Andrew S. Dzurak

Parity readout of spin qubits in silicon quantum dots

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arXiv: April 23, 2020

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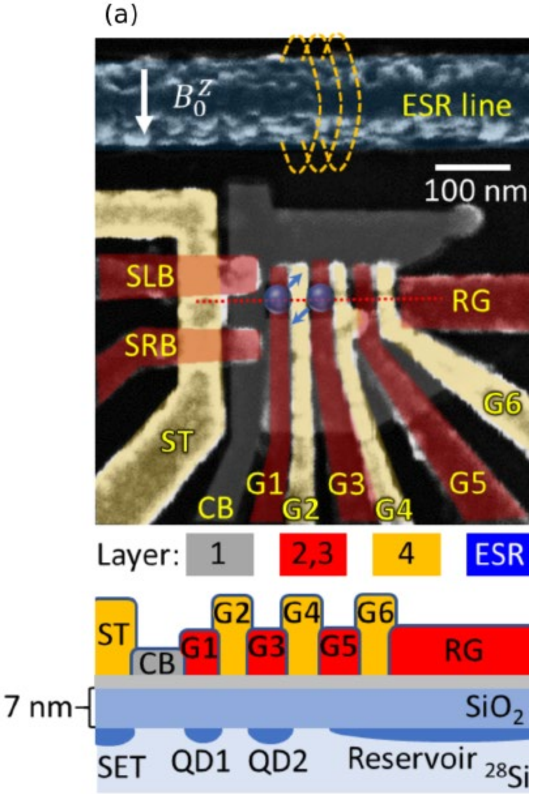
09.10.2020

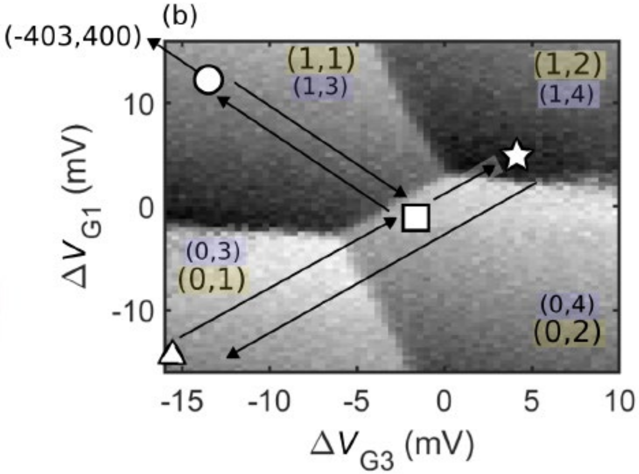
Motivation

- scalable qubit readout
- Pauli spin blockade breakdown
- parity readout
- quantum error correction

Device and operating regime

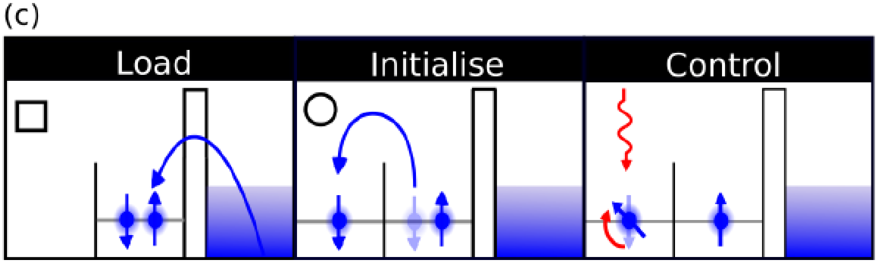


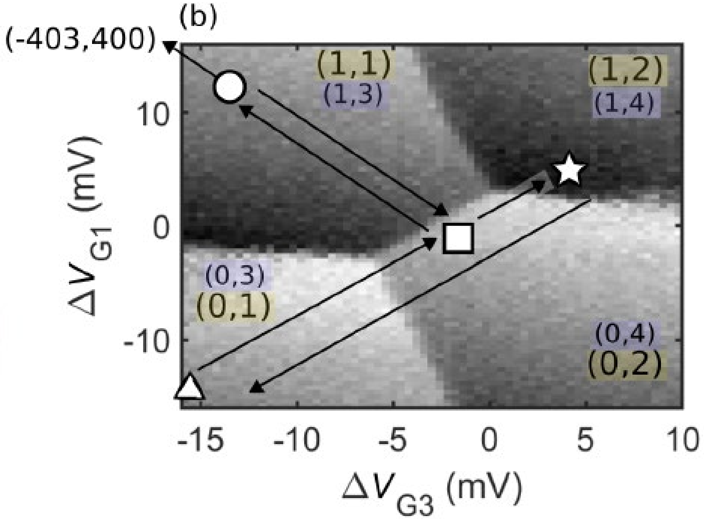
- electron accumulation
- 800 ppm ^{29}Si



