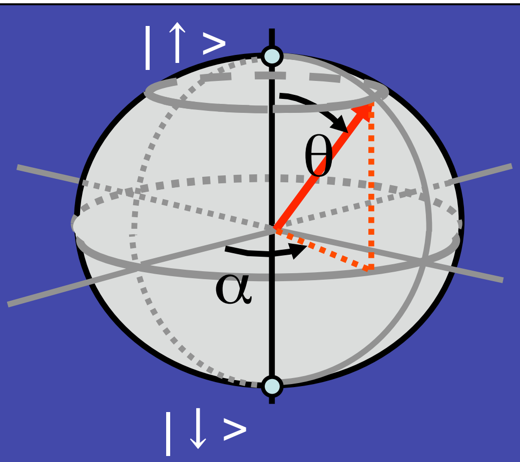
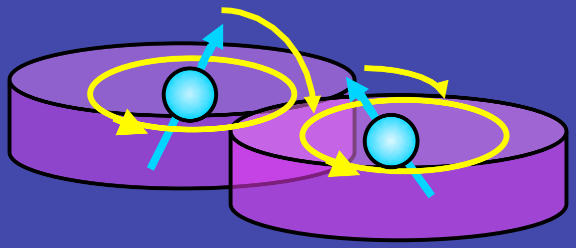




Meeting of FIRST QIP Project/Quantum Cybanetics
Kyoto, Dec. 15, 2011

Manipulation and detection of electron charge/spin qubits

Agenda

- Coherent control of spins
- Measurement of spins
- New gear : spin-orbit interaction
- Unpleasant neighbors : nuclear spins
- Topics

Yasuhiro Tokura

NTT Basic Research Laboratories
FIRST Project, theory subtheme
Quantum Cybanetics, semiconductor nano-system

FIRST research theme

Theory of physical qubits

In collaboration with experimental groups

spin qubit system, quantum interface

- Entanglement of two spin qubits (Tarucha, U. Tokyo)
- Interference circuits to initialize and analyze flying spin qubits (Aharony, Ben Gurion U.)
- Back-action of charge detector (Kubo, poster Thu-3)
- Coherent coupling of flux-qubit and NV ensemble (Semba NTT, Nemoto NII)
- Quantum computing with coherent photon conversion (Munro)

Build/predict long-term research directions through own/integrated theoretical activities in collaboration with experimental groups.

Q cybanetics research theme

Control, detection, and transfer of quantum states in semiconductor nanostructure

Spin manipulation, detection

S. Tarucha, U. Tokyo
T. Ota, NTT BRL

- Control of spin-orbit interaction in QD (Oiwa, Tarucha, U. Tokyo)
- Transport in QD with g-tensor modulation (Ono, Riken)
- Improved spin detection scheme with field gradient
- Quantitative analysis of dynamical nuclear spin pumping (Nazarov, TUD, Ono, Amaha, Riken)
- Quantum capacitance of a few electrons in coupled QD (Ota, NTT)

Coherent control of spins

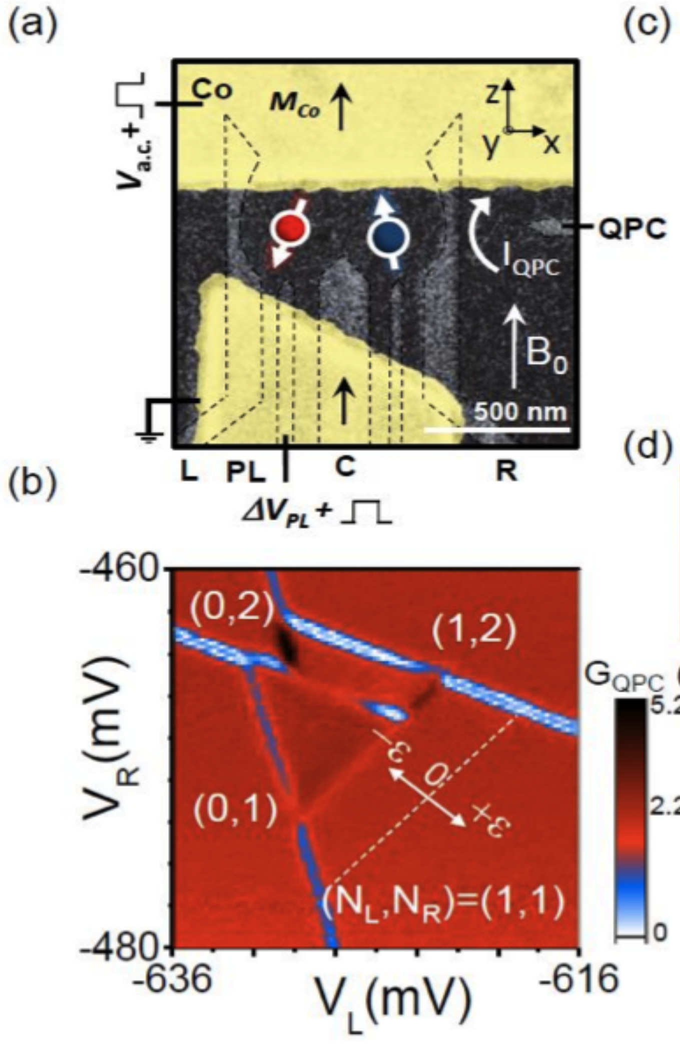
Measurement of spins

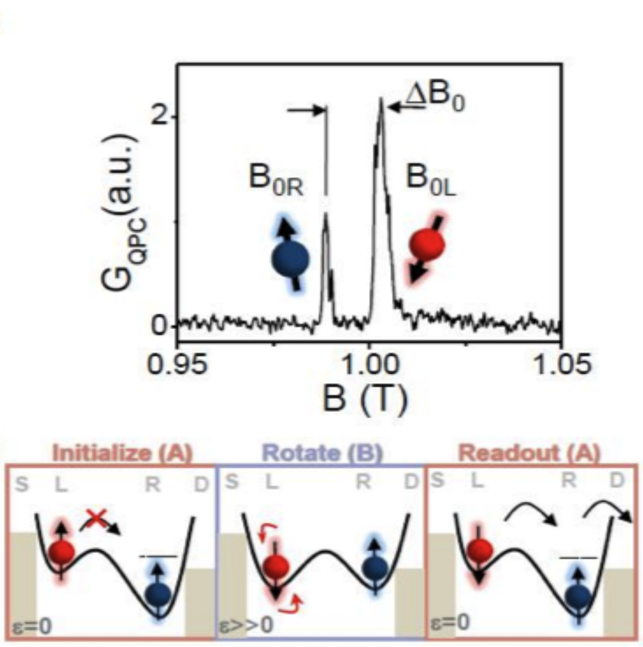
New gear : spin-orbit interaction

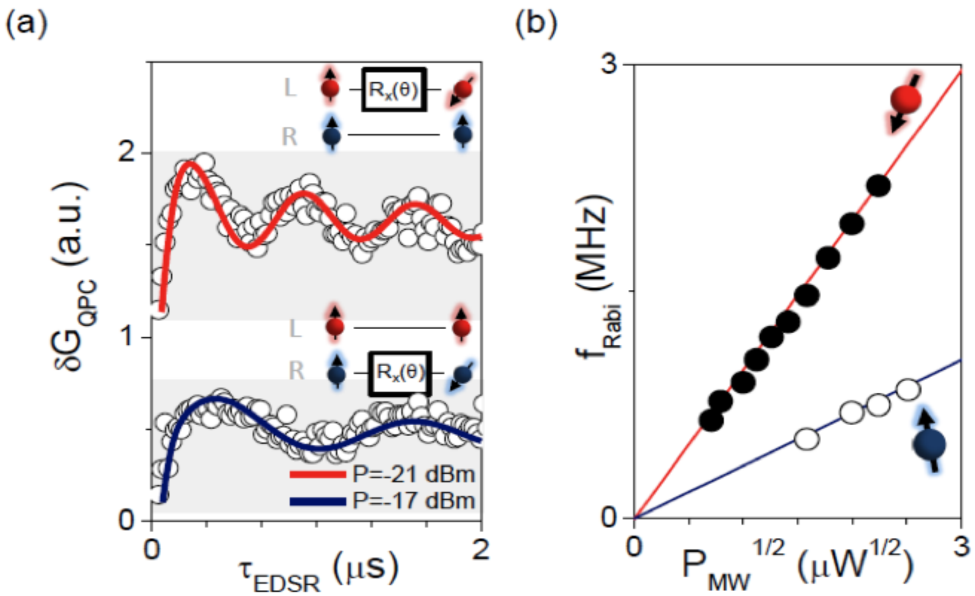
Unpleasant neighbors : nuclear spins

Topics

Two qubits system with split micro-magnets







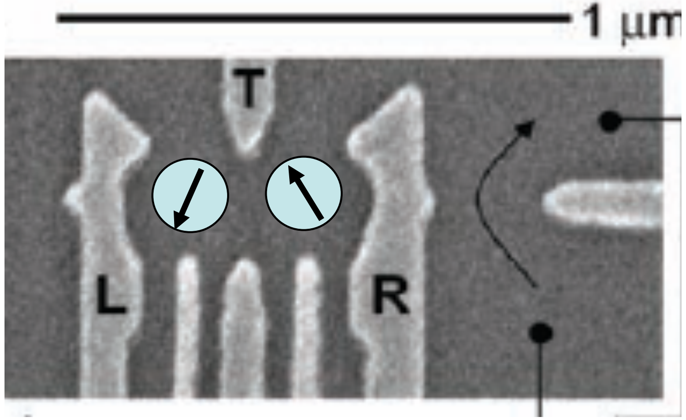
Dumping of the Rabi oscillation is originating from nuclear spin fluctuations

Rabi frequency is order of 1MHz – need to be faster

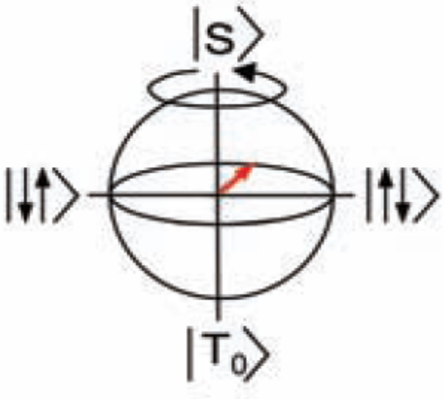
R. Brunner et al., Phys. Rev. Lett. 107, 146801 (2011).

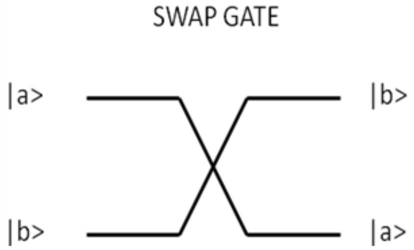
Manipulation of two spin states

J. Petta et al. Science (05)



cf T. Hatano et al. Science (05).





