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# Implementing Gates with Quantum Dots

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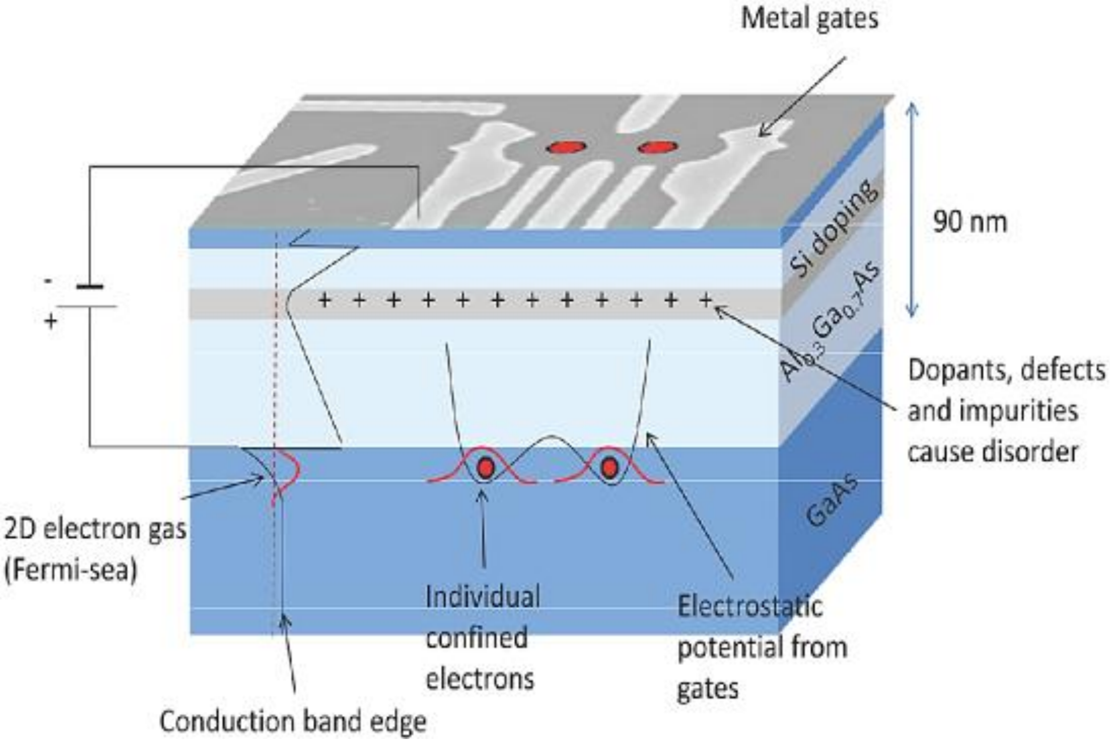
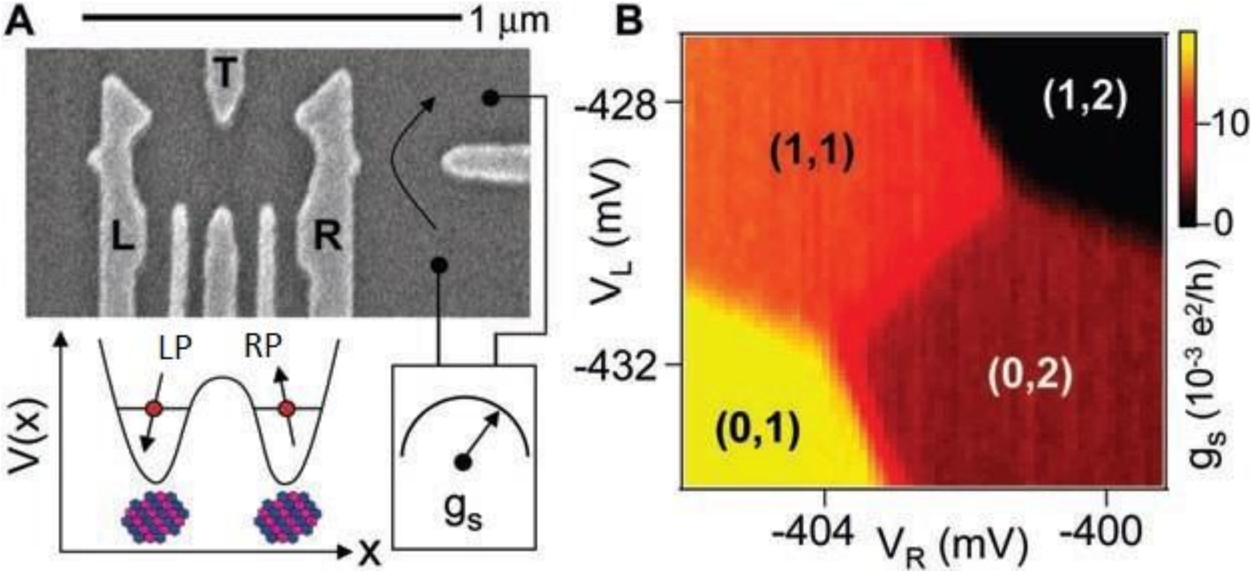
# Double Quantum Dot Architecture