- right dot, two electrons in the lower valley
- the upper valley is >0.1 meV above
- closed shell, no effect on two extra electrons (0,4)→(0,2)

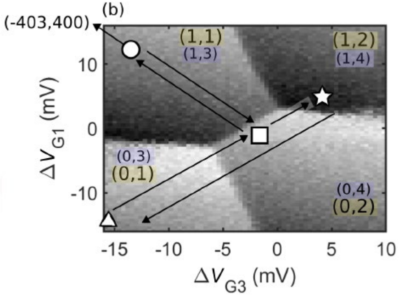
Measurement scheme

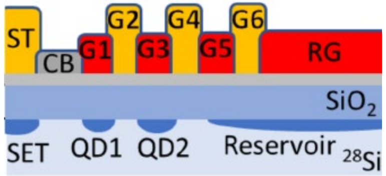


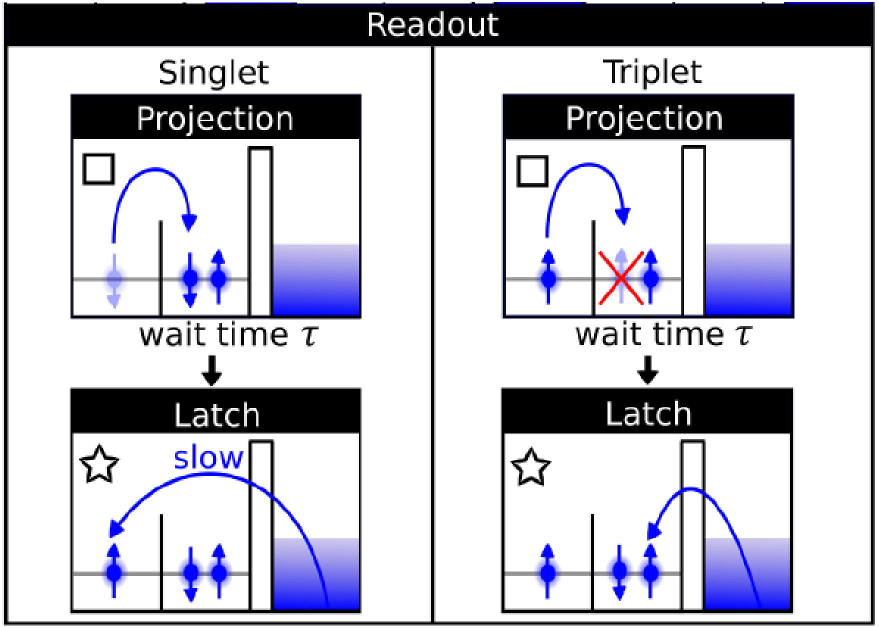


- start at (0,1)
- electron loading into |S(0,2)>
- change detuning (0,2)->(1,1)
- spin state depends on the ramp rate
  anticrossings with $|T_-(1,1)>$ and |S(1,1)>
- manipulation
  - ESR
  - detuning control

Latched single-tripled readout







standard readout

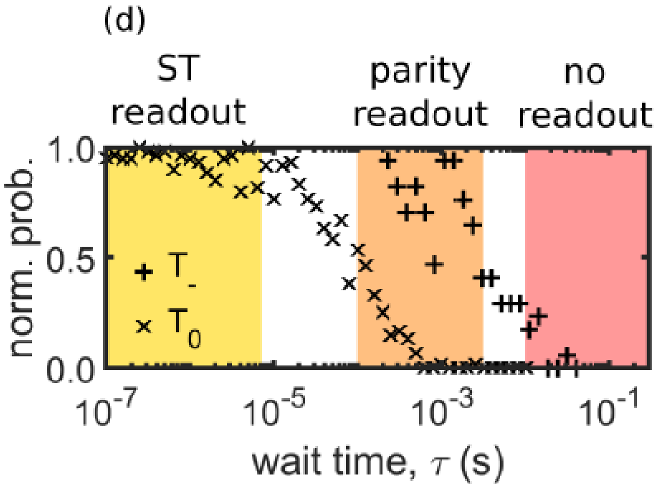
- return to (0,2), □
- only singlet would tunnel
- charge reflects the spin state immediately after reaching □