SWAP operation

One spin manipulation (Hadamard) + two spin SWAP operations

L-ESR 3π/2

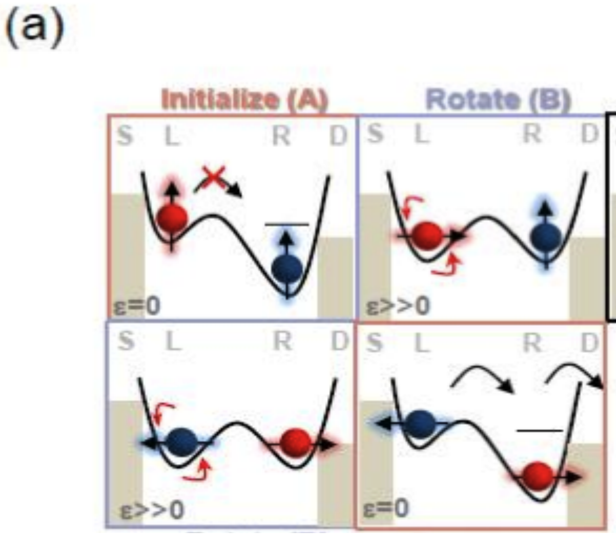
Charge moves

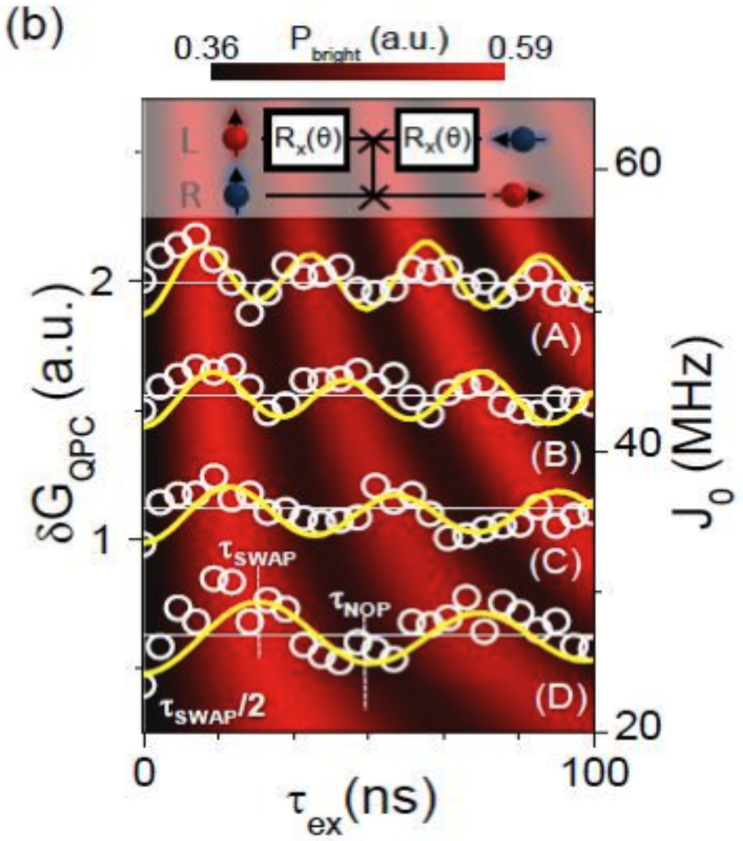
$$|\uparrow,\uparrow\rangle \rightarrow \frac{|\uparrow\rangle + |\downarrow\rangle}{\sqrt{2}} \otimes |\uparrow\rangle \rightarrow \left\{ \begin{array}{lcl} (\mathrm{SWAP} + \text{L-ESR}\frac{\pi}{2}) & \rightarrow & \frac{1}{2}\{|\uparrow,\uparrow\rangle - |\downarrow,\downarrow\rangle - \sqrt{2}S_0\} \\ (\mathrm{SWAP}^2 + \text{L-ESR}\frac{\pi}{2}) & \rightarrow & |\uparrow,\uparrow\rangle \end{array} \right.$$

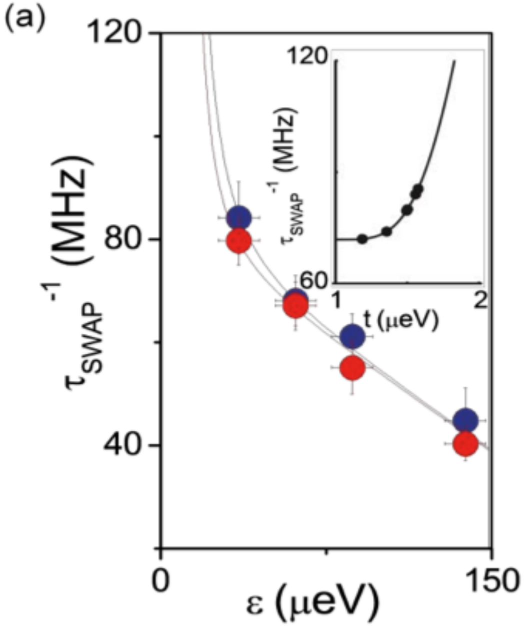
No charge move

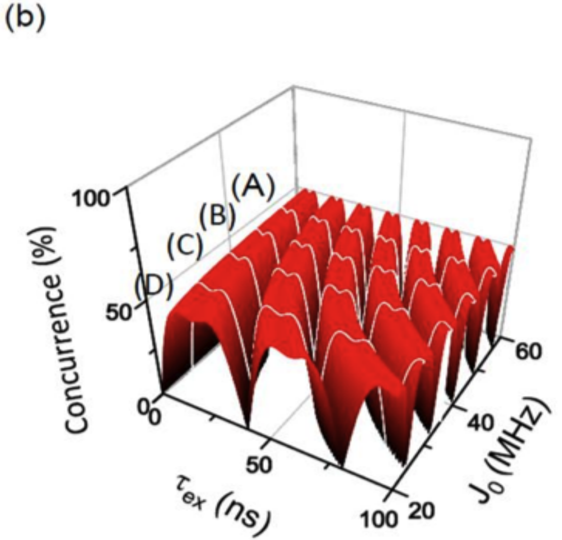
→ Distinguish this change by QPC charge detector

Demonstration of partial SWAP and entanglement









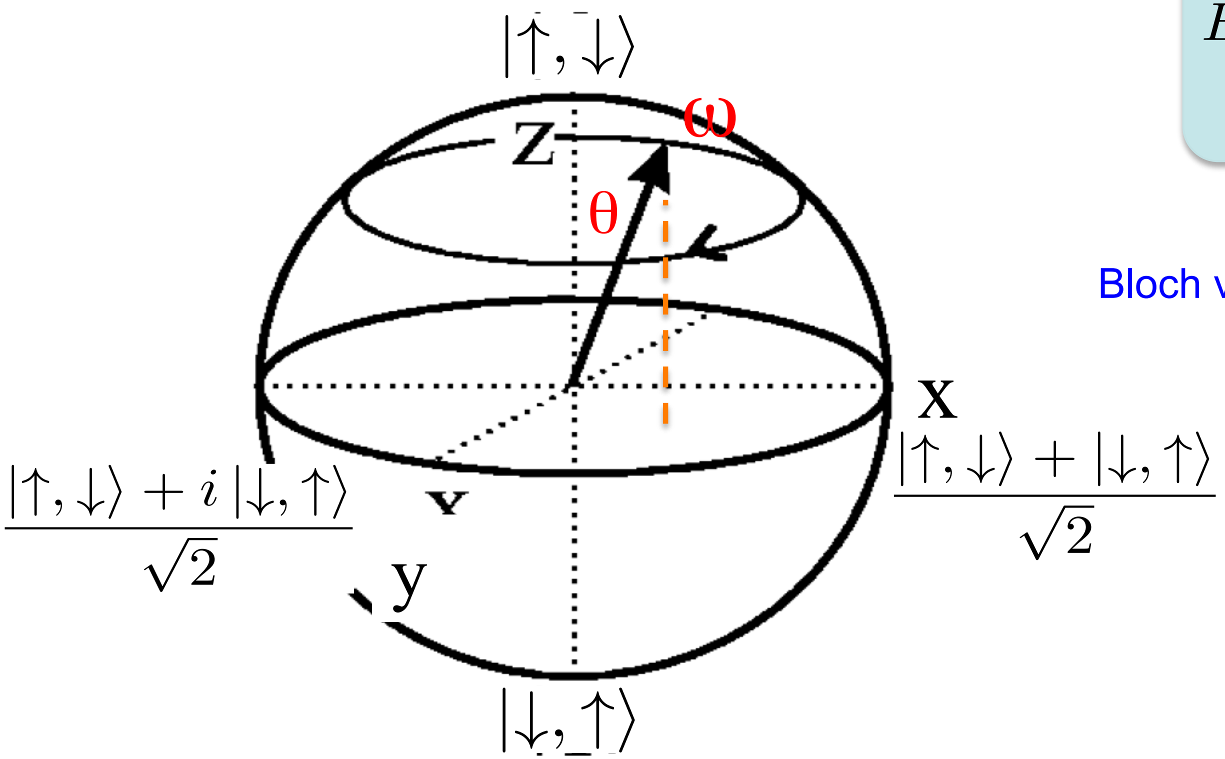
Solid lines: theory with being averaged over the nuclear spin random distribution

Estimation of concurrence: no effect of nuclear spin fluctuation is taken into account.

Two-qubit Hamiltonian with Zeeman offset

$$\begin{aligned}\mathcal{H} &= \frac{1}{2}J_\perp(\hat{\sigma}_{1+}\hat{\sigma}_{2-}+\hat{\sigma}_{1-}\hat{\sigma}_{2+})+\frac{1}{4}J_z\hat{\sigma}_{1z}\hat{\sigma}_{2z}\\ &+\frac{1}{2}E_Z(\hat{\sigma}_{1z}+\hat{\sigma}_{2z})+\frac{1}{4}\delta(\hat{\sigma}_{1z}-\hat{\sigma}_{2z}),\end{aligned}$$

$$\begin{aligned}E_Z &\equiv \frac{1}{2}(E_{1Z}+E_{2Z}),\\ \delta &\equiv E_{1Z}-E_{2Z}\end{aligned}$$



Bloch vector obeys precession frequency

$$\omega \equiv \frac{1}{2\hbar}\sqrt{\delta^2+J_\perp^2}$$

around the axis determined by

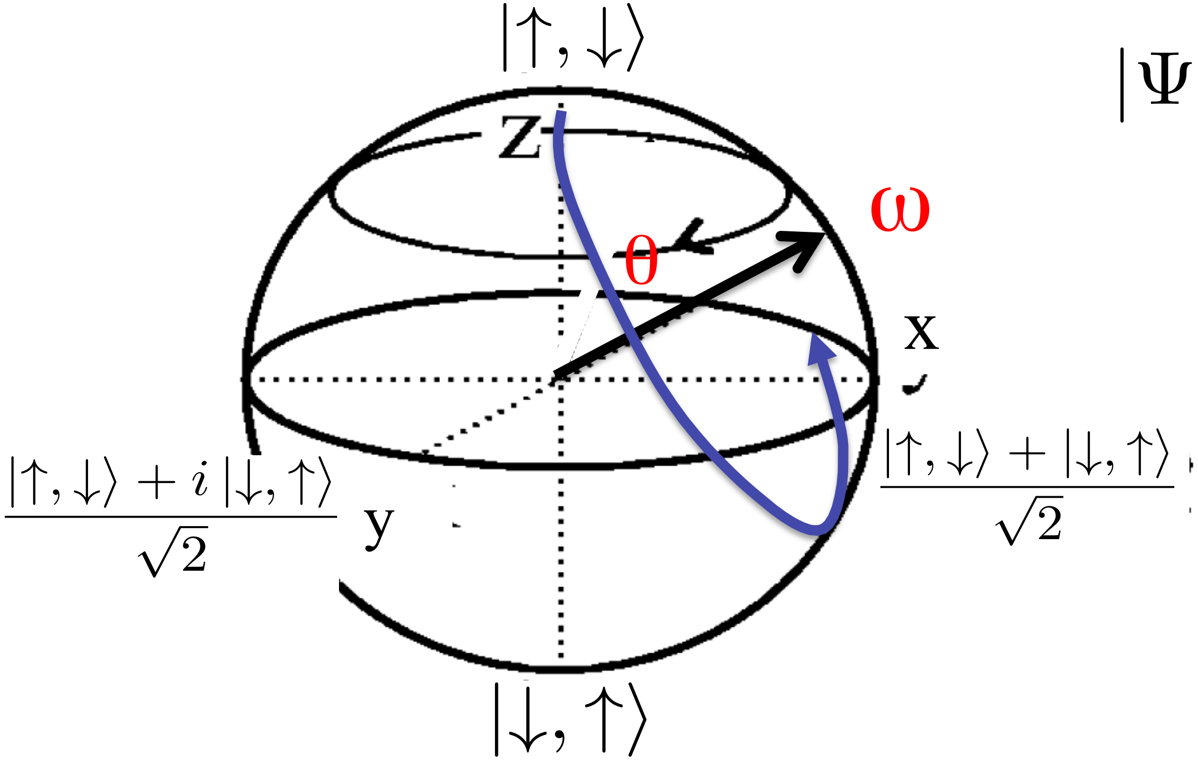
$$\cos\theta = \frac{\delta}{\sqrt{\delta^2+J_\perp^2}}$$

