Two-Qubit Gate of Combined Single-Spin Rotation and Interdot Spin Exchange in a Double Quantum Dot

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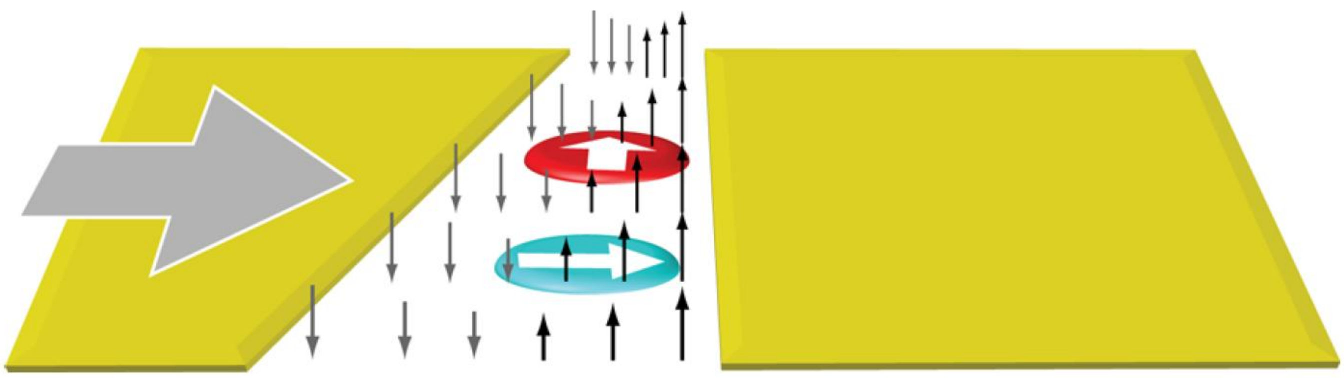


Outline

Introduction

Electron-spin resonance (ESR) and interdot exchange

Experimental setup

→ Single-spin rotation + swap gate

Control of entanglement

Conclusions

Introduction

EDSR

Single-qubit rotations + CNOT gate

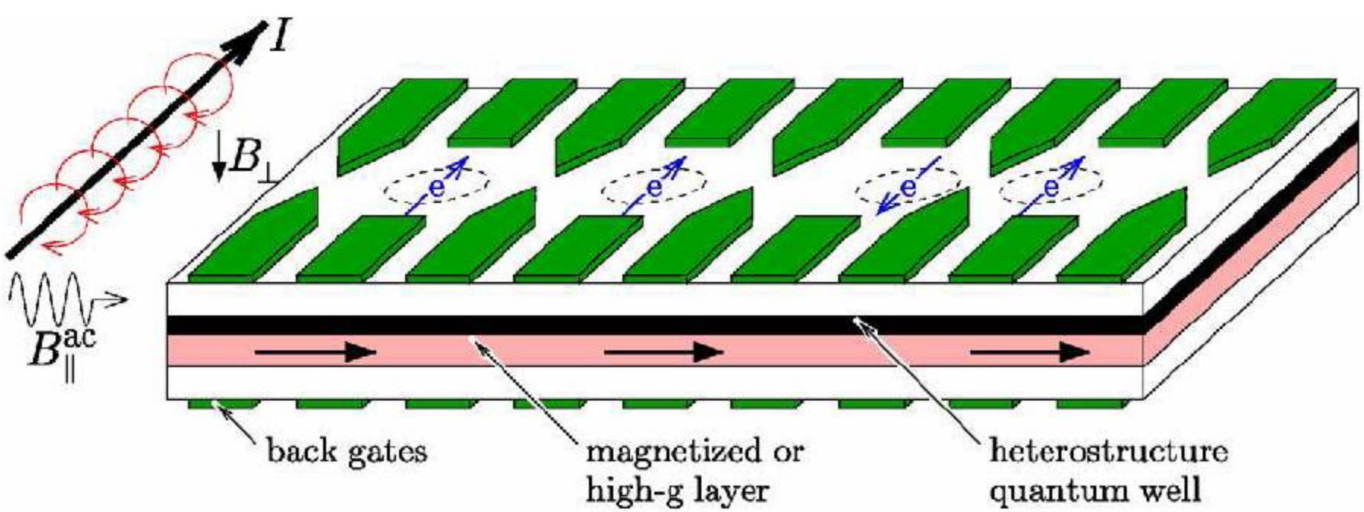
➡ **Universal set of gates**

swap-gate

$$U_{\rm CNOT} = e^{i\pi S_L^z} U_s(\tau_s)^{-1/2} e^{-i(\pi/2)S_L^z} U_s(\tau_s) e^{i(\pi/2)S_L^z} U_s(\tau_s)^{1/2}$$

