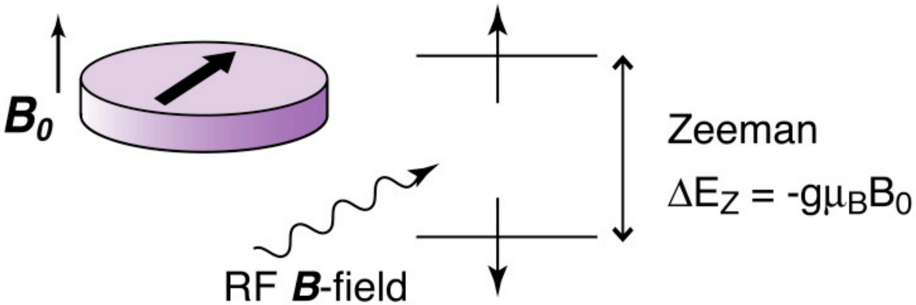


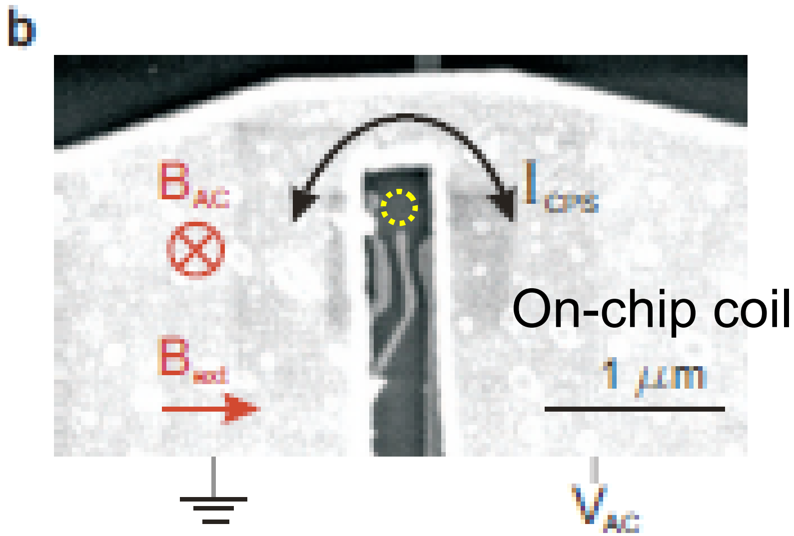


B_{ac} *with* $f = g\mu_B/h = 15$ GHz at $B_0 = 5$T for GaAs QD

ESR to Address Individual Spins

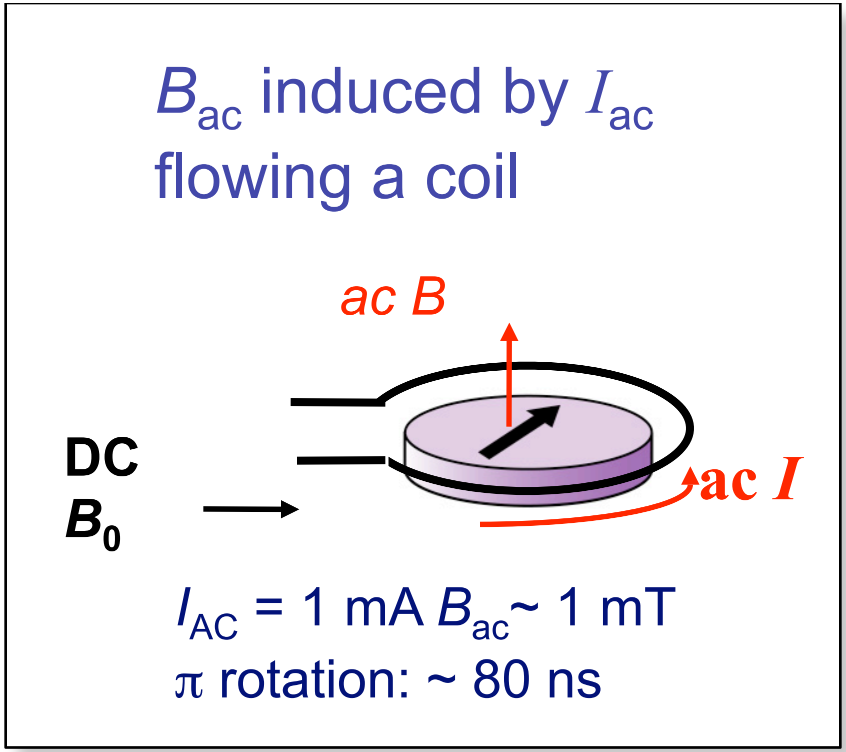
"Global dc B_z and local ac B_x for single spin resonance"





Current driven ESR

F. Koppens et al. *Science* 06



→ ***Heating problem***
Difficult for local access

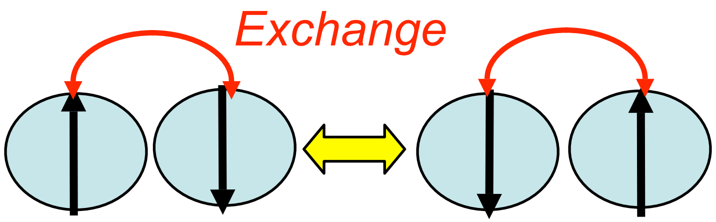
⇧

Voltage-driven ESR

Voltage-driven Single Spin Resonance

Exchange control in a double quantum dot (inter-dot coupling gate modulation)
: Spin qubit with a basis of two-spin states

J. Petta et al. *Nature* 05



Electric dipole spin resonance (EDSR) via local interaction between electron spin and electric field

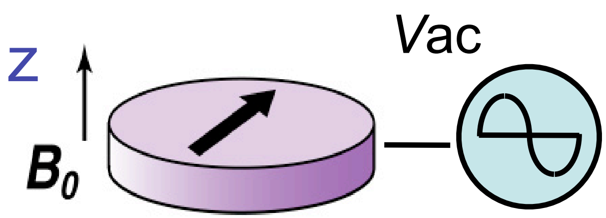
Spin-orbit interaction

V.N. Golovach et al. *PRB* 06 (Theory)

K.C. Nowack *et al*., arXiv0707.3080

Inhomogeneous hyperfine interaction

Laird *et al*., arXiv 0707.0557

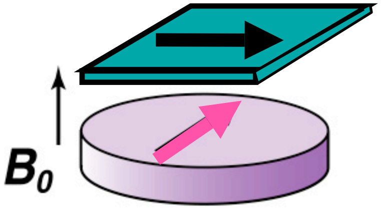


We proposed….

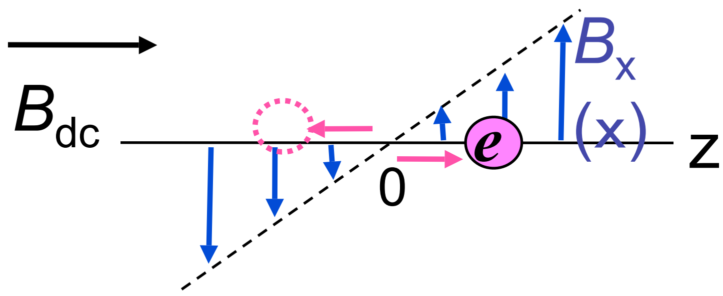
Electron oscillation in a slanting Zeeman field formed by a micro-magnet

Y. Tokura, ST, et al. *PRL* 06   M. Ladriere, ST et al. *APL* 07 (Theory)

Experiment….This talk



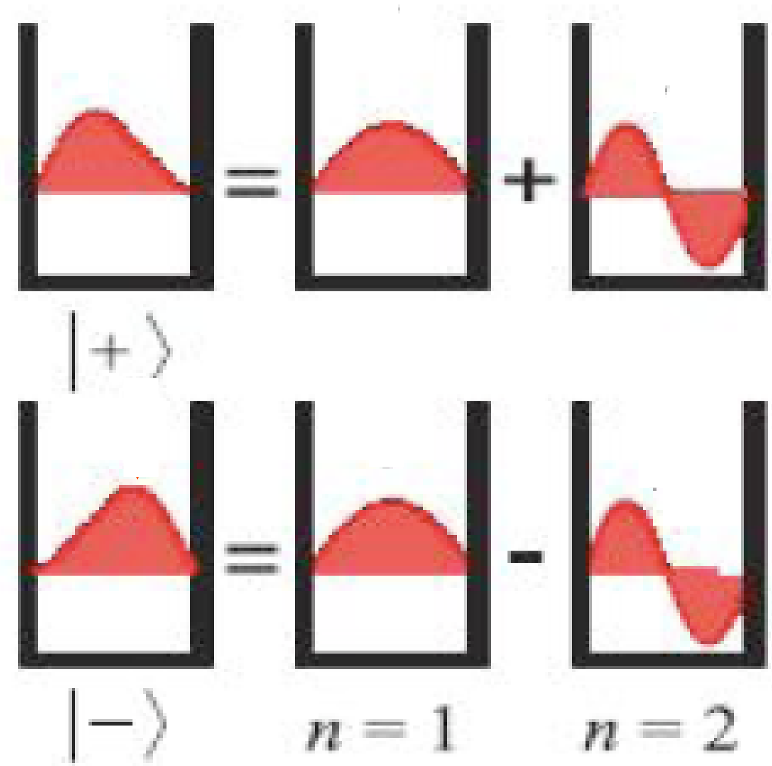
ESR in a Slanting Magnetic Field



DC uniform B_z + B_x gradient
Oscillating *e*-position
= Inducing ac Zeeman field
for the electron