Bloch sphere spanned with two electron S_z=0 basis

SWAP cannot be accomplished by controlling J once

Two spin state dynamics is determined by the evolution operator:

$$\hat{U}(t) = \begin{array}{c} \\ \left(\begin{array}{cccc} |\uparrow,\uparrow\rangle & |\uparrow,\downarrow\rangle & |\downarrow,\uparrow\rangle & |\downarrow,\downarrow\rangle \\ e^{-\frac{i}{\hbar}(\frac{1}{2}J_z+E_Z)t} & 0 & 0 & 0 \\ 0 & \cos\omega t - i\cos\theta\sin\omega t & -i\sin\theta\sin\omega t & 0 \\ 0 & -i\sin\theta\sin\omega t & \cos\omega t + i\cos\theta\sin\omega t & 0 \\ 0 & 0 & 0 & e^{-\frac{i}{\hbar}(\frac{1}{2}J_z-E_Z)t} \end{array} \right) \end{array}.$$

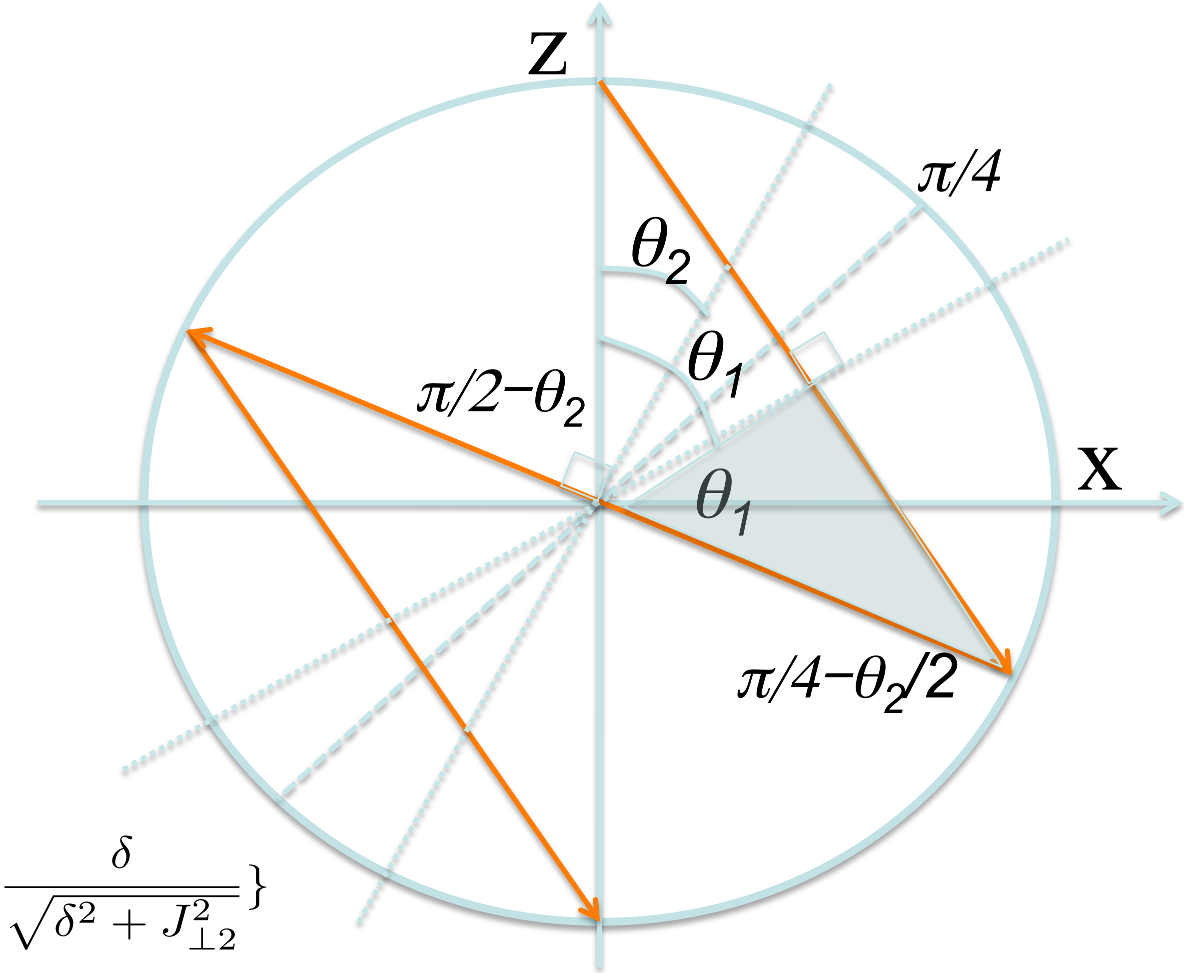


$$|\Psi(t)\rangle = \hat{U}(t)|\Psi(0)\rangle$$

SWAP by three π pulses

SWAP operation is realized with a combination of three π pulses for a given fixed δ.

$$2\theta_1 - \theta_2 = \pi/2$$
$$\pi/4 < \theta_1 < \pi/2$$



$$\begin{aligned} T_{SWAP} &= 2T_{1\pi} + T_{2\pi} \\ &= 2\frac{\pi}{2\omega_1} + \frac{\pi}{2\omega_2} \\ &= \frac{\pi\hbar}{\delta}\{2\frac{\delta}{\sqrt{\delta^2 + J_{\perp 1}^2}} + \frac{\delta}{\sqrt{\delta^2 + J_{\perp 2}^2}}\} \end{aligned}$$

This scheme cannot realize √SWAP.

SWAP by two exchanges and one zero-J pulses

Alternative SWAP operation realized with a combination of three pulses for a given fixed δ, allowing a √SWAP.

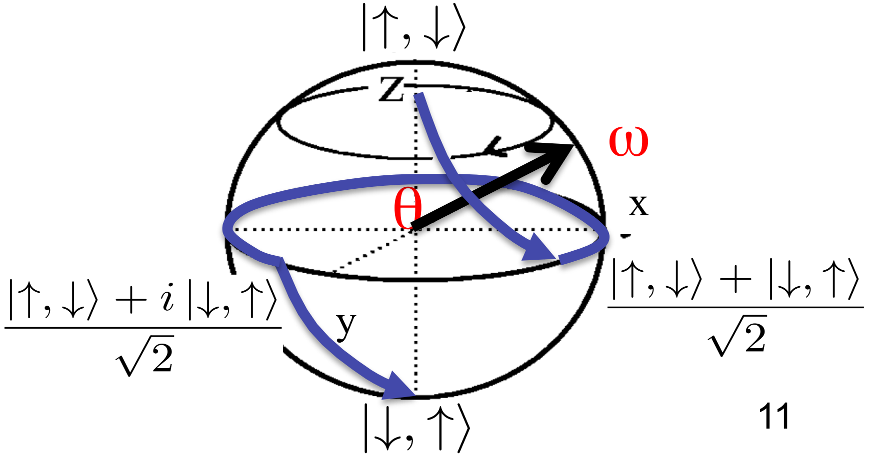
We assume: $J > \delta$

Time evolution operator: $\mathcal{U}(t,J) \equiv e^{-\frac{i}{\hbar}\mathcal{H}_{ex}t}$

$$\begin{aligned} \mathcal{U}_{sw} &= \mathcal{U}(T,J)\cdot\mathcal{U}(\tau,J=0)\cdot\mathcal{U}(T,J) \\ \mathcal{U}_{\sqrt{sw}} &= \mathcal{U}(\frac{\tau}{2},J=0)\cdot\mathcal{U}(T,J)\cdot\mathcal{U}(\frac{\tau}{2},J=0) \end{aligned}$$

Operation times are determined by

$$\begin{aligned} \tau &= \frac{2}{\delta}(\pi - \arcsin\frac{\delta}{\sqrt{J^2-\delta^2}}) \\ T &= \frac{2}{\sqrt{\delta^2+J^2}}\sin^{-1}\frac{\sqrt{\delta^2+J^2}}{\sqrt{2}J} \end{aligned}$$



