Microwave cavity detected spin blockade in a few electron double quantum dot

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We investigate spin states of few electrons in a double quantum dot by coupling them weakly to a magnetic field resilient NbTiN microwave resonator. We observe a reduced resonator transmission if resonator photons and spin singlet states interact. This response vanishes in a magnetic field once the quantum dot ground state changes from a spin singlet into a spin triplet state. Based on this observation, we map the two-electron singlet-triplet crossover by resonant spectroscopy. By measuring the resonator only, we observe Pauli spin blockade known from transport experiments at finite source-drain bias and detect an unconventional spin blockade triggered by the absorption of resonator photons.
Overview / Motivation

• Study spin states in DQD using NbTiN resonator R (previously used for charge related phenomena / valley physics)
  early days: direct transport / charge sensing

• Reduced transmission due to singlet– R interaction

• No response for triplet – R
  => distinguish

• Mapping singlet – triplet crossover by resonant spectroscopy

• Observation of Pauli spin blockade using R only

• Unconventional spin blockade (absorption of R photons)
Device Layout

• Double quantum dot:
  - GaAs / AlGaAs heterostructure
  - Au top gates
  - \( V_L, V_R \) control charge configuration
  - \( V_T \) control interdot tunnelling strength

• Charge sensing:
  - Sensor dot, operated as QPC

Cavity detection:
• Left plunger gate (orange) connected to end of \( \lambda/2 \) coplanar waveguide resonator
• Resonance \( \nu_r = 8.33 \) GHz
• Linewidth \( \kappa/2\pi = 101 \) MHz (\( Q \approx 80 \))
• NbTiN thin film (15nm) => can use up to 2T in-plane field

Cavity, zoomed out (previous work)
• DQD with 1 gate connected to resonator
• M: Ohmic contacts
• C: top gates
• I: Inductor
• \( \text{Al}_x\text{Ga}_{1-x}\text{As} \) heterostructure 35nm below surface

Device Layout

- Double quantum dot: GaAs / AlGaAs heterostructure
  - Au top gates
  - VL, VR control charge configuration
  - VT control interdot tunnelling strength

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- DC transport

- RF measurement (cavity)

- Cavity, zoomed out (previous work)
  - DQD with 1 gate connected to resonator
  - M: Ohmic contacts
  - C: top gates
  - I: Inductor
  - AlxGa1-xAs heterostructure 35nm below surface
Resonant / dispersive readout

- Two electron regime, only singlet / triplet relevant
- Singlet charge qubit (1,1) – (0,2)
- Measure normalized resonator transmission \((A/A_{\text{max}})^2\) at resonance (8.33 GHz)

2 Regimes:
- Dispersive: \(E_{\text{Qubit}} > E_{\text{resonator}}\) \((2t > h\nu_r)\)
- Resonant: \(E_{\text{Qubit}} < E_{\text{resonator}}\) \((2t < h\nu_r)\)

\[E_q = \sqrt{\delta^2 + (2t)^2}\]

\(t/h = 3.4\) GHz
\(t/h = 4.5\) GHz
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Coupling of cavity and DQD
- Electric dipole interaction cavity E-field and charge qubit
- Coupl. strength: \(g_c/2\pi = 28\) MHz
- Qubit decoherence: \(\gamma_2/2\pi = 357\) MHz

\[ \Rightarrow \text{weakly coupled probe } (g_c<<\gamma_2, \kappa), \text{ no coherent influence} \]

- Distance btw triple points: 510\(\mu\)eV (123 GHz) interdot capacitive + tunnel coupling
Singlet - triplet crossover

- Resonator response $R(\delta, B_{\text{inplane}}) @ \approx$ resonance

- $B_{\text{inplane}}$: control $T_-, T_+$ split of from $T_0$ (Zeeman) => can change ground state $S \rightarrow T_+$

Resonator response
- dispersive: single peak
- resonant: double peak, located at $\delta_\pm$
- disappearance of peaks at finite $B$ (change of ground state from singlet to triplet)
- No S-T hybridization (spin-orbit / hyperfine) assumed

Why no signal for $(1,1)T_+$?
- $(1,1)T_+$ symmetric charge configuration  => no dipole moment

Signal for ground state GS
- GS is a mixture of $(1,1)S$ and $(0,2)S$  => not symmetric  => dipole moment

Extraction of amplitudes for further analysis
- Lorentzian line shape fits  => get amplitudes $A_0$, $A_+$, $A_-$
Singlet - triplet crossover II

- Interpretation of qubit – cavity coupling (rot. wave approx.)
  \[ \hat{H}_i = -\hbar g_c \sin(\theta)(a\sigma_+ + a^\dagger\sigma_-) \]
  \[ \sigma_- = |g\rangle \langle e| \]
  \[ \sigma_+ = |e\rangle \langle g| \]
  Qubit: |g\rangle \rightarrow |e\rangle
  Cavity: |n + 1\rangle \rightarrow |n\rangle
  photon creation (annihilation) operator \(a^\dagger\) (a)
  \[ a\sigma_+ |g\rangle = a|e\rangle \langle g|g\rangle = a|e\rangle \]

- transmission \(\sim GS\) occupation probability (Fermi’s Golden rule)
  assume thermal occupation of DQD states
  \[ p_{|g\rangle}(B_\delta) = \frac{1}{1 + e^{\frac{g\mu_B B_\delta}{k_B T}} + e^{\frac{g\mu_B (B-B_\delta)}{k_B T}} + e^{\frac{g\mu_B (B+B_\delta)}{k_B T}}} \]