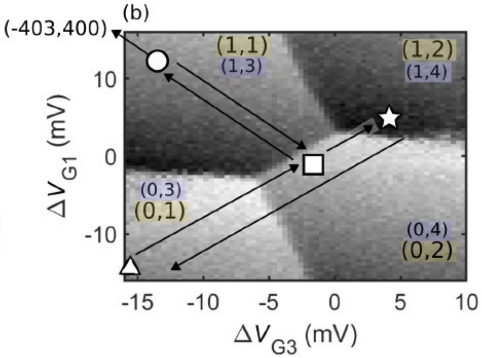
slow charge sensing compromises the spin state

To study the lifetime of the Pauli blockade:

- wait time τ in the (0,2)
- move to the latched region (1,2)
  - singlet will stay in (0,2)
    slow tunneling into the left dot
  - triplet will go to (1,2)
- charge state maps the spin state at the moment of latching

Parity readout





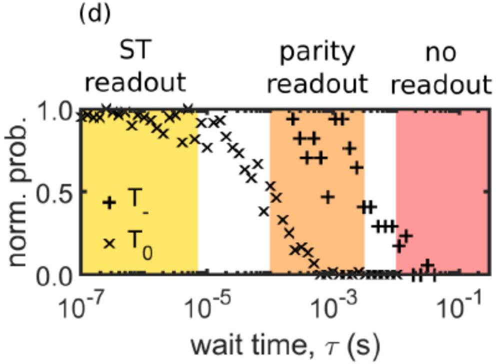
- Triplet states will eventually decay to |S(0,2)>

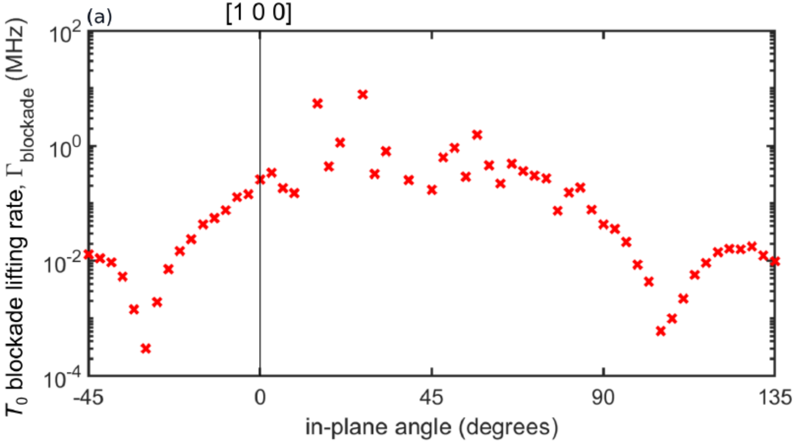
- odd-parity $|T_0>$ decays in 200 us
- $|T_->$ decays in 5 ms
- $|T_+>$ is also long

- if the time for the charge sensing at □ is in orange region, odd-parity states (|S>, $|T_0>$) are indistinguishable

- even-parity states ($|T_+>$, $|T_->$) can be distinguished

Measure $\Gamma_{blockade}$





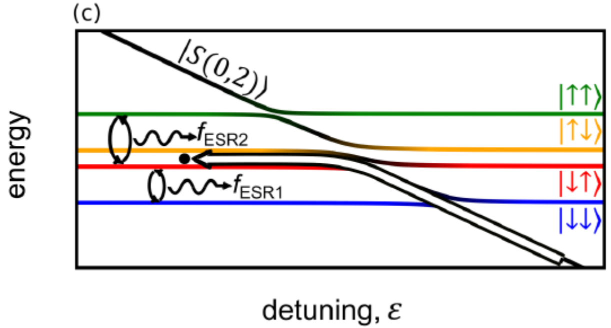
- choose the direction of B
- fit the blockade lifting for the state $|T_0>$

