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Coherent electron spin shuttling in an industrially-manufactured Si/SiGe triple quantum dot device

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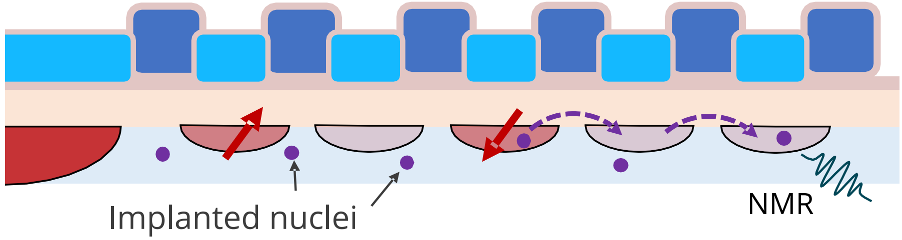
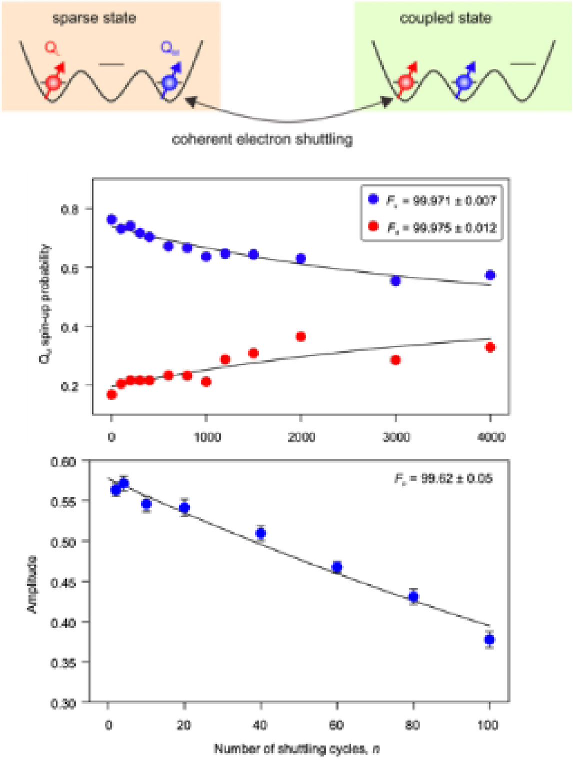
Electron shuttling to mediate remote entanglement

Vision: electron shuttling to entangle distant qubits



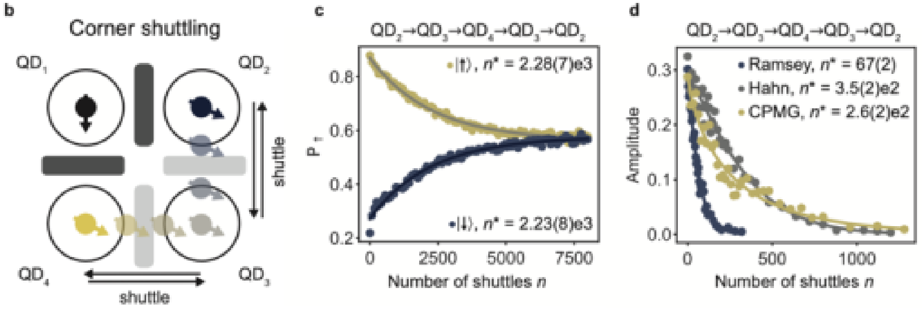
*Chat with Wayne Witzel about his invited talk yesterday or read: *PRX Quantum* **3**, 040320 (2022)

2-qubit CZ gate operation by shuttling



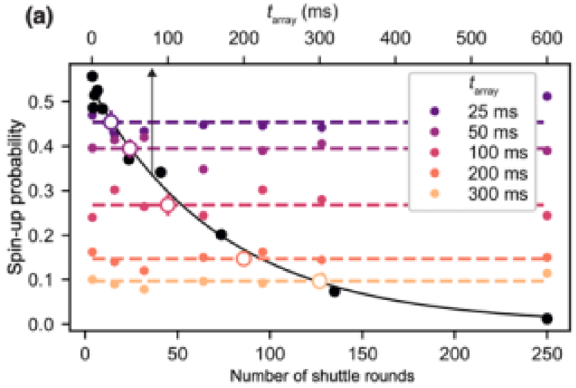
A. Noiri *et al.* *Nat. Comm.* **13** (2022) 5740