Coherent control of spins

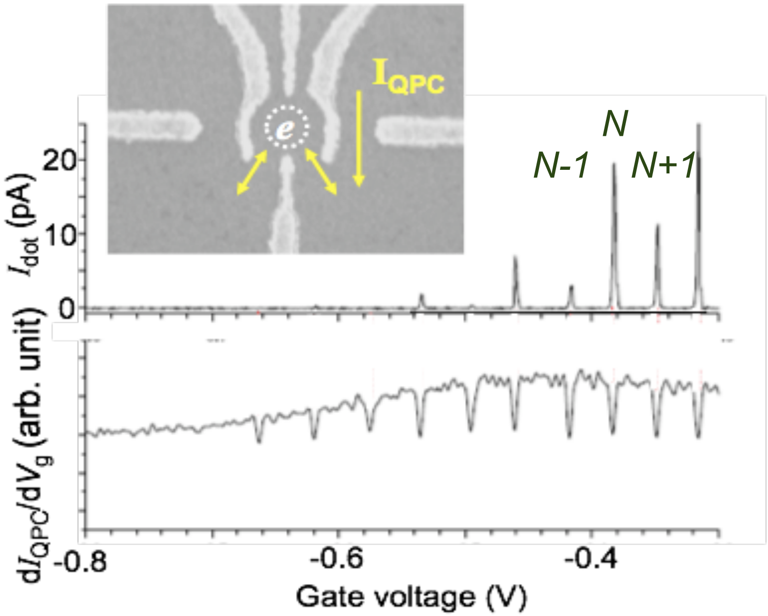
Measurement of spins

New gear : spin-orbit interaction

Unpleasant neighbors : nuclear spins

Topics

Spin-charge conversion/charge detection

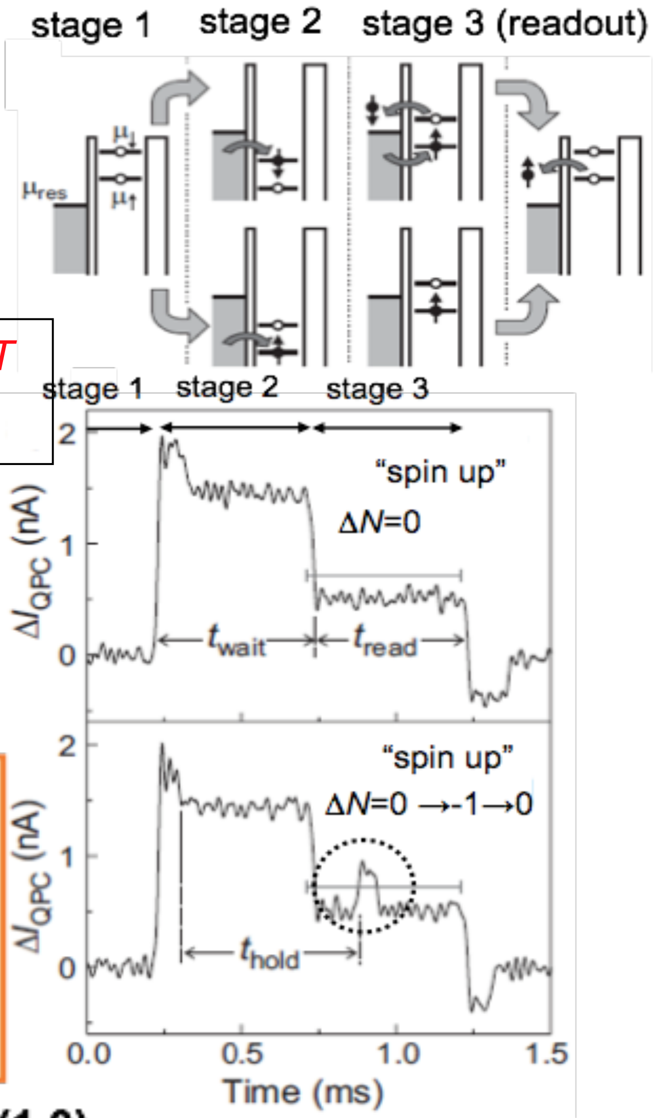


Spin-to-charge conversion

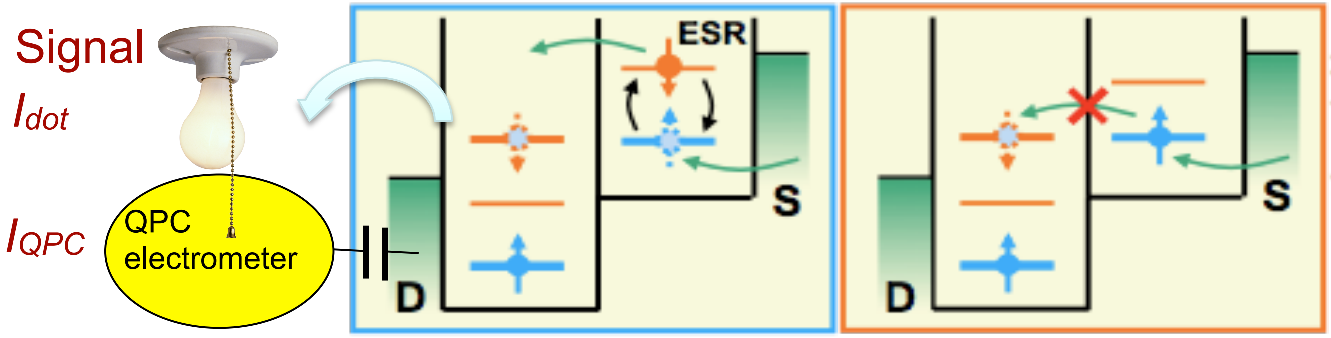
*J. M. Elzerman, et al., Nature **430**, 431 (2004).*

Level separation $E_Z >> k_BT$

Destructive measurement



A high sensitive *charge* sensor is realized by a quantum point contact, but how to detect *spin* ?`



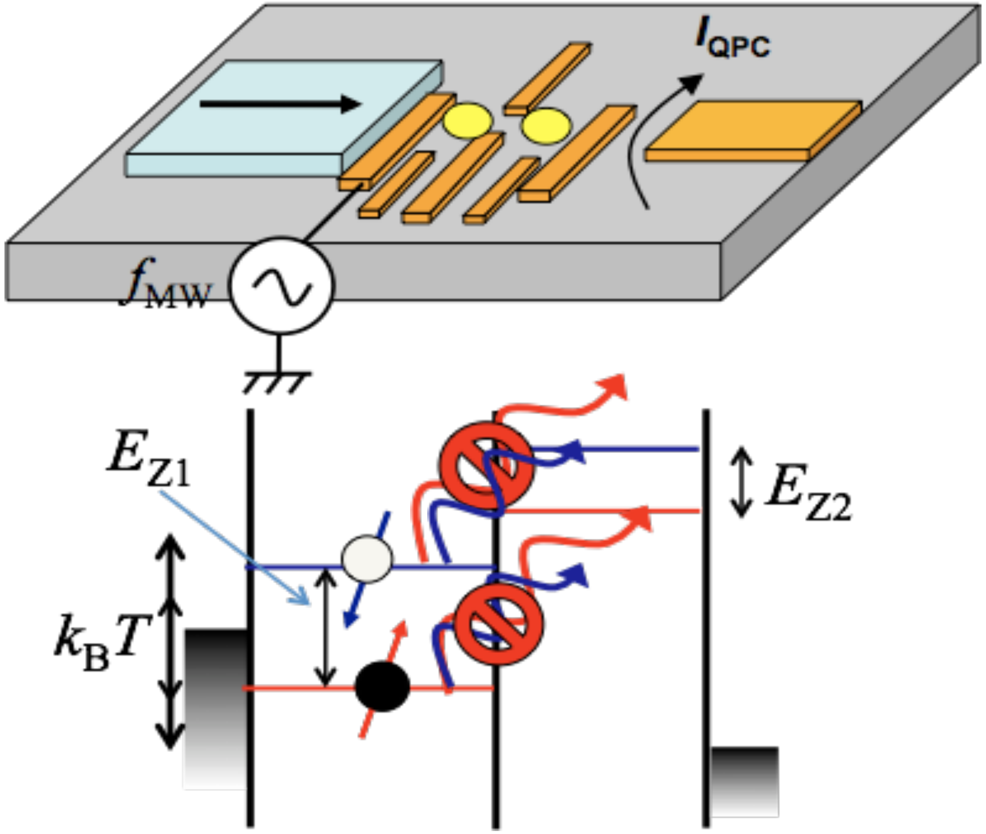
(1,0)←(2,0)←(1,1)←(1,0)   (1,0)←(2,0)←✗(1,1)←(1,0)

Signal only discriminates spin singlet/triplet or just spin flip!

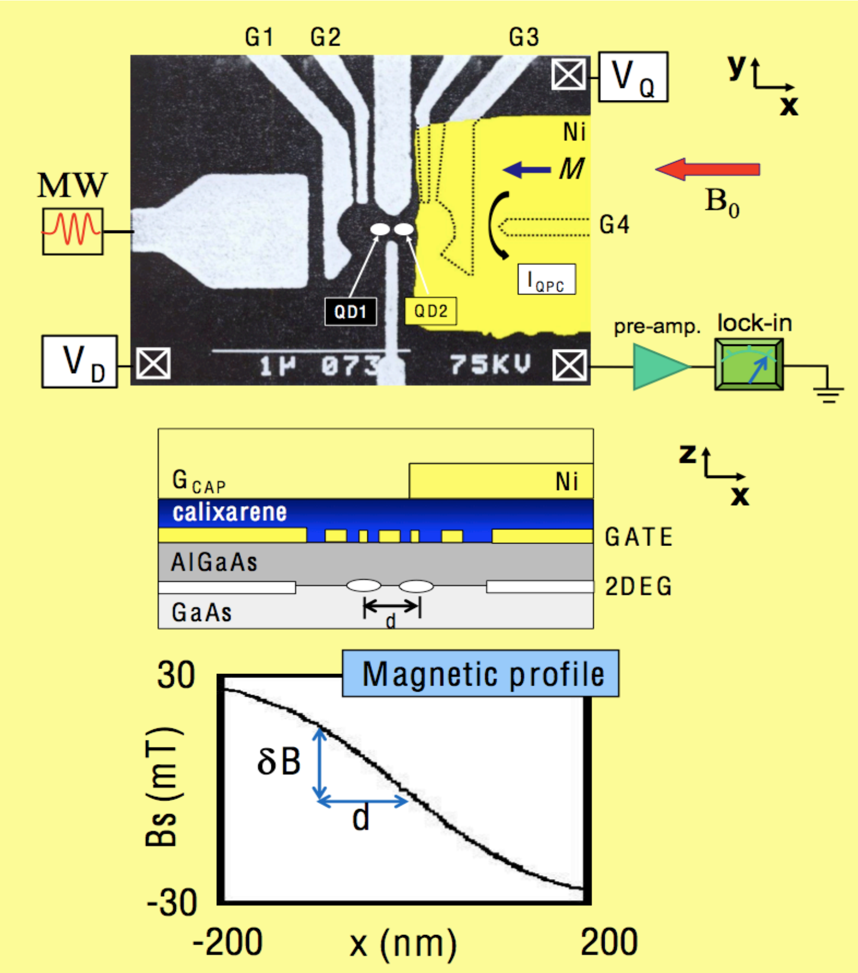
*K. Ono, et al., Science **297**, 1313 (2002).*