interdot spin exchange

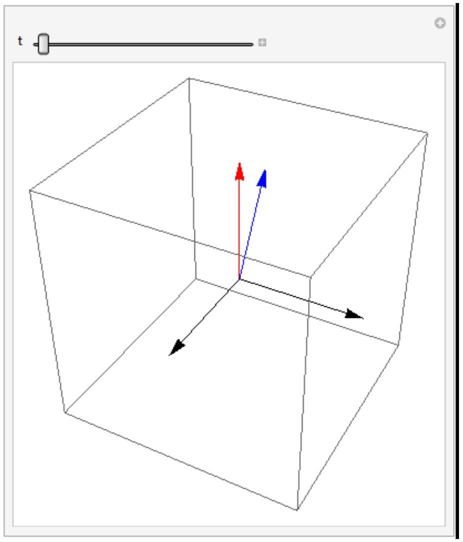
$\sqrt{\rm SWAP}$ ➡ entanglement



Electron spin resonance (ESR) (Single-spin rotation)

Bloch Equation

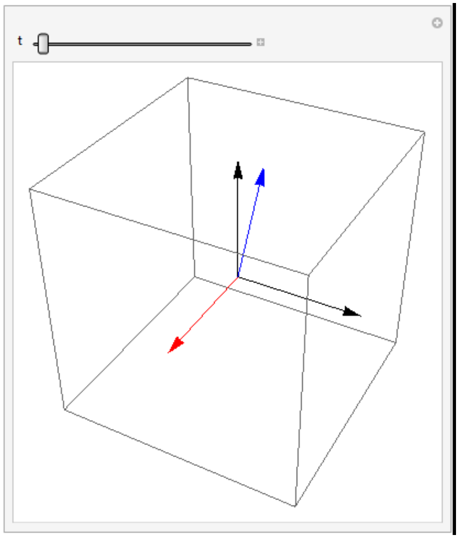
$$\langle \dot{\mathbf{S}} \rangle = \langle \mathbf{S} \rangle \times (\omega_Z \qquad\qquad)$$



$$\omega_Z = g\mu_B \mathbf{B}/\hbar \quad \delta\omega(t) = g\mu_B \widetilde{B}_x \cos(\omega t)/\hbar$$

Spin precesses around axis defined by the direction of **B_z**

Add external oscillating magnetic field **B_x(t)** **perpendicular** to **B_z**



$$\langle \dot{\mathbf{S}} \rangle = \langle \mathbf{S} \rangle \times \left[\omega_Z - \omega \mathbf{e}_z + \frac{g\mu_B}{\hbar} \widetilde{B}_x \mathbf{e}_x \right]$$

$$\omega_{\mathrm{R}} = g\mu_B |B_z| / \hbar$$

Electric control of spins (EDSR)

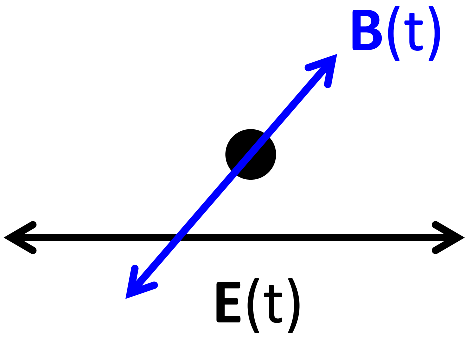
Producing strong oscillating magnetic fields is very challenging

➡ Electric control of spins is highly desirable

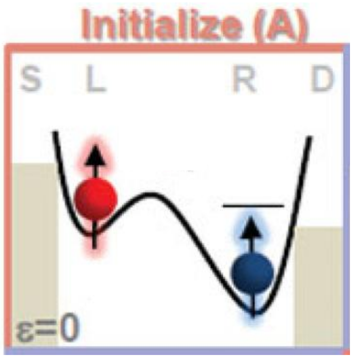
However, electric fields couple to the charge