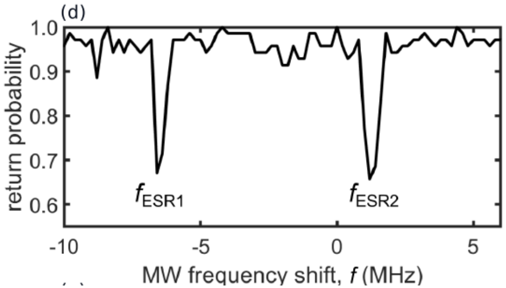
  can change by 3-4 orders of magnitude

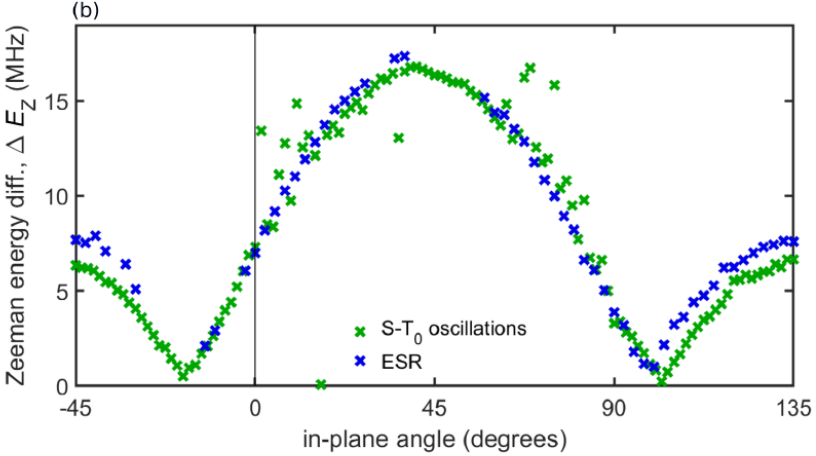
Look for the correlation between $\Gamma_{blockade}$ and $\Delta E_Z = \Delta g \, \mu_B \, B$

- Δg – due to spin-orbit coupling induced by the interface
- large Dresselhaus component, controlled by the direction of B

Measure ΔE_Z using ESR



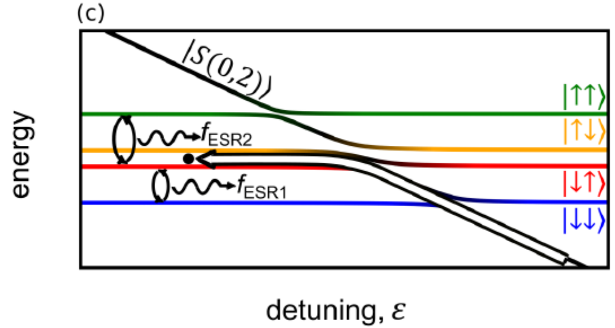


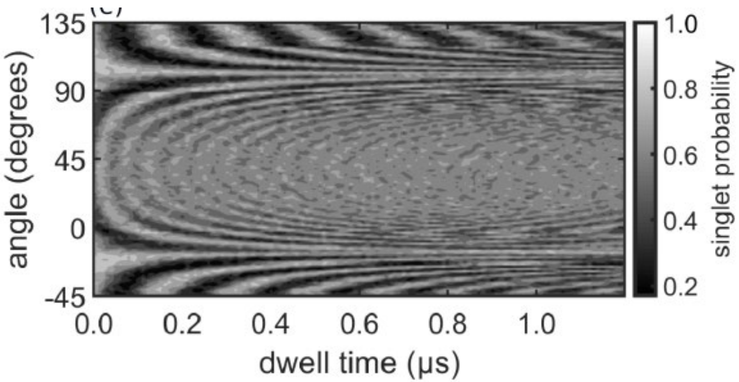


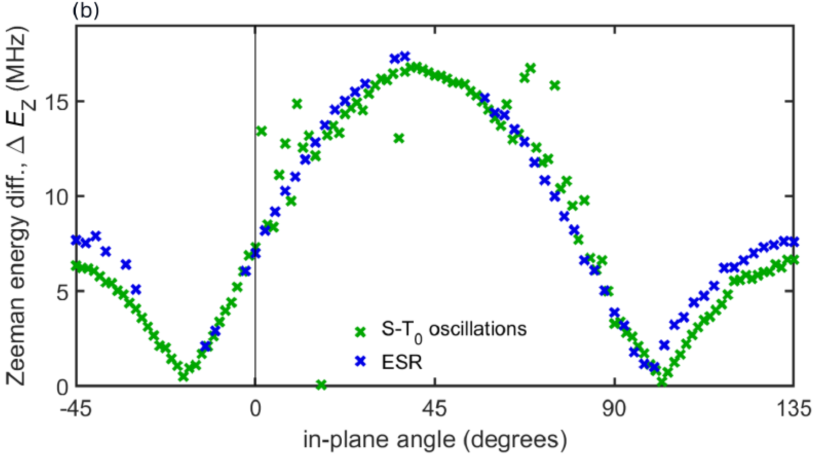
electron spin resonance, rotate one spin