  B-field \(B_\delta\): \(|g\rangle \rightarrow (1,1)T_+\) intersection field
  g-factor: \(g=-0.4\)
  Temperature: \(T_e=60\text{mK}\) (1.3GHz)
  tunnel coupl.: \(t\) (input-output analysis)

\[ B_{0z} [T] \]

resonant regime: \(2t < \hbar v_r\)
dispersive regime: \(2t > \hbar v_r\)
Spin blockade (cavity)

- DC current through DQD below detection limit (<1pA)
- Omit hybridization and Zeeman splitting for qualitative discussion (present in simulation)
- $\Gamma_R >> \Gamma_L$ ($\Gamma_L = \Gamma_S$, the spin flip rate)

Region B:
- 2 electron ground state (not affected by bias)
  $\implies$ same response as in zero bias case for $B > 0.5T$ (spin blockade: only one peak since)

Region A (square) @ negative bias:
- spin blockade lifted once (0,1) is within bias window:
  $(1,1)T_+ \rightarrow (0,1) \rightarrow (0,2)S \rightarrow (1,1)S + \gamma$
- green star $\mu((1,1)T_+) = \mu_d$
- upper end $\mu((0,2)S) = \mu_s$
- above: (0,1) is ground state & does not interact with resonator

Region C @ negative bias
- should be same as A for symm. lead tunnel rates
  $\implies$ dominant (1,2) population
  $\implies$ does not interact with resonator

\[ V_{sd} = 300 \mu V, B = 800 mT \]
Spin blockade (transport)

- DC current through DQD below detection limit (<1pA)
- Omit hybridization and Zeeman splitting for qualitative discussion (present in simulation)
- $\Gamma_R >> \Gamma_L$ ($\Gamma_L \approx \Gamma_S$, the spin flip rate)

Region C (square):
- standard transport spin blockade
- (1,2) within bias window
- process: $(1,2) \rightarrow (1,1)T_+ \Rightarrow$ blocked

Why still transport (nonzero signal)?
- Some relaxation to $(0,2)S$ possible (spin flip)
- small tunnelling rate to left lead
- comparable spin flip rate
=> system $\approx 50\%$ in $(0,2)S$
Spin blockade (unconventional)

- DC current through DQD below detection limit (<1pA)
- Omit hybridization and Zeeman splitting for qualitative discussion (present in simulation)
- $\Gamma_R >> \Gamma_L$ ($\Gamma_L \approx \Gamma_S$, the spin flip rate)

Region B (Square):

- unblocked in standard transport
- Here: small regime of spin blockade

How does it work?

- System should be in (0,2)S ground state
- Photon absorption $\rightarrow$ (1,1)S
- Can fill one electron from right lead: (1,2)
- Decay to $(1,1)T_+ \Rightarrow$ spin blockade

$\Rightarrow$ transport spin blockade triggered by photon absorption
Summary

• Investigation of spin states using a cavity coupled DQD

• Continuous mode operation, no pulsing required

• Observation of singlet – triplet crossover (mapping out transition)

• Various spin blockade mechanisms investigated
  • resonator spin blockade
  • normal transport spin blockade
  • unconventional spin blockade triggered by photon absorption
Since $\kappa \ll \gamma, g_c$, the resonator-qubit interaction is treated as a weak perturbation. In this picture, the Fermi Golden rule determines the rate at which a photon in the resonator and qubit interact as

$$\Gamma_{ph-\mid g\rangle} = \frac{2\pi}{\hbar} |\langle e| \hat{H}_1 \mid g\rangle|^2 p_{\mid g\rangle} = \frac{2\pi}{\hbar} g^2 \sin(\theta)^2 p_{\mid g\rangle} \quad (20)$$

with the electric dipole interaction Hamiltonian $\hat{H}_1$ from Eq. (7) and the ground state occupation probability $p_{\mid g\rangle}$.

If the qubit is in the ground state, it can be excited by absorbing a photon from the resonator. We can model this process with a classical rate equation. The resonator can have one or zero photons with probabilities $p_1$ and $p_0$. In addition to resonator-qubit interaction, the number of photons in the resonator decreases at rate $\kappa_{\text{int}}$ by decay in the resonator. In steady state, the rate equation is

$$\dot{p}_1 = \Gamma_{P} p_0 - (\Gamma_{ph-\mid g\rangle} + \kappa_{\text{int}}) p_1 = 0, \quad (21)$$

where $\Gamma_P$ is the rate at which the resonator probe tone feeds photons into the resonator.

With $p_0 = 1 - p_1$, we arrive at

$$p_1 = \frac{\Gamma_P}{\Gamma_{ph-\mid g\rangle} + \Gamma_P + \kappa_{\text{ext}}} \quad (22)$$

The transmission of a two-port coupled resonator is given as

$$A^2 \propto \frac{\kappa_{\text{ext}}}{2} p_1 = \frac{\Gamma_P \kappa_{\text{ext}}/2}{\Gamma_{ph-\mid g\rangle} + \Gamma_P + \kappa_{\text{int}}} \quad (23)$$

where $\kappa_{\text{ext}}$ is the rate at which resonator photons couple with the ports. For $\Gamma_{ph-\mid g\rangle} \ll \kappa_{\text{int}}, \Gamma_P$, we finally obtain with Eqns. (20) and (23)

$$A^2 \propto 1 - C^* p_{\mid g\rangle} \quad (24)$$

where $C^*$ is a constant.
Tunnel coupling extraction