Proposal:
Y. Tokura, ST *PRL* 06
M. Pioro-Ladriere , ST *APL* 07

Quantum picture

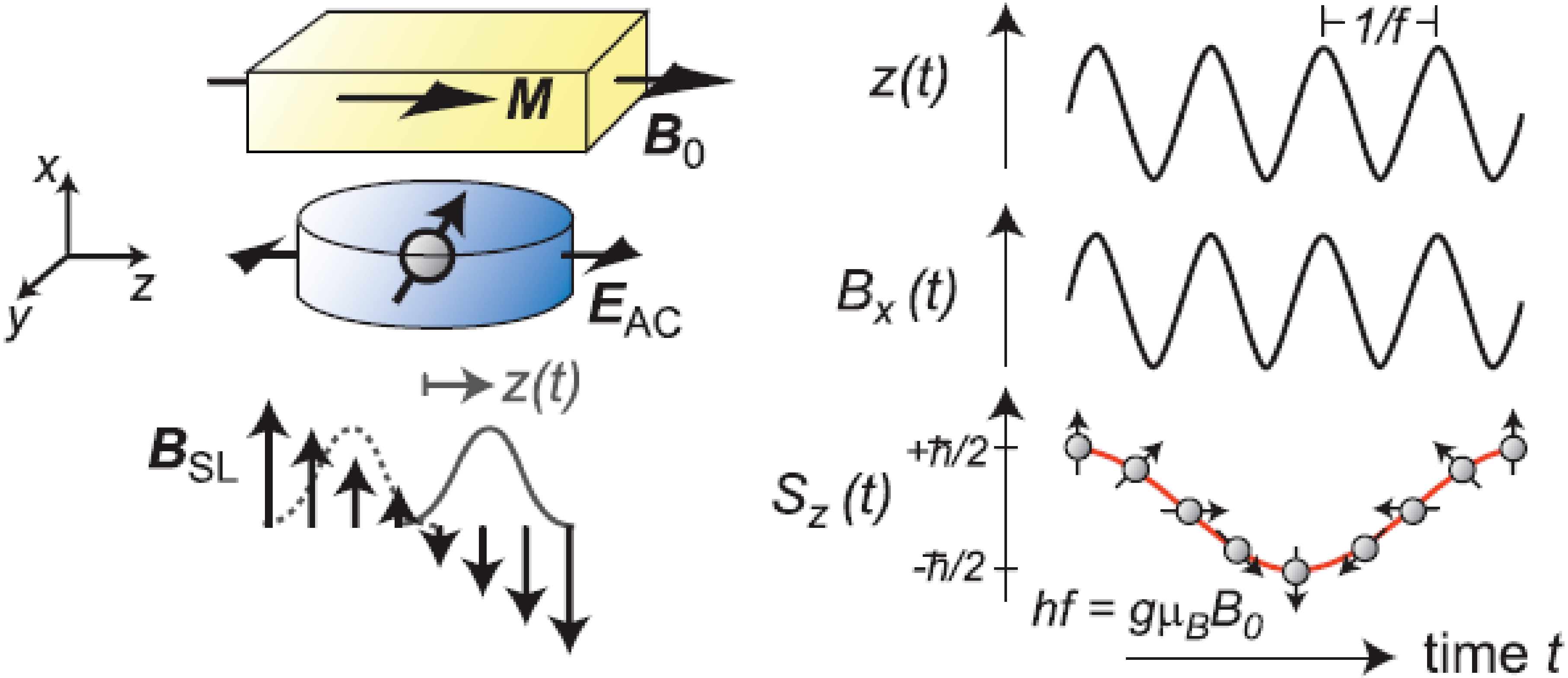


Up and down quasi-spins

$$|G_-\rangle = |1\uparrow\rangle + C_{1\uparrow}|2\downarrow\rangle$$
$$|G_+\rangle = |1\downarrow\rangle + C_{1\downarrow}|2\uparrow\rangle$$

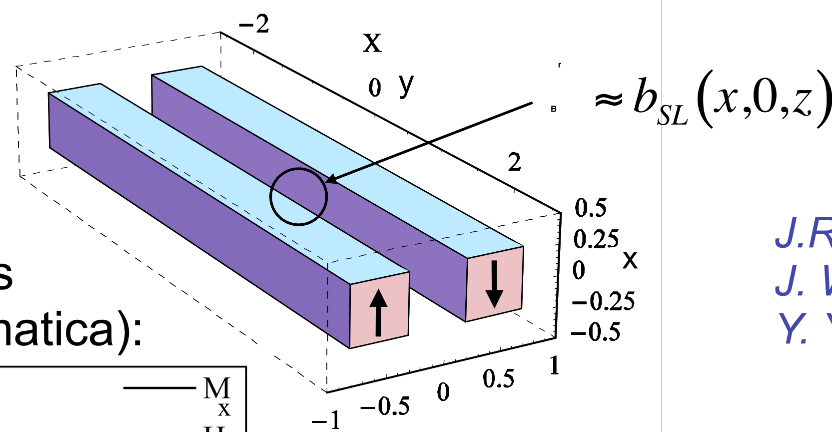
$|C_1| << 1$

Electron Motion in a Slanting Magnetic Field

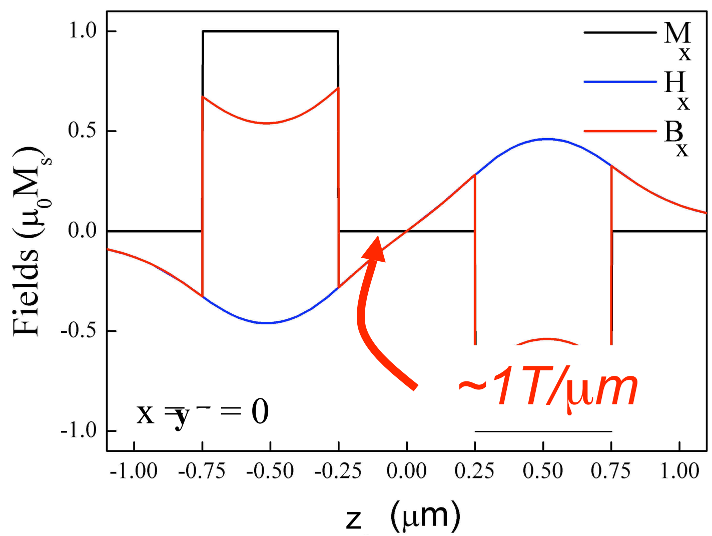


Slanting Field between Ferromagnets

2 permanent magnets (5 mm x 0.5 μm x 0.5 μm)
separated by 0.5 μm gap



Simulation results
(Radia©+Mathematica):

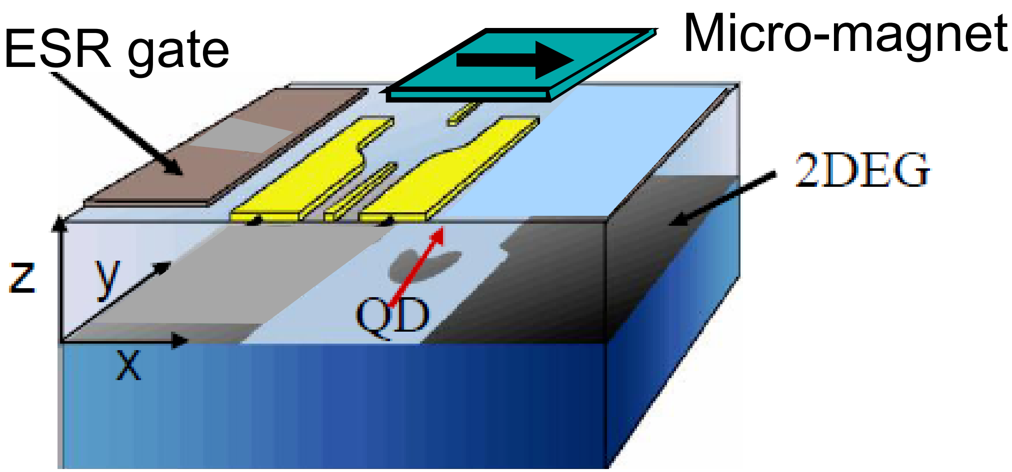


J.R.Goldman et al.,2000
J. Wrobel et al.,2004
Y. Yamamoto et al.

Material	T_C (°C)	$\mu_0 M_S$ (T)	b_{SL} (T/μm)
Fe	770	2.19	2.23
Co	1115	1.82	1.86
Py	596	1.70	1.73
Ni	354	0.64	0.65

Dy, Gd,….