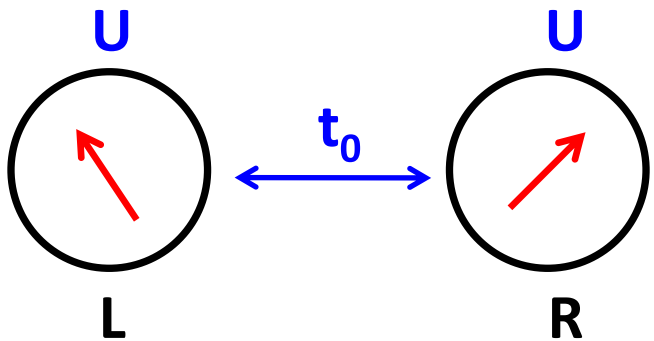
↳ indirect coupling to the spin

- Magnetic field gradient
- Spatially varying **g** tensor
- Spin-orbit coupling



Interdot exchange interaction





U: Coulomb energy

t_0: interdot tunneling
controlled by central gate

$$H_s(t) = J(t)\mathbf{S}_L \cdot \mathbf{S}_R$$

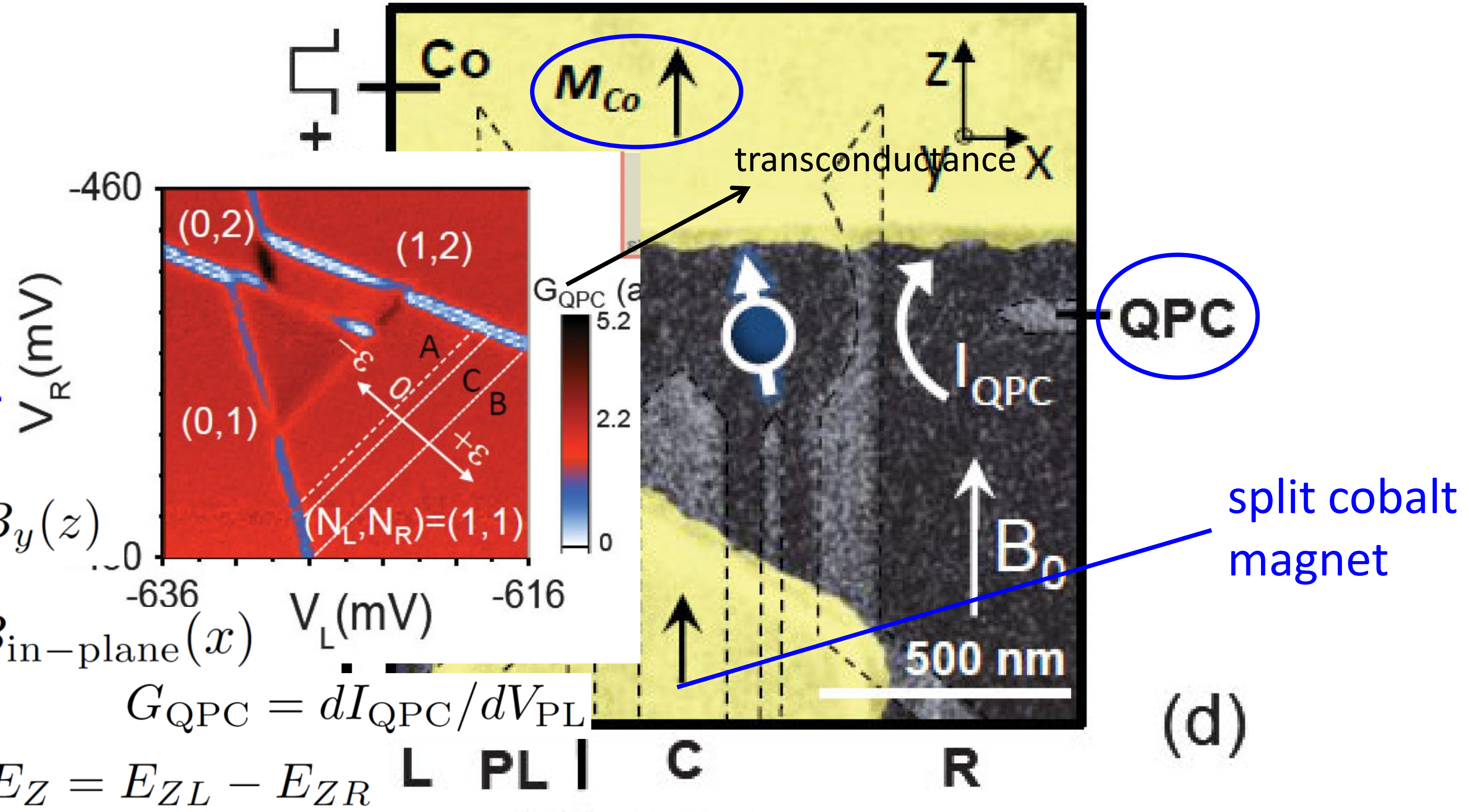
