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

A. J. Landig,[1] J. V. Koski,[1] P. Scarlino,[1] C. Reichl,[1] W. Wegscheider,[1] A. Wallraff,[1] K. Ensslin,[1] and T. Ihn[1]

[1] *Department of Physics, ETH Zürich, CH-8093 Zürich, Switzerland*

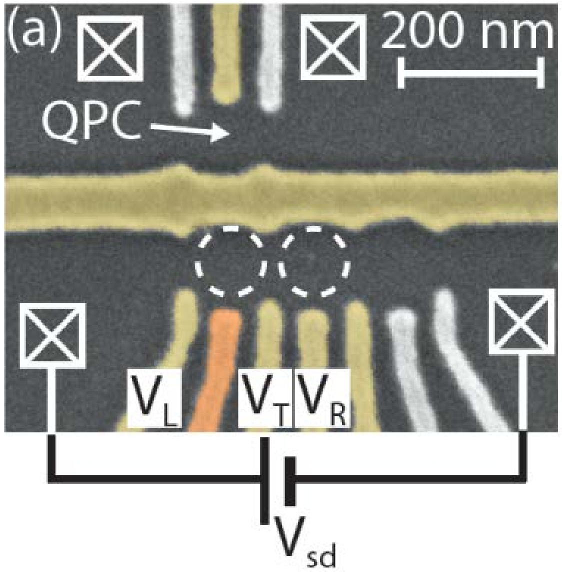
We investigate spin states of few electrons in a double quantum dot by coupling them weakly to a magnetic field resilient NbTiN microwave resonator. We observe a reduced resonator transmission if resonator photons and spin singlet states interact. This response vanishes in a magnetic field once the quantum 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

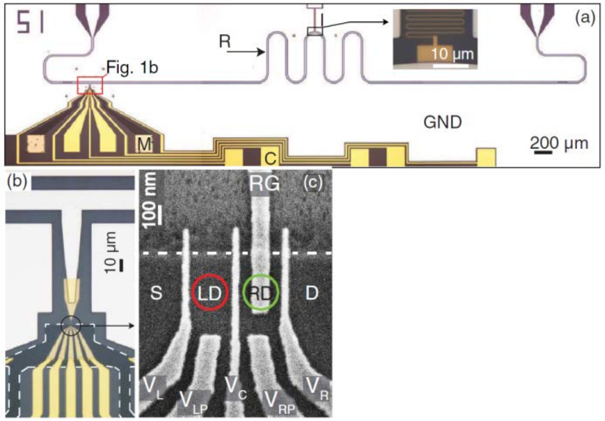


Cavity detection:

- Left plunger gate (orange) connected to end of $\lambda/2$ coplanar waveguide resonator
- Resonance ν_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
- $Al_xGa_{1-x}As$ heterostructure 35nm below surface



T. Frey et al., PRL **108**, 046807 (2012)

Device Layout

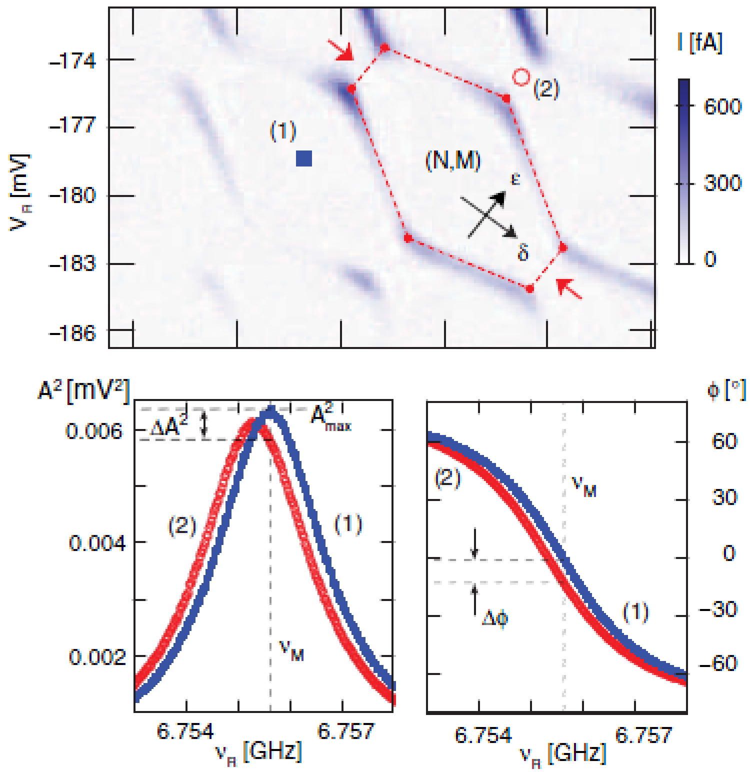
- Double quantum dot:
  - GaAs / AlGaAs heterostructure
  - Au top gates

