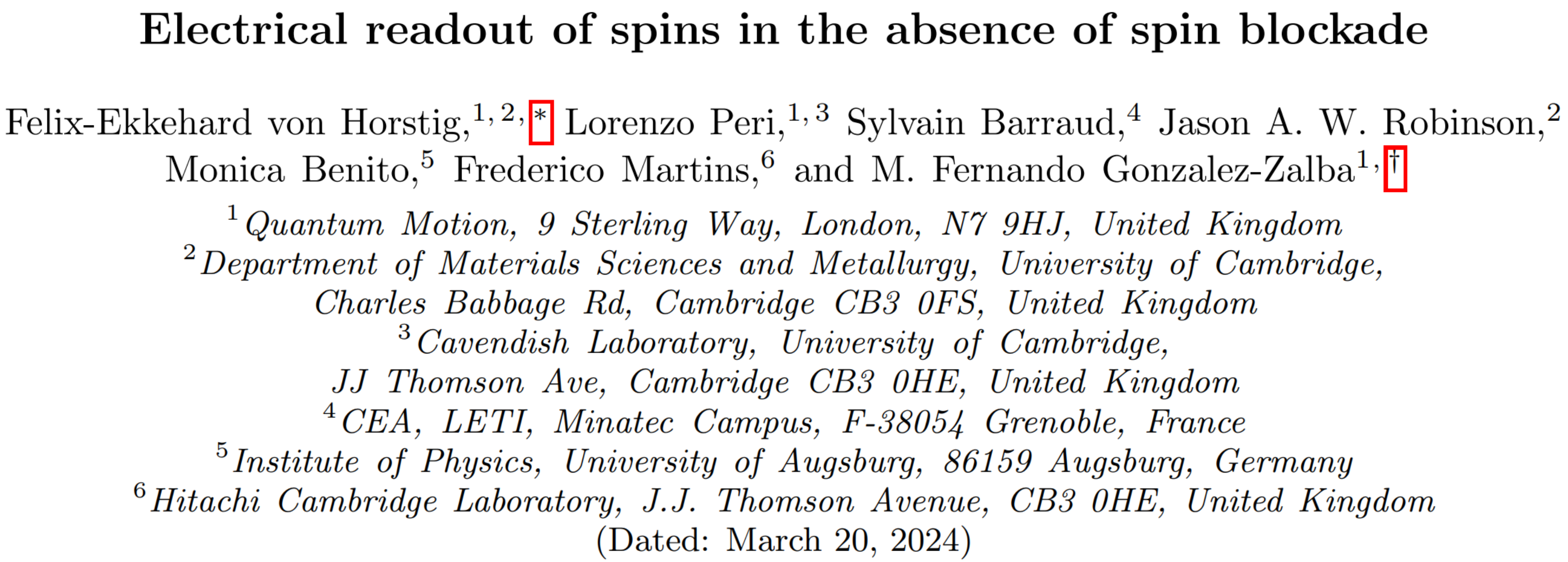
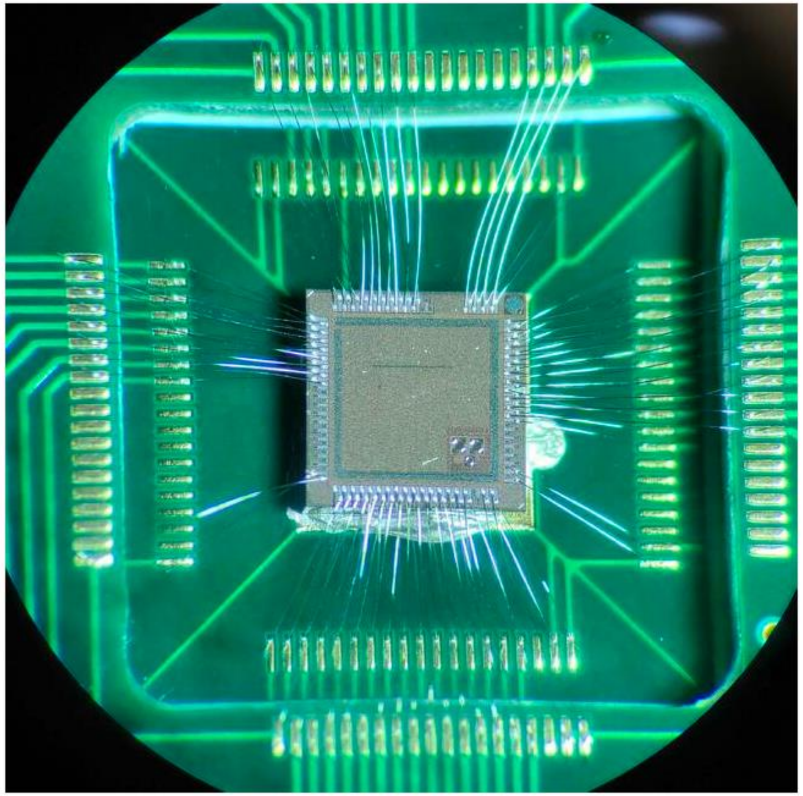
FMM 05.04.2024