$$J(t) \propto t_0^2(t)/U$$

$$U(t) = e^{-i/\hbar \int_0^t J(t')dt' \mathbf{S}_L \cdot \mathbf{S}_R}$$

$$\boxed{U(\tau_s) \equiv \mathrm{SWAP}}$$

J_0: energy splitting between S(1,1) and T_0(1,1)

Experimental Setup



Ti/

$$B_y(z)$$

$$B_{\mathrm{in-plane}}(x)$$

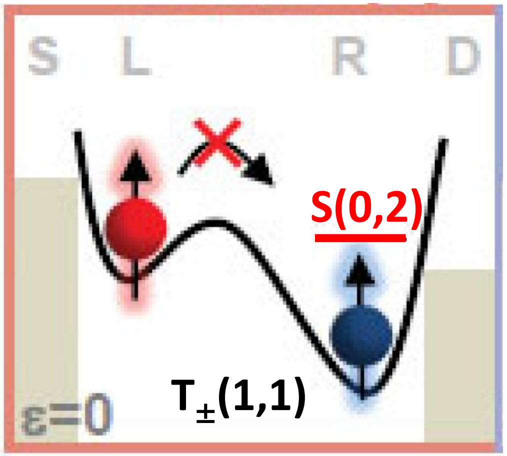
$$G_{\mathrm{QPC}} = dI_{\mathrm{QPC}}/dV_{\mathrm{PL}}$$