Device



- **Few-electron lateral QD**

Isolation of single electrons

M. Ciorga *et al.*, PRL **88** 256804 (2002)

- **Pauli spin blockade**

ESR detection

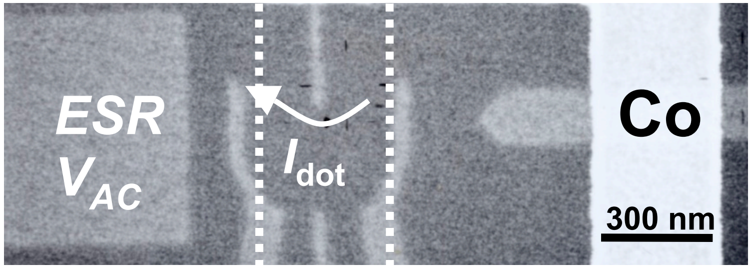
Koppens *et al*. Nature **442** 766 (2006)

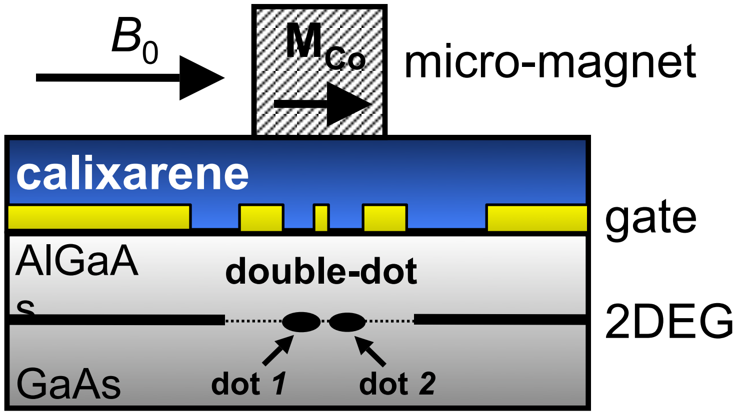
- **ESR gate**

AC electric field $\boldsymbol{E_{AC}}$

MPL *et al*. APL **90** 024105 (2007)

$V_{AC} = V_0 \sin(2\pi f t)$





Stray Magnetic Field Profile: Simulation

Static Zeeman field: $B_0 + \delta B_0$

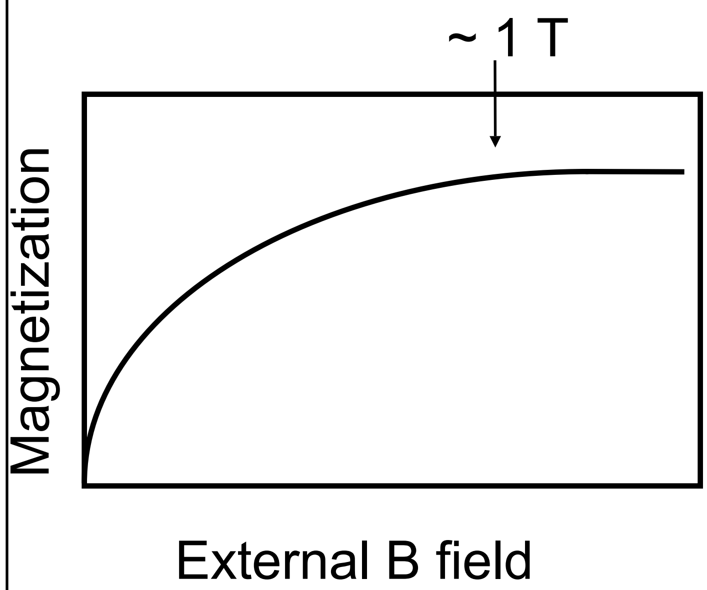
→ Shift of f_{ESR}

In the low B_0 range

Slanting Zeeman field: b_{SL}

→ Change of I_{ESR}

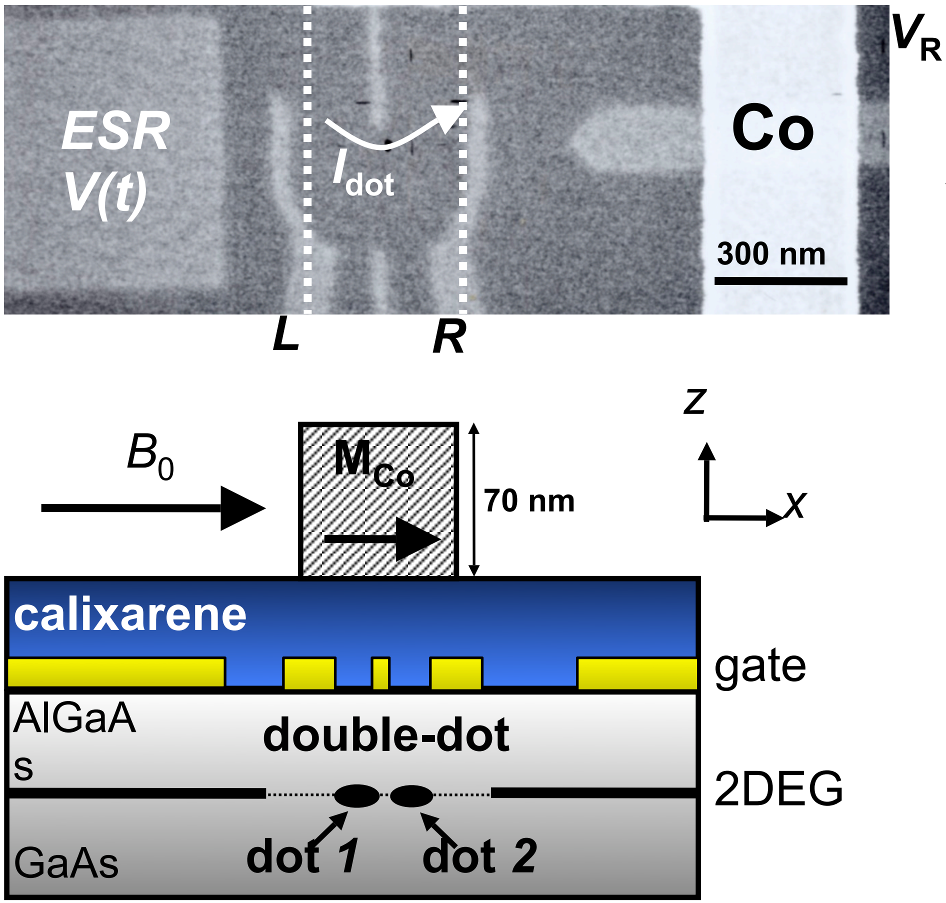
Stray field of micro-magnet



δB_0, b_{SL} $\propto$ Magnetization of micro-magnet

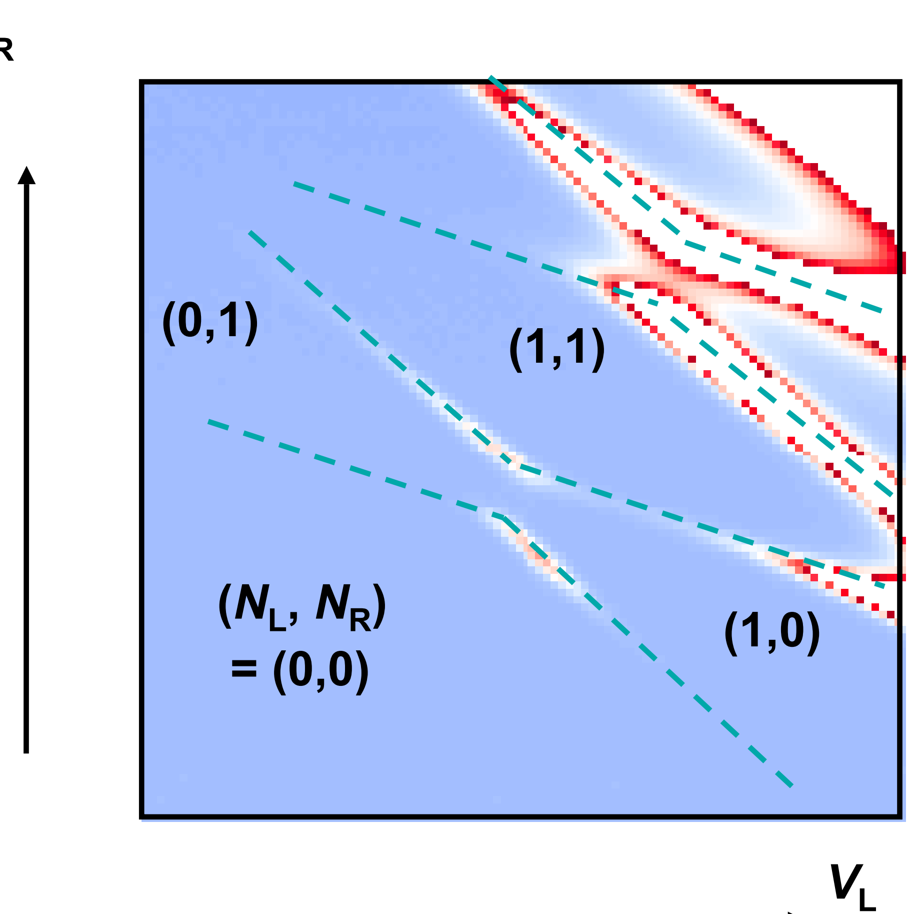
Formation of Double Quantum Dot

$V(t) = V_0 \sin(2\pi f t)$



Dot 1: Target Dot 2: Detector

By adjusting two side gate voltage,
A double quantum dot is formed.