Electrical readout of spins in the absence of spin blockade

Felix-Ekkehard von Horstig,[1, 2, *] Lorenzo Peri,[1, 3] Sylvain Barraud,[4] Jason A. W. Robinson,[2]
Monica Benito,[5] Frederico Martins,[6] and M. Fernando Gonzalez-Zalba[1, †]
[1] *Quantum Motion, 9 Sterling Way, London, N7 9HJ, United Kingdom*
[2] *Department of Materials Sciences and Metallurgy, University of Cambridge,*
Charles Babbage Rd, Cambridge CB3 0FS, United Kingdom
[3] *Cavendish Laboratory, University of Cambridge,*
JJ Thomson Ave, Cambridge CB3 0HE, United Kingdom
[4] *CEA, LETI, Minatec Campus, F-38054 Grenoble, France*
[5] *Institute of Physics, University of Augsburg, 86159 Augsburg, Germany*
[6] *Hitachi Cambridge Laboratory, J.J. Thomson Avenue, CB3 0HE, United Kingdom*

(Dated: March 20, 2024)



(2022) Bloomsbury chip 3*3mm2
Measured 1024 dots in 12min on area 0.1mm2
Device includes control electronics

Quantum Motion Wins Bid To Deliver First Silicon Quantum Computing Prototype To NQCC

Quantum Computing Business, Research, Ukquantum · Matt Swayne • February 10, 2024

(2024) Quantum Motion has been selected by the UK’s National Quantum Computing Centre (NQCC) to build a quantum processor test bed.

Motivation

Motivation

- Hard to measure spin directly (small magn. dipole moment)
- Sizeable charge dipole due to e- tunnelling
- Sensitivities: $\sim 10 \text{ spins}/\sqrt{\text{Hz}}$
  $\sim 10^{-6} \text{ electrons}/\sqrt{\text{Hz}}$
- => charge sensing + spin to charge conversion

Energy filtering

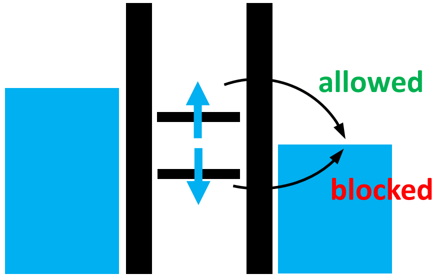
- Zeeman splitting in QD
- Selective tunnelling to lead

Spin blockade

- Selection rules in tunnelling btw. 2 particle states
  (rapid diabatic passage)

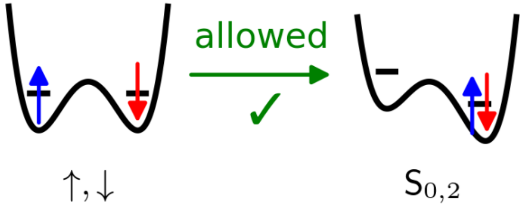
Problems

- Only one subset (spin) triggers detector
  Absence of signal => opposite spin
- Lifting of spin blockade:
  SOI (e.g holes in Ge or Si)
  other orbitals (valleys)