New spin detection scheme

Non-destructive both spin readout with micro-magnet and microwave

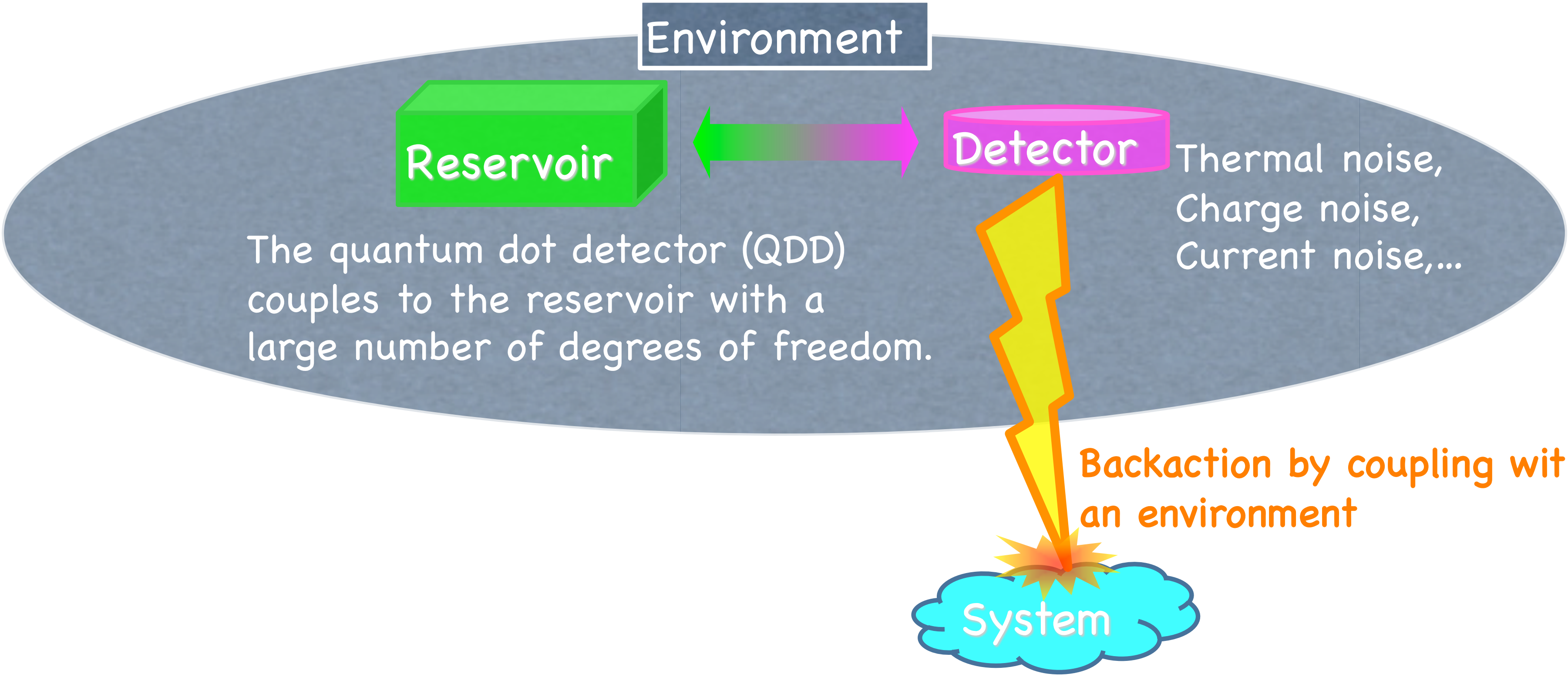


Y. –S. Shin, et al., Phys. Rev. Lett. 104, 046802 (2010).



δB = 17 mT for d = 100 nm

Backaction dephasing by a quantum dot detector



Thermal noise,
Charge noise,
Current noise,...

The quantum dot detector (QDD) couples to the reservoir with a large number of degrees of freedom.

Backaction by coupling with an environment

- Capacitive coupling to neighboring QDs in multi-qubit systems
- Spin-charge conversion in spin qubits

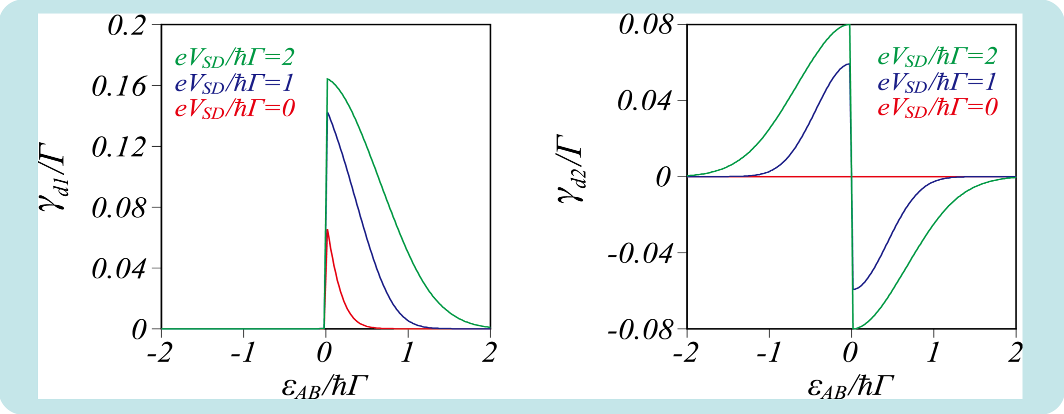
Clarify the mechanism of the backaction dephasing induced by various in QDD charge detector.

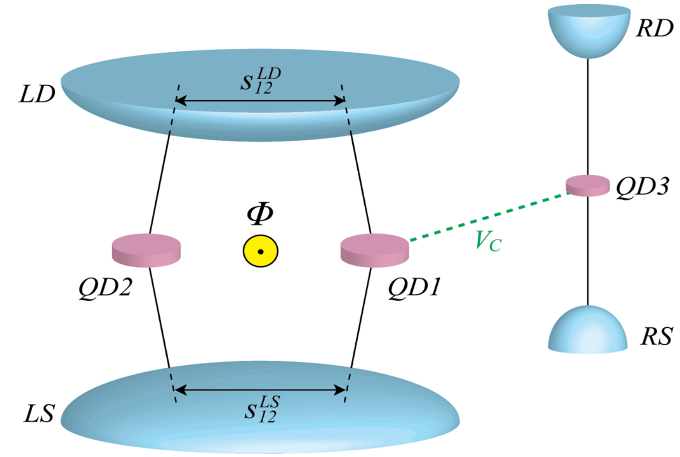
Origin of backaction dephasing

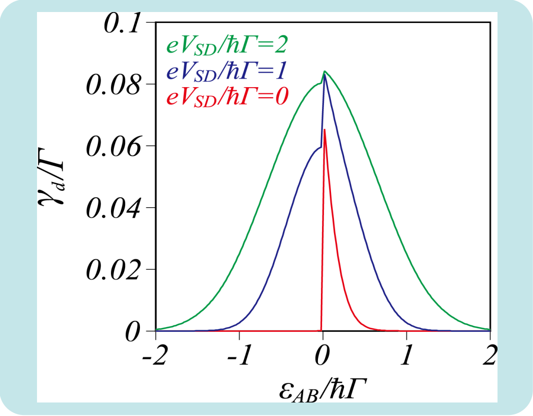
$$\gamma_d = \boxed{\left(\frac{V_C}{\hbar}\right)^2 \int \frac{dE_1}{\hbar}\rho_{11}(E_1)[1-f_{AB}(E_1)]S_{nn}(-E_1)} + \boxed{\left(\frac{V_C}{\hbar}\right)^2 \int \frac{dE_1}{\hbar}\rho_{11}(E_1)\left[f_{AB}(E_1)-\frac{1}{2}\right]S_{II}^{\mathrm{neq}}(E_1)}$$

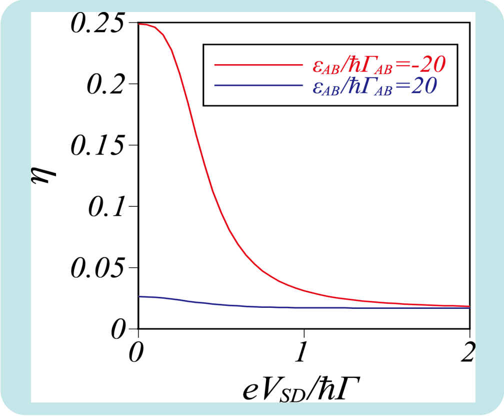
γ_{d1}: Charge noise

γ_{d2}: Nonequilibrium current noise related charge noise









Visibility of AB oscillations in linear conductance

$$\eta \equiv \frac{G_{AB}^{\max} - G_{AB}^{\min}}{G_{AB}^{\max} + G_{AB}^{\min}}$$

T. Kubo, Poster TODAY

Coherent control of spins

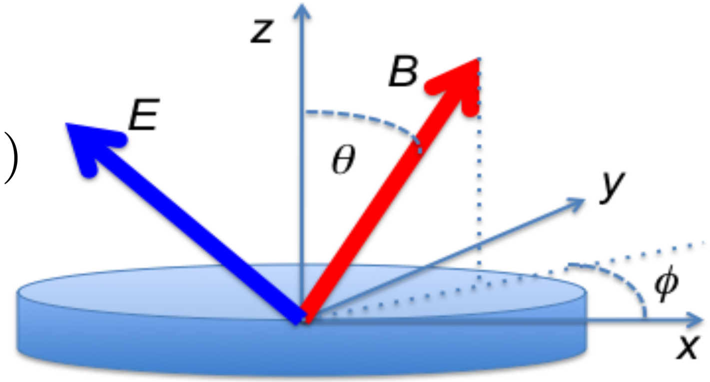
Measurement of spins

New gear : spin-orbit interaction

Unpleasant neighbors : nuclear spins

Topics

SOI in a parabolic quantum dot



External uniform magnetic field

$$\vec{B} = B(\cos\phi\sin\theta, \sin\phi\sin\theta, \cos\theta)$$

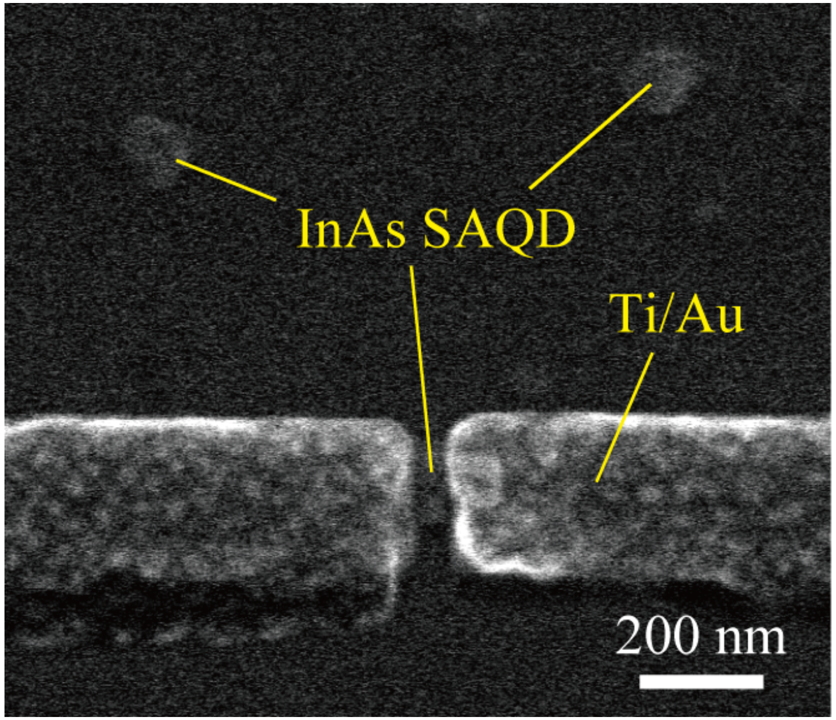
Rashba spin-orbit interaction (SOI) Hamiltonian

$$\mathcal{H}_{SOI} = \lambda_R \vec{E}\times\vec{p}\cdot\vec{\sigma}$$

Effective field is assumed to
normal to plane

$$\vec{E} = (0, 0, E_z)$$

- Self-organized InAs quantum dot on GaAs contacted laterally
- Large (anisotropic) g-factor ~ 5
- Quasi-two dimensional anisotropic confinement potential



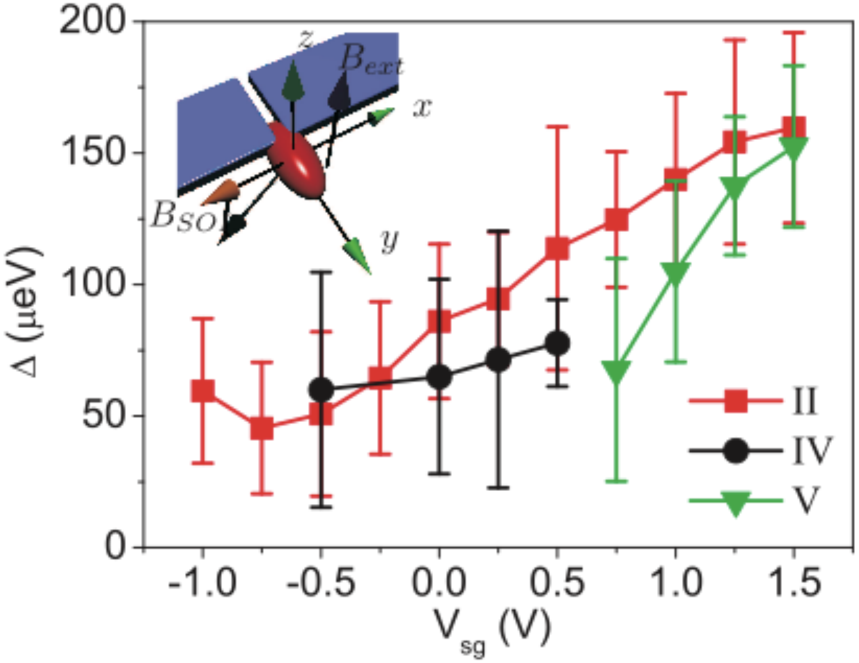
S. Takahashi, et al., Phys. Rev. Lett. ***104****, 246801 (2010).*