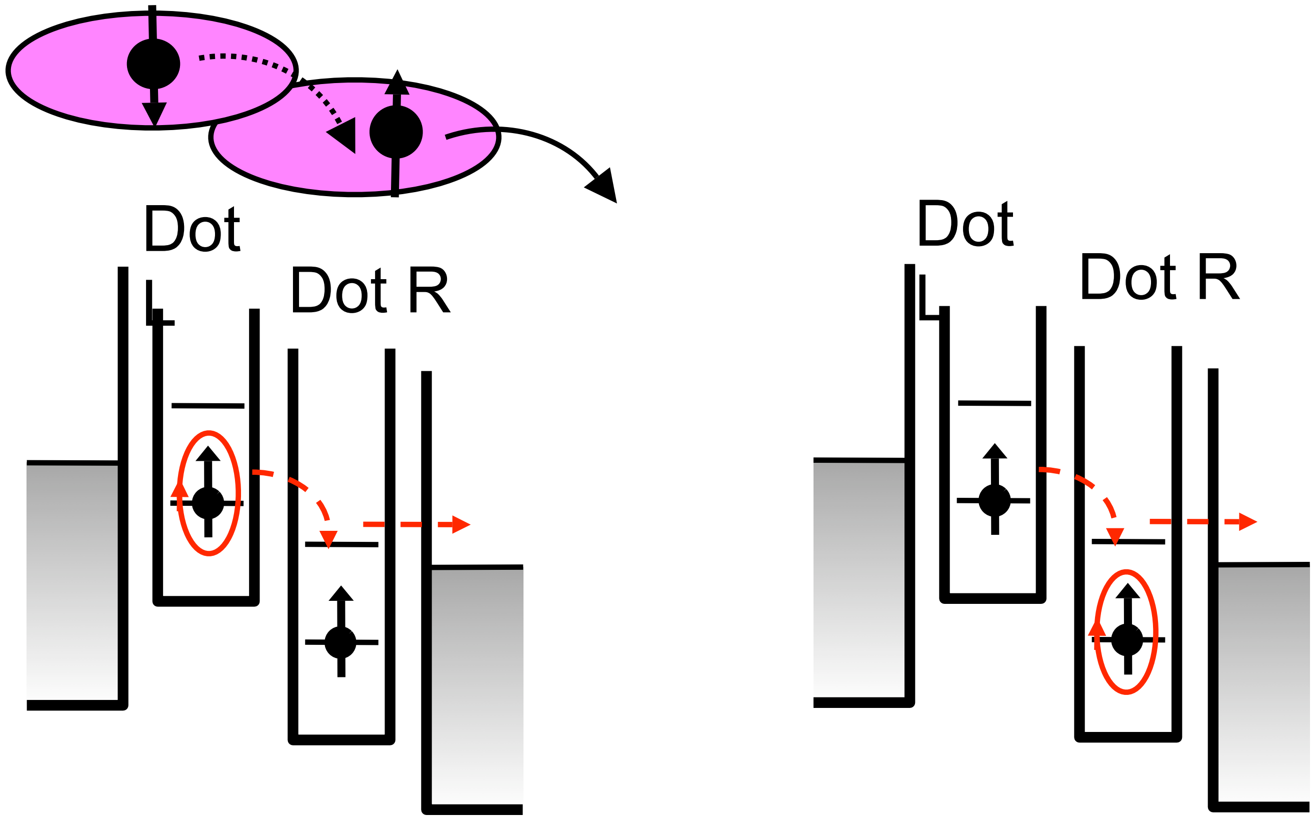
Three contributions coexist…

$$B_{\mathrm{ESR}} = B_{\mathrm{Slant}} + B_{\mathrm{Hyper}} \pm B_{\mathrm{SO}}$$

±: depending on crystal orientation)

They have different dependencies on B_{ext} and E_{ext}.
….can be distinguished

Two Spins in a Displaced Ferro-magnet



If stray field from micro-magnet

$|\delta B_0(\text{Dot L})| \quad > \quad |\delta B_0(\text{Dot R})|$

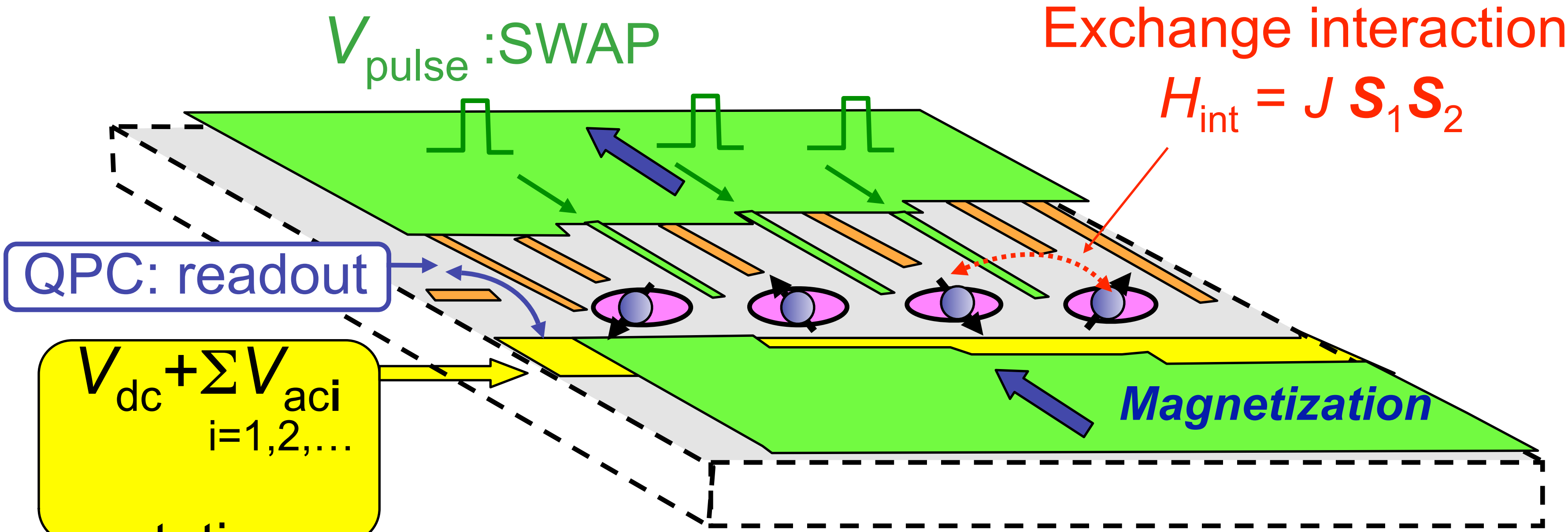
Then

$f_{ESR}(\text{Dot L}) \quad < \quad f_{ESR}(\text{Dot R})$

$\Delta f > 1/T_2^*$

Address two spins
at two different f_{ESR}s

Micro-magnet Design for Scalability



$V_{dc} + \Sigma V_{aci}$
$i=1,2,\ldots$

: rotation

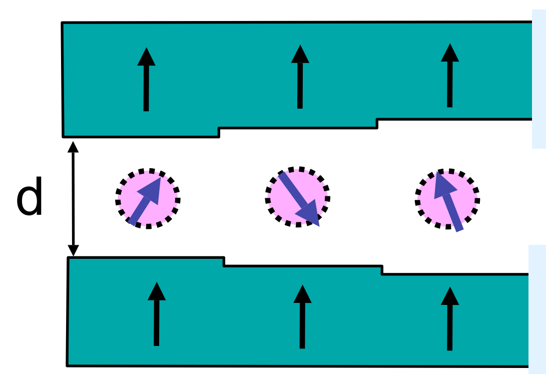
$hf_i = E^i_{Zeeman}$ for V_{aci}

Local Zeeman energy

$E^i_{Zeeman} = g\mu_B B^i_0$

…. V_{ac} frequency mixing

Δf_{ESR} = 10 MHz > $1/T_2^*$: ⇨ 100 qubits with Δd ~3 nm



δB_0 in the range of 200 mT = 1.2 GHz for d=0.1 to 0.4 μm

Micro-magnet

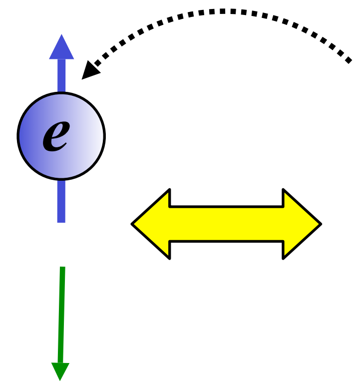
Nuclear Spin Effect

Hyperfine coupling

$$H_{\mathrm{HF}} = A\left|\o(\mathrm{x})\right|^2\left(\frac{I_+S_- + I_-S_+}{2} + I_ZS_Z\right)$$

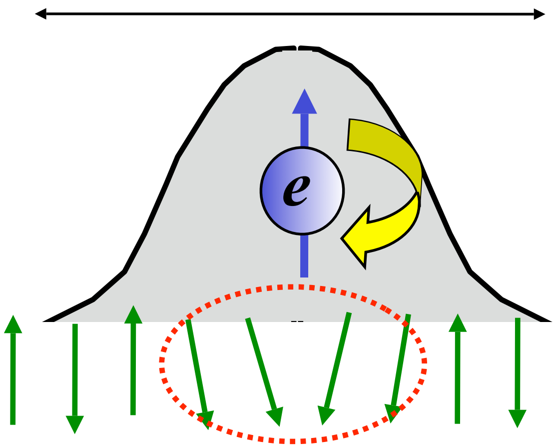
Flip-flop

Recovery due to short lifetime



GaAs quantum dot

50 nm



$10^5 \sim 10^6$ nuclei in QD

Accumulation due to long lifetime (~ min.)