Hole spin shuttling in Ge



F. van Riggelen-Doelman *et al.* arXiv:2308.02406 (2023)

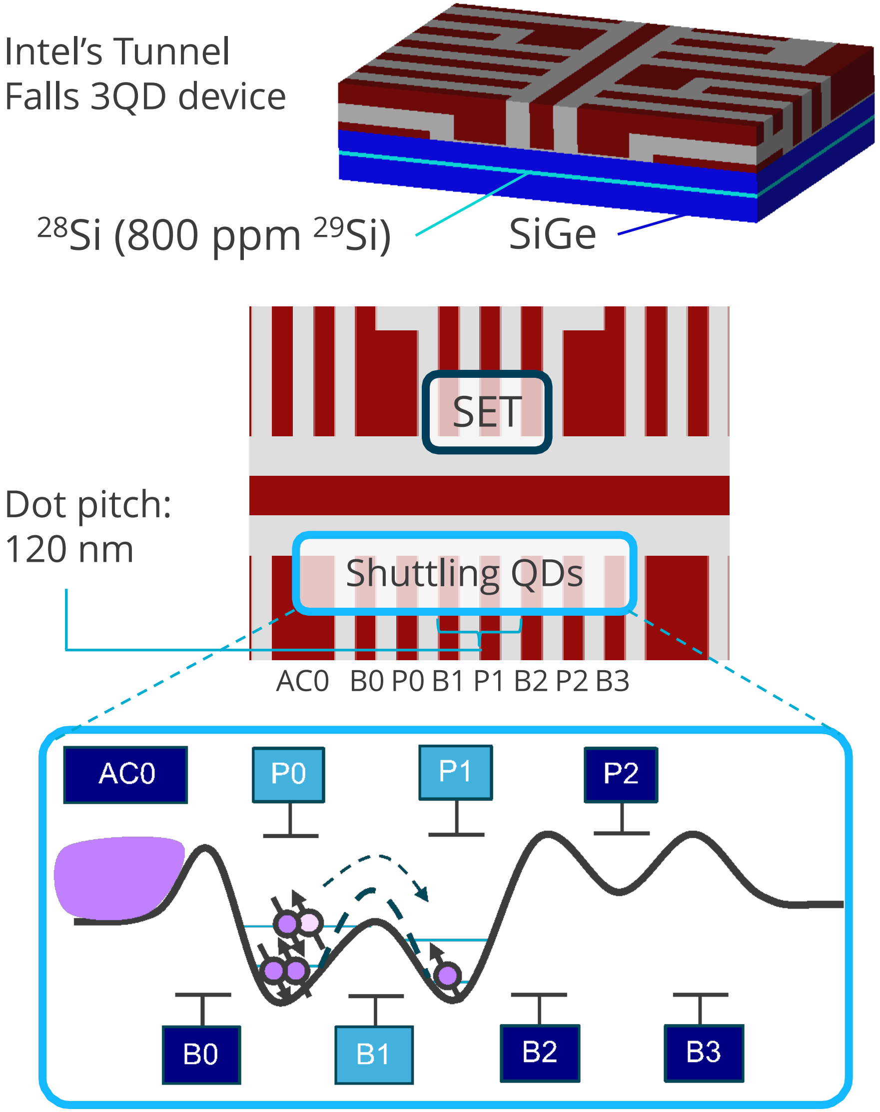
3-dot spin shuttling ~80 μm

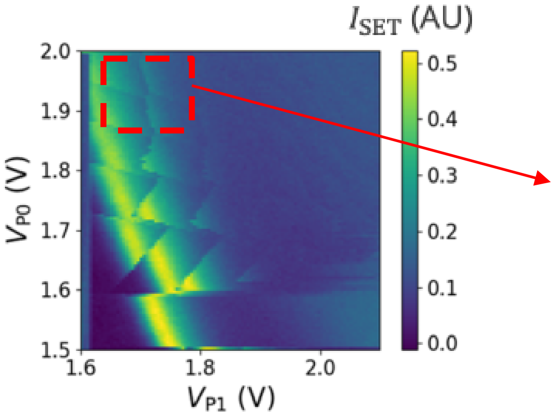


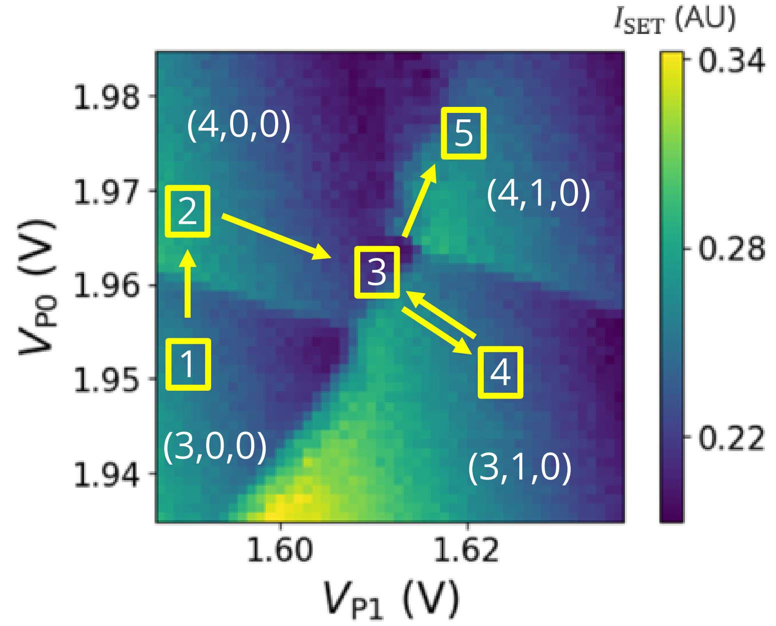