$$\delta E_Z = E_{ZL} - E_{ZR}$$

AlGaAs/GaAs heterostructure

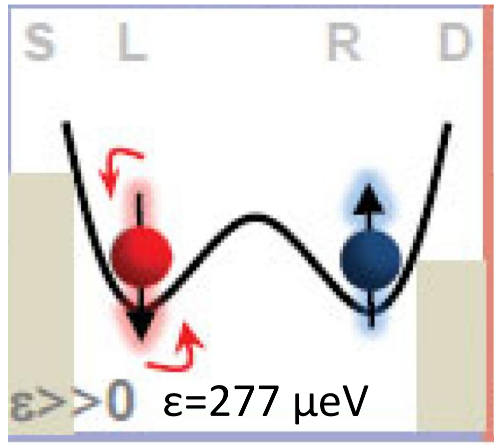
Single-qubit rotations

J_0 finite



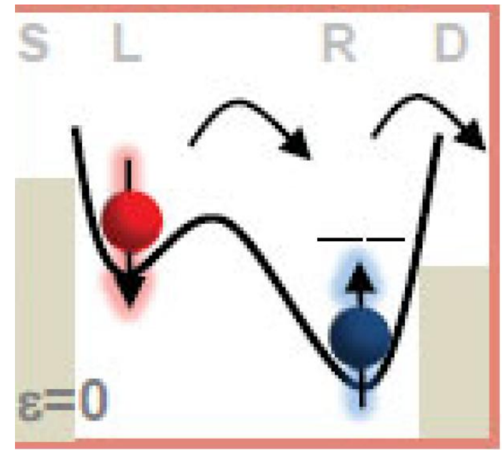
spin-blockade regime

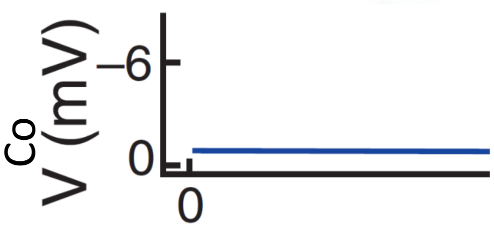
vanishing J_0

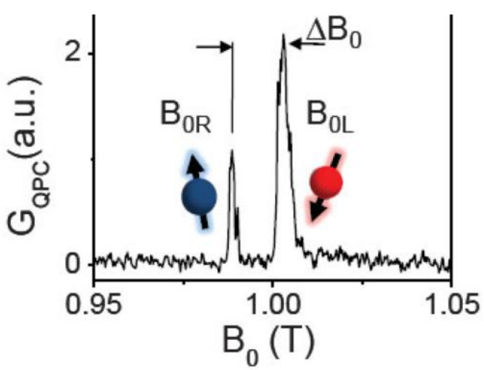


Single-spin rotation
τ_{EDSR}

J_0 finite







$$g = -0.394 \pm 0.001$$

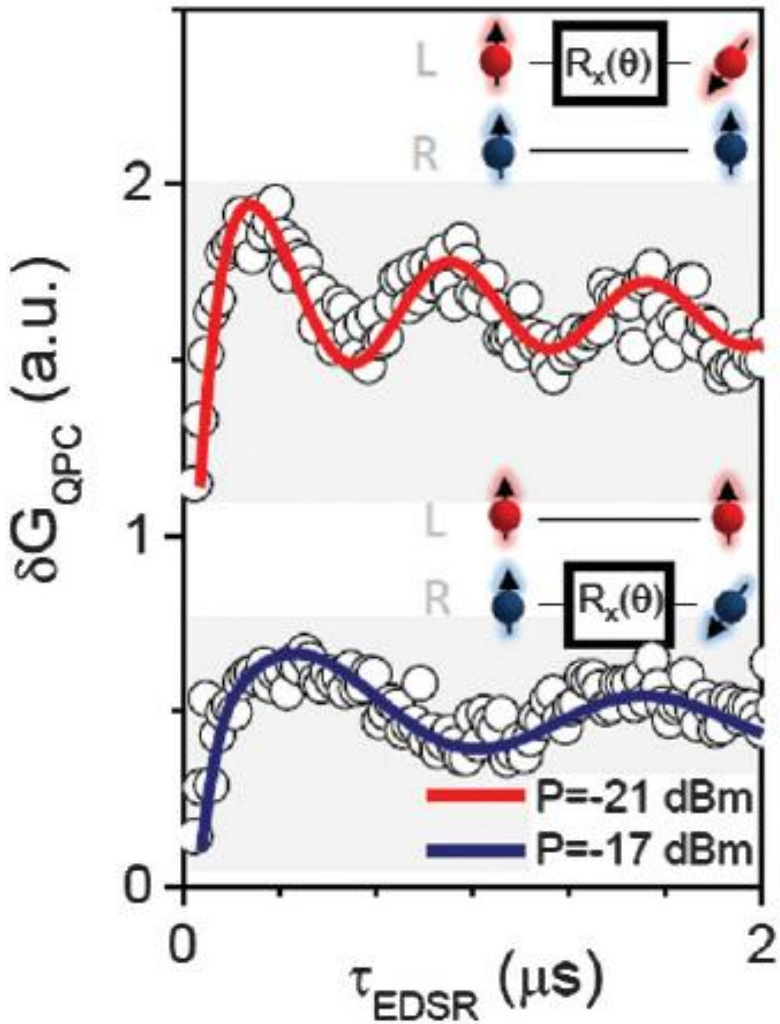
$$f_{\mathrm{ac}} = 5.6\,GHz$$

$$\Delta B_0 = 15 \pm 5\,mT$$

ε:energy splitting between S(0,2) and S(1,1)

