Single-shot measurement of electron spins in Si/SiGe quantum dots

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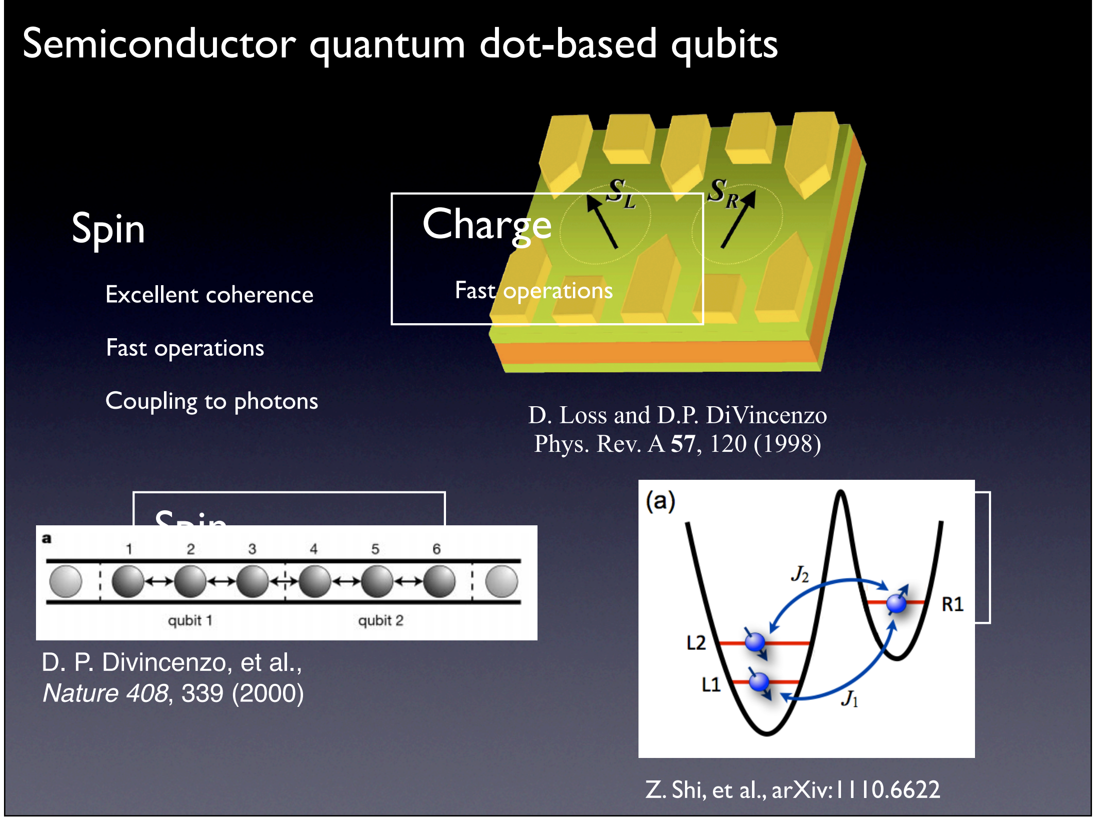
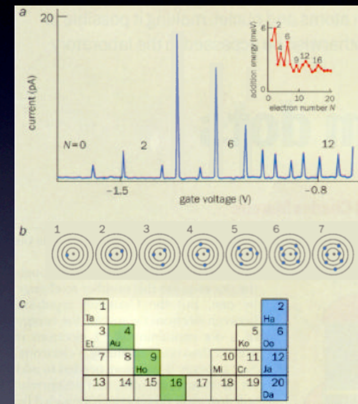


Size of a a qubit is not yet important, but it will become more so in the future. Not only are the dots relatively small, but the control hardware can be quite compact as well (gate-level & system level).

Semiconductor quantum dots as artificial atoms

- Electrically tunable energy eigenstates
- Electrical readout of eigenstates
  - both spin states and orbital states
- Electrical control of state loading
- Approaches exist for the all-electrical control and characterization of spins in quantum dots
  - Much current work is in exactly this area



Kouwenhoven & Marcus *Physics World*, *11*, 35 (1998).

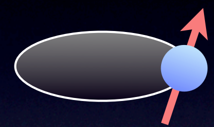
Size of a a qubit is not yet important, but it will become more so in the future. Not only are the dots relatively small, but the control hardware can be quite compact as well (gate-level & system level).

Silicon has excellent spin coherence properties

1. Weak Spin - Orbit Coupling

Interaction of a particle's spin with its orbital motion

Very weak in Si



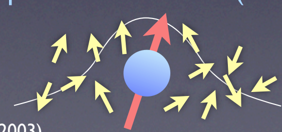
Silicon is a light element

2. Small Hyperfine Interaction

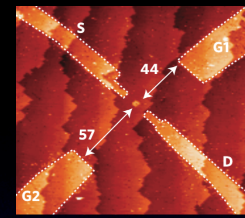
Interaction between electron spin and nuclear spin

Zero nuclear moment in ^{28}Si and ^{30}Si

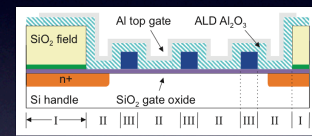
Natural Silicon is nuclear spin-zero abundant (~92%)



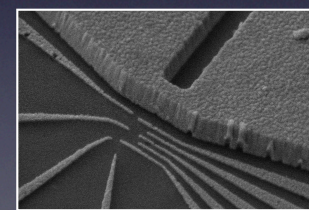
C. Tahan, et al, Phys. Rev. B 66, 035314 (2002)
R. de Sousa et al., Physical Review B 68, 115322 (2003)



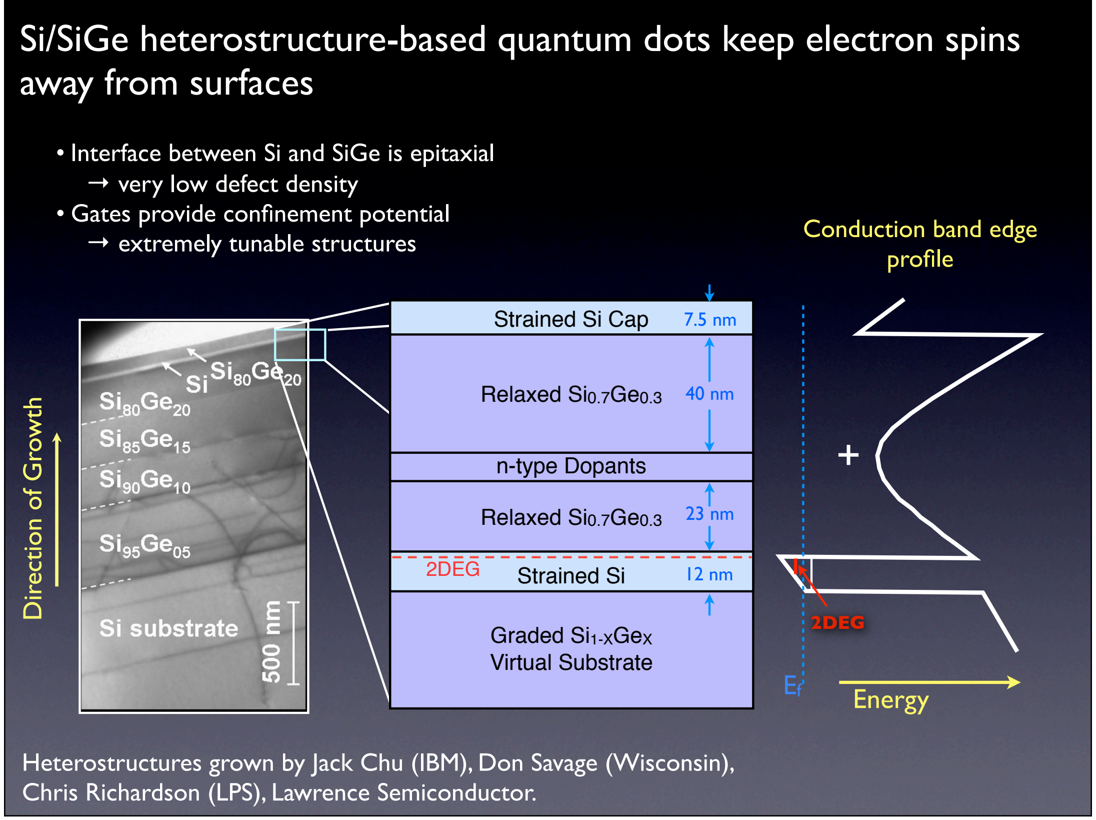
M. Fuechsle, et al. *Nat. Nanotech. 5*, 502 (2010)



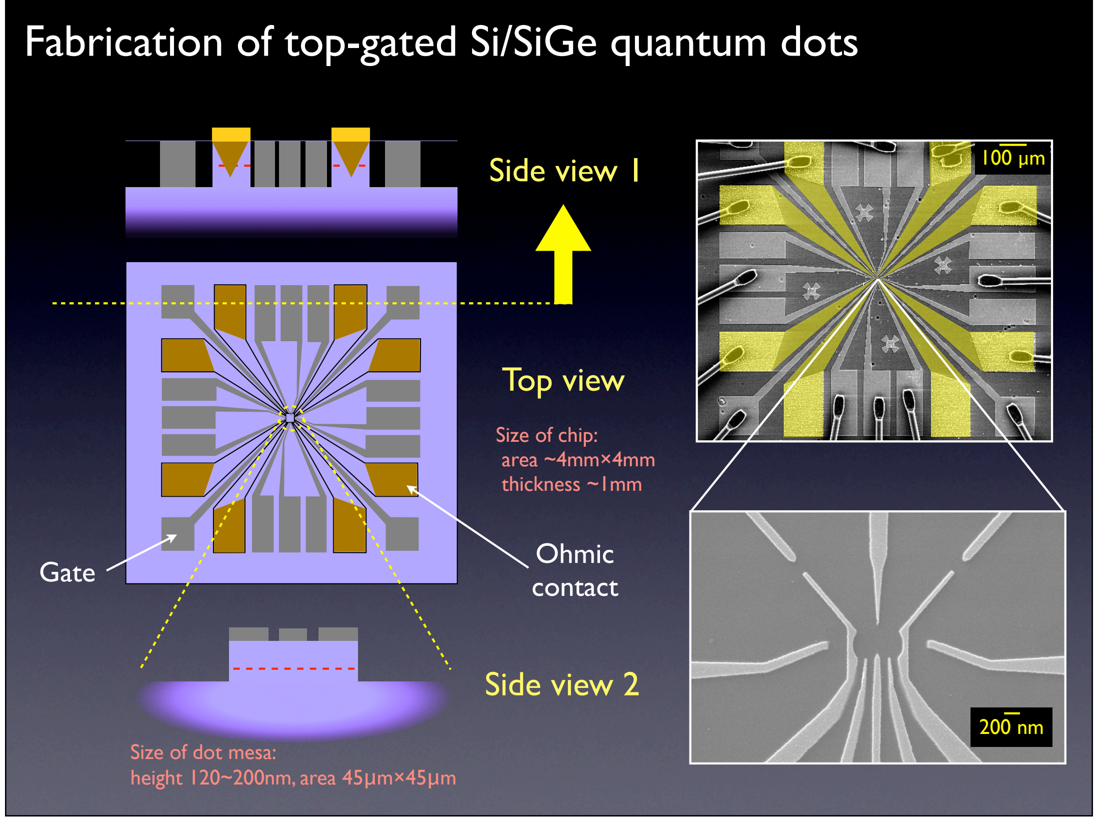
E. P. Nordberg, et al., *Physical Review B 80, 115331* (2009)



J. R. Prance, et al., appearing in *Phys. Rev. Lett.*



This is a schematic of the Si/SiGe heterostructure that we use in our experiment.Si is grown on the SiGe virtual substrate, followed by a relaxed SiGe buffer layer. The reason we use SiGe instead of pure Si is to strain the Si lattice so that resulted strained Si layer acts as a quantum well which confines electrons to 2-D. The structure is also delta doped with phosphorus so that electrons populate the well without being strongly scattered locally. Finally, we put a silicon cap layer after a second buffer to prevent humidity and water. The material is characterized to have a carrier density of ... and a mobility of...



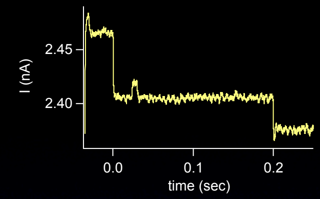
After we get the material, the device is fabricated first by etching a mesa with 2DEG, which is 45um by 45um large. We etch a small mesa to prevent leakage current between the gate and the 2DEG. Then we deposit Au/Sb as ohmic contact metal. The device is annealed after deposition to allow the metal to diffuse down to the 2DEG to make contact. After that, optical and e-beam gates are put down on the surface of the sample to deplete the 2DEG and form the quantum dot.

