Lecture 2: Double quantum dots

- Basics

- Pauli blockade

- Spin initialization and readout in double dots

- Spin relaxation in double quantum dots

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Quick Review

Quantum dot

Single spin qubit

Qubit states:

| 1 ⟩
| 0 ⟩

Long spin relaxation time, $T_1 \sim 1$ sec.

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Review: Coulomb blockade and charging in a single dot

Charging energy $E_c = \frac{e^2}{2C}$

Energy $V_G$

Kastner, RMP 64, 849 (1992)

Sample 1a

Sample 1b

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Double dot charge stability diagram

Two limits:

\( C_M \rightarrow 0 \)

\( C_M/C_{(1,2)} \rightarrow 1 \)

Double dot review article: van der Wiel et al., RMP 75, 1 (2003)

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Double dot charge stability diagram

In between these limits:

Double dot review article: van der Wiel et al., RMP 75, 1 (2003)

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Experimental setup

Parameters:
T = 0.030 K, Feature size < 100 nm, Frequency = 35 GHz

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Double dot measurements

Charge transport

Charge sensing

QPC sensing: Field et al., PRL 70, 1311 (1993)

Petta et al., PRL 93, 186802 (2004)
Elzerman et al., PRB 67, 161308 (2003)
Charge -vs- spin qubits

Charge physics: The one-electron regime
(1,0) vs. (0,1)

Spin physics: The two-electron regime
(0,2) vs. (1,1)

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Gate tunable interdot tunnel coupling

\[ \left\{ \begin{array}{c} M \\ N \end{array} \right\} = \frac{1}{2} \left[ 1 - \frac{\varepsilon}{\Omega} \tanh \left( \frac{\Omega}{2kT} \right) \right] , \quad \Omega = \sqrt{\varepsilon^2 + 4t^2} \]


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Photon assisted tunneling in a one-electron double dot
Charge qubit spectroscopy

On resonance: $\alpha \varepsilon = \sqrt{(hf)^2 - 4t^2}$

$V_t \text{ (V)}$, $2t \text{ (GHz)}$

-1.08, 2.4
-1.04, 6.2
-1.02, 9.2
-1.01, 13.2

See also: Oosterkamp et al., Nature 395, 873 (1998)

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Charge relaxation and dephasing measurement

Petta et al., PRL 93, 186802 (2004)

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Charge qubit: Coherent oscillations

Enhancement in $T_2$ at $\varepsilon=0$

Vion et al., Science (2002)

Hayashi et al., PRL (2003), K. D. Petersson et al., PRL (2010)

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Single spin qubits -vs- Singlet-triplet qubits

**Single spin qubit (Loss and DiVincenzo)**

\[ |1\rangle \quad \uparrow \quad |0\rangle \quad \downarrow \]

\[ E_{\text{Zeeman}} \]

**Encoded spin qubit- “singlet-triplet” qubit (J. Levy)**

Qubit encoded in two-electron spin states

\[
|S\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \quad m_s=0 \\
|T_0\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) \quad m_s=0
\]

**Basis:** S and \( T_0 \), \( m_s=0 \)

Insensitive to field fluctuations

\[ \rightarrow \text{decoherence free subspace} \]

\[
|T_+\rangle = |\uparrow\uparrow\rangle \quad m_s=1 \\
|T_-\rangle = |\downarrow\downarrow\rangle \quad m_s=-1
\]

Work in magnetic field, \( T_+ \) and \( T_- \)

not relevant due to Zeeman energy

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The two electron regime

(1,1) singlet-triplet splitting:
\[ j=\frac{4t^2}{U}=0.4 \text{ } \mu\text{eV} \ll kT \]
with \( U \sim 4 \text{ meV}, t \sim 20 \text{ } \mu\text{eV} \)

(0,2) singlet-triplet splitting:
Theory: \( J \sim 0.3 \text{ meV} \)
Expt.: \( J \sim 0.1 \text{ to } 1 \text{ meV} \)

Kyriakidis et al., PRB 66, 035320 (2002)
Ashoori et al., PRL 71, 613 (1993)

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Double dot finite bias spectroscopy