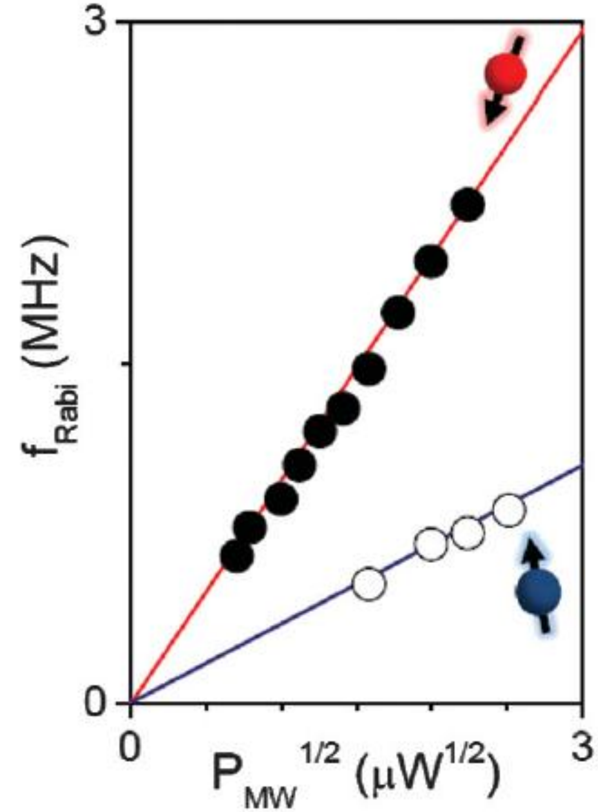
Single-qubit rotations

B_{0L}= 2 T, B_{0R}=1.985 T, f_{ac}=11.1 GHz



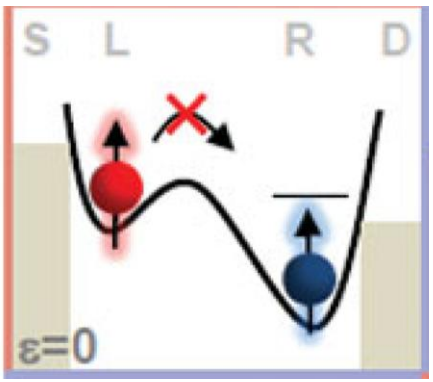
Rabi Oscillations

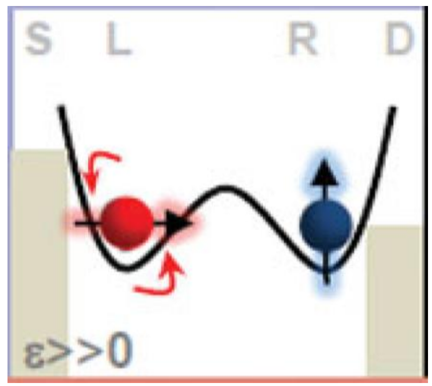
averaged QPC signal is proportional to probability of having antiparallel spins

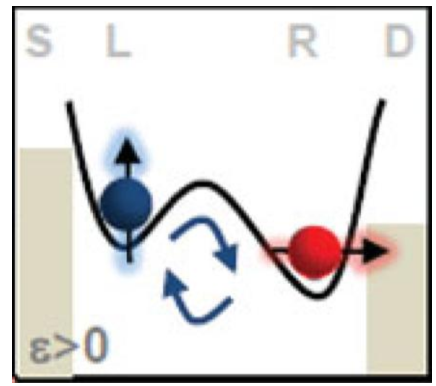


Two-Qubit Gate

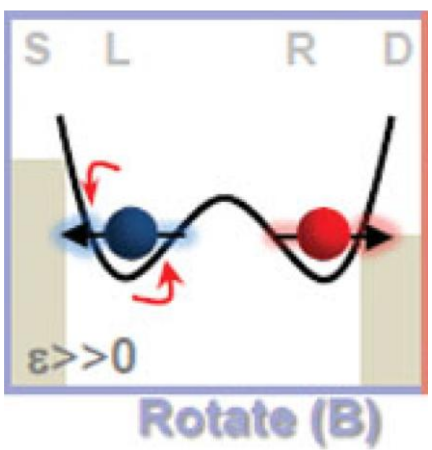
J_0 finite | **vanishing J_0** | **J_0 finite**