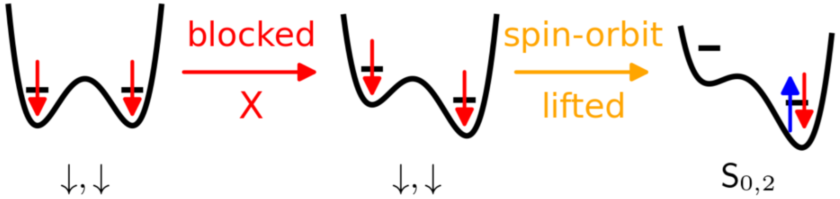


=> Relies on negative-result measurement

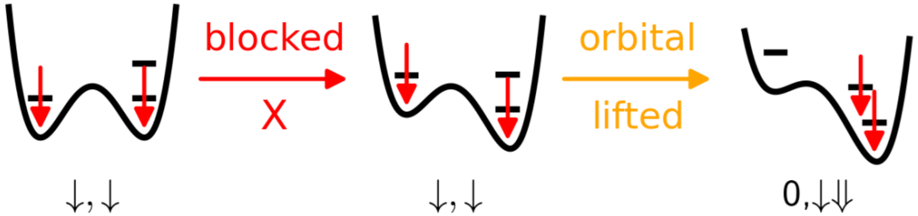
Spin blockade & lifting meachanisms



Blockade lifted by SOI



Blockade lifted by other orbital



Device

Device: Single gate Si on insulator nanowire transistor

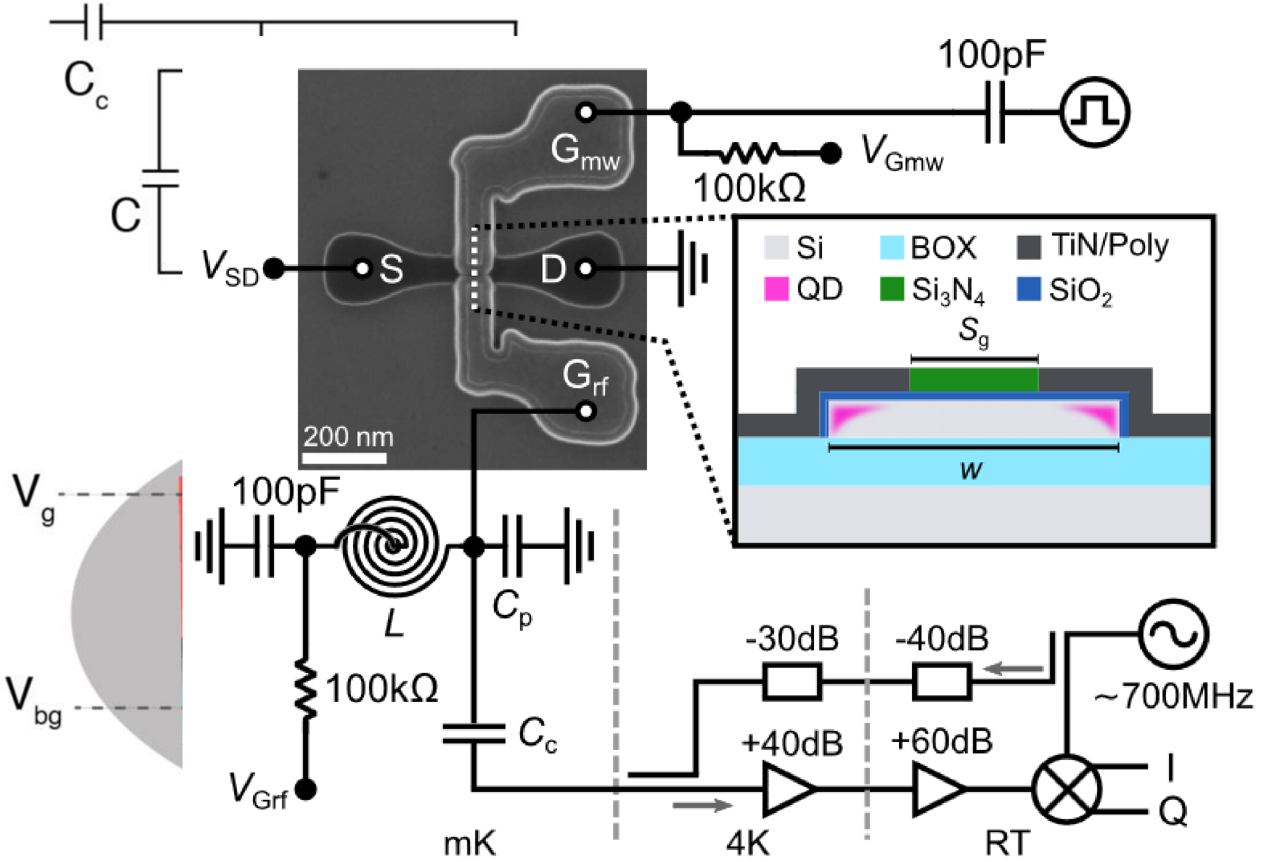
- Si-nanowire L*W*H = 60*120*8 nm^3
- Boron-doping 5*10^{17} cm^{-3}
- BOX: buried oxide 145 nm SiO$_2$
- Implantation in S/D contacts + annealing
- Gate stack
  - 1.9nm HfSiON (=> 1.3nm oxide)
  - 5nm TiN
  - 50nm polycrystalline silicon
- Study DQD: Nanowire corner QD + Boron Atom

Readout

- LC resonator
  - NbTiN spiral inductor (30nH)
  - Cc: coupling capacitor (40fF)
  - Low pass (Star Cryoelectronics)
- Reflected signal amplified at 4K, RT
  - Quadrature demodulation => amplitude & phase