- AlGaAs/GaAs heterostructure
- 2DEG electron gas created, 90 nm below the surface



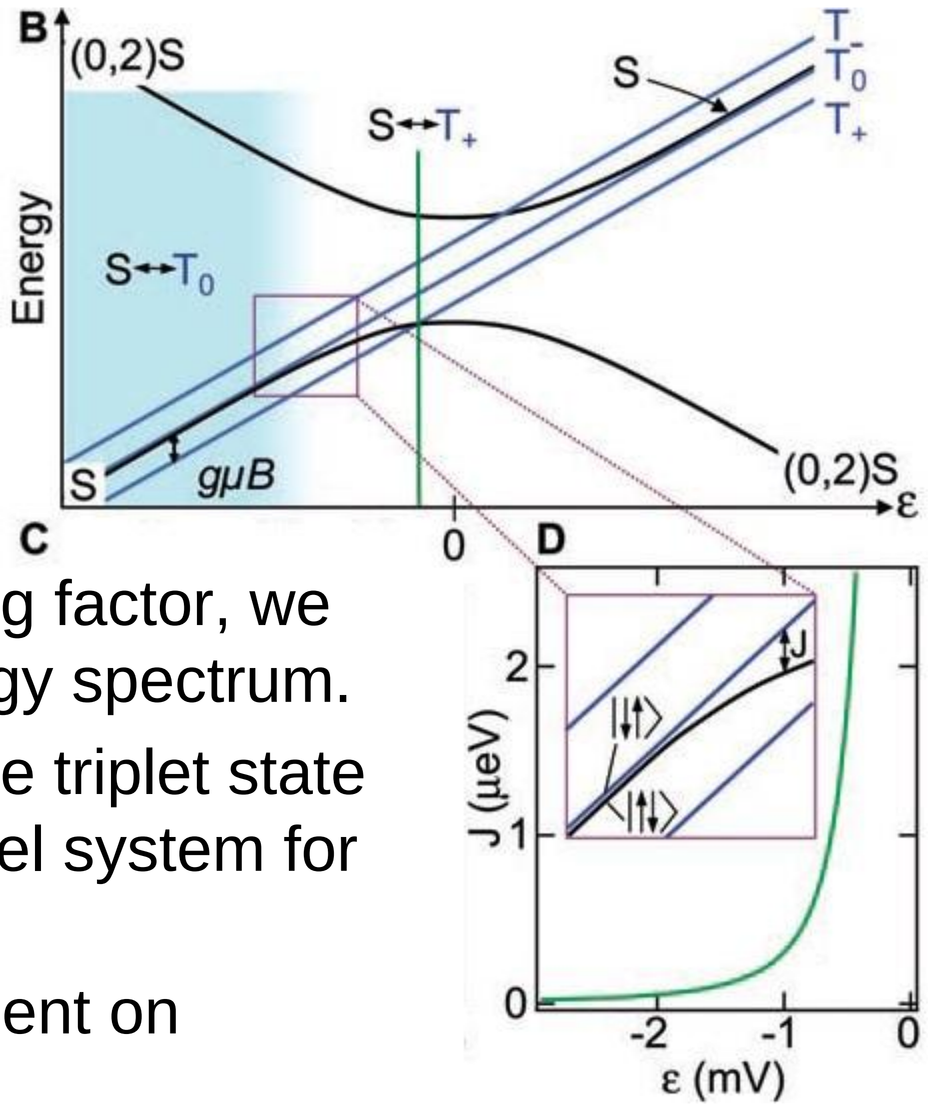
# Creating the Double Dot

- Voltages on terminals (L and R), adjusts tunneling of electrons on and off of the dots
- The T-gate defines the tunneling between the electrons in the two dots
- The plunger voltages vary the well depths
- Detuning factor $\varepsilon = |e|(V_R - V_L)$



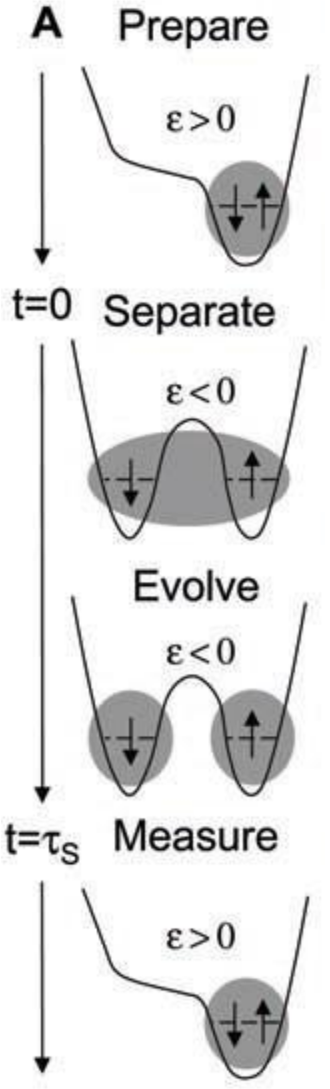
# The S-$T_0$ Qubit

- The energy spectrum of the double dot with Zeeman splitting.
- Insensitive to uniform magnetic fluctuations