- initialize in |↓↑>
  - go adiabatically through |↓↑> - |↑↓> anticrossing
- apply microwave pulse
  - f_{ESR1} to rotate |↓↑> to |↑↑>
  - f_{ESR2} to rotate |↓↑> to |↓↓>
- return to (0,2), dip in the return probability at the resonance frequency
- difference between f_{ESR1} and f_{ESR2} gives ΔE_Z
  - if $\Delta E_Z \geq J$, |T_0(1,1)>-|S(1,1)> splitting

Measure ΔE_Z using S-T oscillations

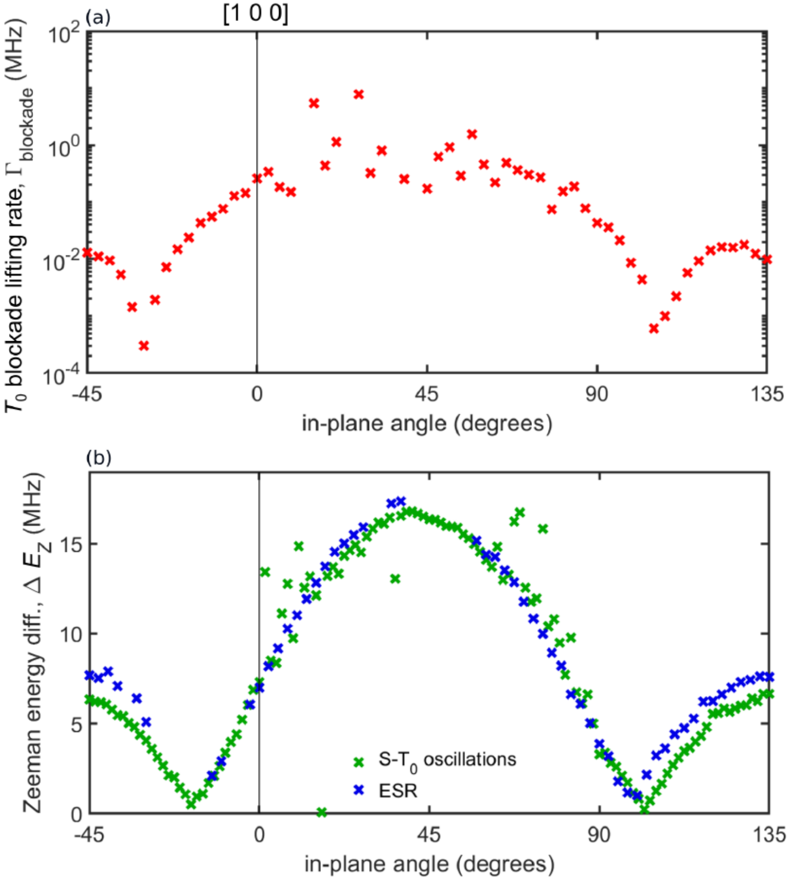






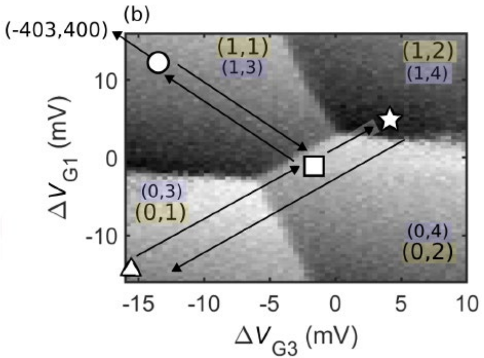
- oscillations between |S(1,1)> and |T_0(1,1)> with frequency ΔE_Z
- initialize in |S(1,1)>
  - ramp quickly through (0,2)-(1,1)
- dwell time – time spent at (1,1) configuration