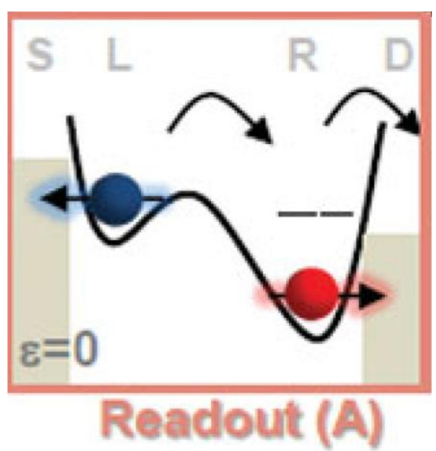






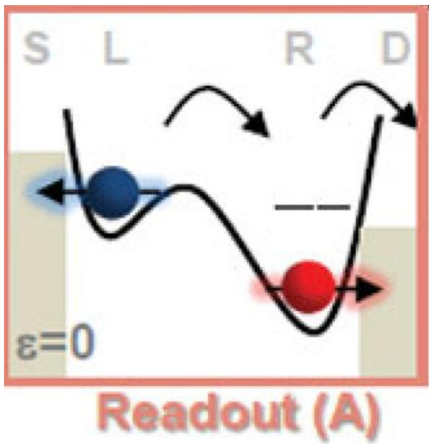
$$T_\pm(1,1) \xrightarrow{3\pi/2} \frac{|\uparrow\rangle \pm i|\downarrow\rangle}{\sqrt{2}} \otimes |\uparrow\rangle \xrightarrow[\tau_{ex}]{\text{SWAP}} |\psi_1\rangle \xrightarrow{\pi/2}$$





$$|\psi_2\rangle$$

Two-Qubit Gate



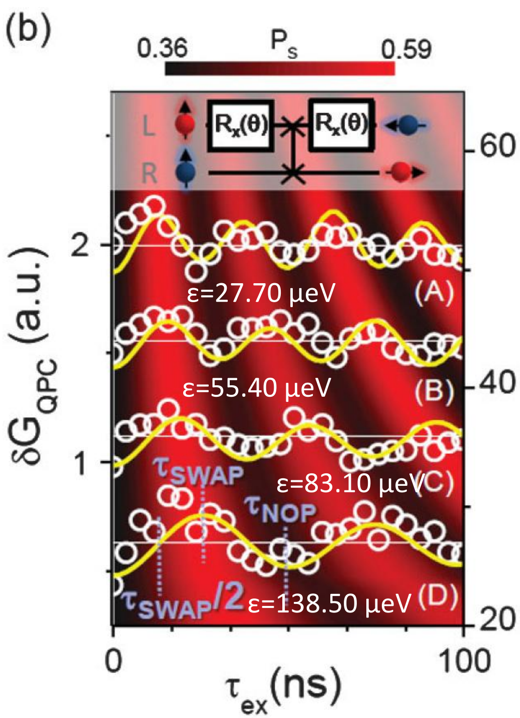
$$\mathrm{SWAP}^{n=0,2,4\dots} \rightarrow |\psi_2\rangle = T_+(1,1)$$

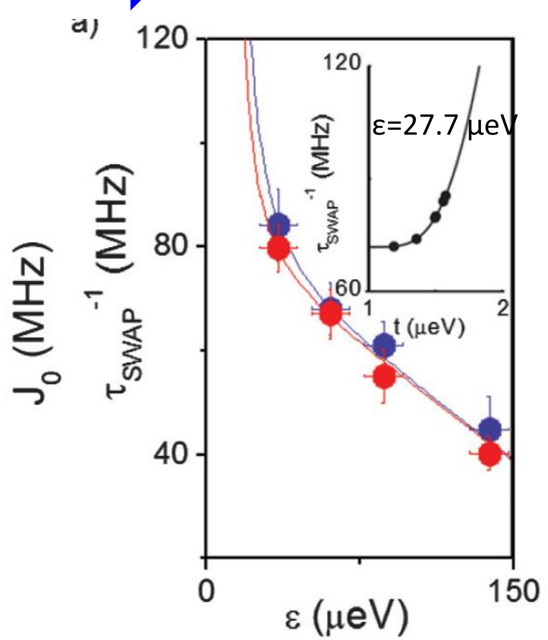
➡ **current is blocked**

$$\mathrm{SWAP}^{n=1,3,5,\dots} \rightarrow |\psi_2\rangle = \frac{1}{2}[T_+(1,1) + T_-(1,1) - \sqrt{2}iS(1,1)]$$