Setup

- Dilution fridge, T = 10mK
- DC: Constantan twisted pair, RC filtered at MC
- RF: Filtered & attenuated coax to coupl. capacitor Cc
- Fast pulses: Attenuated CuNi coax via on PCB bias-T to source

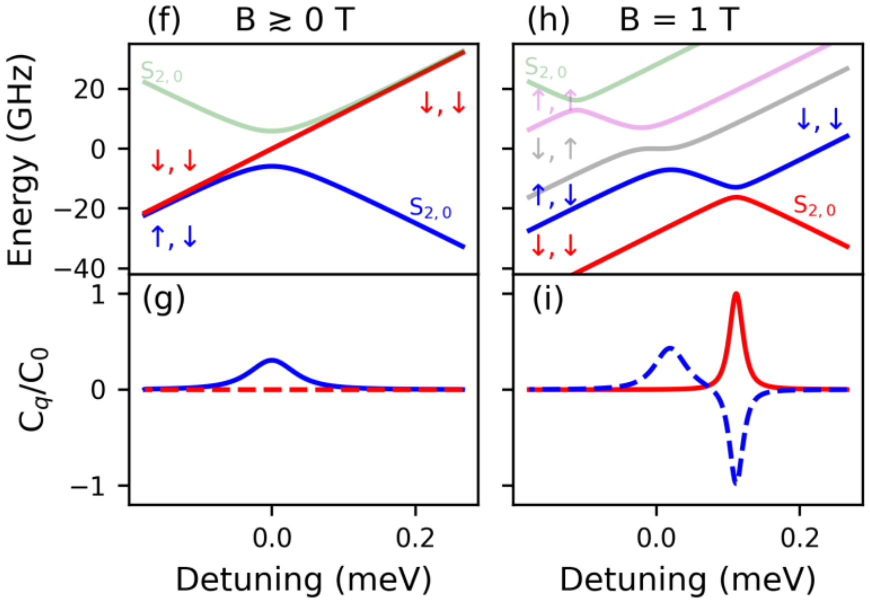


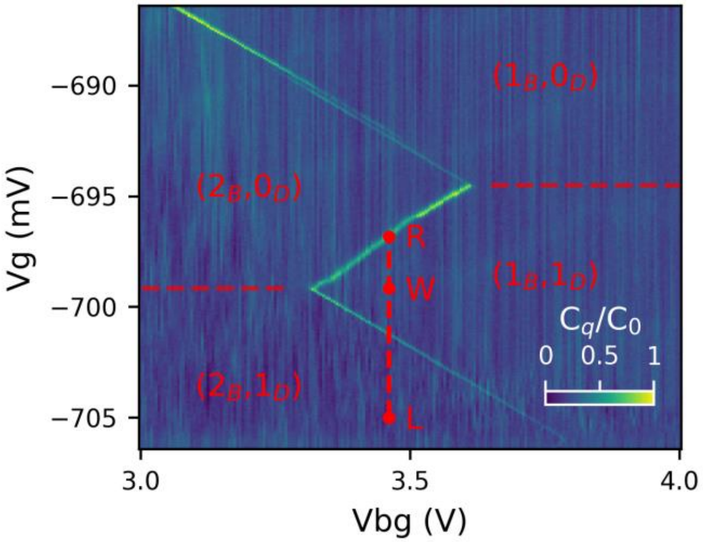
Lundenberg et al., Phys. Rev. X **10**, 041010 (2020)