- Char

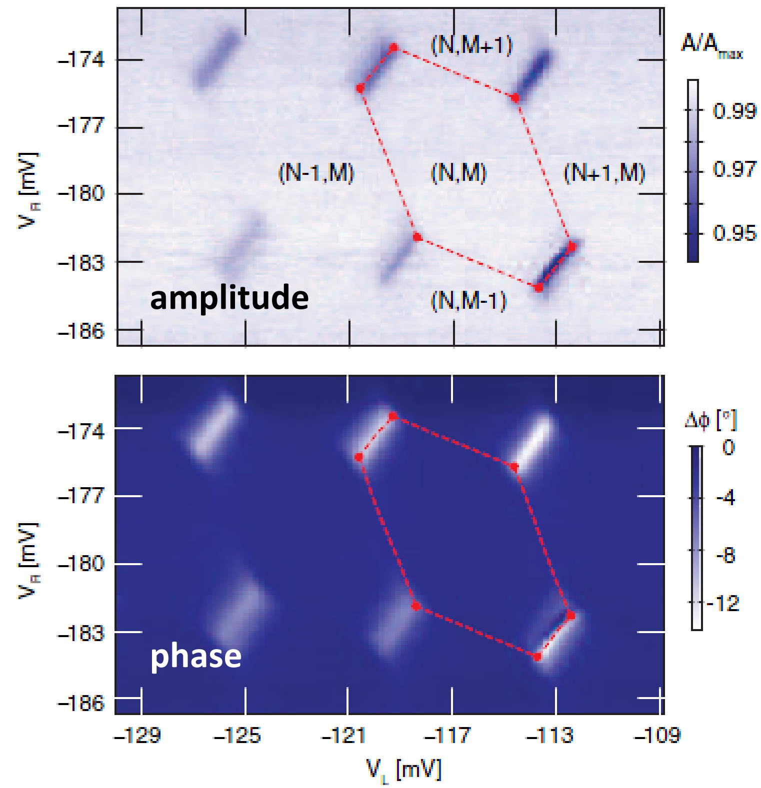
Cavity d

Cavity, z

DC transport



RF measurement (cavity)

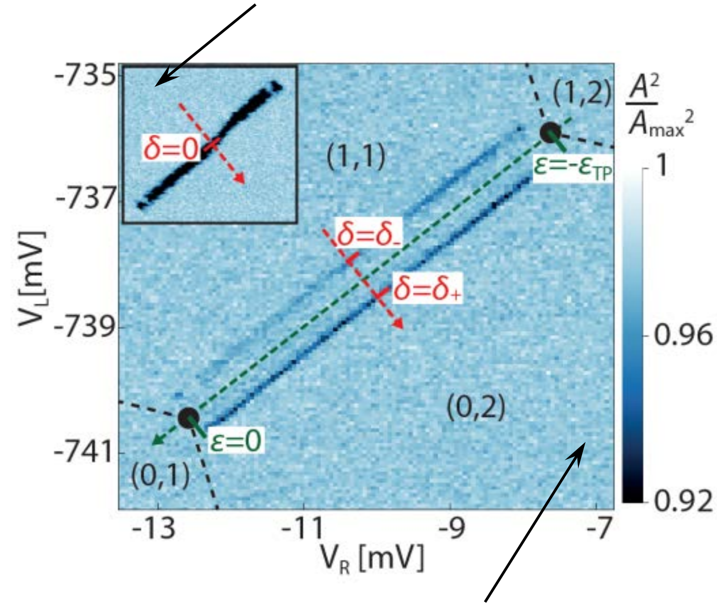


Resonant / dispersive readout

- Two electron regime, only singlet / triplet relevant
- Singlet charge qubit (1,1) – (0,2)