A. M. J. Zwerver *et al.* *PRX Quantum* **4** (2023) 030303

This work: 2-electron coherent and eigenstate shuttling across 3 Si QDs in Si/SiGe

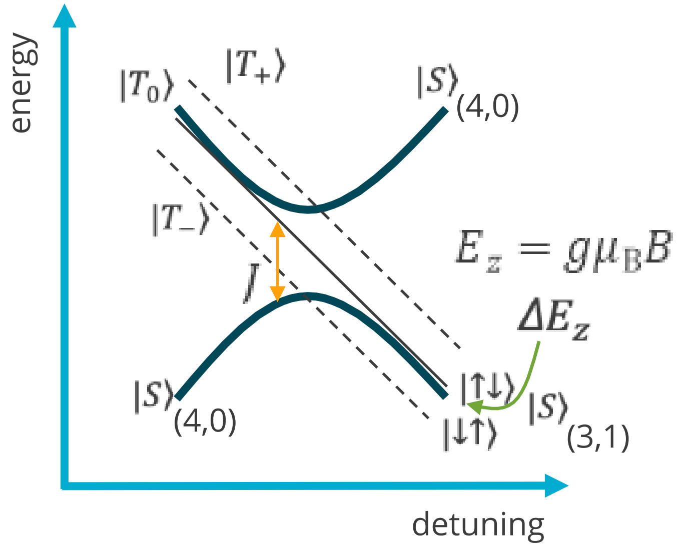
Singlet-triplet qubit in Si/SiGe Tunnel Falls device