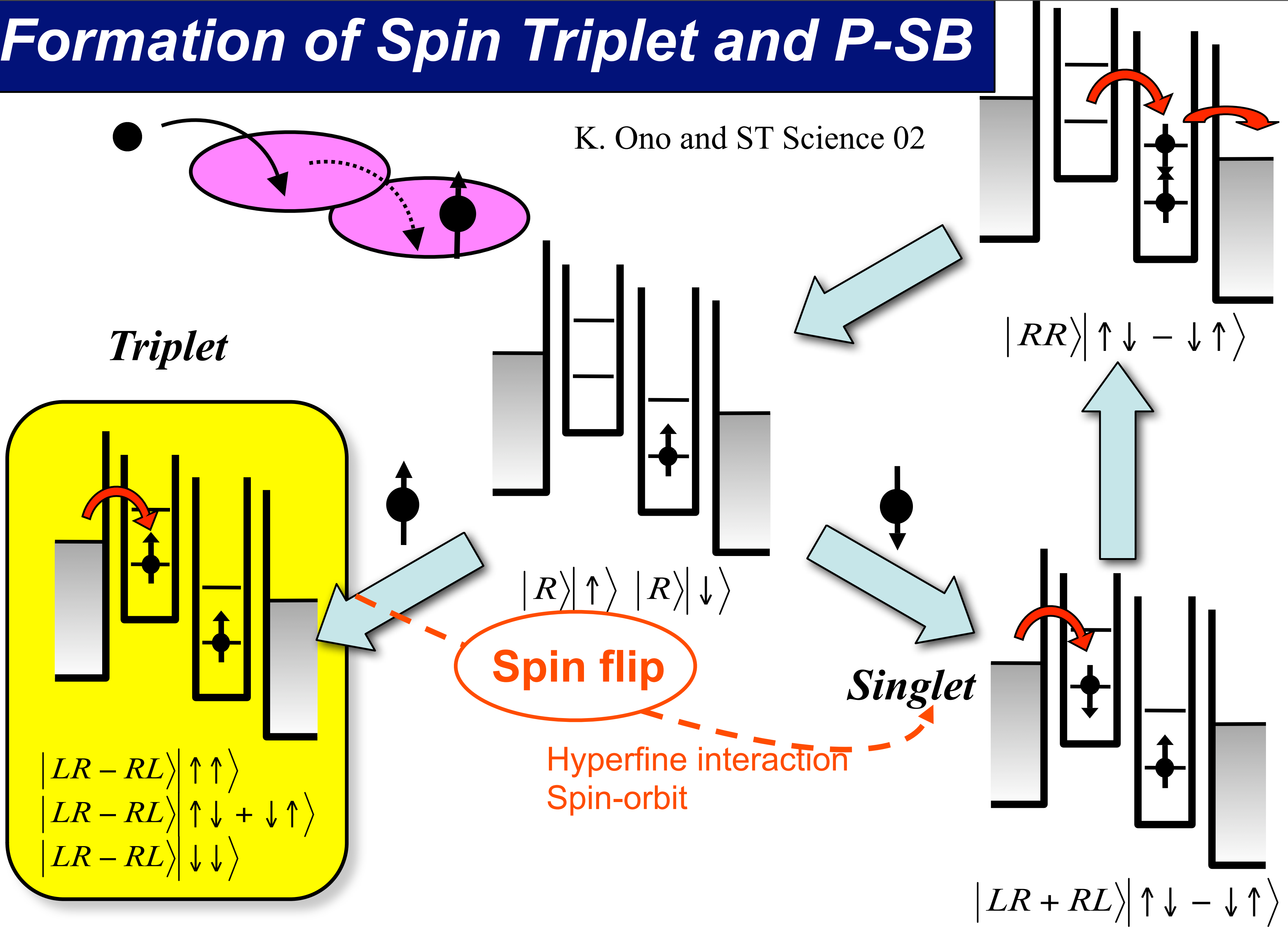
→ Dynamical nuclear spin polarization, which imposes an extra magnetic field on the electronic spin …..Overhauser effect

Nuclear spin polarization up to ~60 %

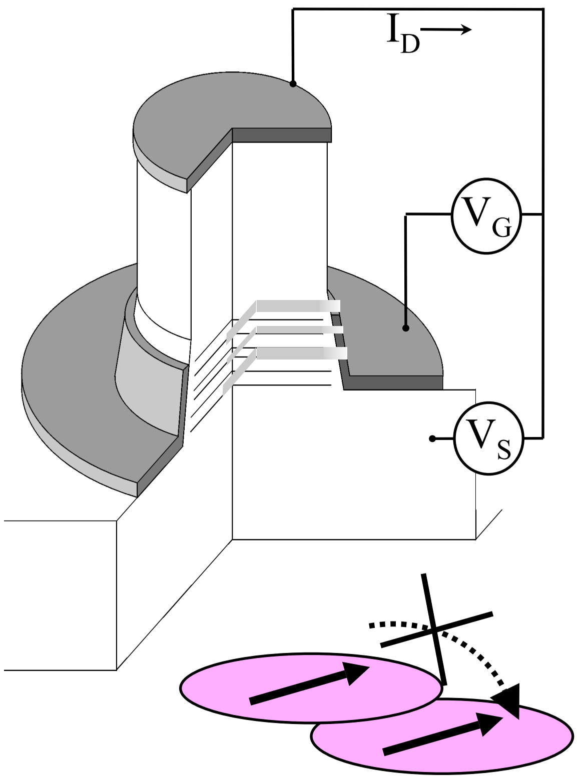
J. Baugh, ST… PRL 07

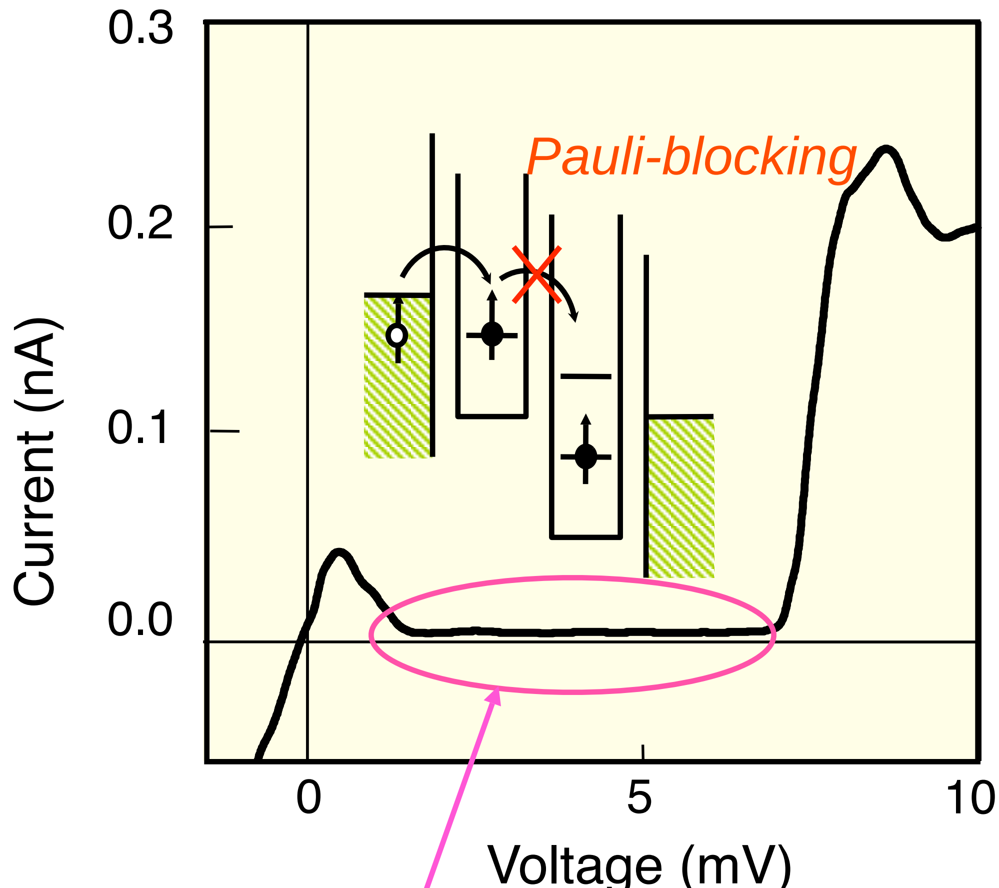
⇨ Can be observed as lifting of Pauli spin blockade