- Measure normalized resonator transmission $(A/A_{max})^2$ at resonance (8.33 GHz)

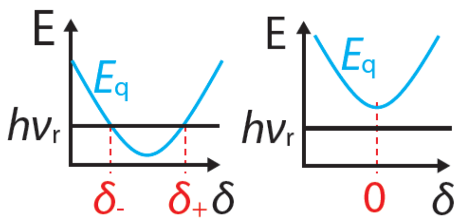
t/h = 4.5 GHz

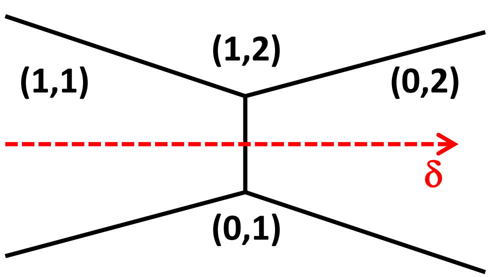


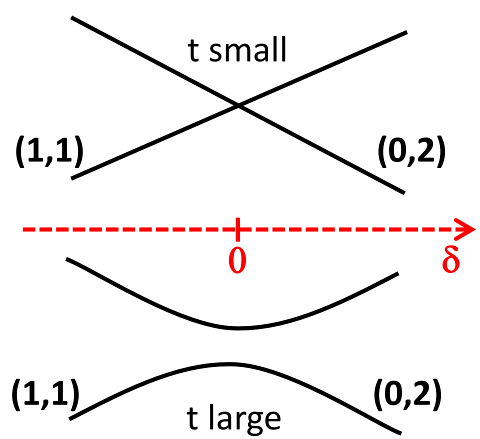
t/h = 3.4 GHz

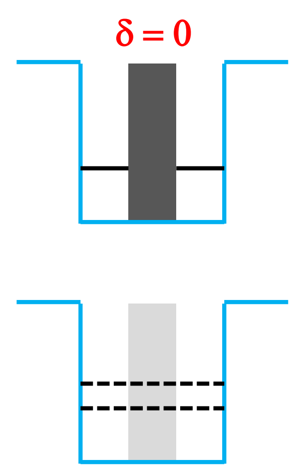
2 Regimes:

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









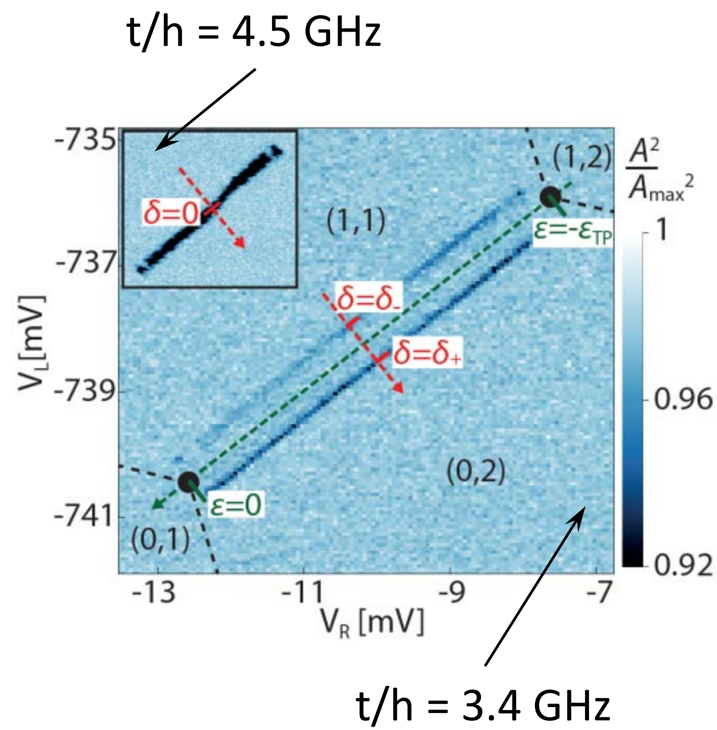
Singlet charge qubit

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

Resonant / dispersive readout

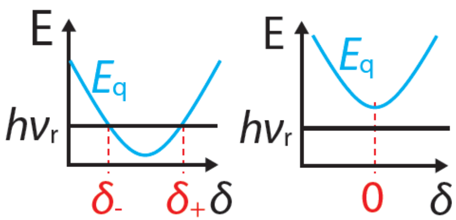
- Two electron regime, only singlet / triplet relevant
- Singlet charge qubit (1,1) – (0,2)