- By controlling the detuning factor, we can move along the energy spectrum.
- The singlet S(1,1) and the triplet state $T_0$(1,1) define the two-level system for the qubit.
- Energy splitting $J$ dependent on detuning factor

# Controlling the Qubit



- Prepare the state by biasing two electrons into the right well. Only the S(0,2)-state is energetically available.

- Adiabatically reduce the detuning voltage to bring the double dot to the qubit regime, which initializes the qubit in the S(1,1) state.

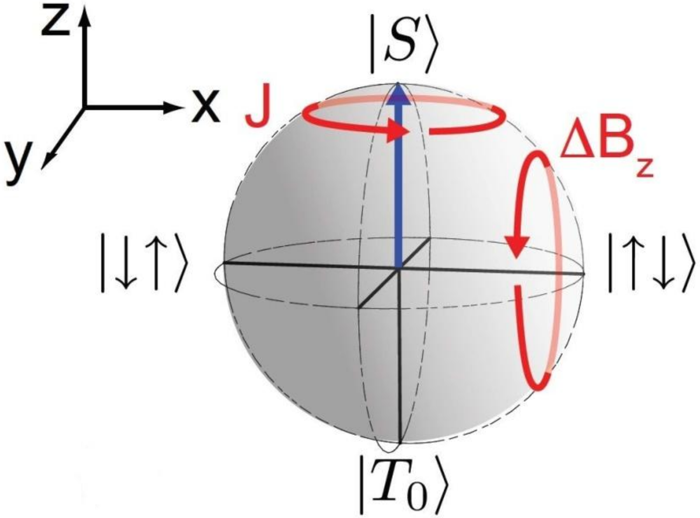
- Perform qubit operation.