Control of SOI by a side gate

Anti-crossing of two two-electron levels

$$\begin{aligned}\Delta_{SO} &= |\langle 1s\downarrow|\hat{H}_{SO}|2p_-\uparrow\rangle| \\ &= \lambda_R E_z|(Q_{x12}\sin\phi - Q_{y12}\cos\phi)\cos\theta \\ &\quad -i(Q_{x12}\cos\phi + Q_{y12}\sin\phi)|, \\ \langle 1s|\hat{p}_\nu|2p_-\rangle &\equiv \frac{1}{i}Q_{\nu 12}\end{aligned}$$

- SOI and g-factor can be controlled with side gate

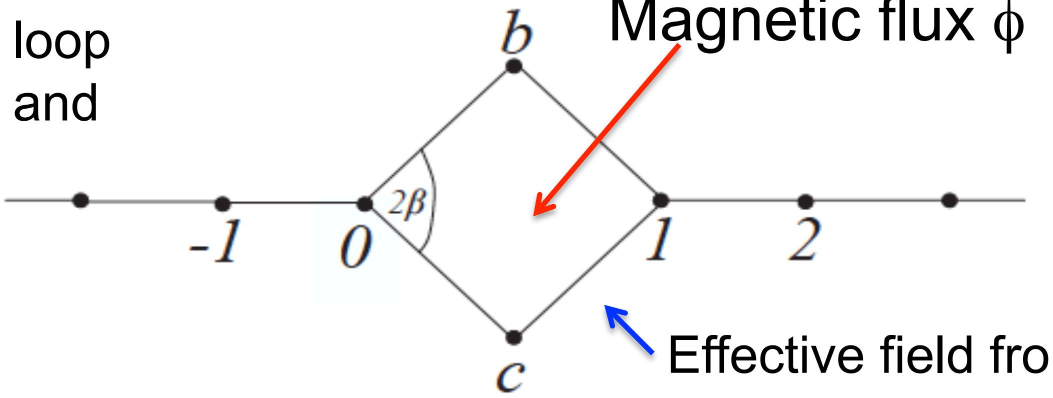


Y. Kanai, et al., Nature Nanotechnology 6 511, (2011).
R. Deacon et al., Phys. Rev. B 84, 041302(R) (2011).

Fig. The strength of SOI, Δ, controlled by a side gate. Inset shows the InAs quantum dot (red) sandwiched with electrodes.

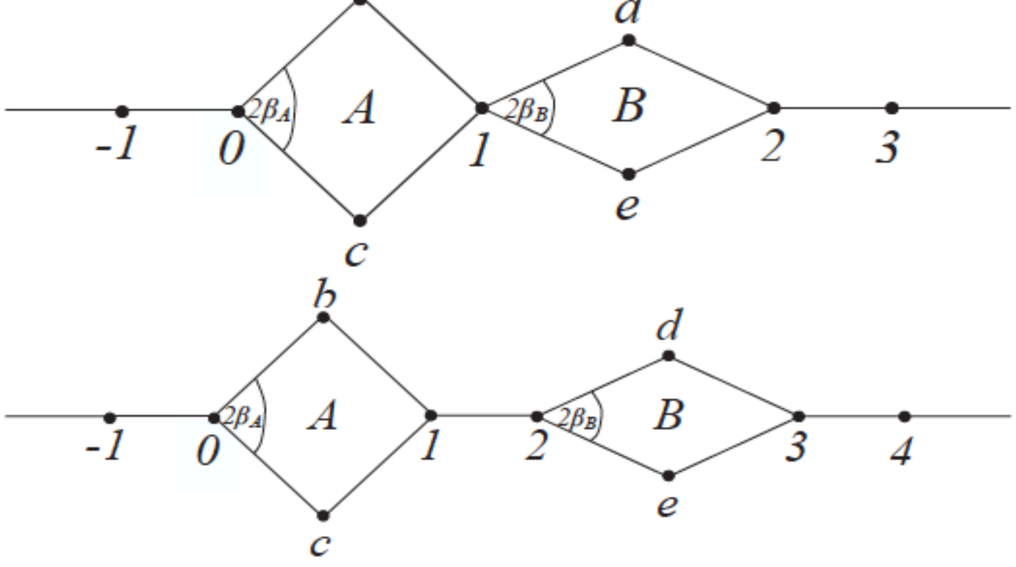
Aharonov-Bohm-Casher interferometer

Controlled spin-orbit interaction and magnetic flux in a diamond-like loop
- works as an emitter, rotator, and detector of flying spin qubits



Magnetic flux ϕ

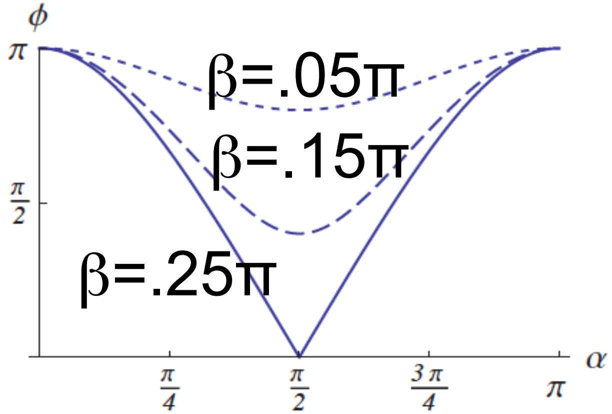
Effective field from Rashba spin-orbit interaction, α



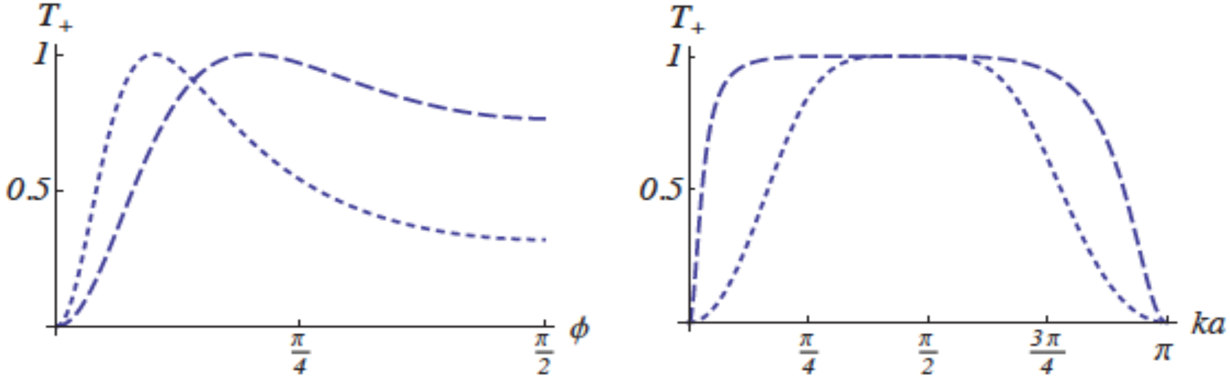
Coupled diamonds offer more flexible, and ideal realization of Datta-Das spin transistor

A. Aharony, Y. Tokura, Guy Z. Cohen, O. Entin-Wohlman, and S. Katsumoto, Phys. Rev. B 84, 035323 (2011).

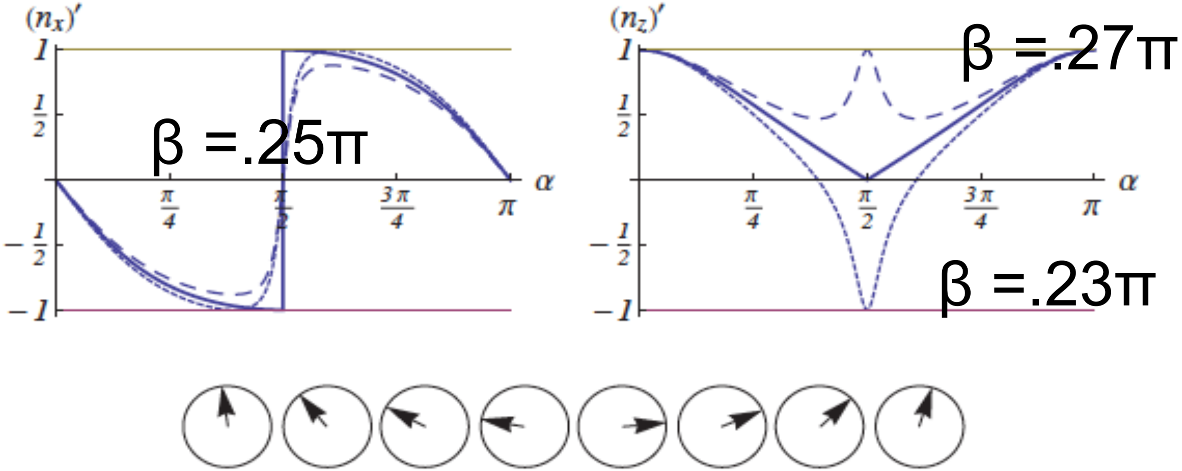
Perfect spin filter



Condition of full filtering between the AB flux ϕ and the Rashba SOI strength α



Transmission of the polarized electrons, T+. LHS: in the band center (ε = 0) versus the AB flux ϕ. RHS: versus ka.



Outgoing spin components as a function of the Rashba SOI strength α. The lower panel shows the actual spin directions in the xz-plane for β =π/4, as a increases from zero to π (left to right).

Coherent control of spins

Measurement of spins

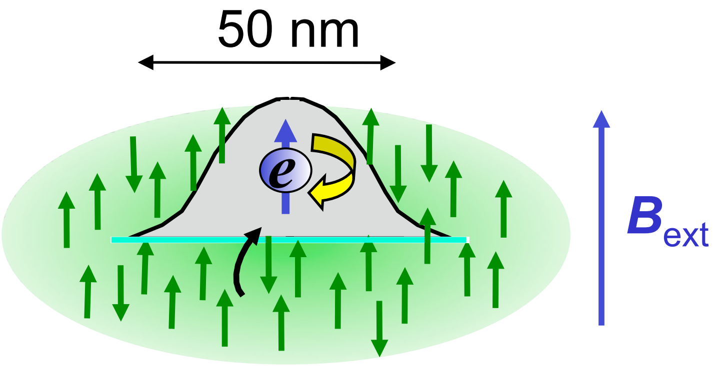
New gear : spin-orbit interaction

Unpleasant neighbors : nuclear spins

Topics

Nuclear Spin Bath Problem

Contact interaction to nuclei: ^{69}Ga, ^{71}Ga, ^{75}As (I=3/2) in GaAs QD



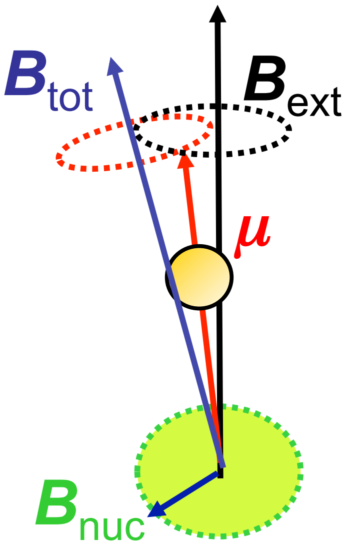
Flip-flop

$$H_{HF} = A\left|\phi(x)\right|^2 \left(\frac{I_+ S_- + I_- S_+}{2} + I_Z S_Z \right)$$

Nuclear spins are dynamically polarized because of the long lifetime (~min.).