- Measure normalized resonator transmission $(A/A_{max})^2$ at resonance (8.33 GHz)



2 Regimes:

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



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

} input – output theory model

$\Rightarrow$ weakly coupled probe ($g_c << \gamma_2, \kappa$), no coherent influence

- Distance btw triple points: 510μeV (123 GHz) interdot capacitive + tunnel coupling

Singlet - triplet crossover

- Resonator response **R**(δ,$B_{inplane}$) @ $\approx$ resonance
- $B_{inplane}$: 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

$\Rightarrow$ no dipole moment

Signal for ground state **GS**

- GS is a mixture of (1,1)S and (0,2)S

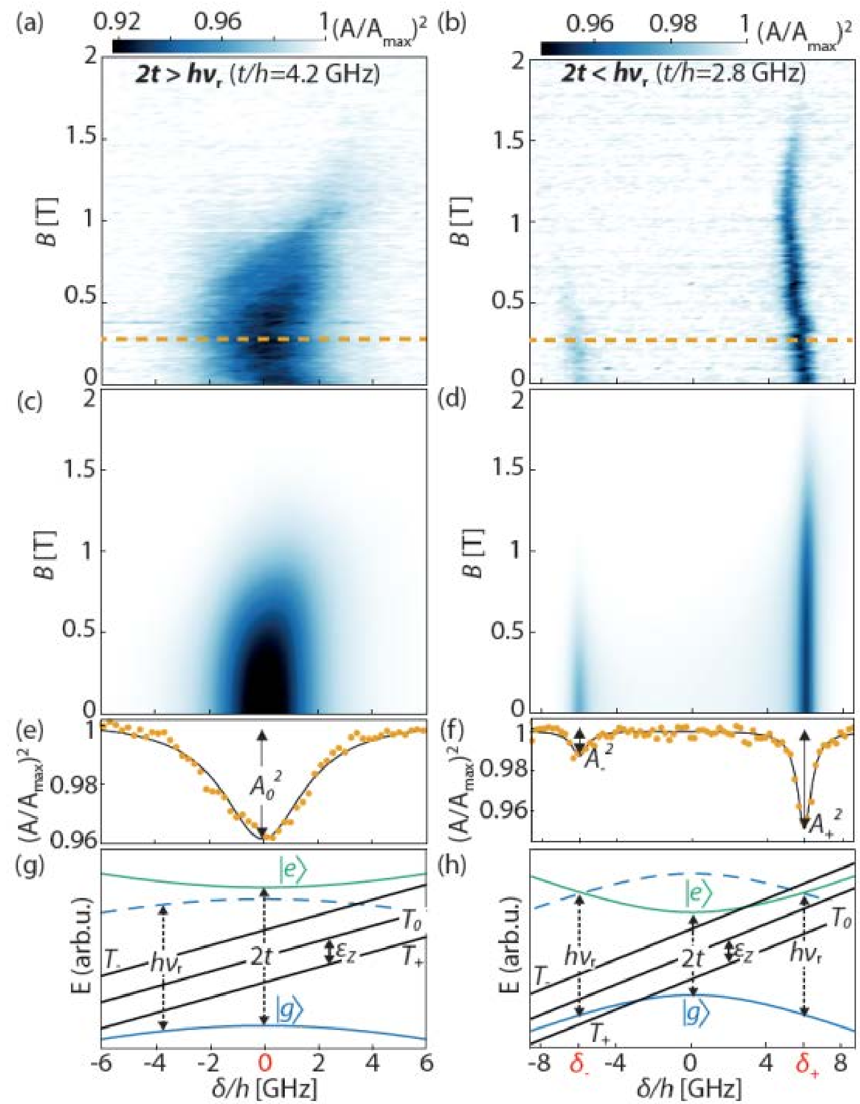
$\Rightarrow$ not symmetric

$\Rightarrow$ dipole moment

Extraction of amplitudes for further analysis

- Lorentzian line shape fits

$\Rightarrow$ get amplitudes A_0, A_+, A_-



Singlet - triplet crossover II

- Interpretation of qubit – cavity coupling (rot. wave approx.)