Formation of Spin Triplet and P-SB



Pauli Spin Blockade in Double QD





Ono and ST, *Science* 02

PRL 04

D~ 30 nm

$N \approx 10^5$

Laterally coupled dots

Johnson et al. *Nature* 05

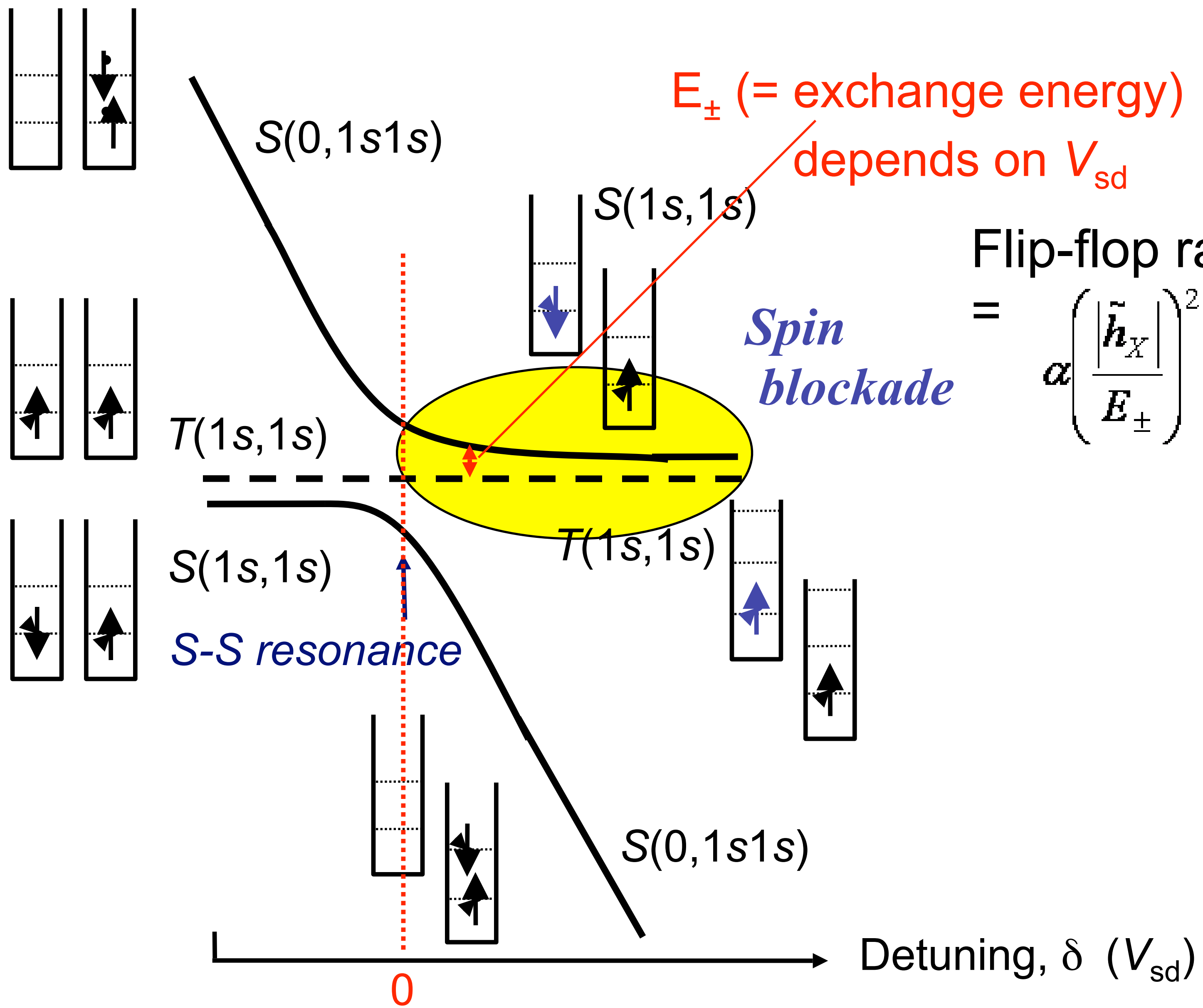
Koppens et al. *Science* 05

Can be lifted by coupling to nuclear spin

GaAs QD:

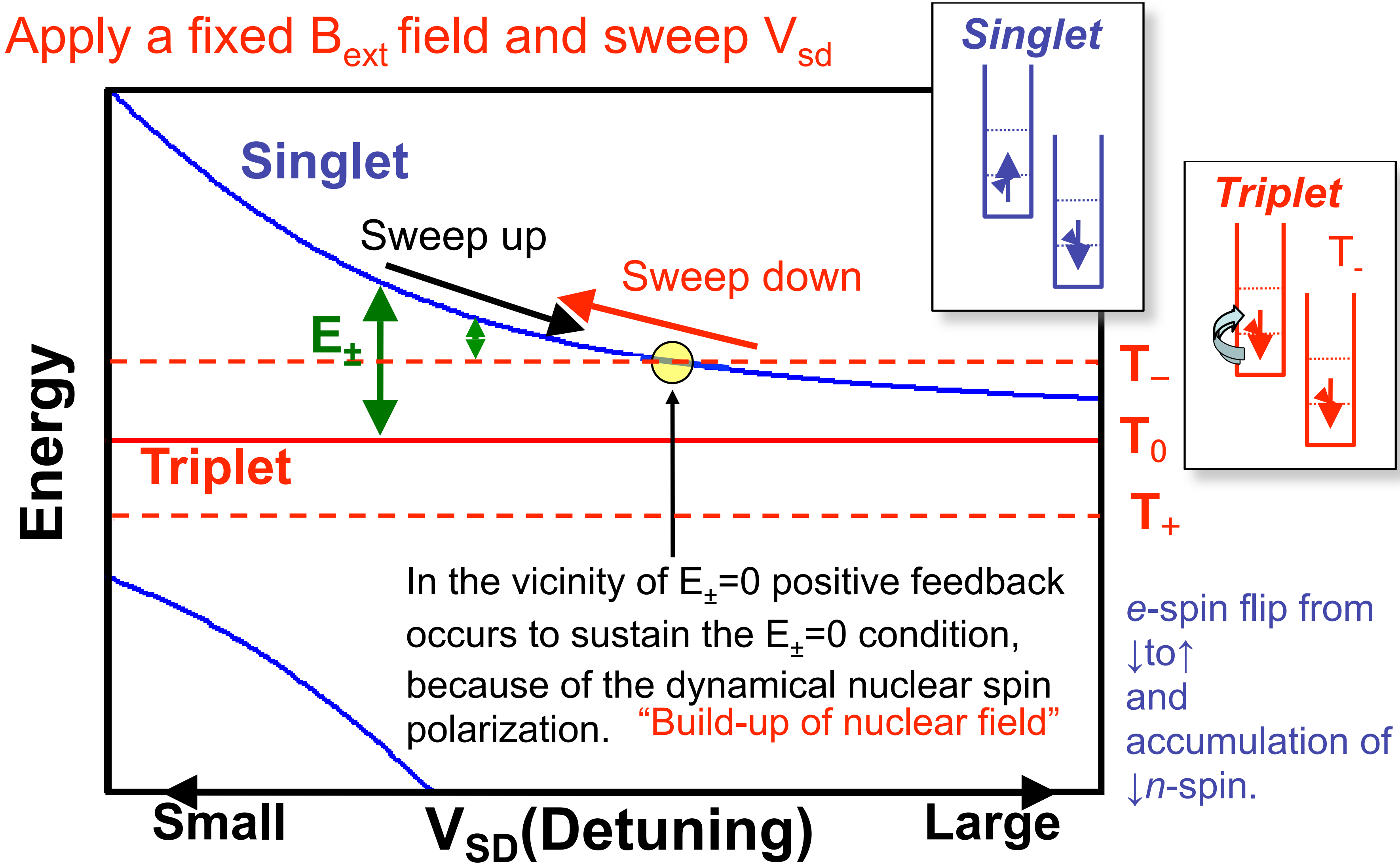
^{71}Ga, ^{69}Ga, ^{75}As: I=3/2

How to electrically control hyperfine coupling



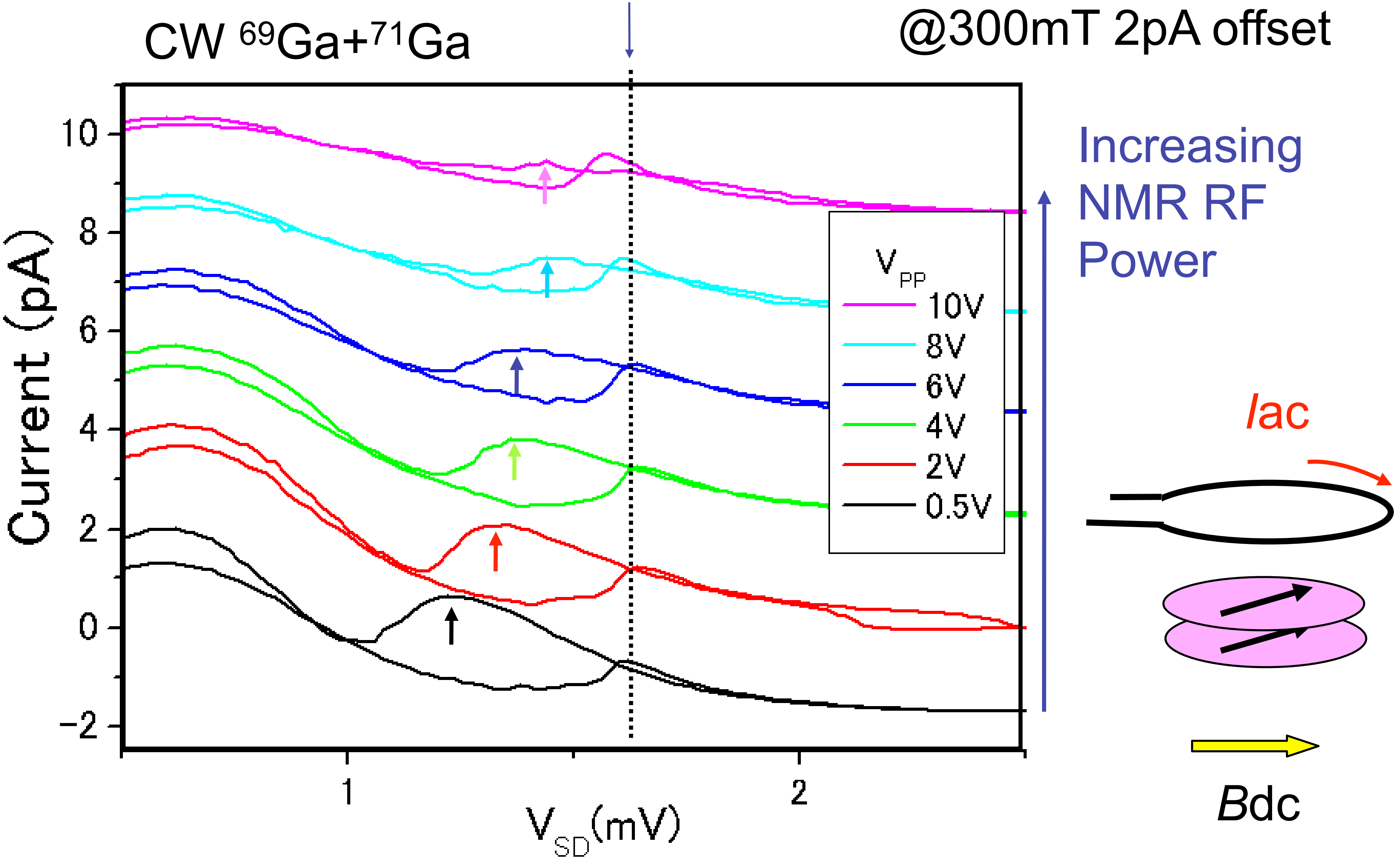
Flip-flop rate $= \alpha \left(\frac{|\tilde{h}_X|}{E_\pm} \right)^2$