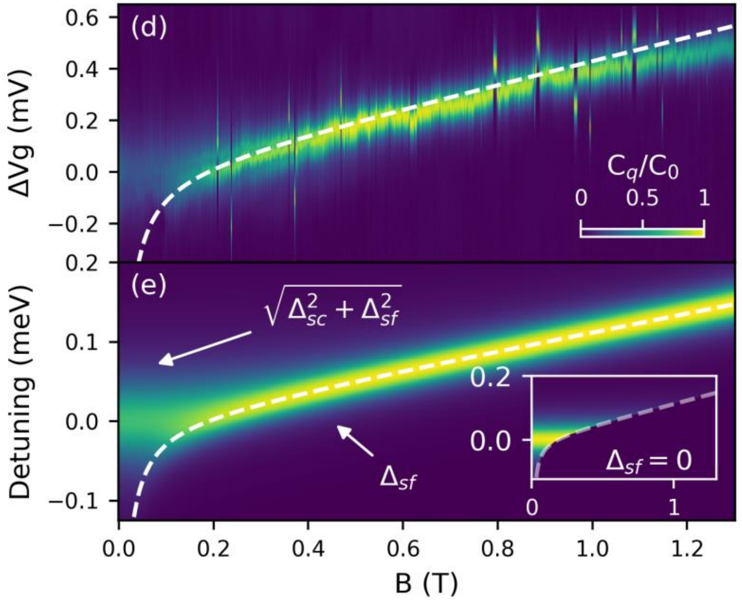
Quantum capacitance & SOI

Charge stability diagram

- Energy dependence of charge polarizability
  - ⇒ State dependent quantum capacitance
- Detect microwave driven tunnelling btw
  - QD/Boron – reservoirs (S/D)
  - QD – Boron (interdot charge transition ICT)
- Device operated at $(2_B,0_D)$-$(1_B,1_D)$ transition







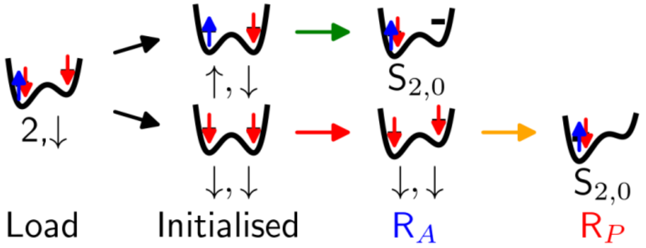
Magneto spectroscopy (at point R)

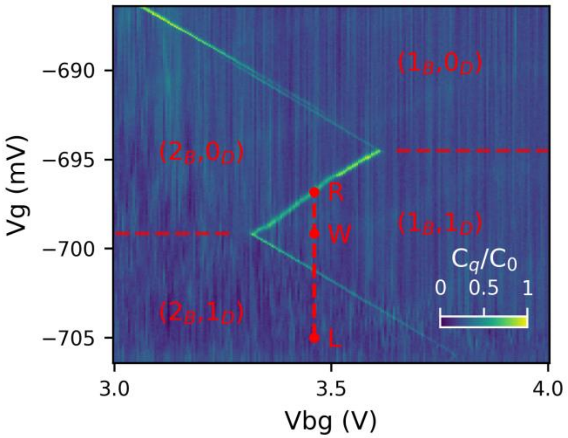
- Weak signal at B=0, ε=0
- Strong signal for B>0.2T, shifting with V_g (ε>0) => SOC lifting of SB
  - Tunneling btw $T^{-}_{1,1}$- $S_{2,0}$
- Theory: Δ_{sc} (spin conserving), Δ_{sf} (spin flip)
  - Total rate (B=0): 10.4 GHz, Δ_{sf} s(large B)=3.4 GHz
- G-factor: from the slope g_{avg}=2
  - B-field shift Boron lead transition (not shown): g_B~1.6, g_D~2.4