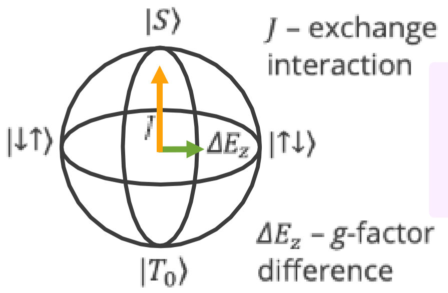






Singlet-triplet qubit

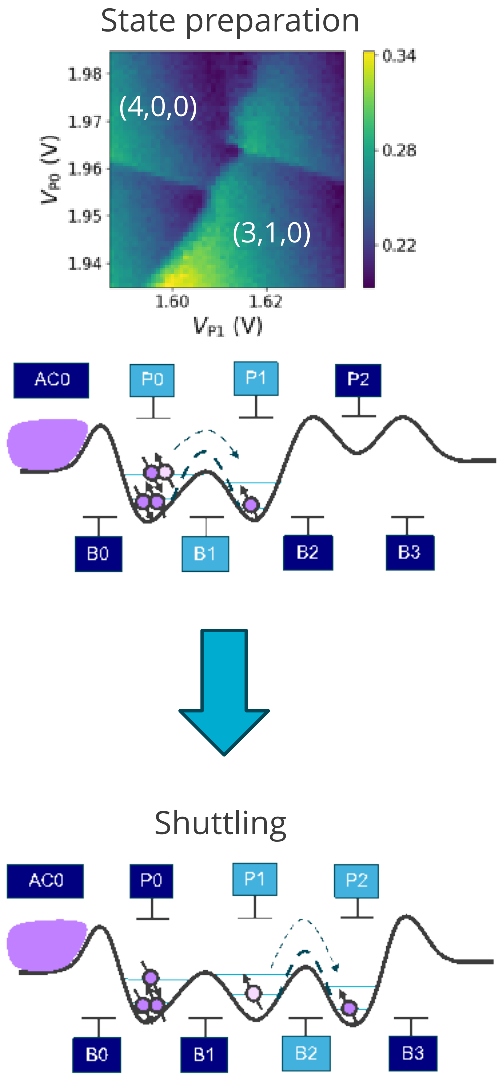


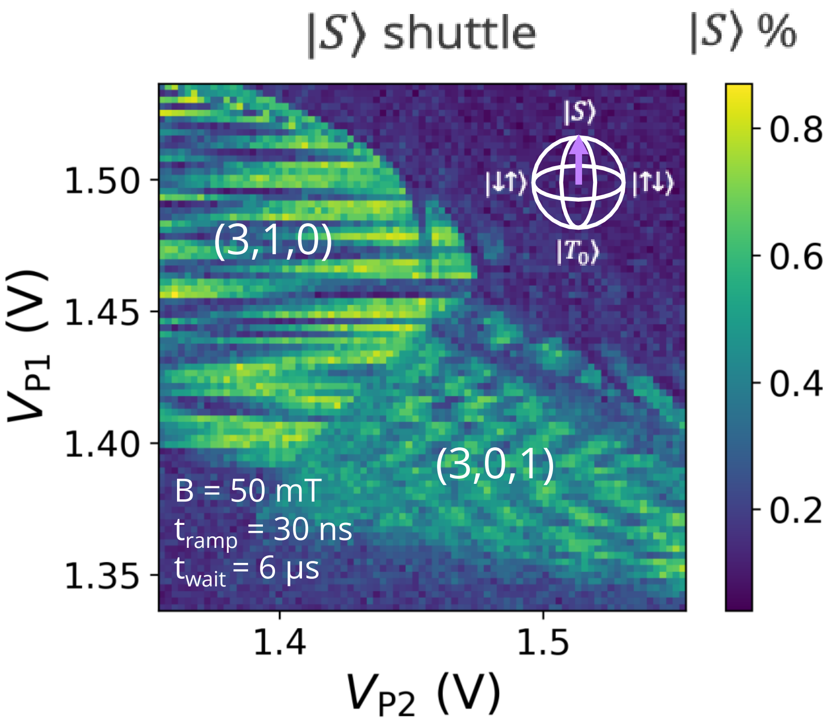


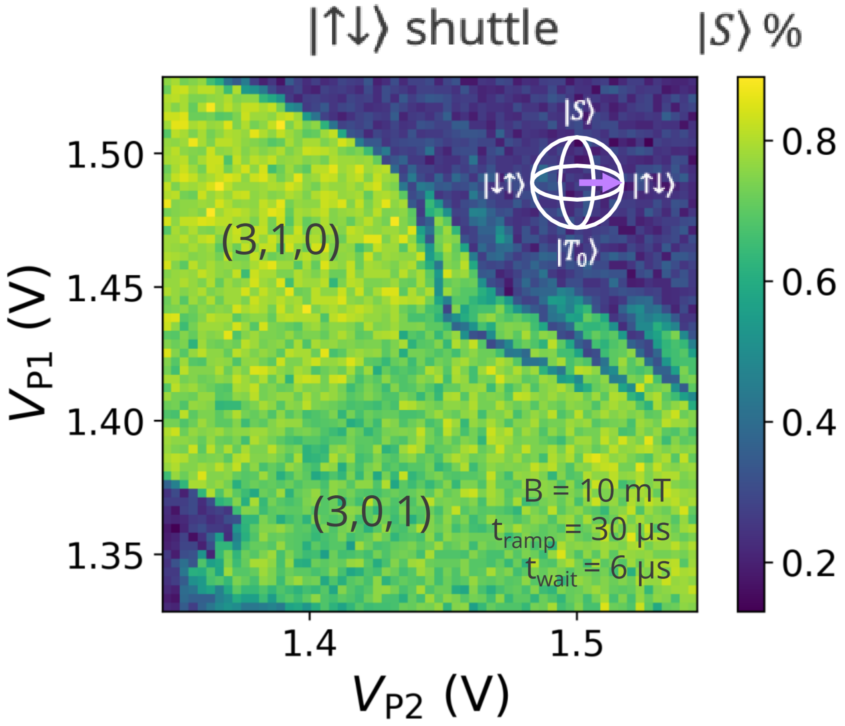
Driven by spin-orbit and hyperfine interactions

Singlet-triplet qubit prepared in (3,1,0)

Singlet-triplet qubit shuttling





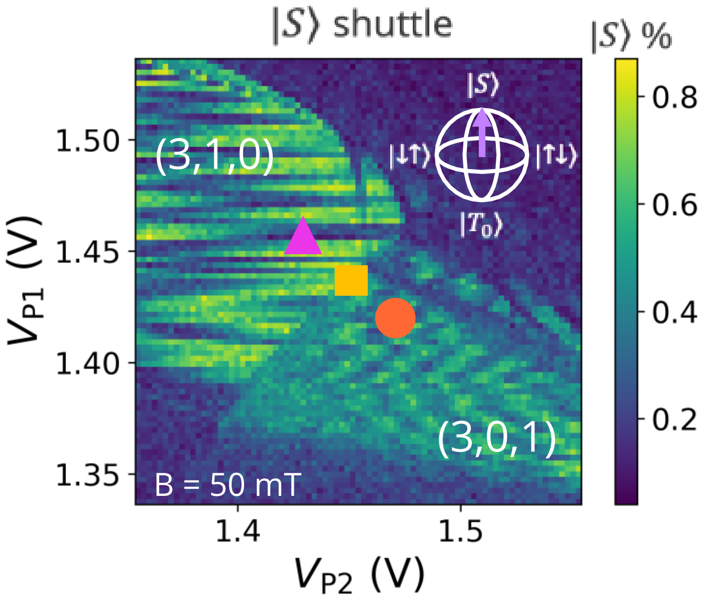


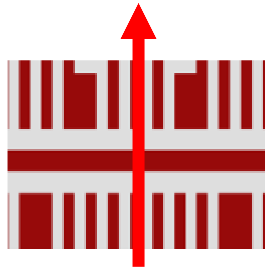
- Rapid adiabatic transfer to (3,1,0)
- Singlet $|S\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$
- Sensitive to magnetic noise
- **Coherent shuttling**

- Slow adiabatic transfer to (3,1,0)
- Eigenstate of field gradient $|\uparrow\downarrow\rangle$
- Sensitive to spin flips

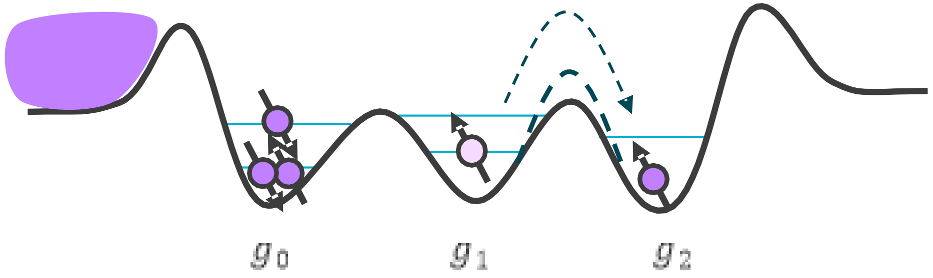
Demonstrated shuttling of both coherent and basis ST qubit states