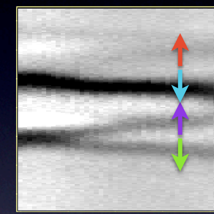
• Single-shot readout of single spins in Si/SiGe quantum dots

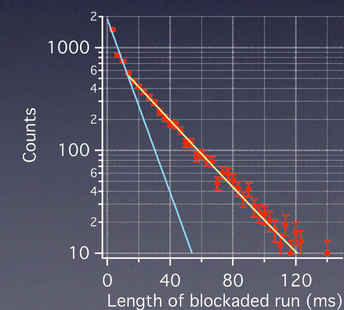
• Controllable loading of spin-up and spin-down states

• Controlling the tunnel coupling in Si/SiGe double quantum dots

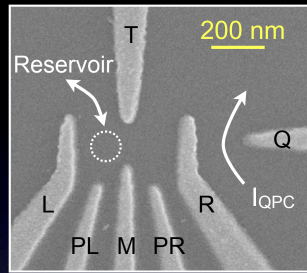
• Single-shot measurement of 2-electron singlet and triplet states

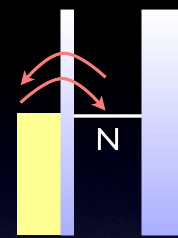






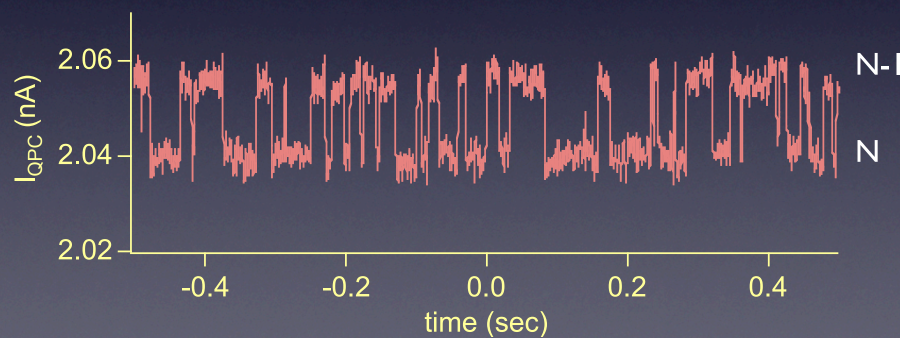
Real-time readout of dot occupation





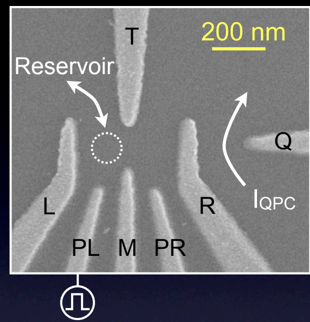
Distinct values of I_{QPC} for N and N-1 electrons on the quantum dot

Individual tunnel events observable



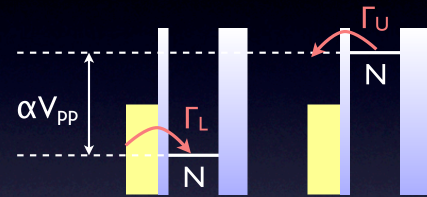
data: 092210

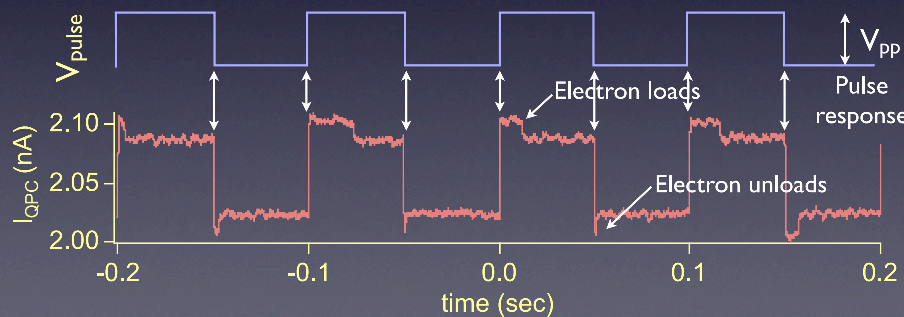
Single shot readout of electron tunneling



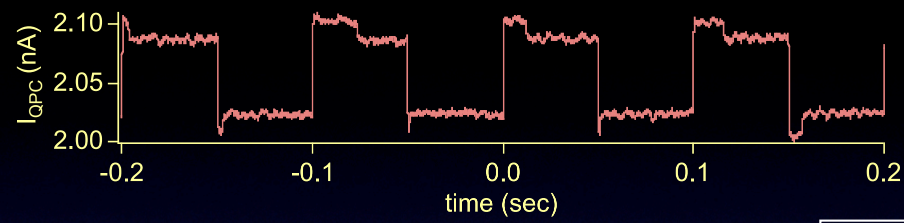
Pulsed gate voltage used to controllably load/unload a single electron

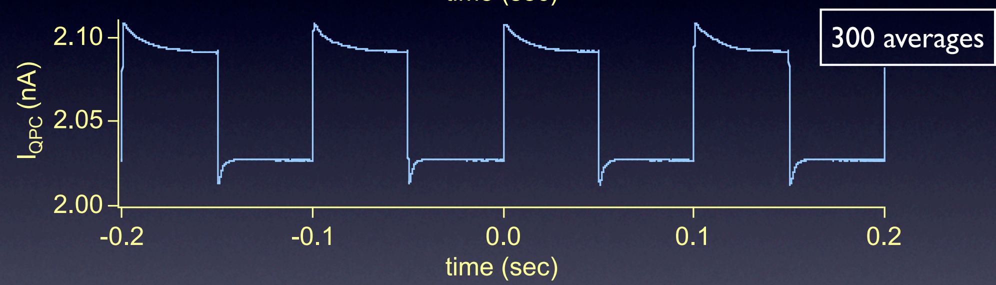
Time resolution: 1 ms





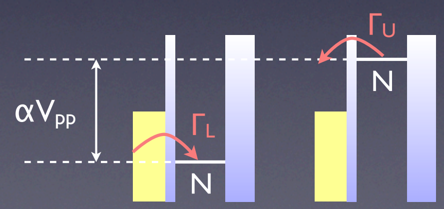
Measurement of electron tunneling rates



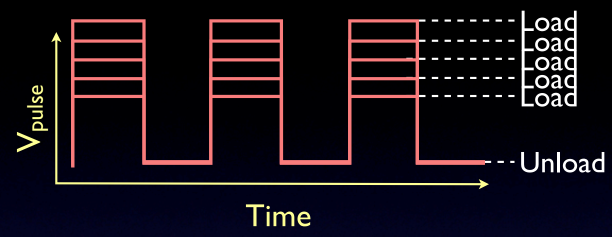


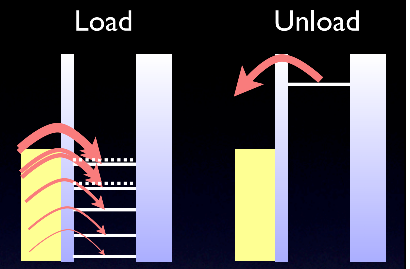
By averaging the single shot traces, we observe clear exponential decays indicating the electron tunnel rates

For the data shown here, Γ_L = 91 Hz and Γ_U = 590 Hz



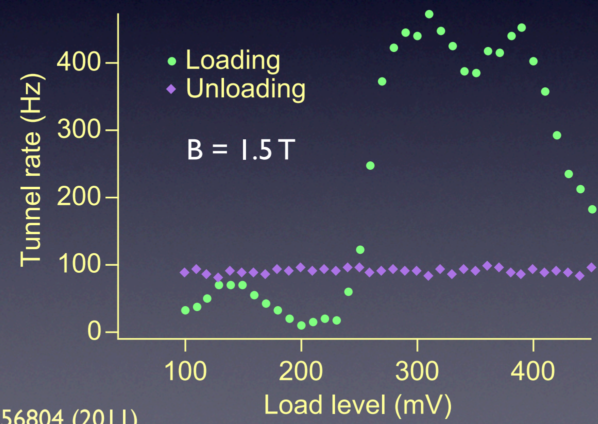
Tunneling rate excited state spectroscopy





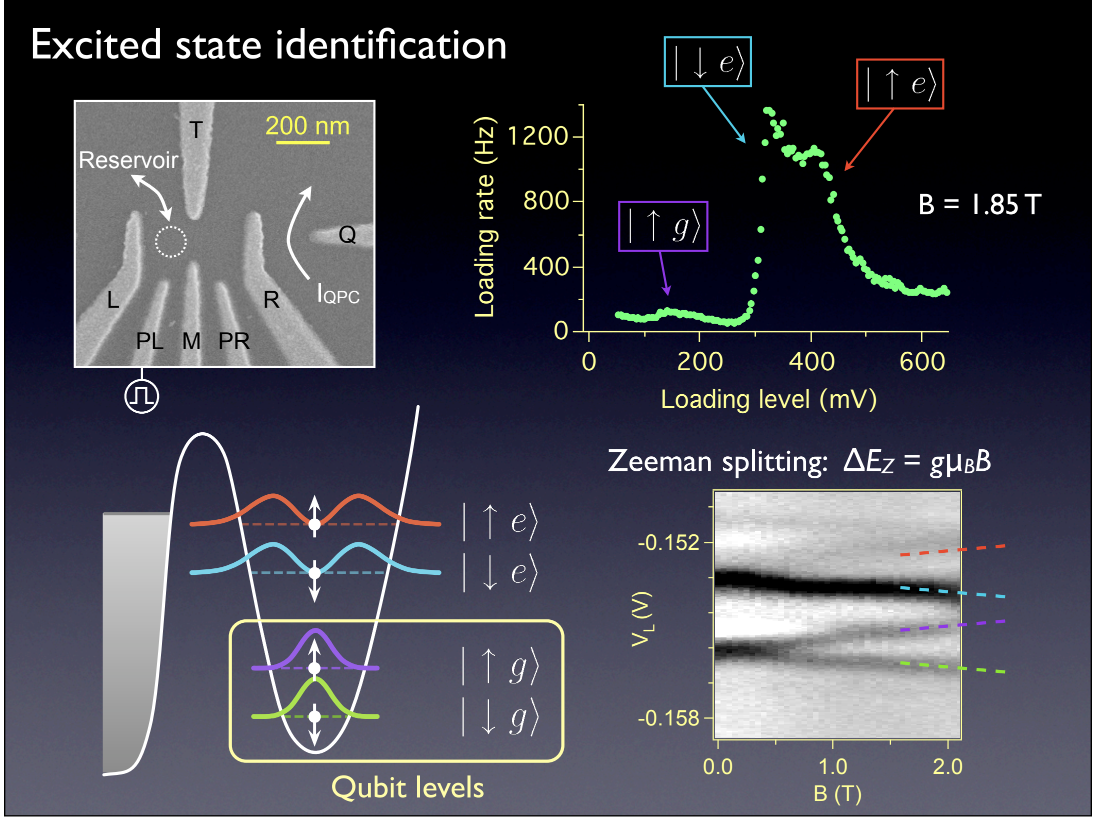
- Due to energy-dependent tunneling, Γ_L decreases as the loading level increases (energy decreases)
- Excited states act as additional, parallel loading channels

  ⇒ increase loading rate



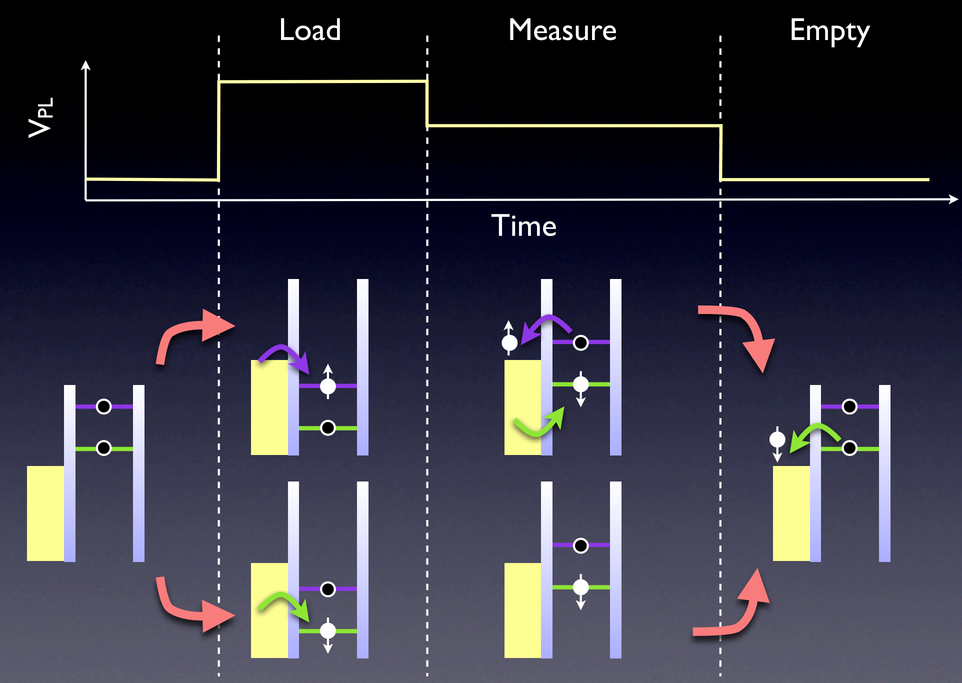
C. B. Simmons et al., *Phys. Rev. Lett.* 106, 156804 (2011).