- Adiabatically increase the detuning voltage, and measure the qubit state with QPC

# Manipulating The Qubit

- The exchange parameter, $J(\varepsilon)$ defines level splitting between S(1,1) and $T_0$(1,1)
- $\Delta B^Z_{\text{nuc}}$ = random magnetic field gradient created from hyper-fine coupling to nearby nuclei ~1-5 mT
- When J~0 the levels are degenerate and the magnetic field causes rotations in the S,$T_0$ plane
- Pulsing $J(\varepsilon)$ causes rotations around Z-axis

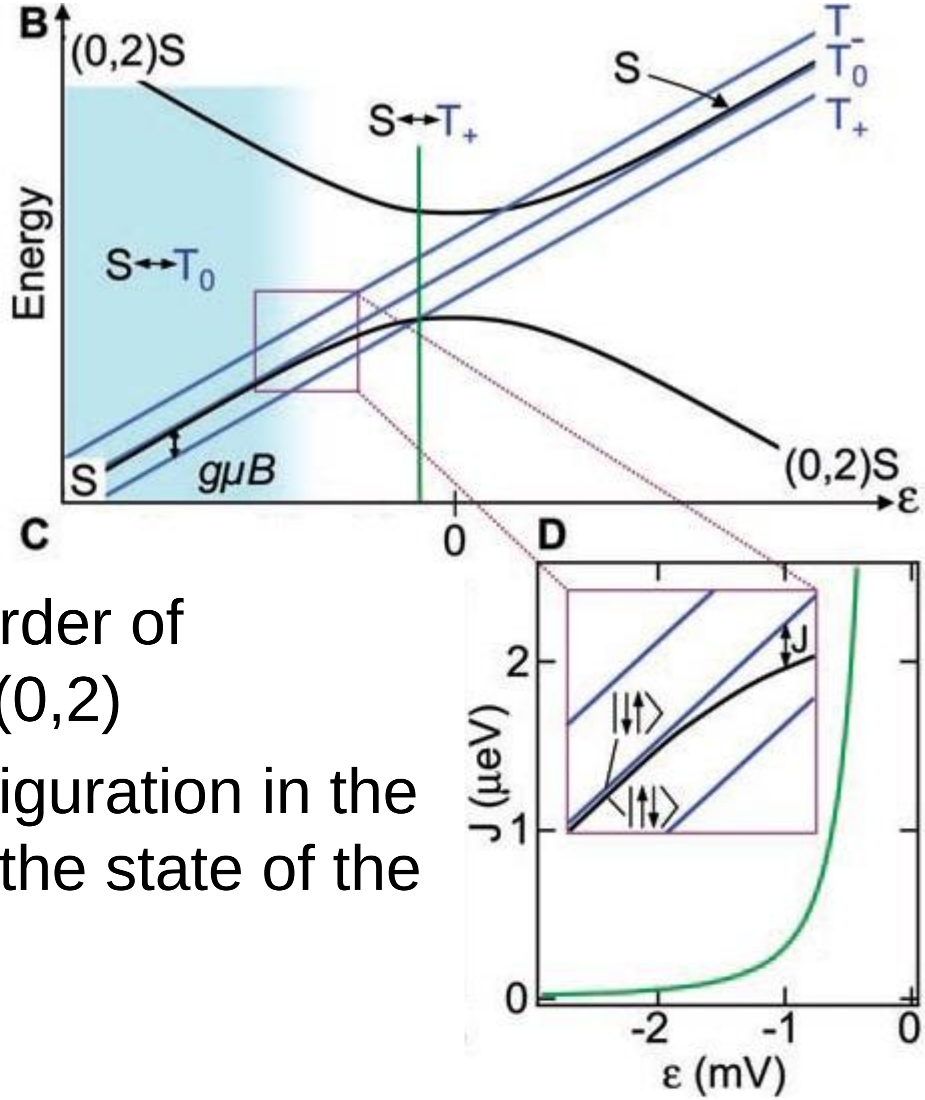
$$H = \begin{pmatrix} J(\varepsilon) & \Delta B^z_{\text{nuc}} \\ \Delta B^z_{\text{nuc}} & 0 \end{pmatrix}$$