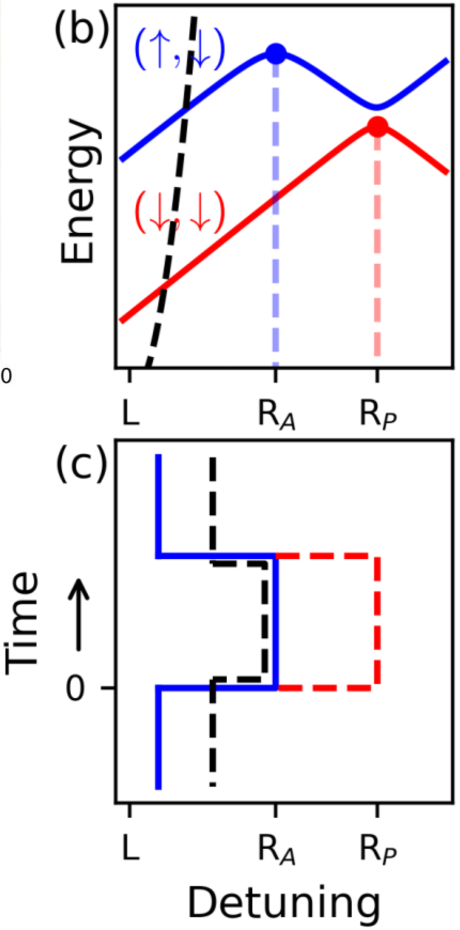
Spin detection

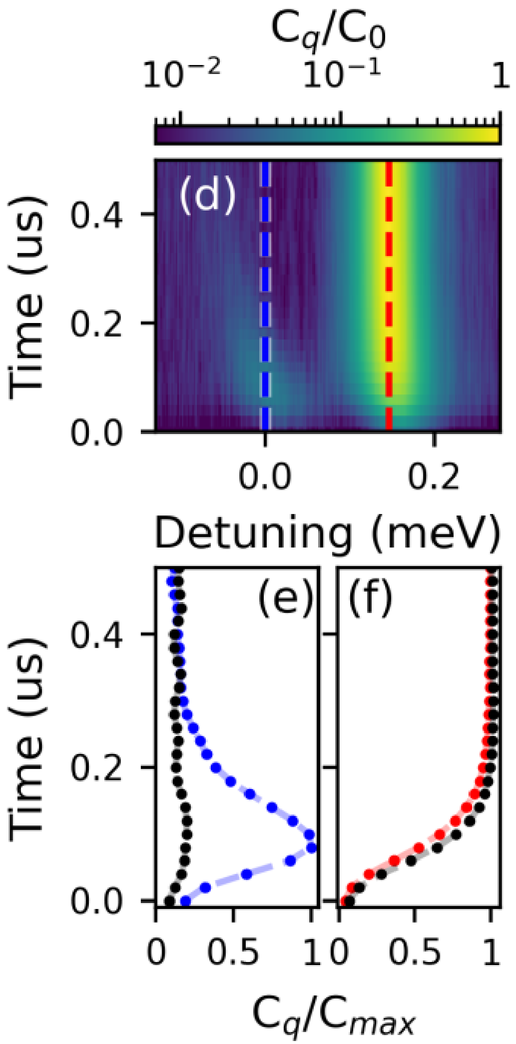
Gate V_g pulsing scheme

- Load: $(2_B,1_D)$
- Pulse above lead transition: $(1_B,1_D)$
  - $S_{1,1}$, ↑,↓ or $T^-_{1,1}$ ↓,↓
- Measure C_q vs time at given detuning
  - B=1T : $T^-_{1,1}$ is ground state









2 Readout spots (pulse-depth)

- R_A : $S_{1,1}$ and $S_{2,0}$ mix
- R_B : $T^-_{1,1}$ and $S_{2,0}$ mix (negative C_q contribution from singlet)
  - Control pulse: load $T^-_{1,1}$
  - Wait in (1,1) for potential singlet decay
- 100k pulses per detuning

T_1 time (R_A)

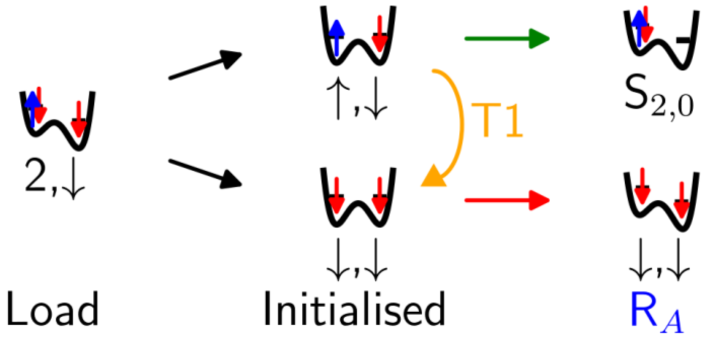
- Ring up time resonator ~80ns ⇔ BW
- Decay => T_1 ~100ns
- Control pulse flat

R_B Ring up & decay to triplet (singlet cause delay vs control pulse)