data:072910

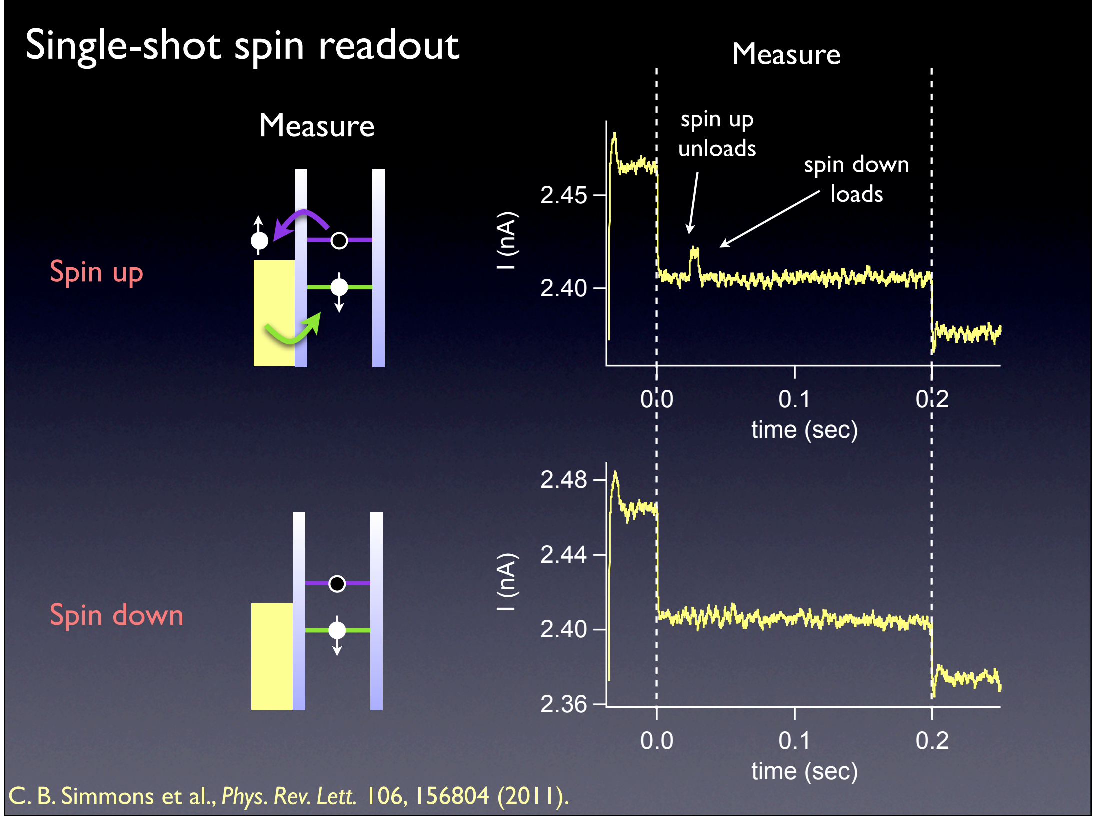


data: 070710 exported as 4.8 x 3.9 and bjornteckresultsforpaper

Single-shot spin readout

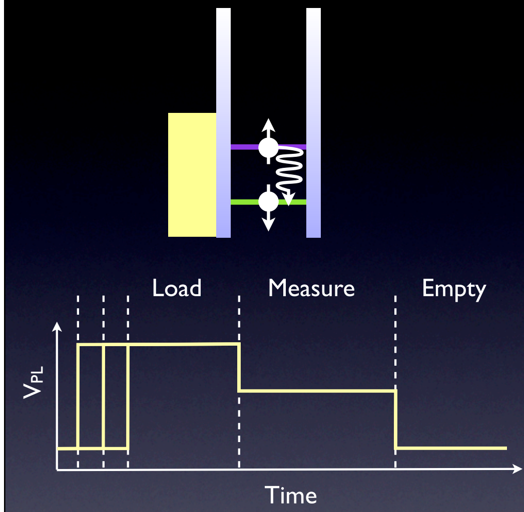


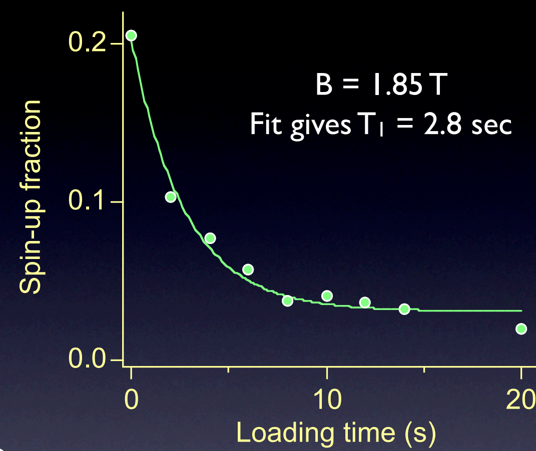
Spin readout scheme first demonstrated by: Elzerman et al. Nature (2004) vol. 430 pp. 431-435



data: 081110 exported as 4.5 x 2.8

T_1 spin relaxation measurement





- Interactions with the environment cause up spins to relax to down spins on the time scale T_1
- T_1 is determined by measuring the fraction of up spins as a function of the time electrons are held on the dot

C. B. Simmons et al., *Phys. Rev. Lett.* 106, 156804 (2011).

data: bjornteckresultsforpaper 5x4

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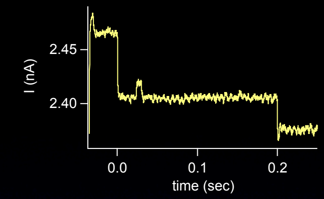
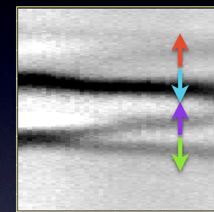
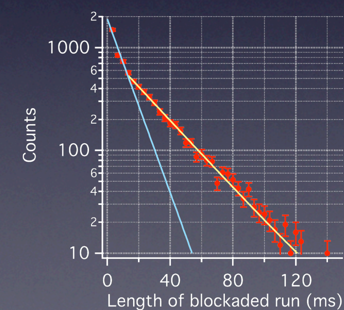


• Controllable loading of spin-up and spin-down states

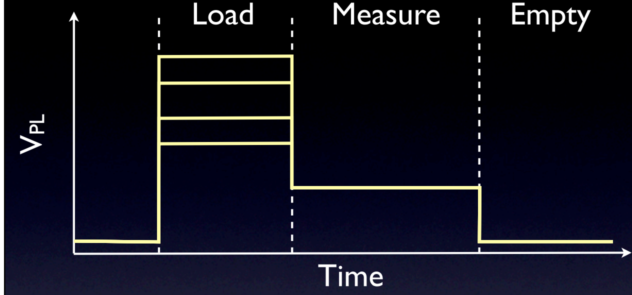


• Controlling the tunnel coupling in Si/SiGe double quantum dots

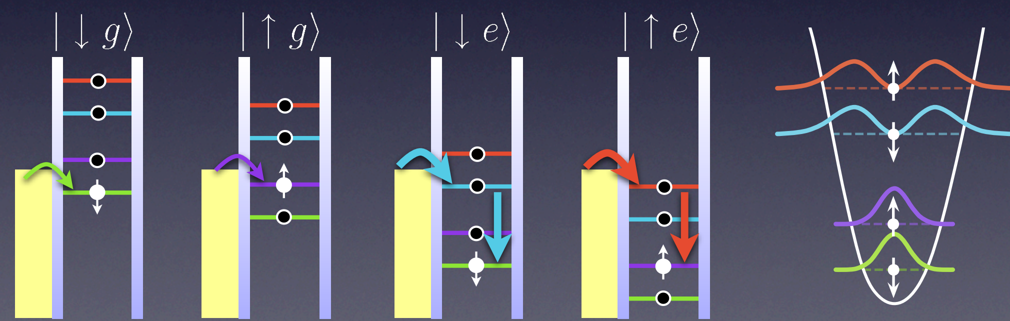
• Single-shot measurement of 2-electron singlet and triplet states



Tunable loading



- Loading rates into specific spin states are a maximum when the state is near resonance with the Fermi level
- Tuning the loading level allows for preferential loading
- Orbital relaxation is very fast compared to the experimental time scale

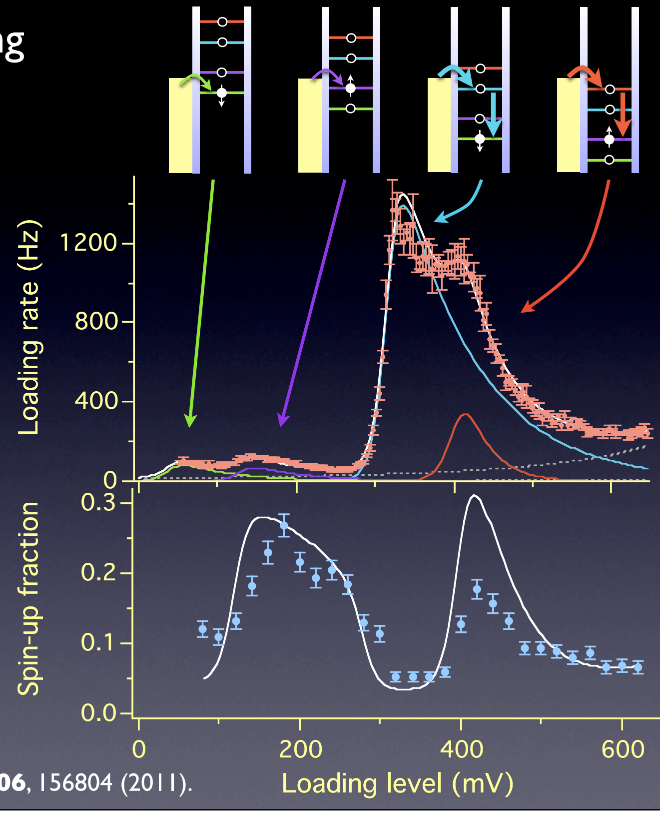


Spin-selective loading

- Spin-up fraction measured by single-shot spin readout
- Probability of loading spin-up:

$$\Gamma_{\uparrow}/\Gamma_{L}$$

- $\Gamma_{\uparrow}$ is the sum of the rates for all spin-up channels
- Γ_{L} is the total loading rate
- The two peaks in the spin-up fraction correspond to $|\uparrow g\rangle$ and $|\uparrow e\rangle$



C. B. Simmons et al., *Phys. Rev. Lett.* **106**, 156804 (2011).

data: bjornteckresultsforpaper 6.2x3.7,6.2x3

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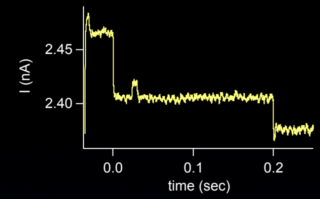
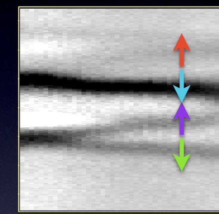
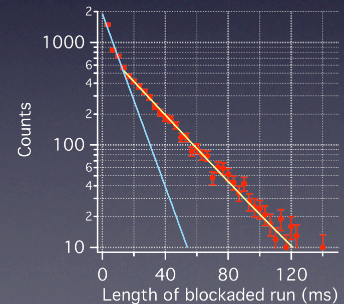
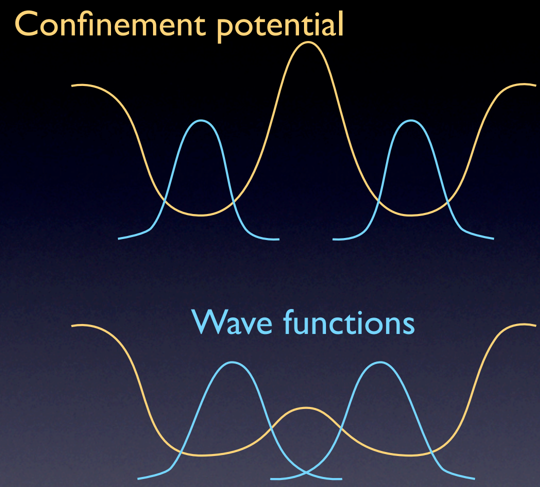