$$\theta = \frac{J(\varepsilon)t_{rot}}{\hbar}$$

# Readout

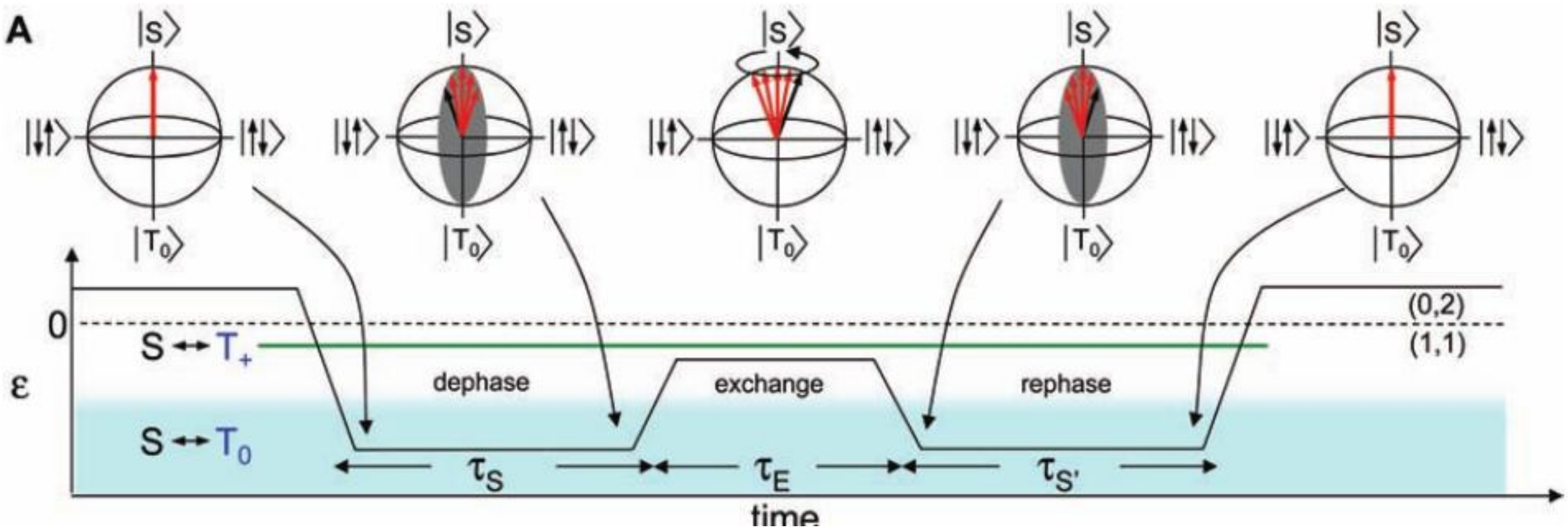
- Tunneling preserves spin
- S(1,1) to S(0,2) is allowed while T(1,1) to T(0,2) is energetically forbidden; Spin-blockaded



- Relaxation time is on the order of miliseconds for T(1,1) to S(0,2)
- Therefore, the charge configuration in the double dot is correlated to the state of the qubit.
- QPC reads charge state

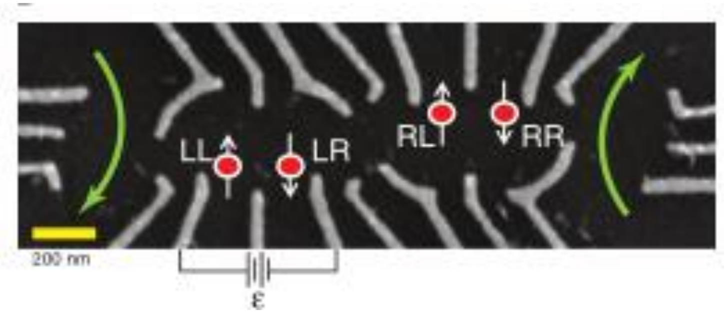
# Spin Echo Technique

- Coherence time of physically seperated qubits ~ 10 nanoseconds
- In middle of qubit manipulation perform a pi-pulse about the z axis
- Effectively rephases the electrons leading to coherence times of microseconds
- Low frequency noise cancelation