Finite bias “triangles”

(1,0)  (1,1)  (0,1)  (0,0)

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Singlet-triplet spin blockade in dc transport

Current Rectification by Pauli Exclusion in a Weakly Coupled Double Quantum Dot System

K. Ono, D. G. Austing, Y. Tokura, S. Tarucha


Jason Petta, Princeton University
Singlet-triplet spin blockade in dc transport

(0,2) \rightarrow (1,1) transport is allowed

(1,1) \rightarrow (0,2) transport is spin blocked


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Singlet-triplet spin blockade in charge sensing

\[ \Gamma_R \quad \Gamma_{\text{int}} \quad (0,0) \to (0,1) \to (1,0) \quad \Gamma_L \]

\[ G_{S2} \left( 10^{-3} \text{ e}^2/\text{h} \right) \]

(a) \( N=1, 0.1 \text{ T} \)
+0.5 mV

(b) \( N=2, 0.1 \text{ T} \)
+0.5 mV

(c) \( N=1, 0.1 \text{ T} \)
-0.5 mV

(d) \( N=2, 0.1 \text{ T} \)
-0.5 mV

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• Prepare spin in ground state
• “Spin to charge conversion”
• $T_1$, $T_2^*$, $T_2$
• ESR for single spin rotations
• Exchange interaction
• Standard semiconductor fabrication

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Spin singlet state initialization

\[ (0,1) \quad (0,2) \quad (1,1) \quad (1,2) \]

\[ V_L (mV) \quad V_R (mV) \]

\[ S \approx kT \]

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• Prepare spin in ground state

• “Spin to charge conversion”

• $T_1$, $T_2^*$, $T_2$

• ESR for single spin rotations

• Exchange interaction

• Standard semiconductor fabrication

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Spin state measurement (spin-to-charge conversion)

Singlet measurement

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Spin state measurement (spin-to-charge conversion)

Triplet measurement

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• Prepare spin in ground state

• “Spin to charge conversion”

• $T_1, T_2^*, T_2$

• ESR for single spin rotations

• Exchange interaction

• Standard semiconductor fabrication

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Spin Relaxation and Dephasing: The Two-Electron System


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Pulsed-Gate Measurement of Spin Relaxation


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Pulsed-Gate Measurement of Spin Relaxation


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Pulsed-Gate Measurement of Spin Relaxation

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Pulsed-Gate Measurement of Spin Relaxation


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Spin relaxation: Getting stuck in (1,1)

In “measurement triangle”

dark: transition to (0,2) occurs

light: transition to (0,2) blockaded

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Enhanced, energy-dependent relaxation at zero field

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Effective nuclear field from hyperfine interaction

Large ensemble with random spin orientations, slow internal dynamics...

Quasistatic effective field

\[ B_{nuc} = b_0 \sum_k |\psi(r_k)|^2 I_k \]

\[ \text{rms } B_{nuc} = b_0 \sqrt{I_0(I_0 + 1)/N} \]

GaAs: \( b_0 = 3.47 \text{ T}, \ I_0 = 3/2 \)

Our device: \( N \sim 10^6 - 10^7 \)

\( B_{nuc} \sim 2 - 6 \text{ mT}, \ t_{nuc} \sim 3 - 10 \text{ ns} \)

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\[ B_{\text{Zeeman}} \sim B_{\text{Nuclear}} \]

\[ B_{\text{Zeeman}} \gg B_{\text{Nuclear}} \]

\[ B_{\text{Nuclear}} \]

\[ B_{\text{Total}} \]

\[ B_{\text{Zeeman}} \]

\[ T_1, T_2 \text{ short} \]

\[ T_1 \text{ long}; T_2 \text{ short} \]

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Measuring the nuclear field: Energy dependence of tunnel rates

Deviation above 1 ms
Additional decay mechanism?

\[ \frac{t(B)}{t(0)} = \left( \frac{B}{B_{nuc}} \right)^2 + 1 \]

\[ B_{nuc} = 2.8 \pm 0.2 \text{ mT} \]

\[ t_{nuc} \sim 10 \text{ ns} = T_2? \]

Jason Petta, Princeton University