Control of wavefunction overlap enables qubit operations



Large tunnel barrier:

⇒ small overlap
⇒ weak exchange coupling

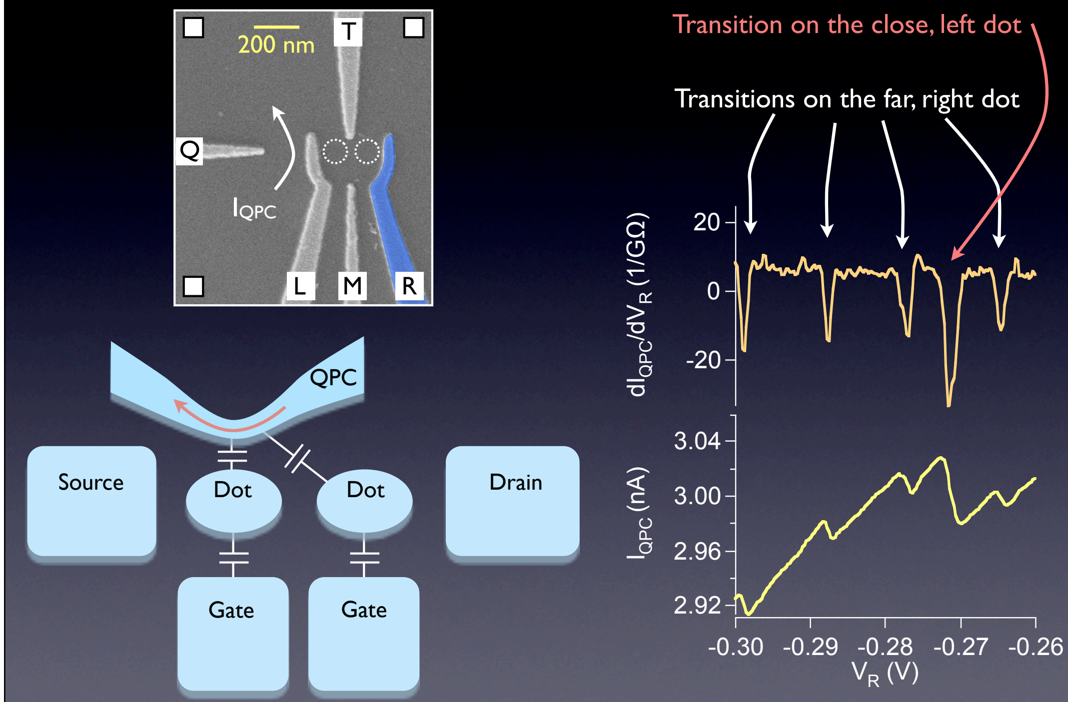
Small tunnel barrier:

⇒ large overlap
⇒ strong exchange coupling

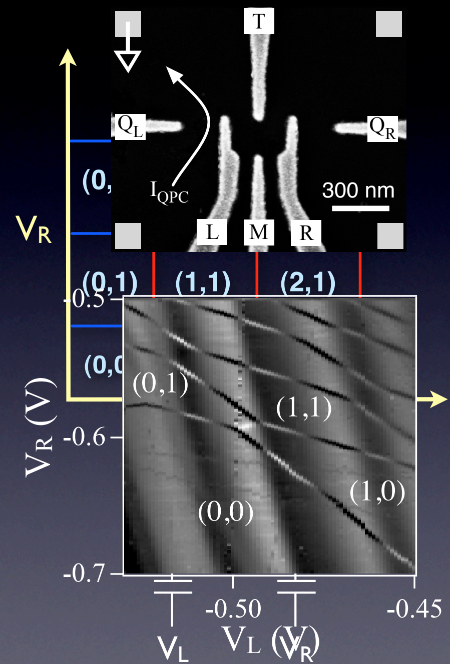
Applications of exchange coupling:

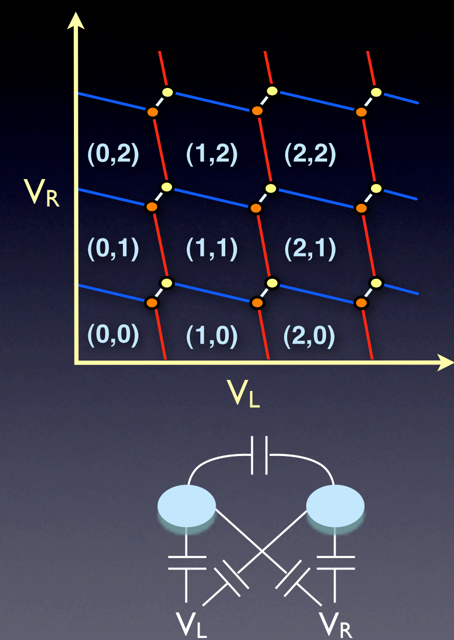
- SWAP gate (1-electron qubits): D. Loss & D.P. DiVincenzo Phys. Rev. A 57, 120 (1998).
- Z-rotations (2-electron qubits): Petta et al., Science 309, 2180 (2005).

Double quantum dot schematic and charge sensing



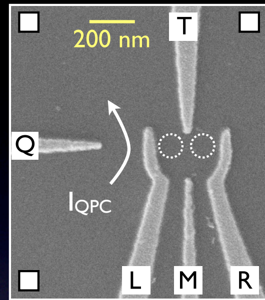
Double dot charge stability diagram: single electron occupation





M. Thalakulam, et al., *Appl. Phys. Lett.* **96**, 183104 (2010)

Interdot charge transition is tunable

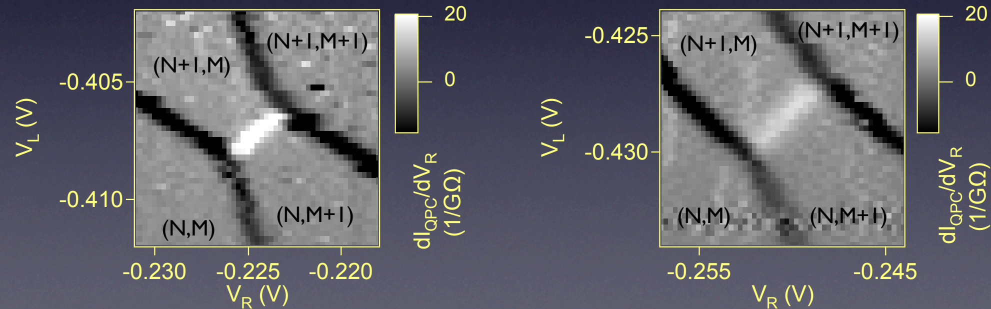


Tunnel coupling controlled with the voltage on the middle gate (M)

Stronger tunnel coupling broadens the interdot charge transition

Weak tunnel coupling:
$V_M = -1.0$ V

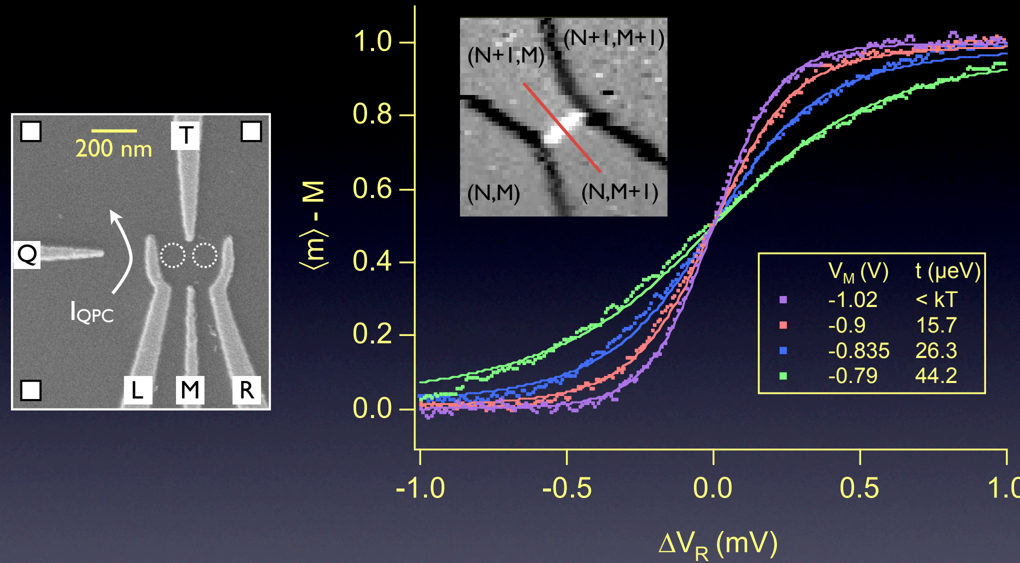
Strong tunnel coupling:
$V_M = -0.825$ V



C. B. Simmons et al., *Nano Letters* **9**, 3234 (2009)

data: 111308 and 111408

Demonstration of tunable tunnel coupling

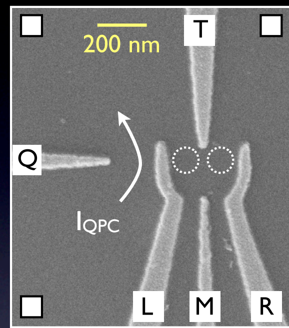


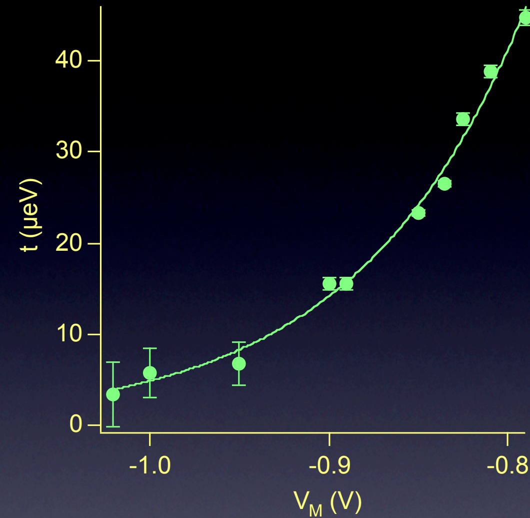
- Data cuts along the detuning diagonal show the interdot transition of a single electron
- The charge transition is visibly broader when V_M is more positive
- The tunnel coupling, t, is extracted from fits to these curves

C. B. Simmons et al., *Nano Letters* **9**, 3234 (2009)

plots from: TunnelCouplingAnalysisNew

Demonstration of tunable tunnel coupling





- The tunnel coupling, t, is an exponential function of V_M
- t varies by a factor >10 ⟹ J varies by a factor >100

⟹ SWAP operation time: 110 ns to 590 ps

C. B. Simmons et al., *Nano Letters* **9**, 3234 (2009)

J = 4t2/EC
Ec~2.3meV
t: ~3.3ueV to ~45ueV
thus J: 19 neV to 3.5 ueV
SWAP time = hbar*pi/J
thus SWAP time: 110 ns to 590 ps

plots from: TunnelCouplingAnalysisNew

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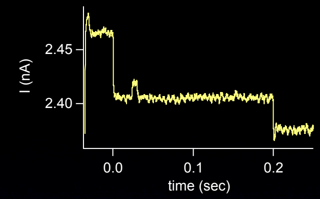
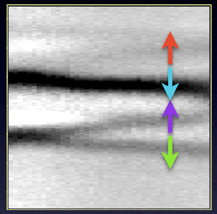
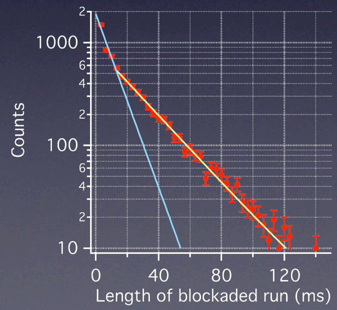
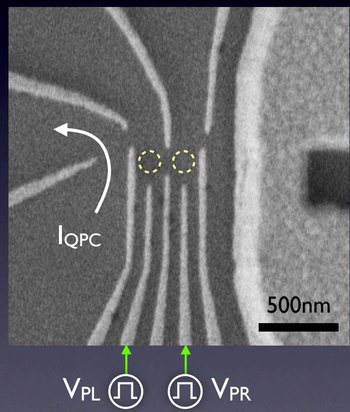
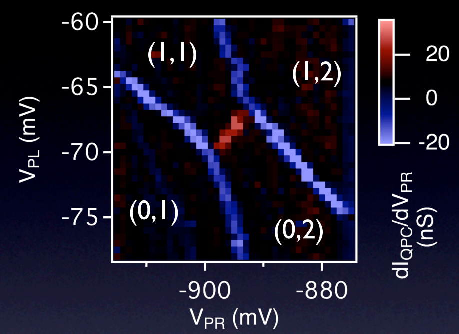