N=10^5 to 10^6 nuclei in GaAs QD

Overhauser shift (ΔE_{Zeeman})
…Shift of ESR condition



Inhomogeneous broadening of ESR condition

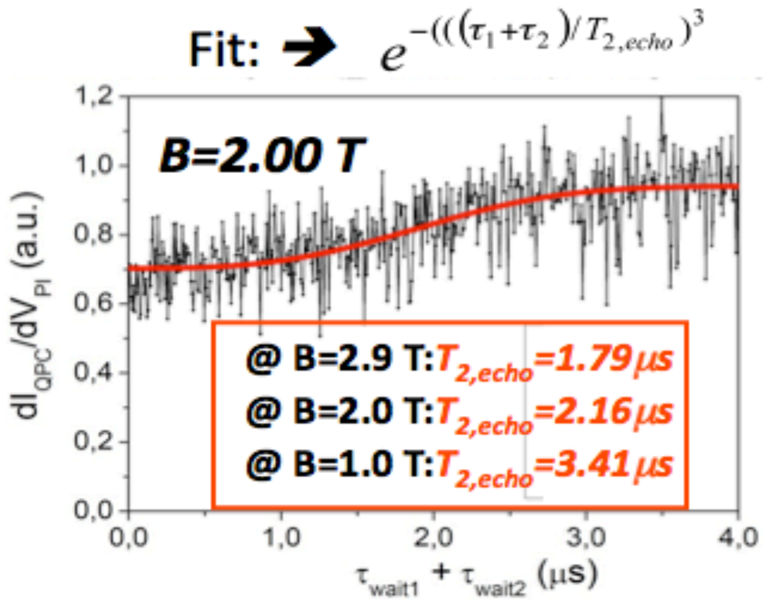
Phase fluctuation (or dephasing) in the ensemble measurement → T_2*=10 to 30 ns

Decoherence mechanism by electron spin mediated spin diffusion T_2~> 1μs

L. Cywinski, et al., Phys. Rev. B 79, 245314 (2009).
W. A. Coish, et al., Phys. Rev. B 81, 165316 (2010).

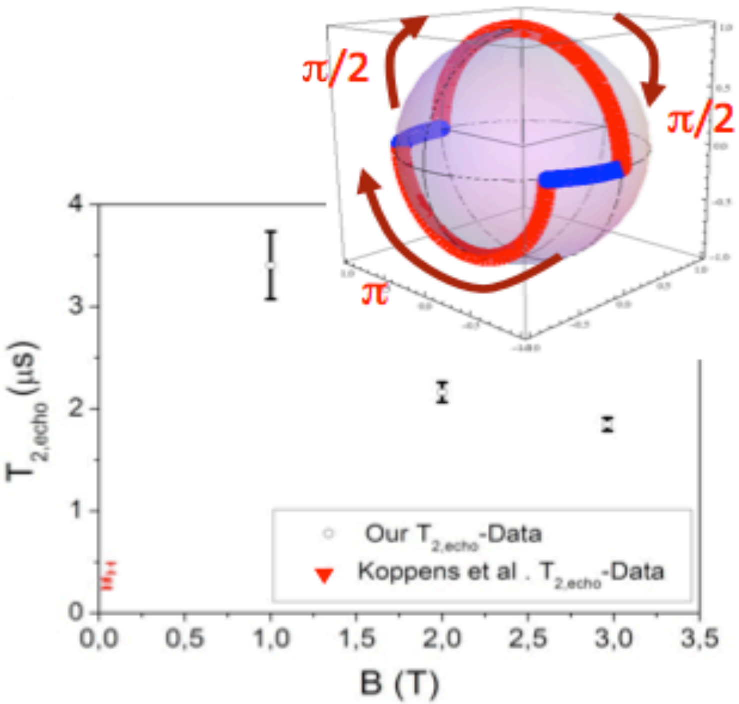
Coherence time of spin qubits

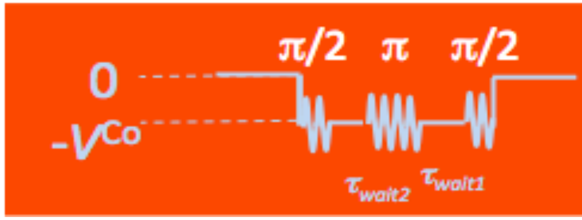
- Hyperfine coupling with the nuclear spins is the dominant factor



Fit: → $e^{-(((\tau_1+\tau_2)/T_{2,echo})^3}$

@ B=2.9 T: $T_{2,echo}$=1.79 µs
@ B=2.0 T: $T_{2,echo}$=2.16 µs
@ B=1.0 T: $T_{2,echo}$=3.41 µs





τ_{REP} & Burst Time τ_1, τ_2 = const & change

$\tau_{wait1} + \tau_{wait2}$

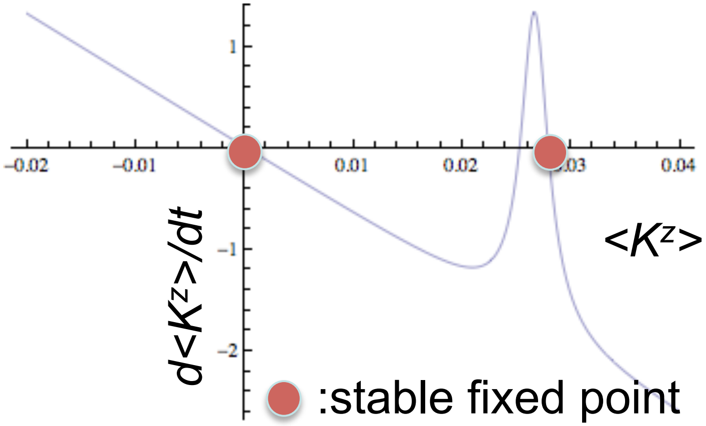
R. Brunner, et al., to be submitted.

Dynamical nuclear spin pumping: DNP

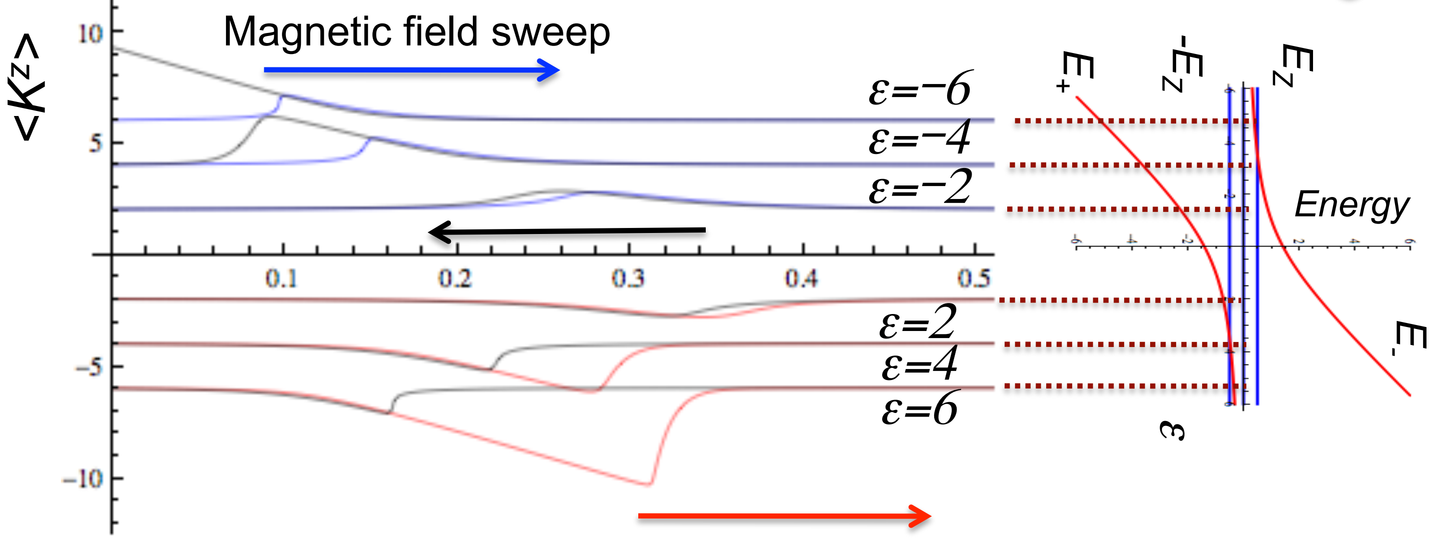
Instead of conventional Fermi's golden rule, we calculate DNP rate using new scheme by electron spin response and correlation function.

Danon and Nazarov, Phys. Rev. B 83, 245306 (2011).

$$\frac{d\langle K^z\rangle}{dt} = \frac{P_{\pm peak}}{1+[C_\pm(K_{0\pm}-\langle K^z\rangle)]^2} - \frac{\langle K^z\rangle}{\tau_N}$$



● :stable fixed point



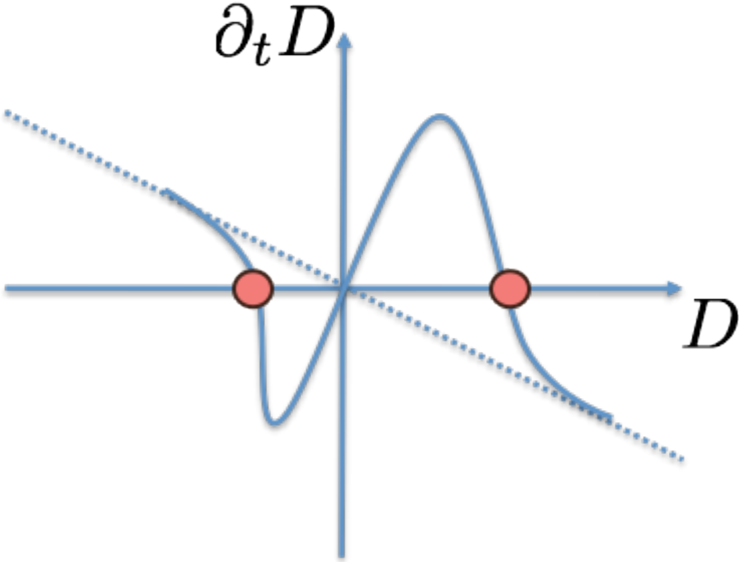
Hysteresis loops of nuclear spin polarization

Spontaneous symmetry breaking

We found the condition when the difference of the nuclear spin polarizations between the two QDs becomes finite.

$$D \equiv \langle K_L^z \rangle - \langle K_R^z \rangle \neq 0 \qquad \alpha\gamma \sim -D$$

$$\partial_t D = \frac{\rho_0}{16} A_{nR}^2 (-2\alpha\gamma) \frac{\Gamma}{(E_z - A\langle K^{ext} \rangle + E_{S_+})^2 + (\frac{\Gamma}{2})^2} - \frac{D}{\tau_N}$$



Note:

- The physical origin of τ_N: diffusion
- Statistical fluctuation about the average value
- Limit cycle around unstable fixed point
- Quantum entanglement, interaction with the environment

Coherent control of spins

Measurement of spins

New gear : spin-orbit interaction

Unpleasant neighbors : nuclear spins

Topics

LETTER

doi:10.1038/nature10463

Efficient quantum computing using coherent photon conversion

Nature 478, 360 (2011)

N. K. Langford[1,2,3], S. Ramelow[1,2], R. Prevedel[1,4], W. J. Munro[5,6], G. J. Milburn[7,1] & A. Zeilinger[1,2]

The story so far ...