$$\tilde{H}_{\mathrm{i}} = -\hbar g_{\mathrm{c}} \sin(\theta)(a\sigma_+ + a^\dagger\sigma_-)$$

$$\sigma_- = |g\rangle\langle e|$$

$$\sigma_+ = |e\rangle\langle g|$$

Qubit: $|g\rangle \rightarrow |e\rangle$
Cavity: $|n+1\rangle \rightarrow |n\rangle$

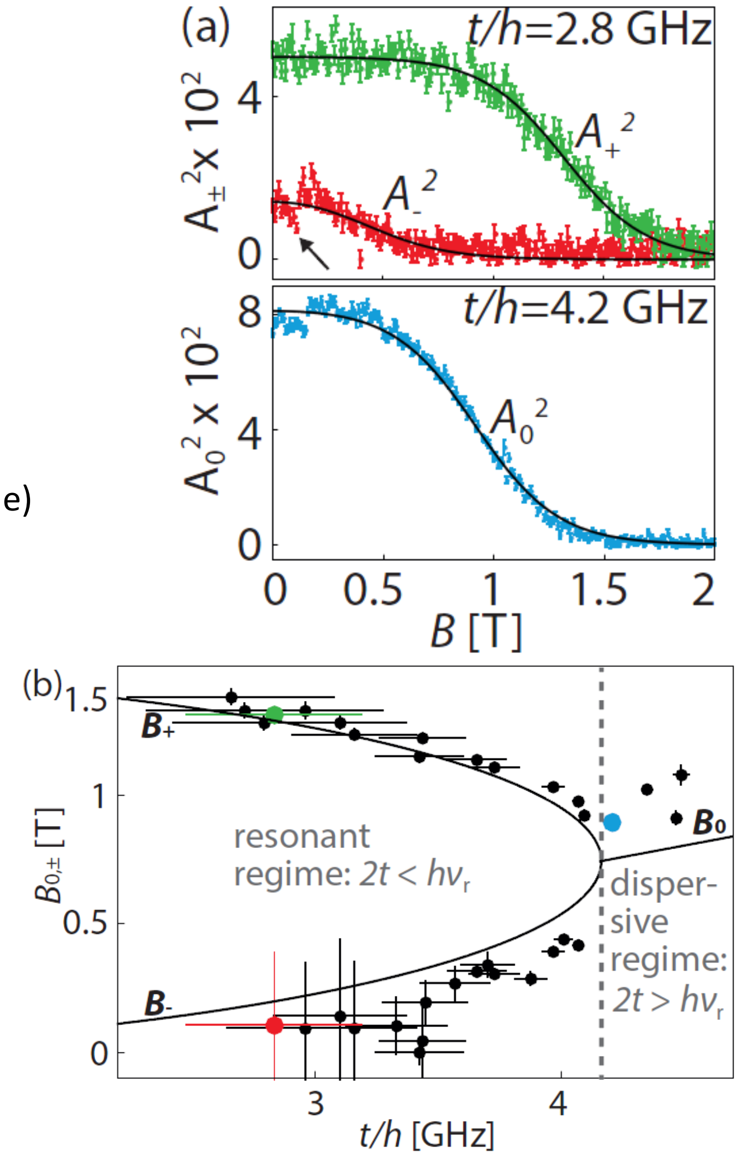
photon creation (annihilation) operator $a^\dagger$ (a)

$$a\sigma_+|g\rangle = a|e\rangle\langle g|g\rangle = a|e\rangle$$

- transmission ~ **GS** occupation probability (Fermi's Golden rule)
  assume thermal occupation of DQD states