How to control nuclear spin coupling

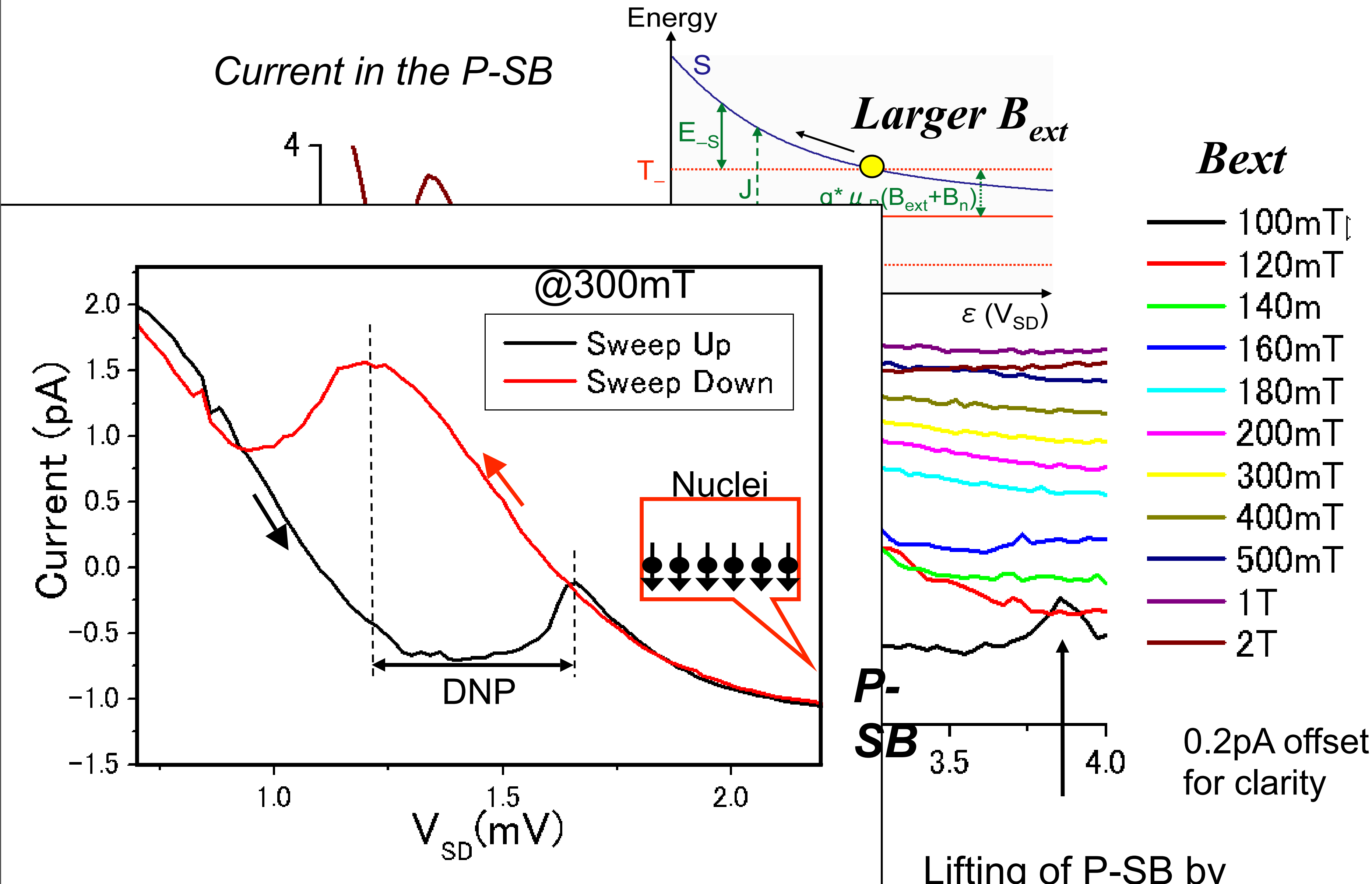


Nuclear Spin Depolarization by CW NMR RF

Hysteresis=DNP? ⟵ Test using NMR to depolarize the nuclei
Weak nuclear spin pumping