- Efficient linear optics QC: Knill, Laflamme & Milburn, Nature **409**, 46 (2001)
- Optical cluster-state QC: Nielsen, PRL **93**, 040503 (2004)
- …

What we have now…

- One process to provide a whole toolbox of components for “QCMC” applications
  e.g. ⇒ addresses all DiVincenzo Criteria
  ⇒ high-quality, heralded single-photon sources
  ⇒ Fock-state filter

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Parametric Processes

$$H_{\text{dc}} \sim \hbar\gamma\, a b^\dagger c^\dagger + \hbar\gamma^*\, a^\dagger b c$$

Standard Spontaneous Parametric Down-conversion (SPDC)

$$\approx |\alpha\rangle_a$$

(*non-depleted pump*)

photon pairs

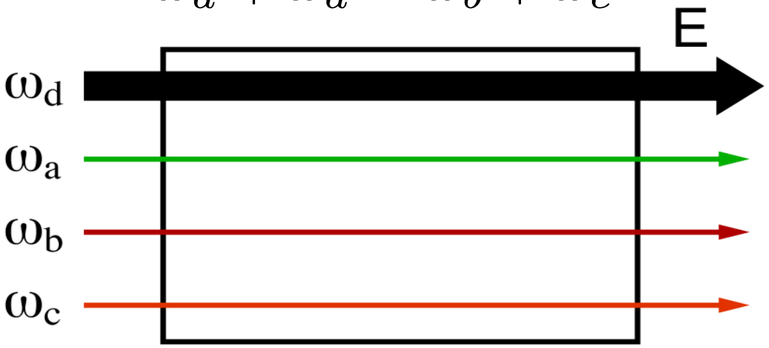
$$\Big\}|00\rangle + (\gamma\alpha L)\,|11\rangle \longleftarrow p_{\text{best}} \sim 10^{-6}$$

$$+ (\gamma\alpha L)^2\,|22\rangle + \ldots$$

higher-order terms

Stronger $\chi^{(2)}$ nonlinearities via pumped $\chi^{(3)}$ (4-wave mixing) processes

$$\omega_a + \omega_d = \omega_b + \omega_c$$

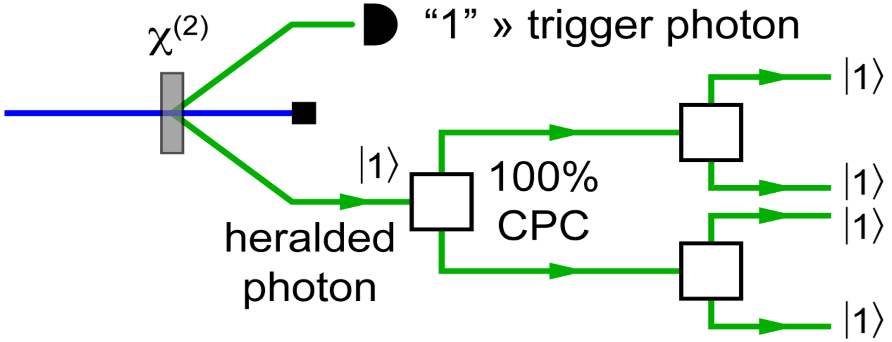


$$\gamma \propto E\chi^{(3)}$$

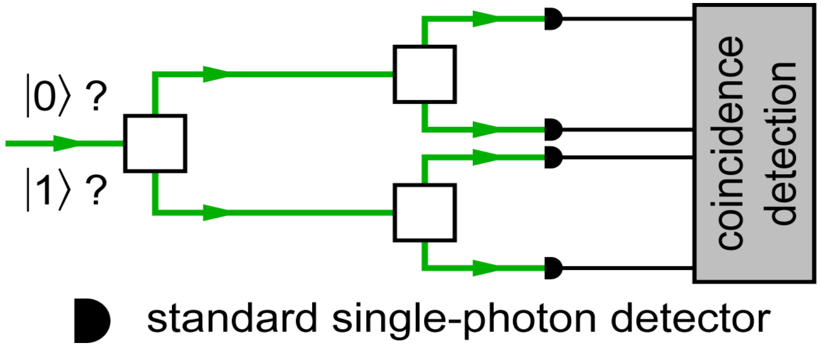
- $\chi^{(3)}$ nonlinearities < $\chi^{(2)}$
- nonlinearity can be **enhanced** (and tuned) by a pump laser
- near-degenerate frequencies possible (e.g., all in telecom band)
- all materials possess $\chi^{(3)}$ nonlinearity

Applications

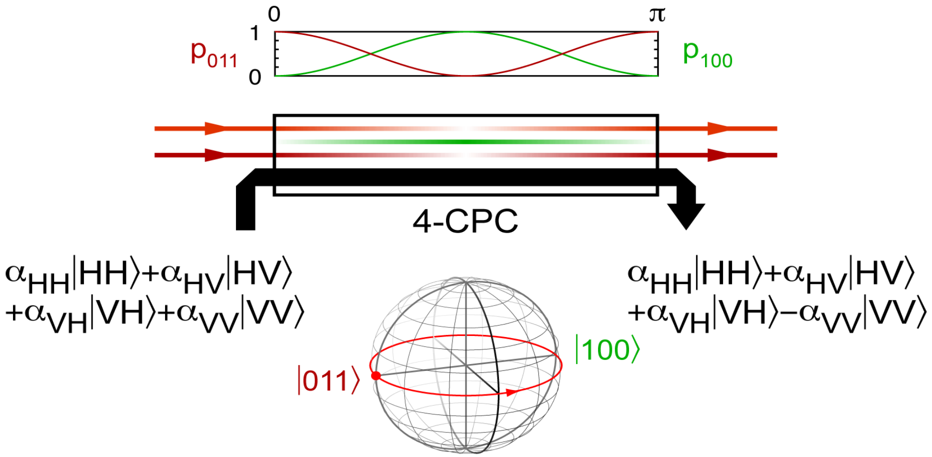
Solving the DiVincenzo Criteria - scaleable photon QC with CPC



initialised multiphoton sources



high-efficiency measurement

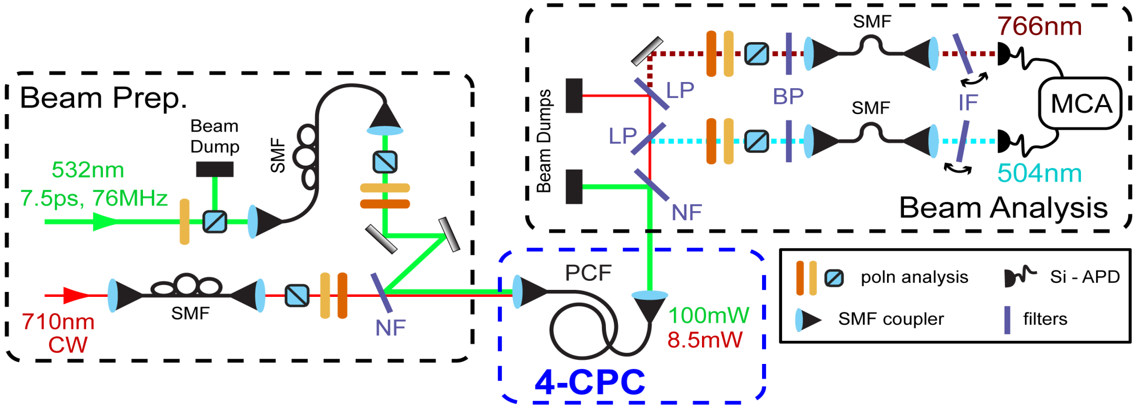


two-qubit entangling (CZ) gates

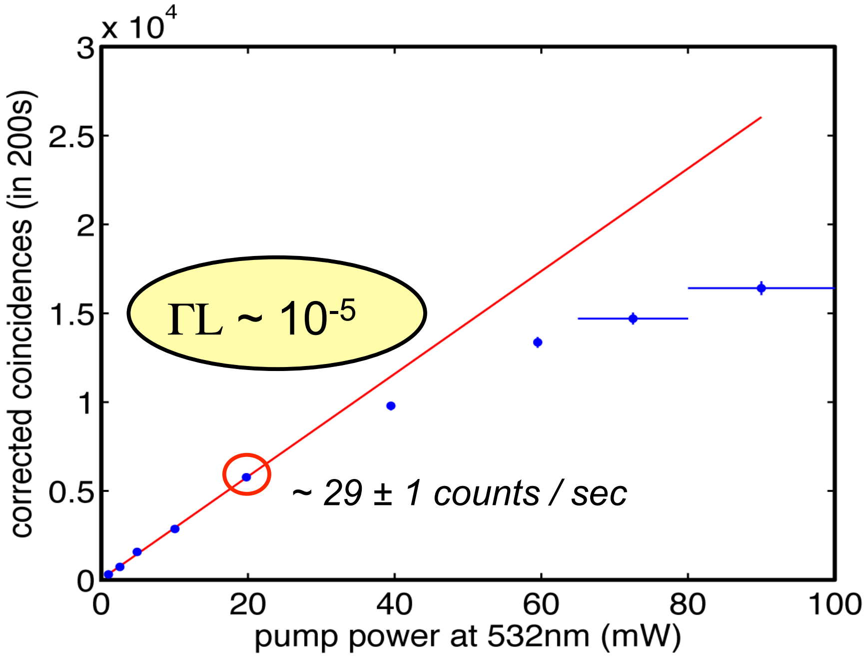
Other Applications

- heralded entangled states (Bell pairs, GHZ states)
- error correction protocols
- single-photon sources
- n-photon Fock filters
- better down-conversion
- switchable gates for QC circuits
- …

Very early results



- $\Gamma L \sim 10^{-4}$ for 1W 532nm
- $\Gamma L \sim \pi/2$ for 100%
- $\chi^{(3)}$ (chalcogenide)
  $\sim 10^3\ \chi^{(3)}$ (silica)
  $\Rightarrow 10^3$ improvement



•Measured efficiency with “off-the-shelf” components shows we’re within reach of deterministic regime with PCFs (using chalcogenides)

Future work

•experiment with chalcogenide PCFs

Future directions

Spin measurement

Non-demolition measurement and characterize the back-action

Amicable relationship to nuclei

Quantum nature of ensemble nuclear spins through DNP
Explore to suppress the fluctuation of nuclear spins

Small scale quantum circuits
Propose faster operation scheme and evaluate its fidelity

New directions
Explore possible quantum interfaces: local spin/flying qubits (Q-bus)