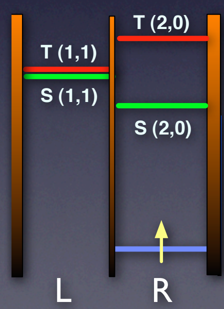




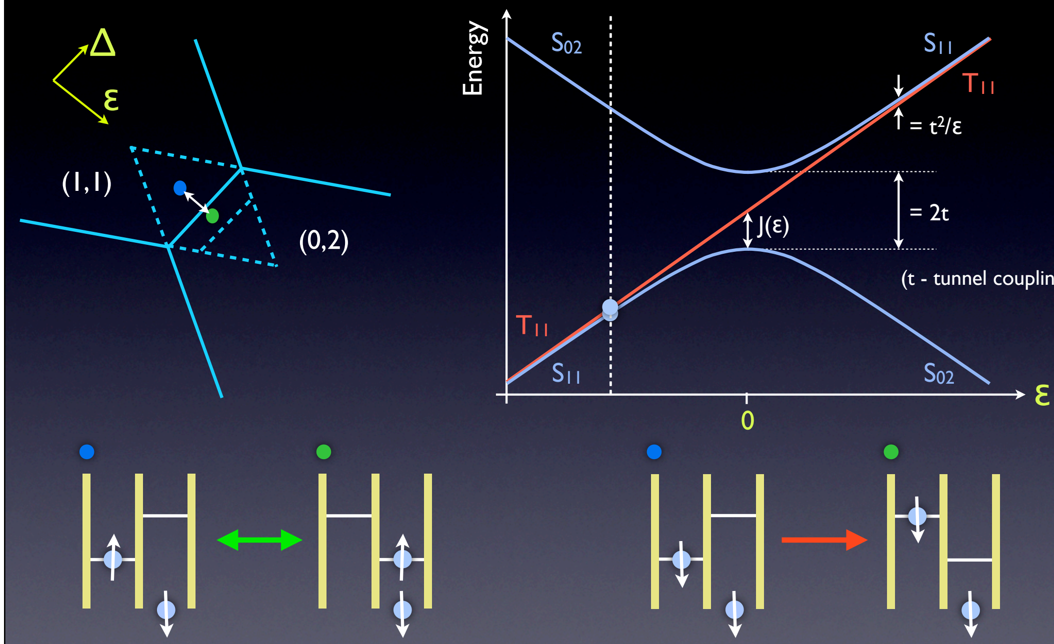
Singlet and triplet states in a 2-electron double quantum dot







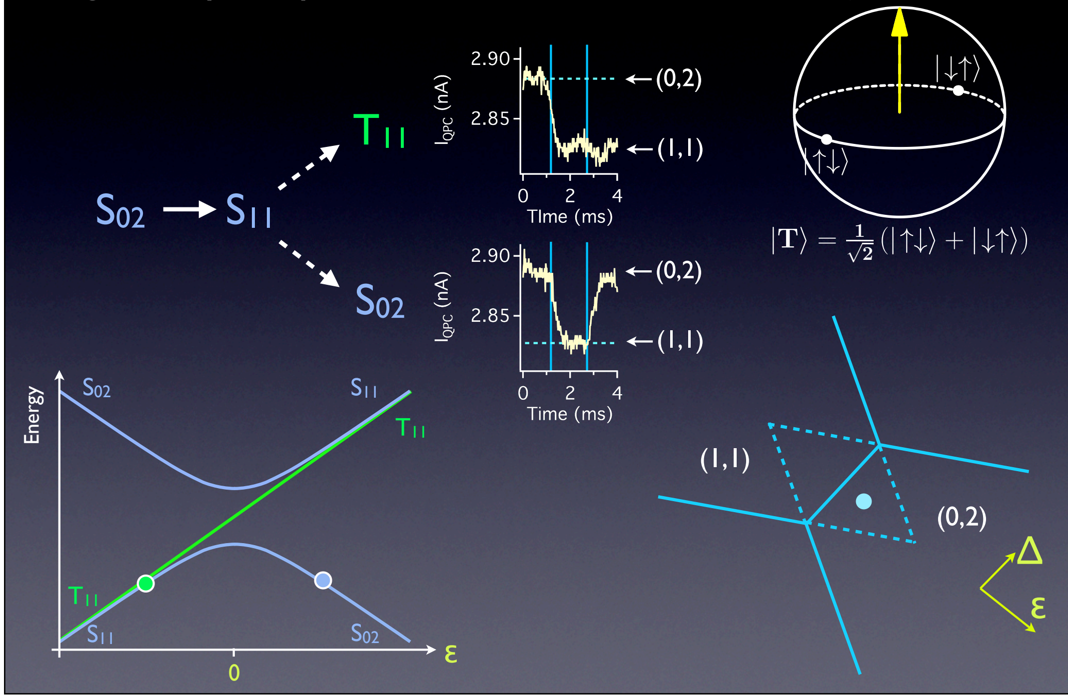
Probing spin blockade with detuning pulses



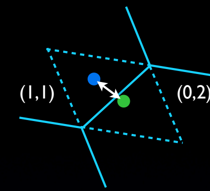
Transitions between (1,1) and (0,2) singlets are always allowed

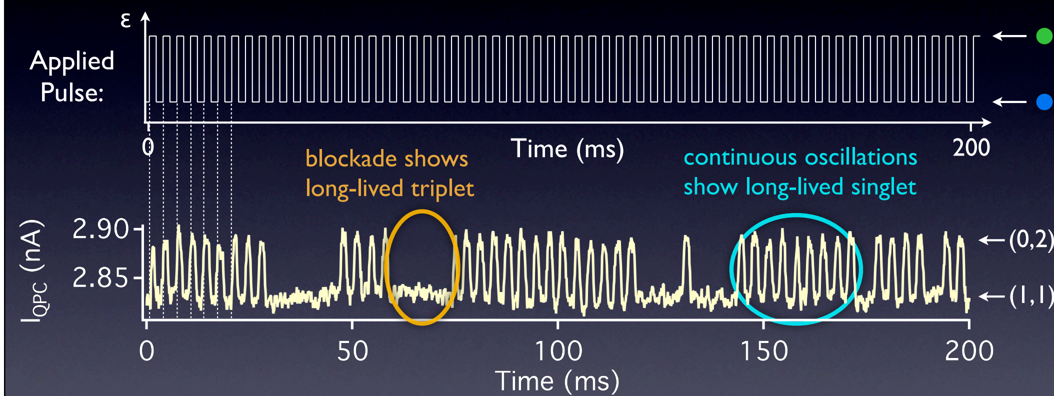
Triplets cannot transition to (0,2). (Pauli blockade)

Initialization and single-shot readout of singlet-triplet qubit states



Repeated pulses show evidence of long-lived triplets



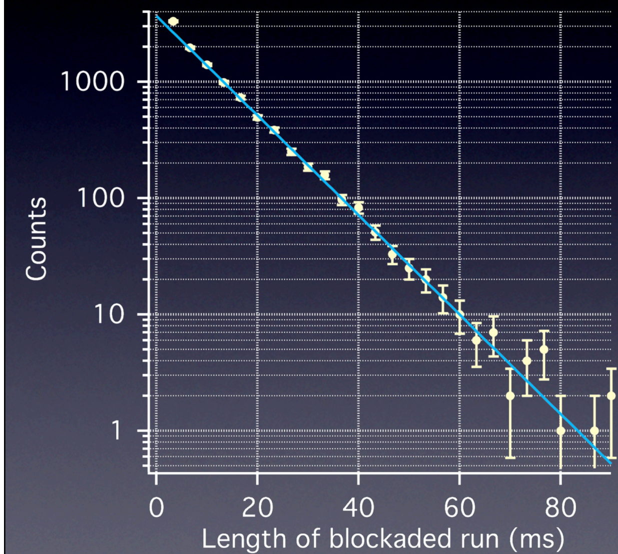


B = 0 T
Pulse frequency = 300 Hz

J. Prance, et al., ArXiv:1110.6431
(accepted for publication in Phys. Rev. Lett.)

Statistics of blockade signals quantify the triplet-singlet relaxation time.

Statistics from 6.4 minutes of real-time data
(115,200 pulse cycles):



Fitted exponential decay at zero magnetic field:

Triplet lifetime = 9.5 ms

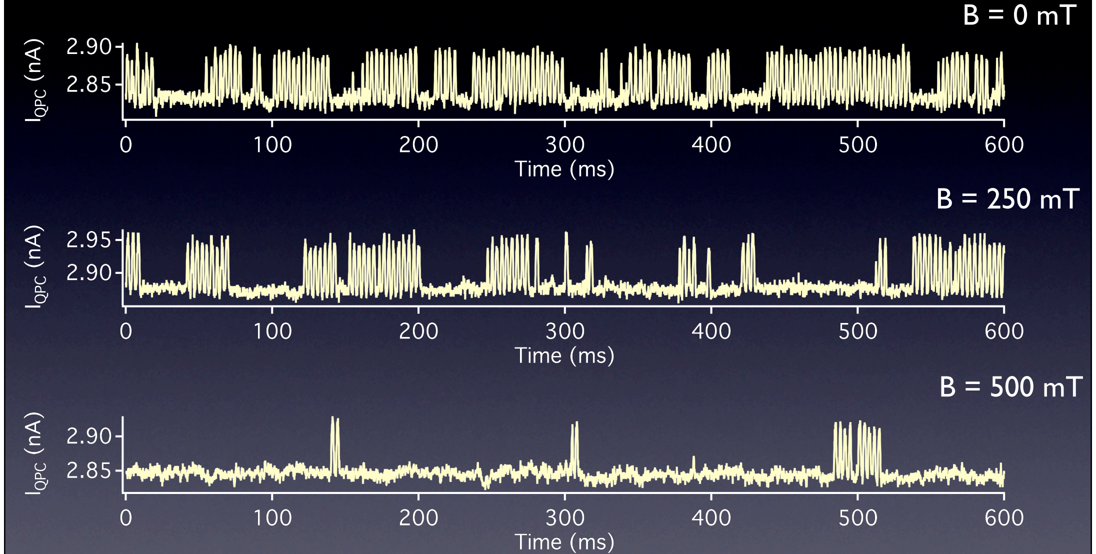
~1000 times longer than in GaAs [1]

B = 0 T
Pulse frequency = 300 Hz

[1] Johnson et al., Naure 435, 925 (2005)

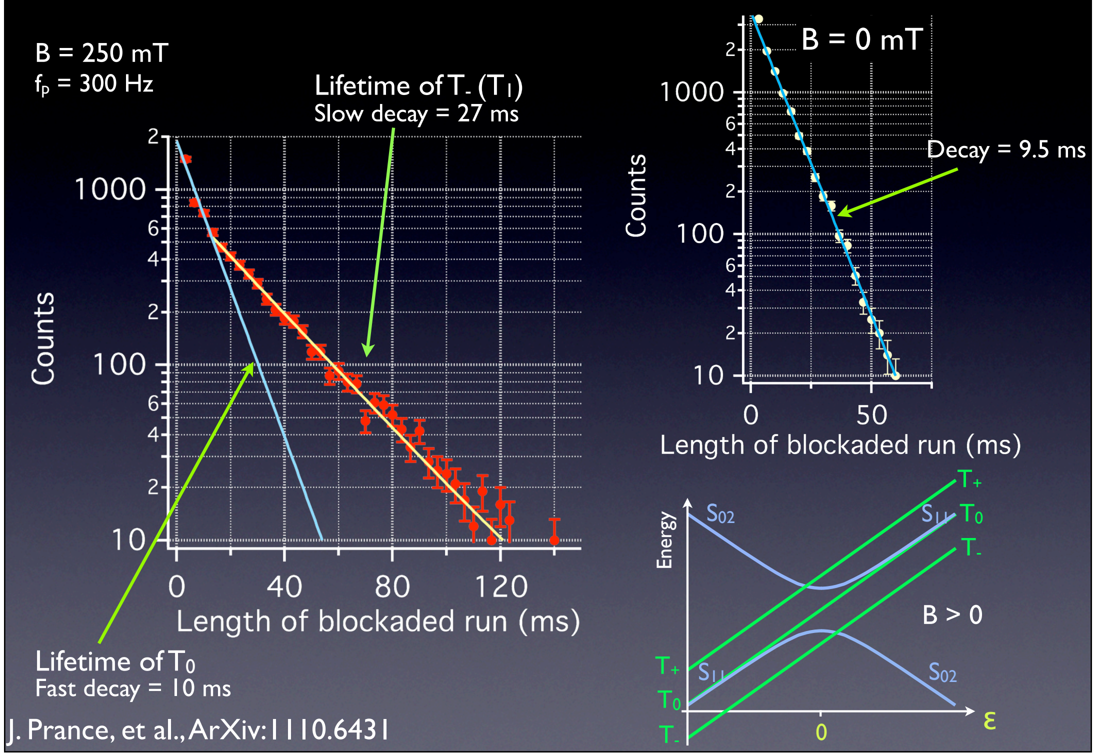
Lifetime of blockaded runs increases with field