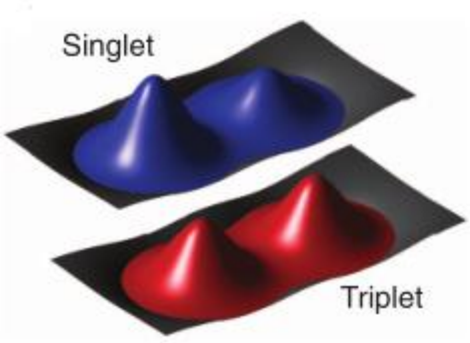
# Qubit-Coupling and Quantum Gates

- 2012, M. D. Shulman et al.
- 2 DQD next to each other capacitevly coupled
- Electrostatic interaction makes the state of one qubit dependent on the other



$$H_{2\text{qbit}} = \frac{\hbar}{2}\left(J_1\left(\hat{\sigma}_z \otimes I\right) + J_2\left(I \otimes \hat{\sigma}_z\right) + J_{12}\left(\hat{\sigma}_z - I\right)\otimes\left(\hat{\sigma}_z - I\right) + \Delta B_1\left(\hat{\sigma}_x \otimes I\right) + \Delta B_2\left(\hat{\sigma}_x \otimes I\right)\right)$$

- $J_{12} \sim J_1 J_2$
- Natural mixing occurs



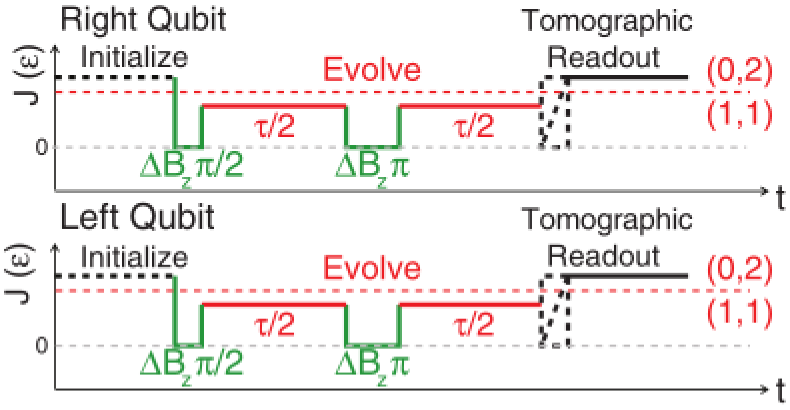
# Cphase Gate

- The natural evolution is a Cphase gate in {SS,T$_0$S,ST$_0$,T$_0$T$_0$} basis

$$H_{\text{Cphase}} = \begin{bmatrix} e^{-i\frac{\theta}{2}} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{-i\frac{\theta}{2}} \end{bmatrix}$$

- An evolution time of $t = \frac{\pi}{2J_{12}}$ creates maximum entanglement

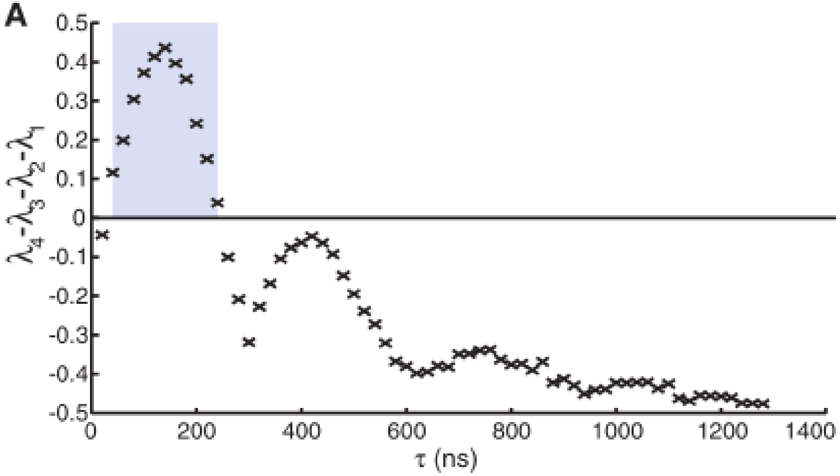
- Production of maximally entangled state takes too long, so spin echo technique is used on both qubits simultaneously



