Long-distance coherent coupling in a quantum dot array

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Outline

• Motivation/Idea
• Sample/Methods
• Charge stability diagram
• Transport through triple QD via co-tunneling
• Coherent tunneling
• Summary and outlook
Motivation/Idea

- Charge and Spin in QD to implement qubits
- For quantum logic gate one needs coherent transport and manipulation of qubits over large distance:
  - SWAP operations (difficult)
  - Quantum bus (trapped ions and superconducting qubits)

Idea:

Exponential decay of tunnel coupling in QD $\rightarrow$ quantum bus in QD:

- use cotunneling to achieve long distance coupling
- process possible since $\Delta t = \hbar/\Delta E$
Sample/Methods

- Sensor QD (SQD) operated on flank of Coulomb peak
- Measurement of $I_{SQD}$ via radiofrequency reflectometry (RRF) and in D.C mode
  - Apply an RF signal
  - Reflected signal is modulated depending on the resistance of the device
  - High sensitivity and high bandwidth, circumvents the high capacitance and resistance between RT electronics and cryostat.
- Dots in few electron regime
- Tunnel rates to leads $\sim 100$ Hz; between dots $>100$ Hz
Charge stability diagram

- Time averaged differential D.C. conductance
- Numerical derivative of $I_{SQD}$ along $V_{LP}$
- Independent tuning of the barriers and dots
- Opaque barriers (lower tunneling rates)
- Difference in stepsize height due to distance to SQD

(1,1,0) $\rightarrow$ (0,1,0)

(0,1,1) $\rightarrow$ (0,1,0) and

2x (0,1,0) $\rightarrow$ (0,1,1)

Zero detuning between (0,1,1) and (1,1,0); tunneling between outer dots

= tunneling in

= tunneling out
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Evidence for outer dot transport

- Upper trace: mostly (0,1,1)
- Lower trace: mostly (1,1,0)
- Middle trace: transport between the outer dots
- $\delta_1$ fixed at $\sim 300 \mu$eV; $\varepsilon = [49 \mu$eV, $-61 \mu$eV]
- Transfer of electrons between the outer dots via cotunneling of middle dot
• Cotunneling processes via 2 path ways
• Set $\mu_L(1,1,0)=\mu_R(0,1,1)$
•Opaque barriers to leads
• $\delta_1=\mu_M(0,2,0)-\mu_R(1,1,0)$ and $\delta_2=\mu_L(1,0,1)-\mu_M(1,1,0)$; $\delta_1=f(\delta_2)$

**Couplings between states:**

$\mathbf{t_{l1}}$: $|110>$ and $|020>$  
$\mathbf{t_{r1}}$: $|020>$ and $|011>$  
$\mathbf{t_{l2}}$: $|101>$ and $|011>$  
$\mathbf{t_{r2}}$: $|110>$ and $|101>$

$H = \begin{pmatrix} -\epsilon'/2 & t_{co} \\ t_{co} & \epsilon'/2 \end{pmatrix}$

$t_{co} = \frac{t_{l1}t_{r1}}{\delta_1} + \frac{t_{l2}t_{r2}}{\delta_2}$

For $t_{l1}, t_{r1}, t_{l2}, t_{r2}, \epsilon \ll \delta_1, \delta_2$

• $t_{co}$: co-tunnel-coupling strength
Tunnelrate

- Change $V_{MP} \sim \delta_1 \sim \delta_2$
- Mostly 2 state fluctuation
- $T_2$ charge dephasing time $\sim 1\text{ns}$
- Non-monotonous tunnelrate $\rightarrow$ transfer via virtual states

\[ \Gamma = \frac{2T_2}{\hbar} \left( \frac{t_{l1}^2 t_{r1}^2}{\delta_1^2} + \frac{t_{l2}^2 t_{r2}^2}{\delta_2^2} \right) \]
• Apply microwave to LP gate
• Make two detuned dot levels resonant via microwaves: \( \varepsilon_0 = n\hbar \omega \) (\( n > 1 \) ↔ multiphoton processes)
• Sidebands in CSD at L and R due to conventional PAT
  • Slopes of the sidebands at L and R such that \( \varepsilon_0 = n\hbar \omega \)
  • Slopes of the resonance at point C different \( \rightarrow \) PACT
• Investigate coherent dynamics at point C between the states \( |110\rangle \) and \( |011\rangle \) via Landauer-Zener-Stückelberg (LZS) interference
• LZS Hamiltonian (as in 2 level system) with microwave modulation at frequency \( \omega \)

\[ H = \begin{pmatrix} -\epsilon'/2 - Ae^{i\omega t} & t_{co} \\ t_{co} & \epsilon'/2 + Ae^{i\omega t} \end{pmatrix} \]
Apply microwave to LP gate

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\]
LZS interference

- Larger tunnel coupling between the neighbouring dots $\rightarrow$ strong PACT response
- Set detuning $\varepsilon_0$; apply mw to LP at 15 GHz
- Modulation of detuning by mw
- States in the 2 level system evolve $\rightarrow$ gain of phase between two passings through anticrossing during one mw period/tunable via mw power; peaks at $\varepsilon_{0n} = nh\nu$

$$\Delta \theta_{12} = \frac{1}{\hbar} \int_{t_1}^{t_2} \epsilon(t) \, dt = 2\pi n = 2\pi \varepsilon_0 / \hbar \nu$$

- Coherent oscillations between excited and ground state $\rightarrow$ coherent co-tunneling

Contrast = occupation of excited state
Summary and Outlook

Summary:

- Observation of coherent co-tunnel coupling across a triple QD array
- Long distance coupling via co-tunneling process via virtual intermediate state
  → non monotonous tunnel rate upon detuning (theory fits experiment well)

Outlook:

- Show that spin is not affected during these oscillations → non local spin exchange
- Possible study of superexchange → understanding high temperature superconductors