f_p = 300 Hz



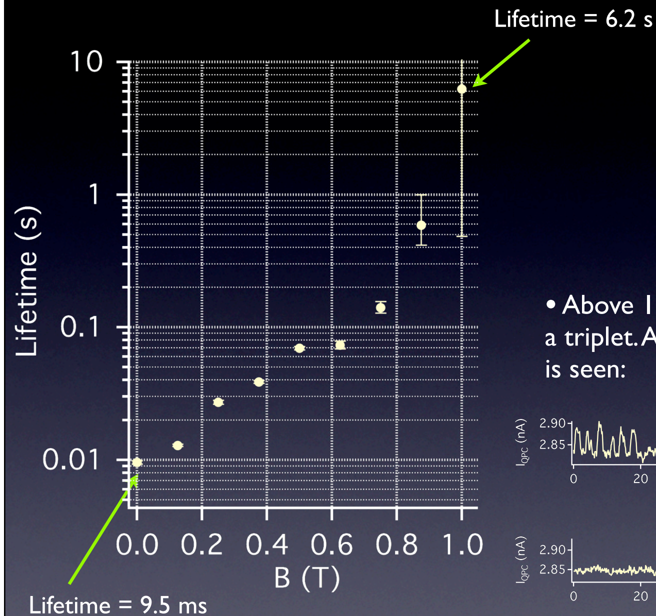
J. Prance, et al., ArXiv:1110.6431

Non-zero B: two different rates are observed

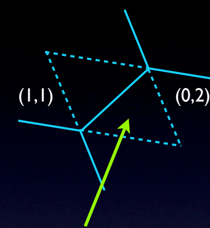


J. Prance, et al., ArXiv:1110.6431

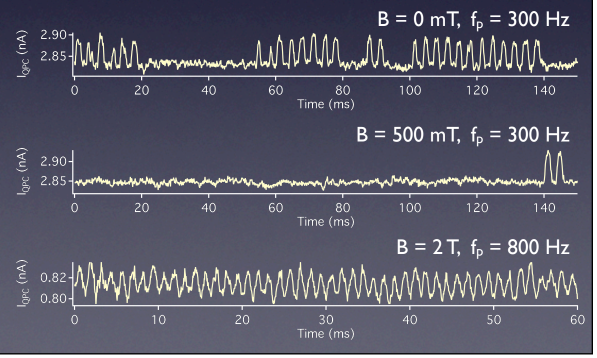
T_- (1,1) lifetime as a function of magnetic field



Pulse frequency f_p = 300 Hz



- Above 1.5 T the (0,2) ground state becomes a triplet. After this, only free charge-shuttling is seen:



J. Prance, et al., ArXiv:1110.6431

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Lieven Vandersypen

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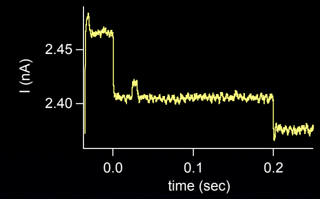
qc.physics.wisc.edu

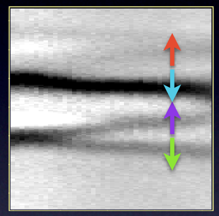
• Single-shot readout of single spins in Si/SiGe quantum dots

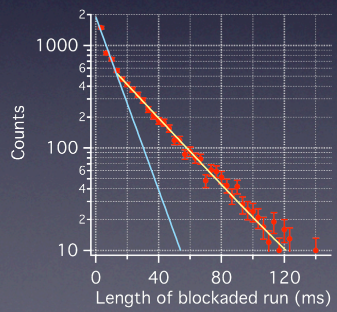
• Controllable loading of spin-up and spin-down states

• Controlling the tunnel coupling in Si/SiGe double quantum dots

• Single-shot measurement of 2-electron singlet and triplet states



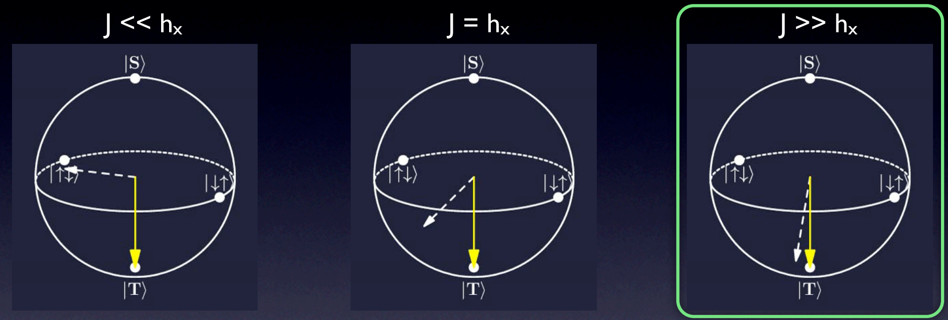


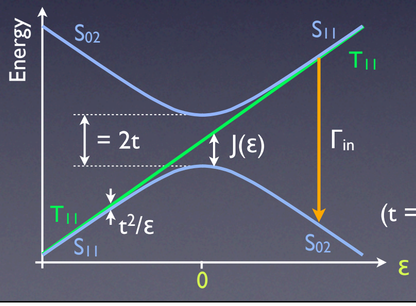


Interpretation of triplet lifetime at B = 0

For small exchange (J), hyperfine coupling to nuclei (h_x) should drive singlet-triplet mixing [1]

Large J reduces the effectiveness of hyperfine mixing





$$\Gamma = \Gamma_{in}\left(\frac{h_x^2}{h_x^2+J^2}\right)$$

(t = tunnel coupling)

[1] Assali et al., PRB 83, 165301 (2011)

Outline

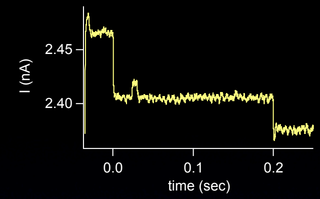
- Single-shot readout of single spins in Si/SiGe quantum dots

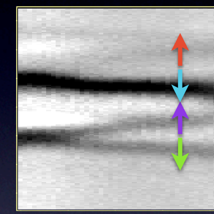
- Controllable loading of spin-up and spin-down states

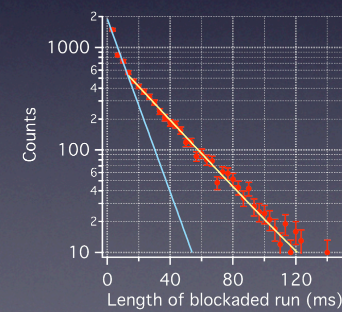
- Controlling the tunnel coupling in Si/SiGe double quantum dots

- Single-shot measurement of 2-electron singlet and triplet states

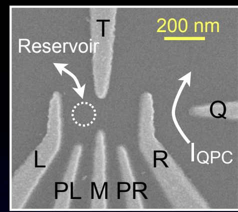
- Controlling the singlet-triplet energy splitting in Si/SiGe double quantum dots.

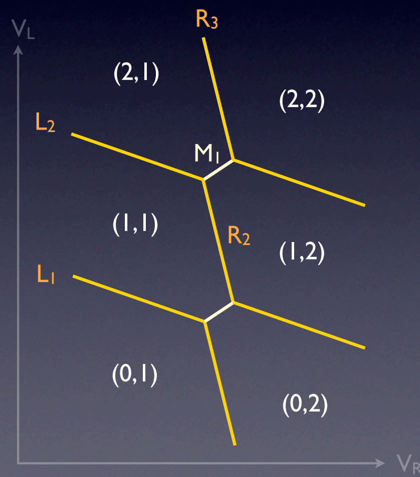


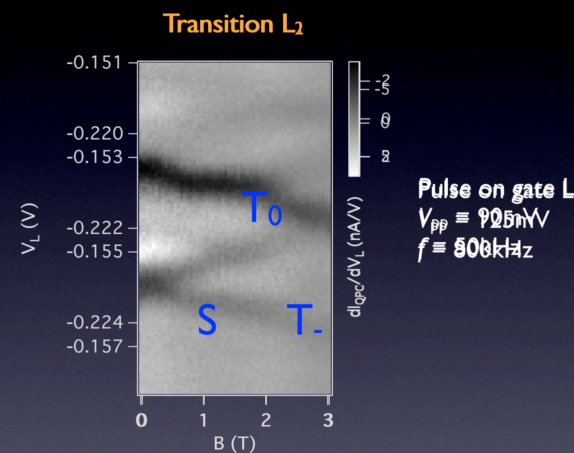




Magnetospectroscopy is very useful for state identification

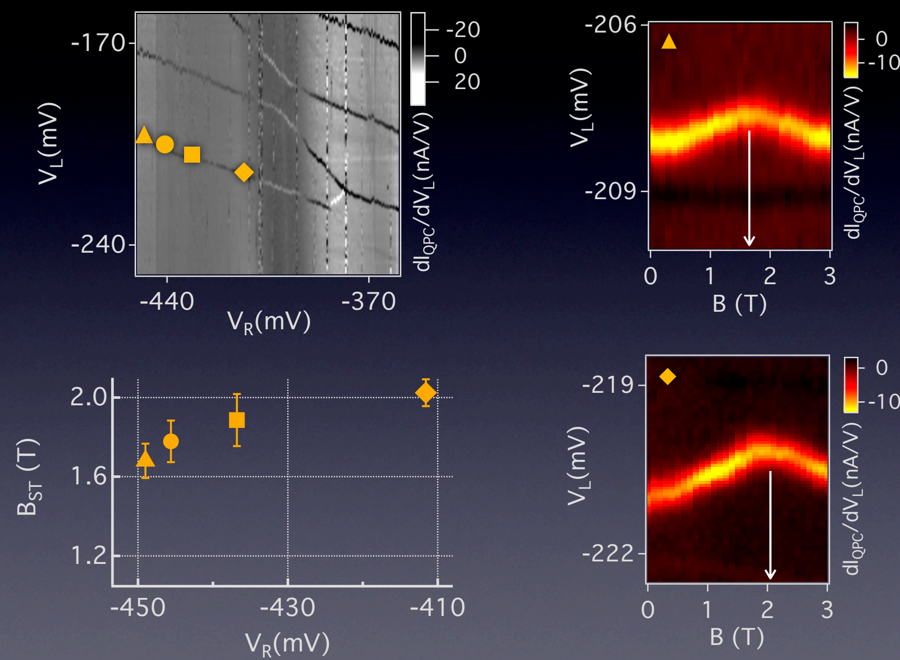






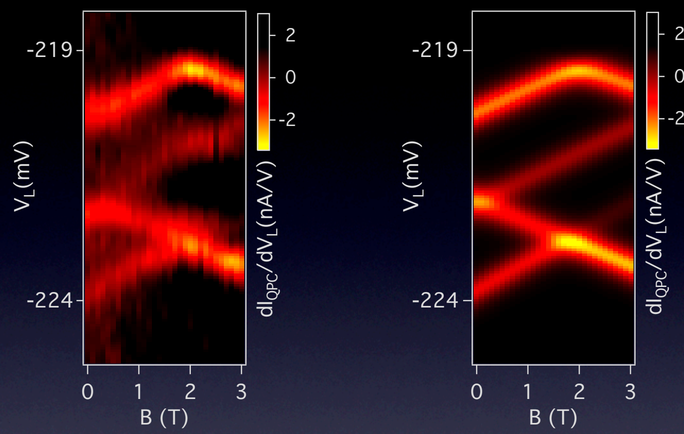
- Transition L_1, L_2 are effective transitions of 0 to 1 and 1 to 2 in the left dot

Gate voltages can control singlet-triplet splitting



Z. Shi et al., ArXiv: 1109.0511

Extracting tunnel rates by fitting the data to rate equations



Loading rates:

$\Gamma_L^S = 45.1kHz$

$\Gamma_L^{T_-} = 216kHz$

$\Gamma_L^{T_0} = 377kHz$

Unloading rates:

$\Gamma_U^S = 164kHz$

$\Gamma_U^{T_-} = 354kHz$

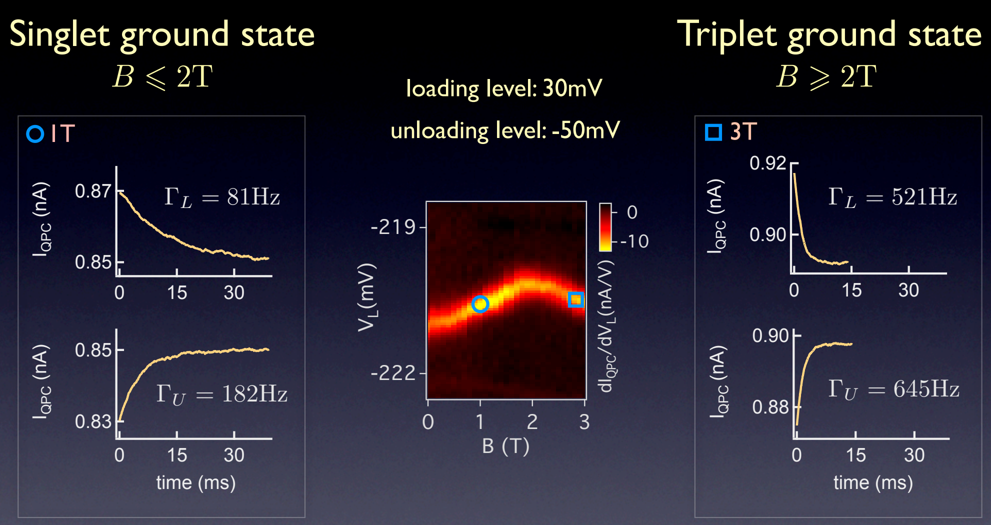
$\Gamma_U^{T_0} = 183kHz$

Theoretical simulation performed using coupled rate equation model:

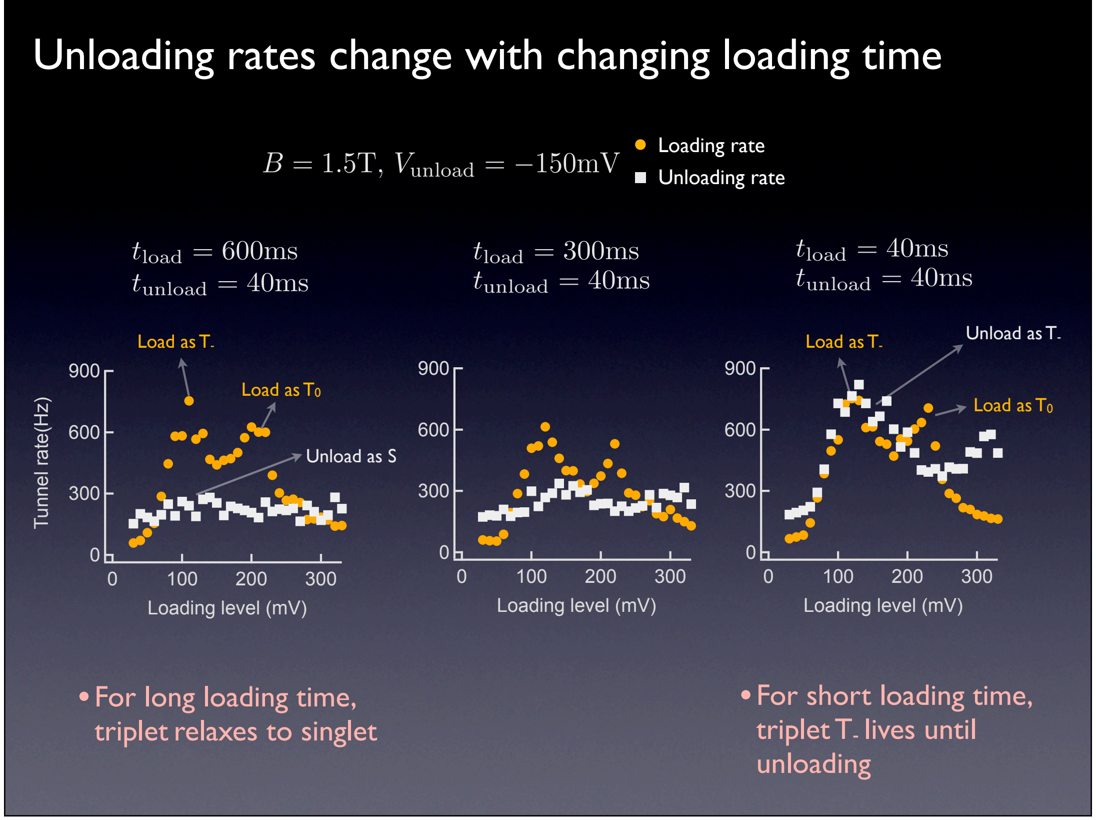
$$\frac{dp_S}{dt} = (1 - \sum_{i=S,T} p_i)\Gamma_S^L \qquad \frac{dp_{T_k}}{dt} = (1 - \sum_{i=S,T} p_i)\Gamma_{T_k}^L \quad (k = -, 0, +)$$

Z. Shi et al., ArXiv: 1109.0511

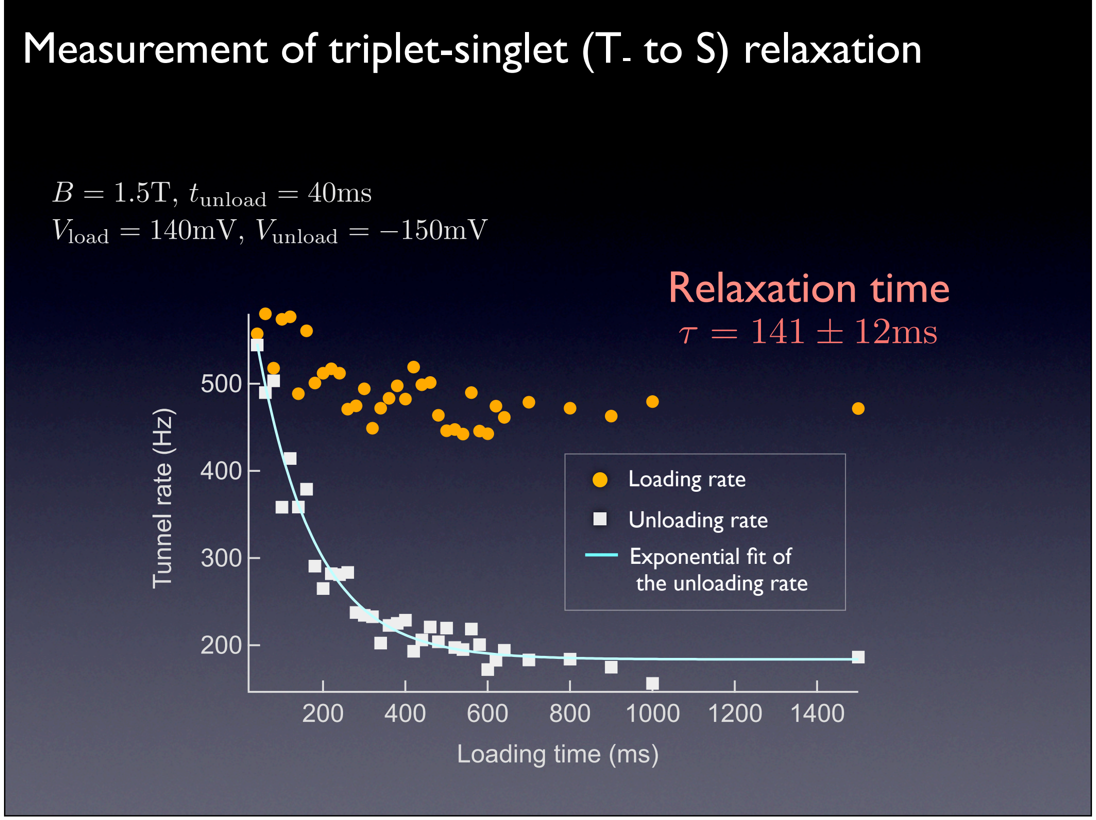
Field dependance of ground state loading/unloading rates



Triplet state loads and unloads much faster than singlet, providing a way to perform spectroscopy and lifetime measurement.

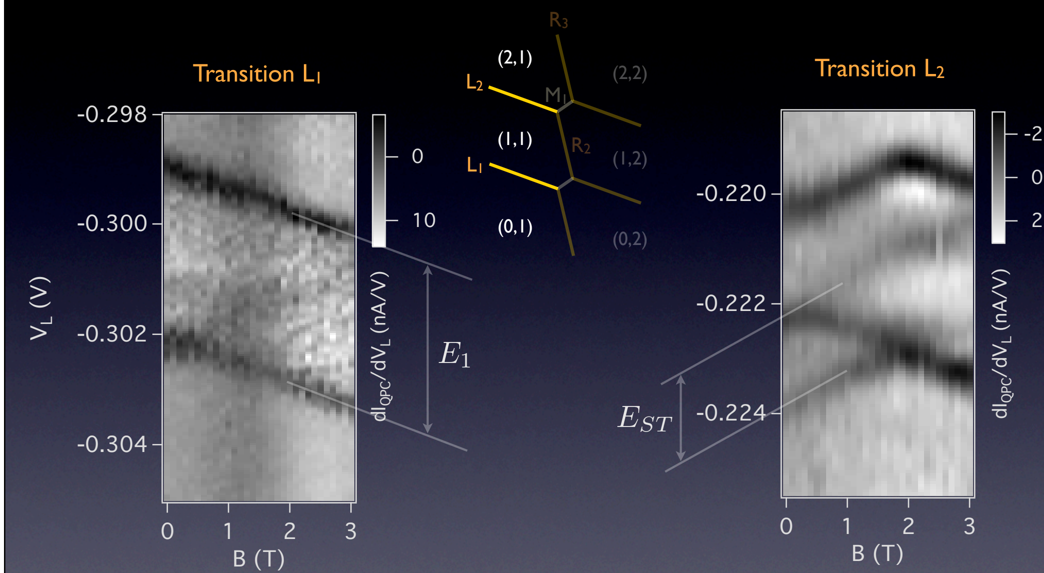


Then the next thing we do is we sit at a certain field, say 1.5 T, and we keep the unloading level constant and change the loading level, and see how the loading and unloading rate change as a function of loading level. Here is an example. At 1.5 T the ground state is still singlet, and it is slow. As we increase the loading depth we see two peaks in the loading rate, which we believe is the T− state and T0 state being pulsed down the fermi level. And the unloading rate does not change with the loading level, which indicates the electron always unload from the same state, the singlet. Since the loading time here is 600ms, which is relatively long, even if we load the T− and T0, they decay to the singlet quickly so the electron always unloads from the singlet. So a natural thought is if we make the load time short so that electron loading to the T−and T0 doesn't decay, will we see a change in the unloading rate?
Then, we change the loading time to be 300ms and do the same thing, we discover that there is a little bump in the unloading rate when we preferably load T−. Then, if we make the loading time 40ms, we see a peak in the unloading rate when we load the T−.
The decay from T− to S is a T1 process, since there is a big difference in the unloading rate between S and T−, if we sit at a loading level where we preferably load T− and we change the loading time and see how the unloading rate change, we should be able to get T1



So we sit at a loading level of 140mV, we vary the loading time and see how the unloading rate change as a function of loading time. Here we see the loading rate doesn't change much with the loading time but the unloading rate decays exponentially with the increase of loading time. And the fit gives us the characteristic time of this decay, 141ms, which we believe is T1.

Extracting exchange energy using magnetospectroscopy



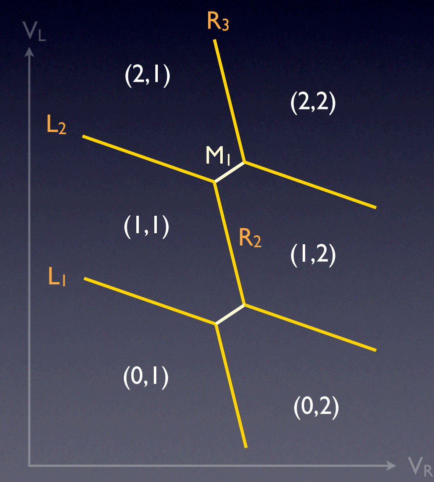
$E_1 = 3.24 \pm 0.02$ mV

$E_{ST} = 1.57 \pm 0.02$ mV

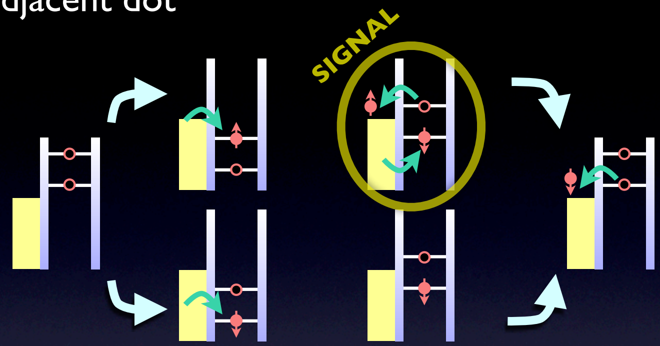
$J = 1.67 \pm 0.4\text{mV} \Rightarrow 209 \pm 11\mu\text{eV}$

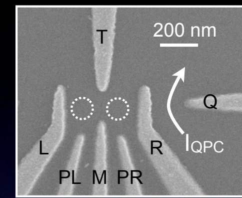
S. N. Coppersmith and collaborators: new spin qubit proposal using (2,1)-(1,2) electron occupation states in a double quantum dot.