Measure ΔE_Z using S-T oscillations



- excellent agreement between theses two ΔE_Z extraction methods
- horizontal shift due to Stark shift
  - ΔE_Z was measured deep in (1,1)
  - $\Gamma_{blockade}$ was measured at (0,2)

- $\Gamma_{blockade}$ increases as ΔE_Z increases



Model

$$\hat{H} = \begin{pmatrix} -\varepsilon & t & 0 \\ t & 0 & \Delta E_Z \\ 0 & \Delta E_Z & 0 \end{pmatrix}$$

|S(0,2)>
|S(1,1)>
|T_0(1,1)>

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}, \hat{\rho}] + \hat{\hat{\mathcal{L}}}[\hat{a}](\hat{\rho}).$$

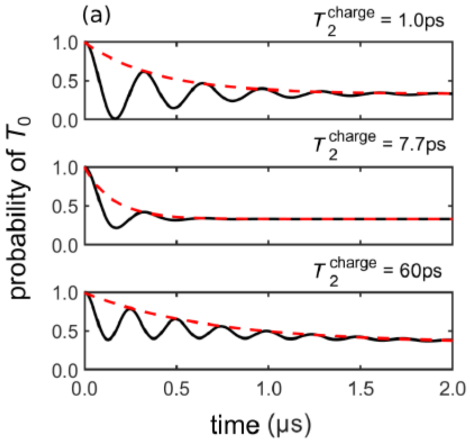
master equation for the density matrix

$$\hat{\hat{\mathcal{L}}}[\hat{a}](\hat{\rho}) = \hat{a}\hat{\rho}\hat{a}^\dagger - \frac{1}{2}(\hat{a}\hat{a}^\dagger\hat{\rho} + \hat{\rho}\hat{a}\hat{a}^\dagger).$$

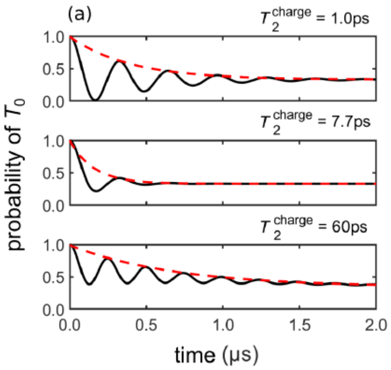
$$\hat{a}_{\text{dephasing}} = \begin{pmatrix} \frac{1}{\sqrt{2T_2}} & 0 & 0 \\ 0 & -\frac{1}{\sqrt{2T_2}} & 0 \\ 0 & 0 & -\frac{1}{\sqrt{2T_2}} \end{pmatrix}$$

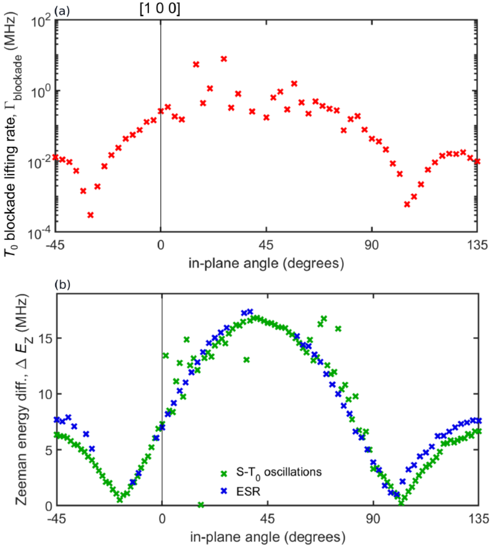
$$\hat{a}_{\text{relaxation}} = \begin{pmatrix} 0 & \frac{1}{\sqrt{T_1}} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