# Entangled States Proof 1

- A positive concurrence is definitive proof of entanglement

- Concurrence= $\lambda_4$-$\lambda_3$-$\lambda_2$-$\lambda_1$ where $\lambda_i$ are the eigenvalues of the R matrix in decending order of magnitude



$$R = \sqrt{\sqrt{\rho}\left(\hat{\sigma}_y \otimes \hat{\sigma}_y\right)\rho^*\left(\hat{\sigma}_y \otimes \hat{\sigma}_y\right)\sqrt{\rho}}$$

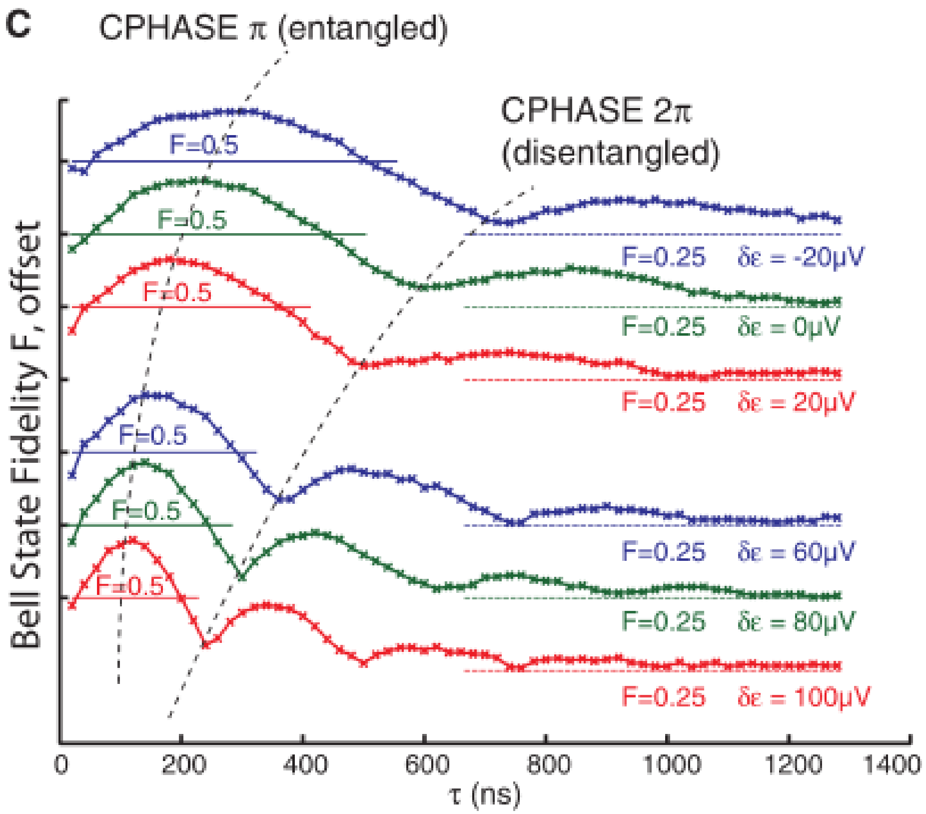
# Entangled States Proof 2

- Can also calculate Fidelity of states

$$F = \langle \Psi_{\mathrm{ent}} | \rho | \Psi_{\mathrm{ent}} \rangle$$

$$|\Psi_{ent}\rangle = e^{i\pi(I\otimes\sigma_y+\sigma_y\otimes I)/8}\left(1/\sqrt{2}\right)\left(|SS\rangle - |T_0T_0\rangle\right)$$

- Not entangled if F<0.5
- Maximum Fidelity achieved ~75%



# Summary

- A 2DEG gas in semidconductors can be used to create a quantum dot and trap a single electron
- A double quantum dot can trap two electrons, whose coupling can create a two level system, ideal for a qubit.
- Universal control of qubit state was achieved using only electric fields
- Spin Echo techniques lengthens coherence time to >1μs
- Coupling of 2 qubits was achieved creating an effective Cphase gate for entangling qubits.

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