ArXiv:1110.6622

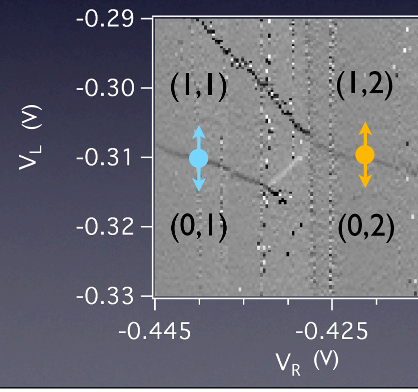


Single-shot T_1 measurement with/without an extra spin in the adjacent dot





Right dot occupation	Measured T_1 values
1	164 ms, 156 ms
2	97 ms, 114 ms



$B_{||}$ = 1.85 T

Conclusions

- The spin state of a two-electron double dot was read out in real-time

- Statistical analysis of the real-time data gives the lifetime of the (1,1) triplet states.

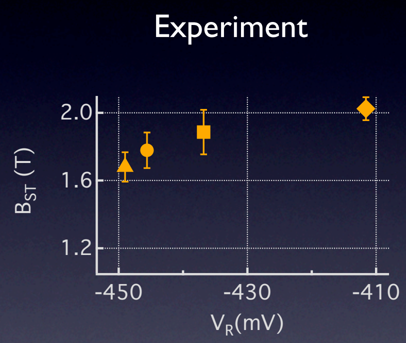
- The lifetime of the T_- (1,1) state was seen to increase with applied magnetic field, reaching ~6s at 1T.

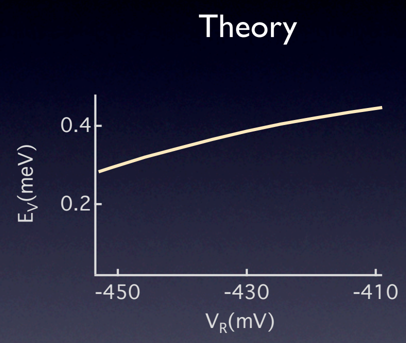
- At B = 0T, the triplet lifetime is ~10ms.

- We attribute the long, zero-field lifetime to a strong coupling between the dots. This suppresses the effect of hyperfine induced singlet-triplet mixing close to the (1,1)-(0,2) transition.

- The singlet-triplet splitting is tunable by gate voltages in Si/SiGe double quantum dots

Valley splitting changed by displacement of the dot





Quantum logic gate: SWAP

Qubit operations performed by controlling the exchange coupling, J, as a function of time

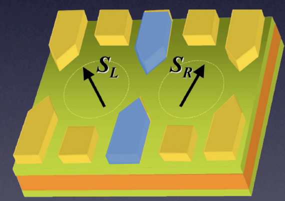
$$|\uparrow\downarrow\rangle \overset{\text{SWAP}}{\Rightarrow} |\downarrow\uparrow\rangle$$

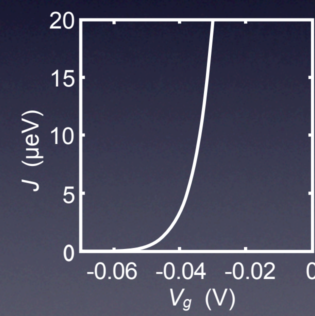
$$\int J[V(t)]dt = \pi\hbar \ (\text{mod}2\pi)$$

Control J using tunnel coupling, t:

$J = 4t^2/E_C$

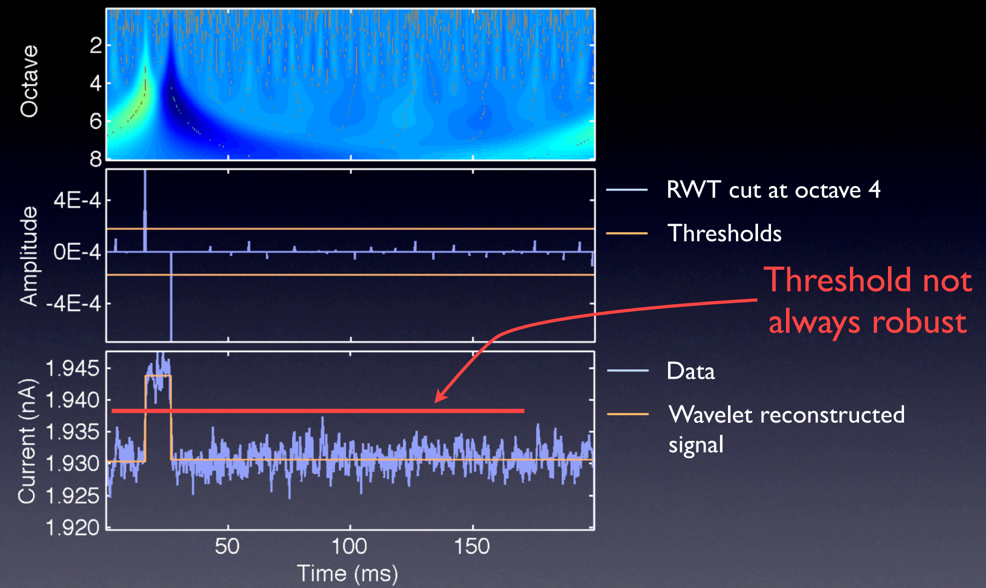
E_C is the charging energy





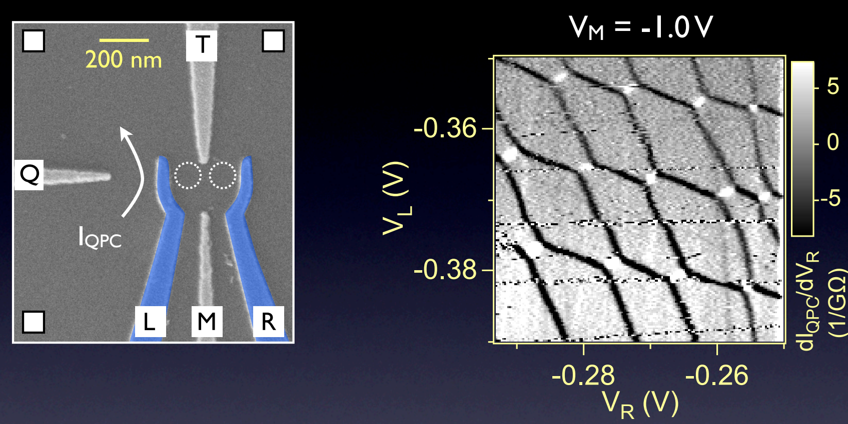
D. Loss & D.P. DiVincenzo Phys. Rev. A 57, 120 (1998).

Event detection using the real wavelet transformation



Algorithm: 1) Calculate the Real Wavelet Transform and its modulus maxima
2) Take a cut of the RWT at a course scale and select maxima
3) Trace maxima to finest scale

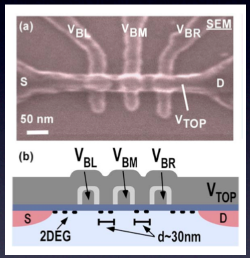
Double dot charge stability diagram



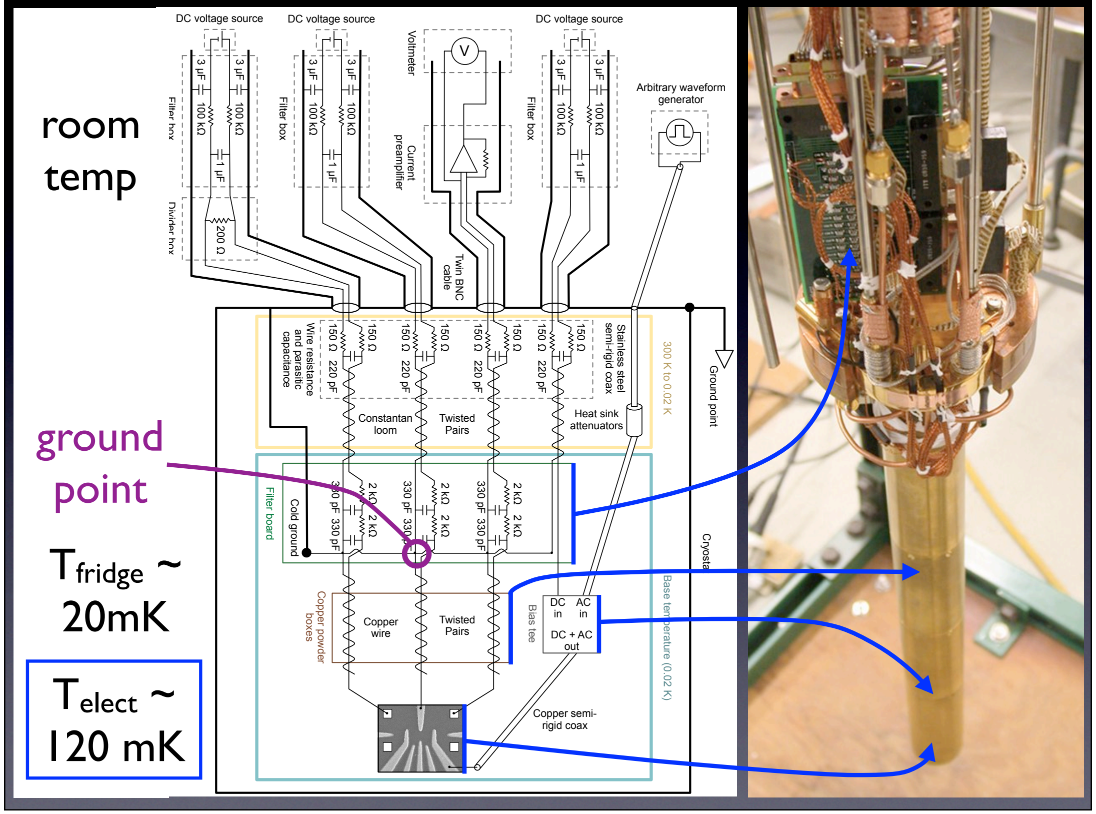
- Measure dI_{QPC}/dV to identify charge transitions as a function of the left (L) and right (R) gate voltages

- Black and white lines indicate charge transitions on the double quantum dot

data: 101108



Lim, W. H., *Applied Physics Letters 94*, 173502 (2009)

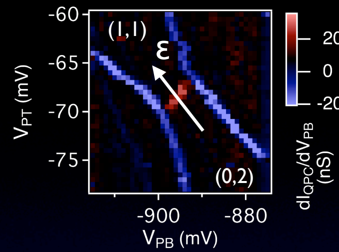


room temp
ground point
T fridge ~ 20mK
T elect ~ 120 mK
DC voltage source
DC voltage source
Voltmeter
DC voltage source
Arbitrary waveform generator
Filter box
Divider box
Current preamplifier
Twin BNC cable
Ground point
Wire resistance and parasitic capacitance
Stainless steel semi-rigid coax
300 K to 0.02 K
Constantan loom
Twisted Pairs
Heat sink attenuators
Filter board
Cold ground
Cryostat
Base temperature (0.02 K)
Copper powder boxes
Copper wire
Twisted Pairs
Bias tee
DC in
AC in
DC + AC out
Copper semi-rigid coax

Time-averaged charge state

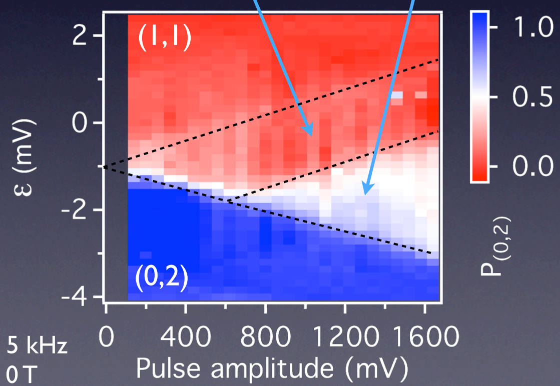
- The time-averaged charge state is measured as a function of pulse amplitude and of offset along the detuning axis (ε)

Probability in being in (0,2) ($P_{(0,2)} = 1 - P_{(1,1)}$) is calculated by comparing I_{QPC} with its values in the (1,1) and (0,2) regions.



We observe a region in the pulse window where $P_{(0,2)} << 0.5$

For large pulse amplitudes, a region appears where $P_{(0,2)} \approx 0.5$



f_p = 5 kHz
B = 0 T

- Region of suppressed $P_{(0,2)}$ is due to Pauli blockade of (1,1) triplet states.
- Lifting of blockade occurs when the (0,2) triplet states are brought within the pulse window.