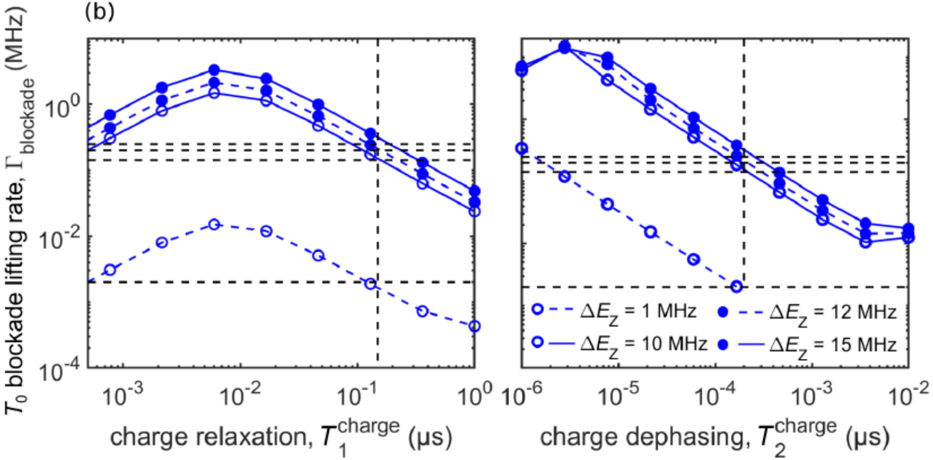
- |S(0,2)> and |S(1,1)> coupled with t
- |S(1,1)> and |T_0(1,1)> coupled through ΔE_Z
- charge dephasing, ε fluctuations, T_2
- charge relaxations, |S(1,1)> into |S(0,2)>, T_1
- initialise in pure |T_0(1,1)>, oscillations with exponential decay $Ae^{-t\Gamma_{\text{blockade}}} + B$



Charge relaxation and dephasing times

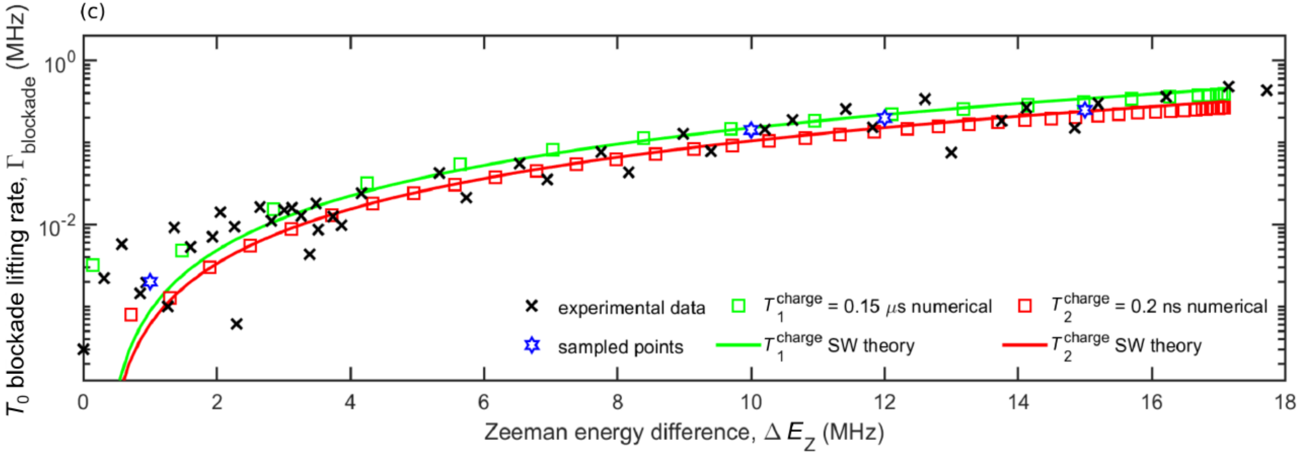






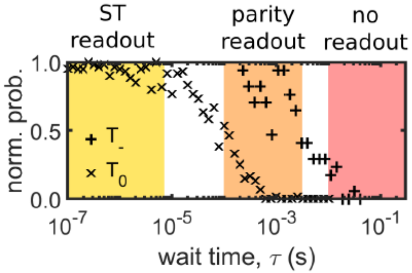
- T_1^{charge} and T_2^{charge} are unknown
- fit: $T_1^{charge} = 0.2$ μs and $T_2^{charge} = 0.2$ ns
- T_2^{charge} fits better with the literature – dephasing may be the decay mechanism

Analytical method



$$\Gamma_{\rm blockade} \approx \frac{2\Delta E_Z^2}{T_2^{\rm charge}} \frac{t^2+\varepsilon^2}{t^2\varepsilon^2} \qquad \Gamma_{\rm blockade} \approx \frac{2\Delta E_Z^2}{T_1^{\rm charge}} \frac{t^2+\varepsilon^2}{t^4}$$

- improve parity readout fidelity by reducing t



Conclusion

- origin of the parity readout
- blockade lifting rate as a function of T_1^{charge} and T_2^{charge}
- found indication that charge dephasing causes blockade lifting