➡ **current flows**

do not contribute to the current flow





t=1.13 μeV t=0.98 μeV

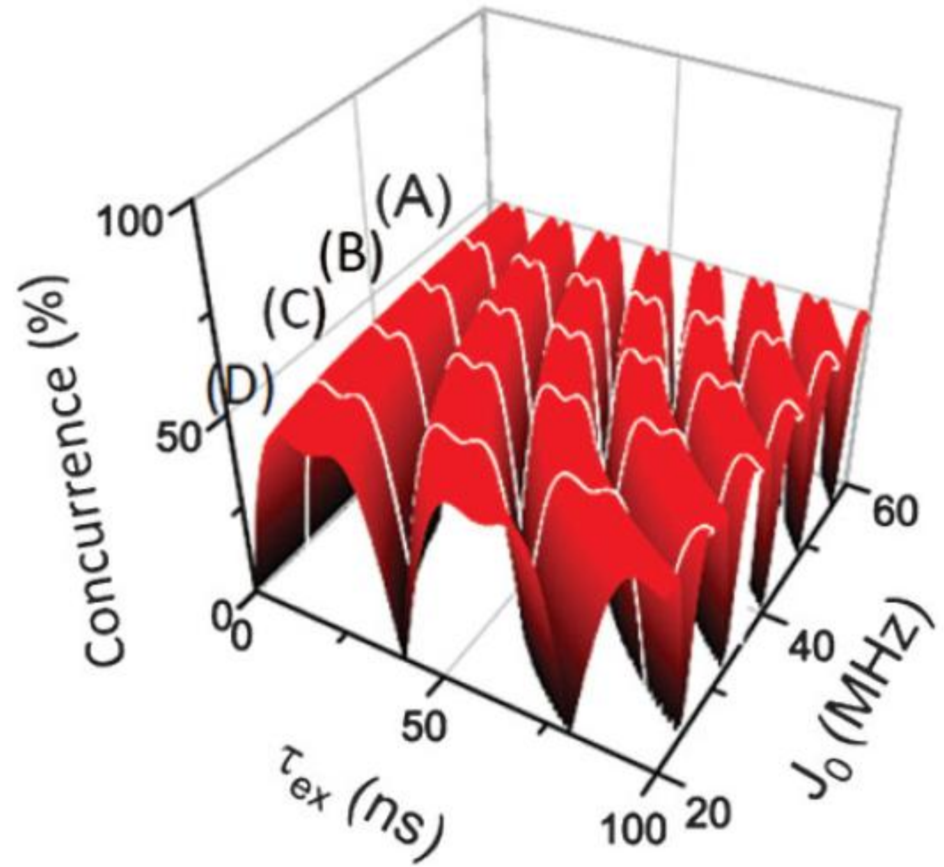
Readout is a direct measurement of entanglement

$$P_S = |\langle S|\psi_2\rangle|^2$$

Entanglement Control

$$C(\rho) = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)$$

$$\sqrt{\sqrt{\rho}\tilde{\rho}\sqrt{\rho}} \quad \tilde{\rho} = (\sigma_y \otimes \sigma_y)\rho^*(\sigma_y \otimes \sigma_y)$$



C=0: uncorrelated

C=1: maximally entangled

$$\Delta \equiv \delta E_Z / J_0 \qquad \alpha \equiv J_0 \tau_{ex}/2$$

$$\mathcal{C} = \frac{|\sin\sqrt{1+\Delta^2}\alpha|}{1+\Delta^2} \times \sqrt{(1+\Delta^2)\cos^2\sqrt{1+\Delta^2}\alpha + \Delta^2\sin^2\sqrt{1+\Delta^2}\alpha}$$

Control of degree of entanglement with τ_{ex}

Conclusions

All-electrical controlled two-qubit gate

→ Single spin rotation + interdot spin exchange

Control of entanglement through operation time τ

Important step in the realization of a quantum computer

Thank you for your attention !