T_1 vs detuning

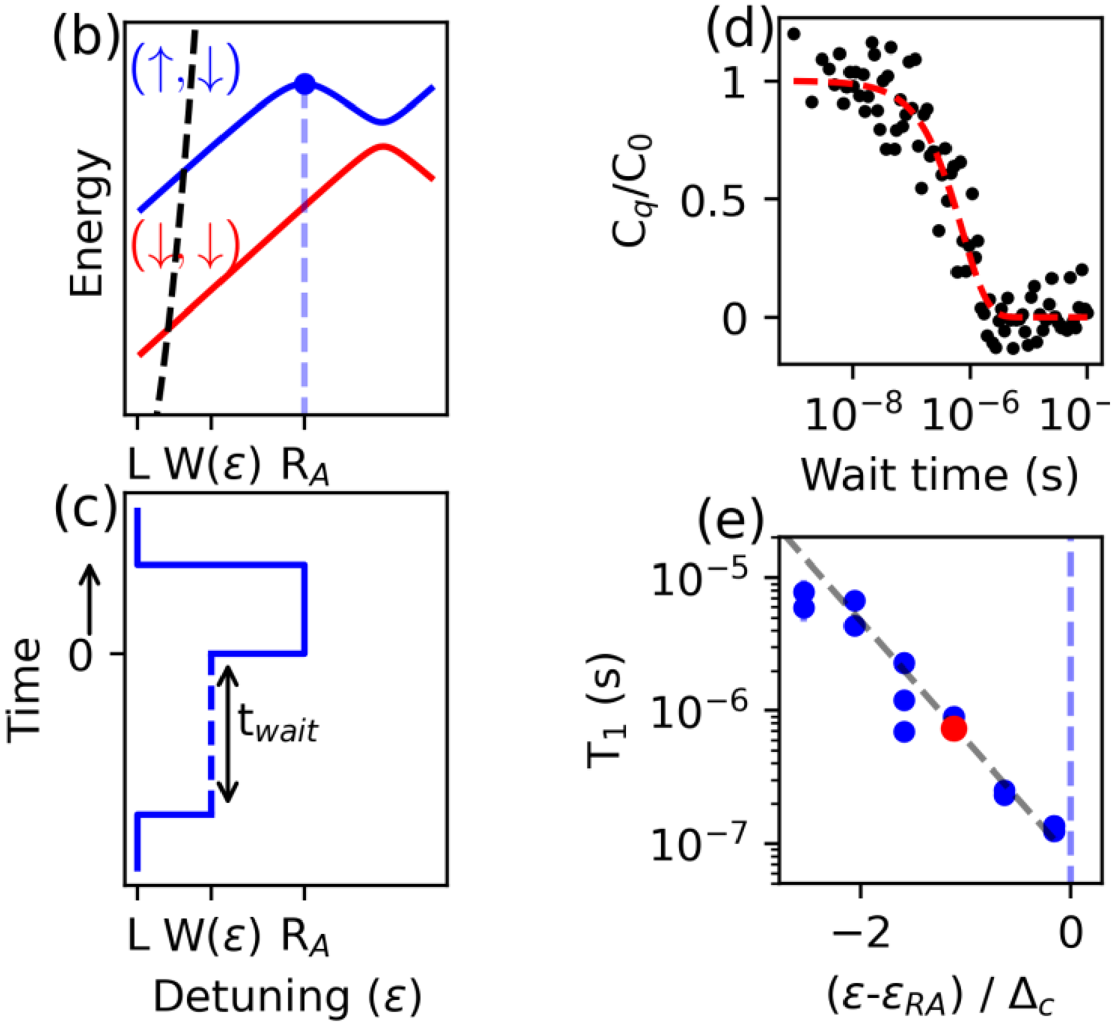
Gate pulsing scheme

- Initialize $S_{1,1}$ / $T^-_{1,1}$
- Wait: $S_{1,1}$ to $T^-_{1,1}$ relaxation
- Measure at R_A ($S_{1,1}$ - $S_{2,0}$ transition)



T_1 vs detuning

- T_1 btw 100ns and 8μs
- Exponential dependence on detuning during wait



Orbital relaxation (SOI)

Orbital relaxation

- Other transition: 2/1 e in dot, 1/0 in Boron
- QD with 2 low orbital => low energy $T_{0,2}$ possible
- C_q from S and T mixing (different detuning)
  $S_{1,1} \Leftrightarrow S_{0,2}$ and $T^-_{1,1} \Leftrightarrow T^-_{0,2}$