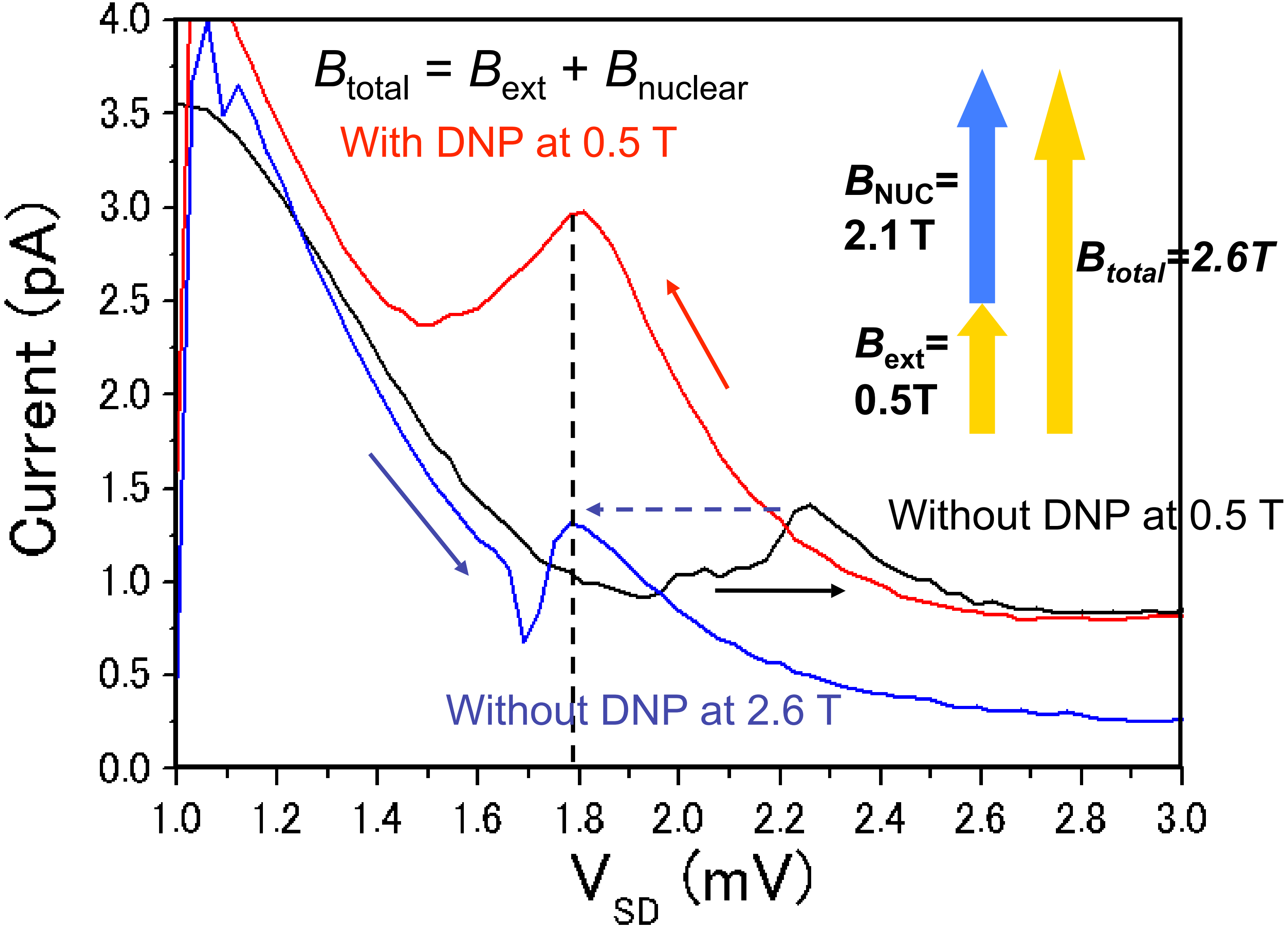


$|T_{-}\rangle$-$|S\rangle$ Degeneracy Depending on B_{ext}

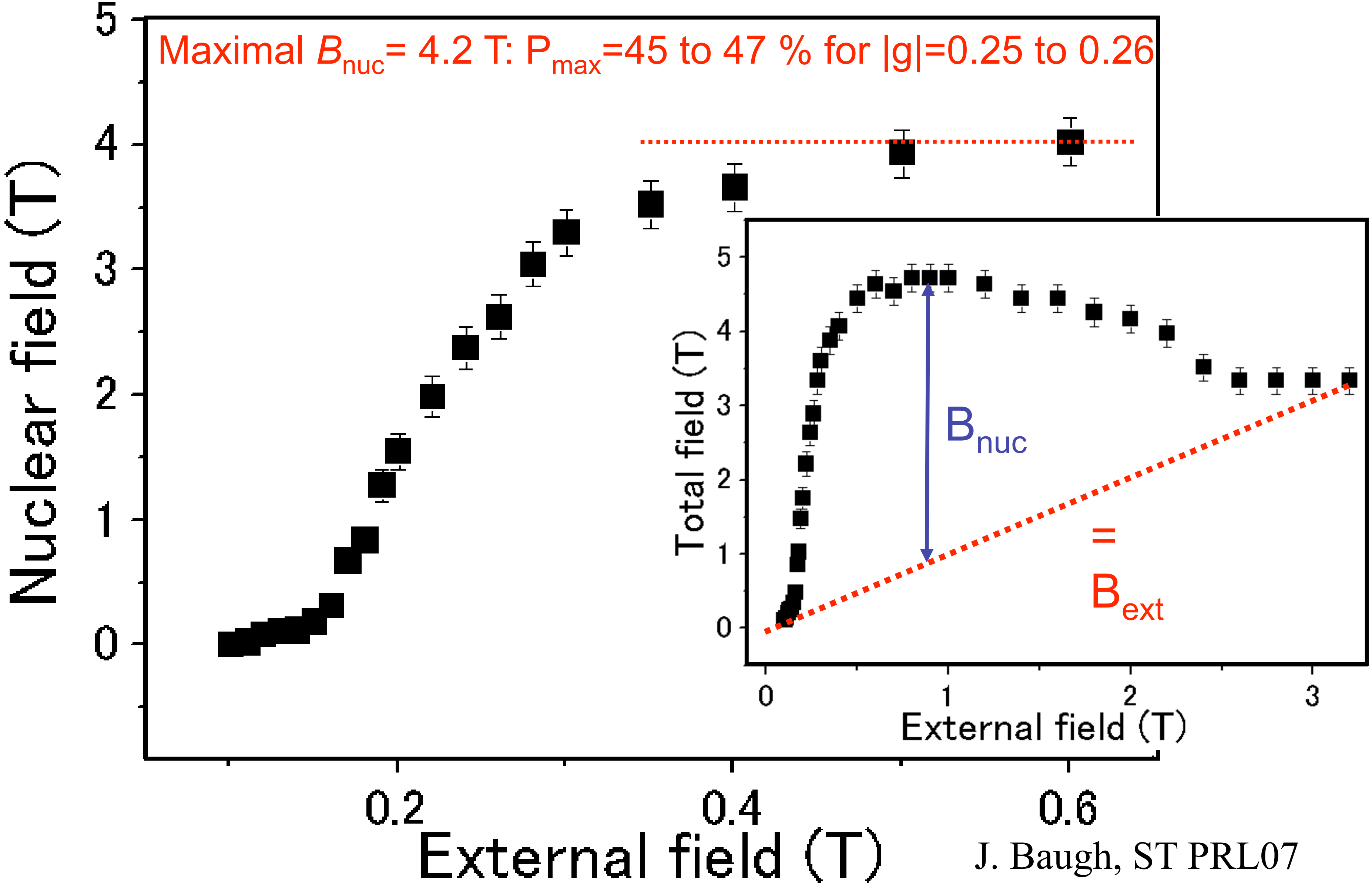


Lifting of P-SB by V_{sd} induced $|T_{-}\rangle=|S\rangle$

Nuclear Field due to DNP

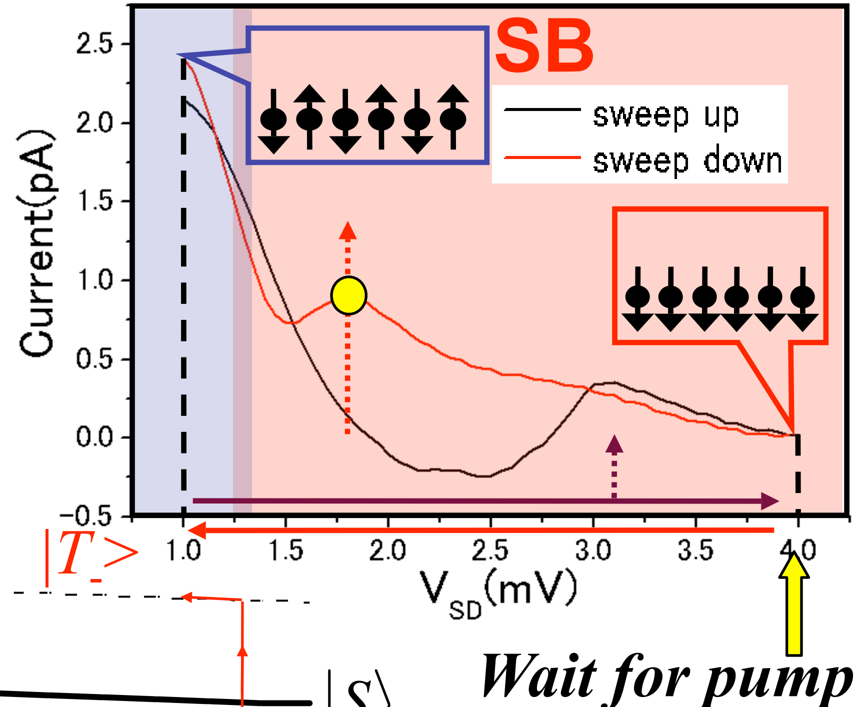


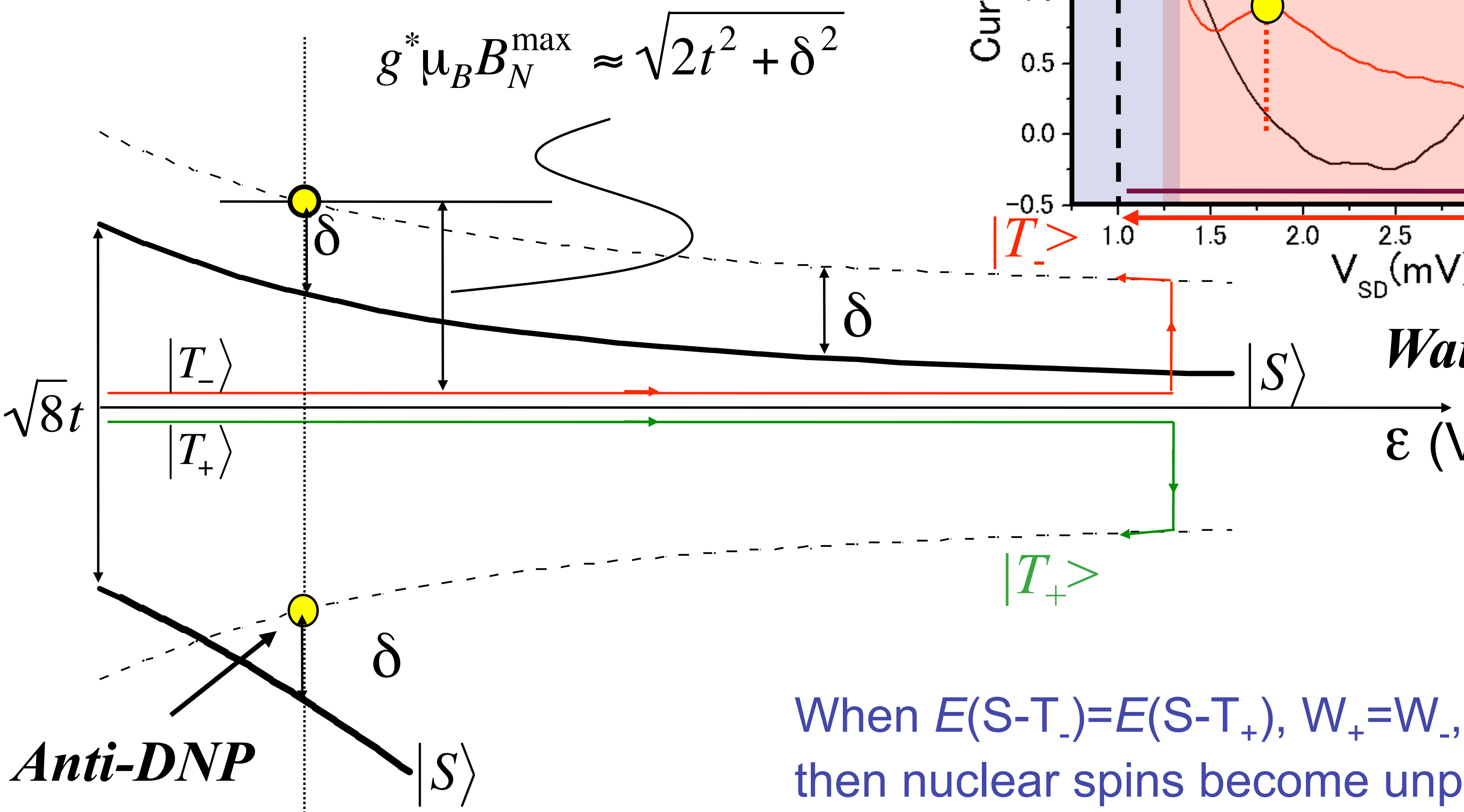
Control of Nuclear Spin Polarization



J. Baugh, ST PRL07

Approach to full polarization (simple picture)





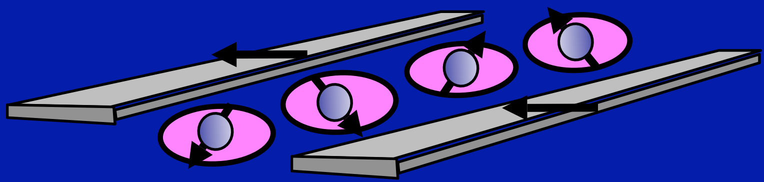
When E(S-T_-)=E(S-T_+), W_+=W_-,
then nuclear spins become unpolarized.

B_N^{max} $\sim 10T$ (full polarization) for $t \sim 70\mu eV$

$t \gg \delta$

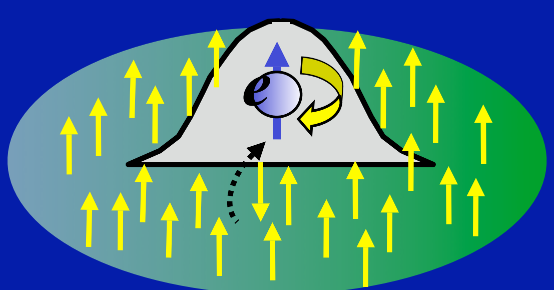
Conclusion

Voltage-driven single spin resonance using a slanting Zeeman field



- Developed a spin resonance technique with QDs using a micro-magnet
- Demonstrated two-spin addressing, which can provide a technique for multiple qubit operation … good for scalability

Electrical control of dynamical nuclear polarization



- Demonstrated tunable polarization from 0 to ~50 %, using a voltage-controlled exchange coupling and Pauli spin-blockade
- Discussed a possible approach for full polarization