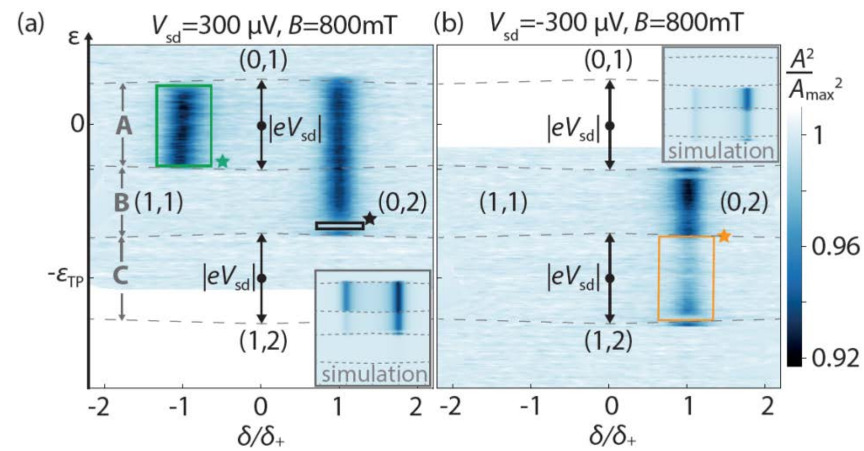
$$p_{|g\rangle}(B_\delta) = 1/\left(1 + e^{\frac{g\mu_B B_\delta}{k_B T}} + e^{\frac{g\mu_B (B-B_\delta)}{k_B T}} + e^{\frac{g\mu_B (B+B_\delta)}{k_B T}}\right)$$

B-field B_δ: $|g\rangle - (1,1)T_+$ intersection field
g-factor: g=-0.4
Temperature: T_e=60mK (1.3GHz)
tunnel coupl.: t (input-output analysis



Spin blockade (cavity)

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



Region B:

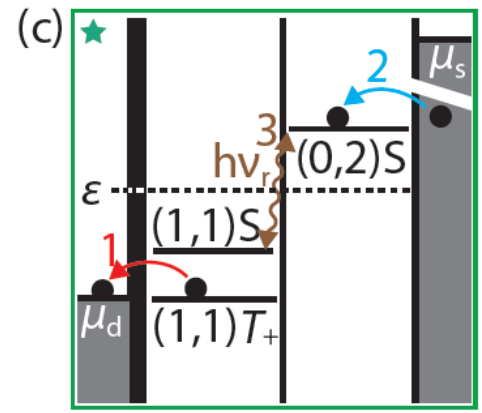
- 2 electron ground state (not affected by bias)
- ⇒ same response as in zero bias case for B>0.5T (spin blockade: only one peak since)

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 $\mu\big((1,1)T_+\big) = \mu_d$
- upper end $\mu\big((0,2)S\big) = \mu_s$
- above: (0,1) is ground state & does not interact with resonator

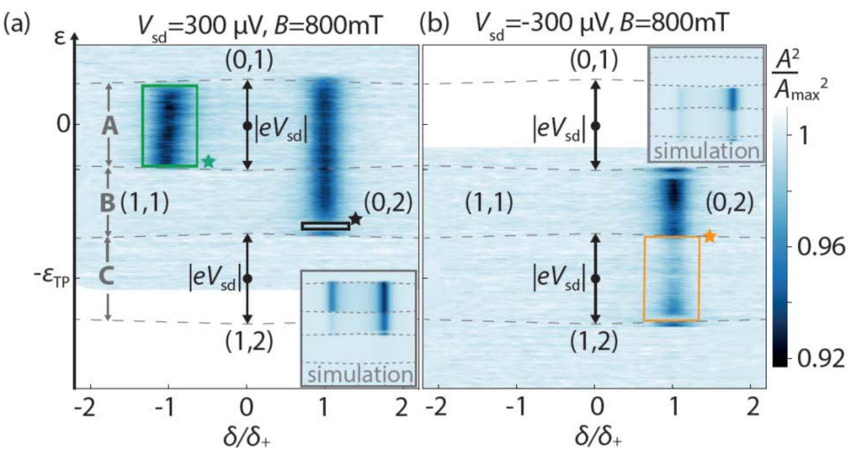


Region C @ negative bias

- should be same as A for symm. lead tunnel rates
- ⇒ dominant (1,2) population
- ⇒ does not interact with resonator

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)



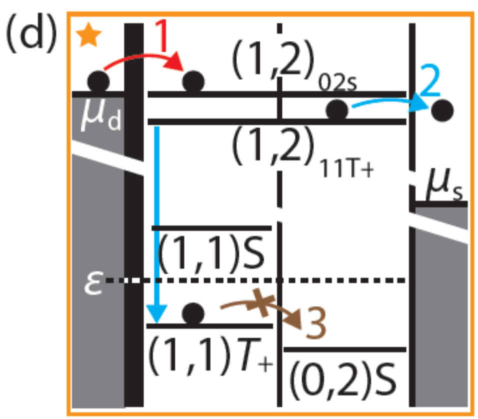
Region C (square):

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

Why still transport (nonzero signal)?