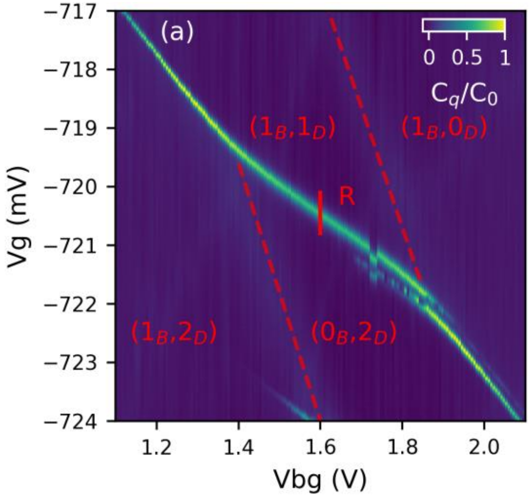
Magnetospectroscopy

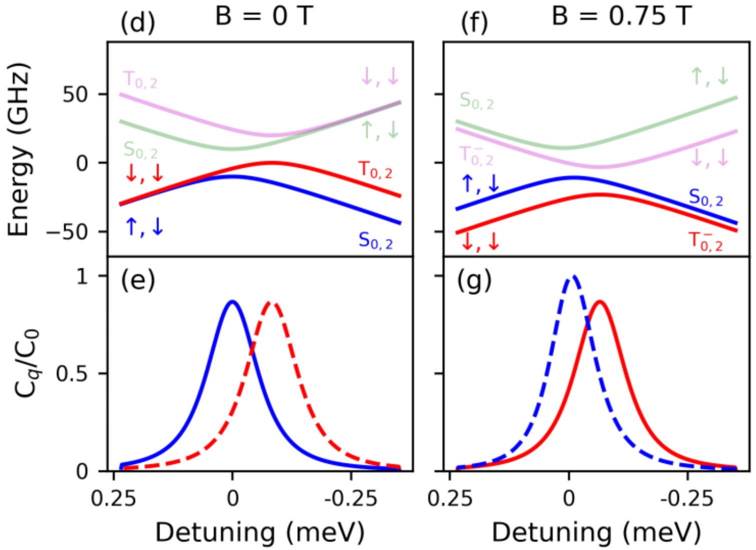
3 Regimes visible (theory)

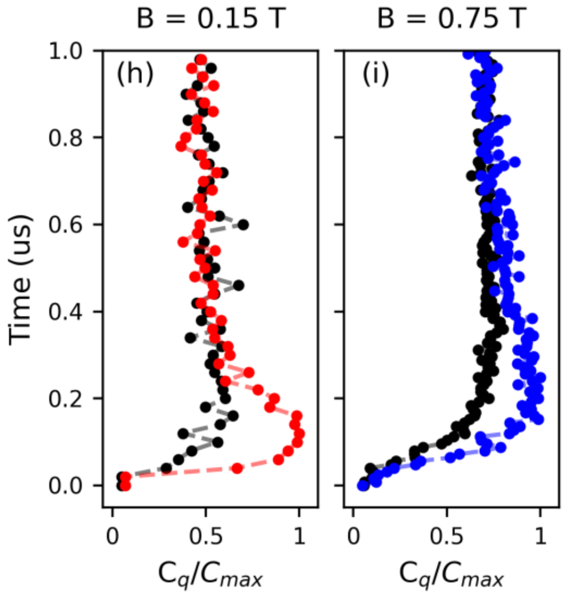
- < 300mT spin conserve. + spin flip
- 300-600 mT spin flip tunnelling (SOC)
- >600 mT spin conserv. higher orbital $T^-_{1,1} \Leftrightarrow T^-_{0,2}$

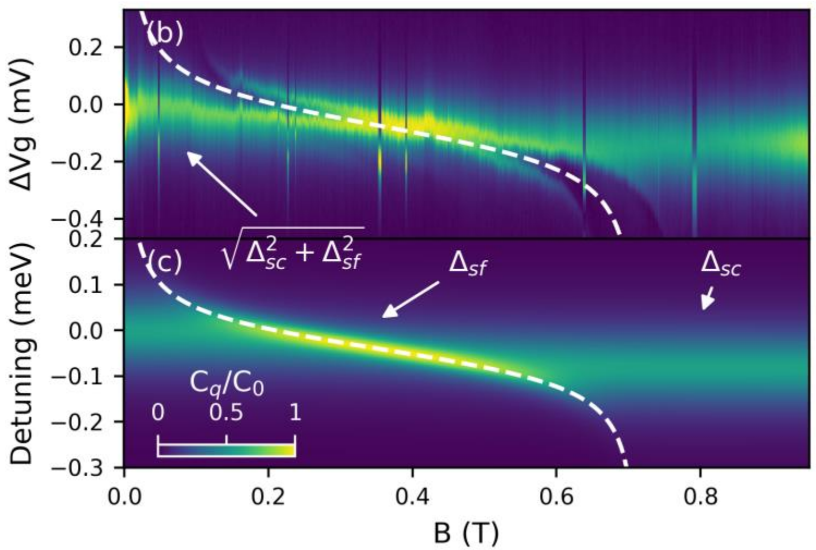
Gate pulsing scheme

- Low field B=0.15T
  initialize deep in (1,1): $T^-_{1,1}$
  diabatic passage ($T^-_{1,1} \Leftrightarrow S_{0,2}$): $T^-_{1,1}$
  readout @ $T^-_{1,1} \Leftrightarrow T^-_{0,2}$
  control: initialize $S_{0,2}$ (see only resonator rise time)
  Decay (red) => T_1~140ns
- High field B=0.75T
  initialize deep in (0,2): $S_{0,2}$
  diabatic passage at large ε ($T^-_{1,1} \Leftrightarrow S_{0,2}$): $S_{0,2}$
  readout @ $S_{1,1} \Leftrightarrow S_{0,2}$
  Decay (red) => T_1~270ns









Summary

- Novel spin readout based on quantum capacitance
- Works in presence of SOC, orbital states
- Can detect both spin species
- Sensitivity (far from single shot)?
- Measure T_1 (100ns – 8μs) vs detuning using this method