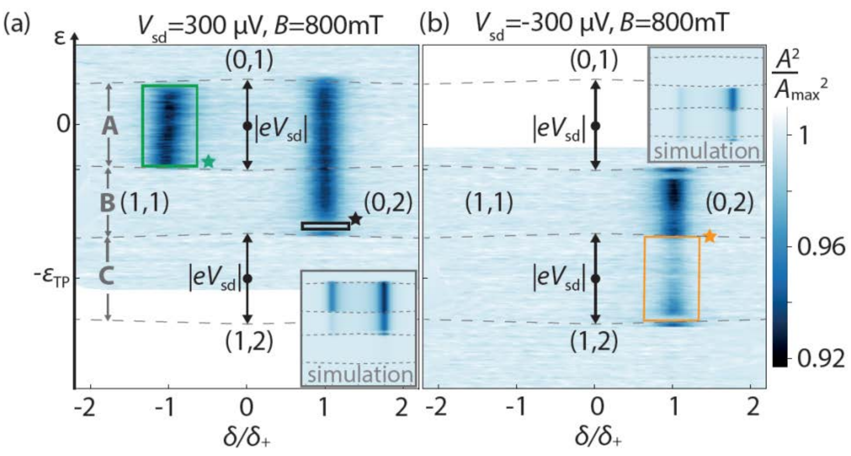
- Some relaxation to (0,2)S possible (spin flip)
- small tunnelling rate to left lead
- comparable spin flip rate

=> system ≈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)



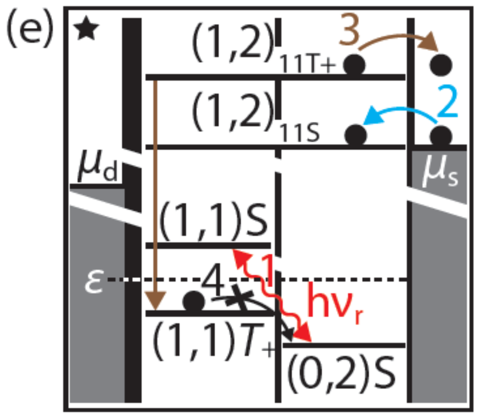
Region B (Square):

- 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 → (1,1)S
- Can fill one electron from right lead: (1,2)
- Decay to $(1,1)T_+$ => spin blockade

⇒ 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

Singlet - triplet crossover II

Since $\kappa \ll \gamma_2, g_c$, 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

$$\Gamma_{ph-|g\rangle} = \frac{2\pi}{\hbar} |\langle e| \tilde{H}_i |g\rangle|^2 p_{|g\rangle} = \frac{2\pi}{\hbar} g^2 \sin(\theta)^2 p_{|g\rangle} \tag{20}$$

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

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 κ_{int} by decay in the resonator. In steady state, the rate equation is

$$\dot{p}_1 = \Gamma_P p_0 - (\Gamma_{ph-|g\rangle} + \kappa_{int}) p_1 = 0, \tag{21}$$

where Γ_P is the rate at which the resonator probe tone feeds photons into the resonator.
With $p_0 = 1 - p_1$, we arrive at

$$p_1 = \frac{\Gamma_P}{\Gamma_{ph-|g\rangle} + \Gamma_P + \kappa_{ext}}. \tag{22}$$

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

$$A^2 \propto \frac{\kappa_{ext}}{2} p_1 = \frac{\Gamma_P \kappa_{ext}/2}{\Gamma_{ph-|g\rangle} + \Gamma_P + \kappa_{int}}, \tag{23}$$

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

$$A^2 \propto 1 - C^* p_{|g\rangle}, \tag{24}$$

where C^* is a constant.

Tunnel coupling extraction