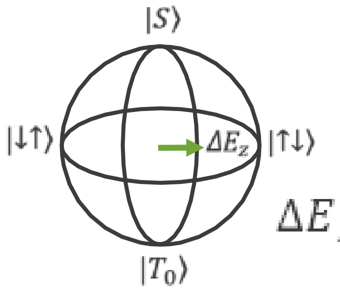
T_2* limitations



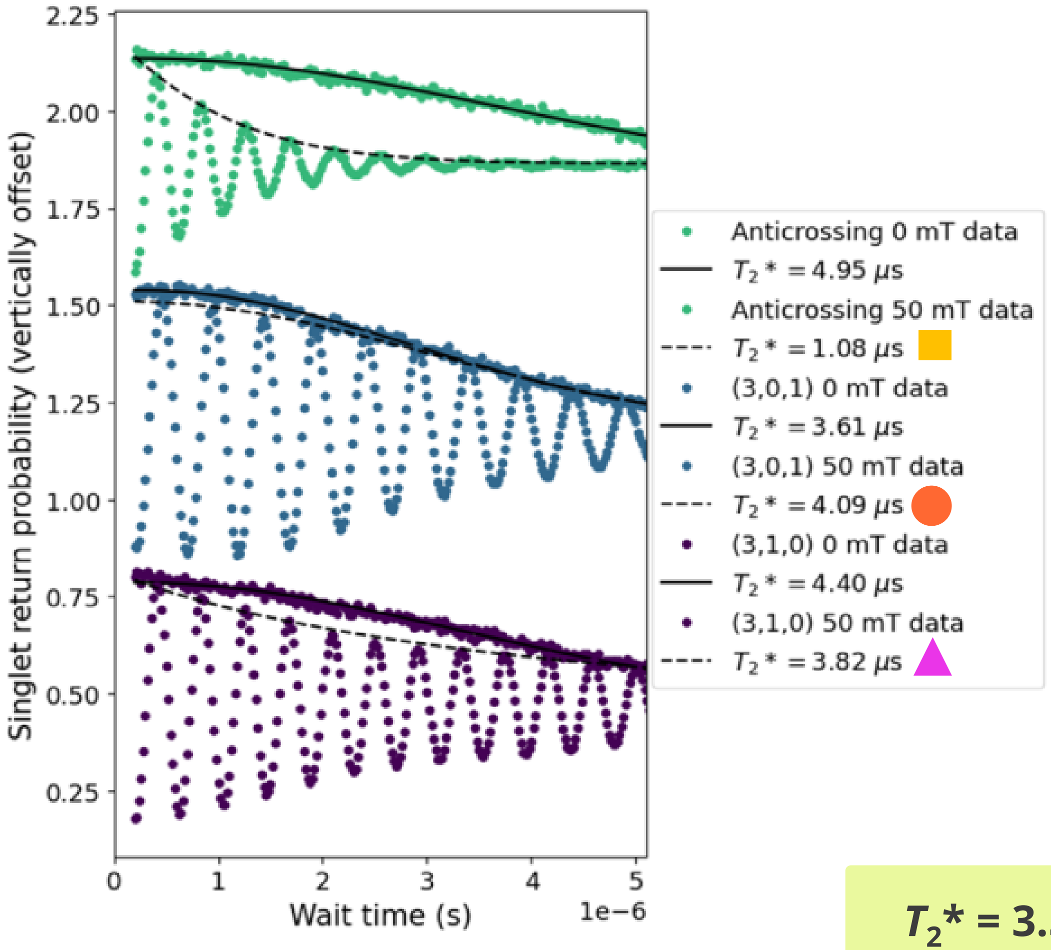


$\vec{B} = B_0\hat{z}$ [110]





$\Delta E_z = \Delta g \mu_B B$

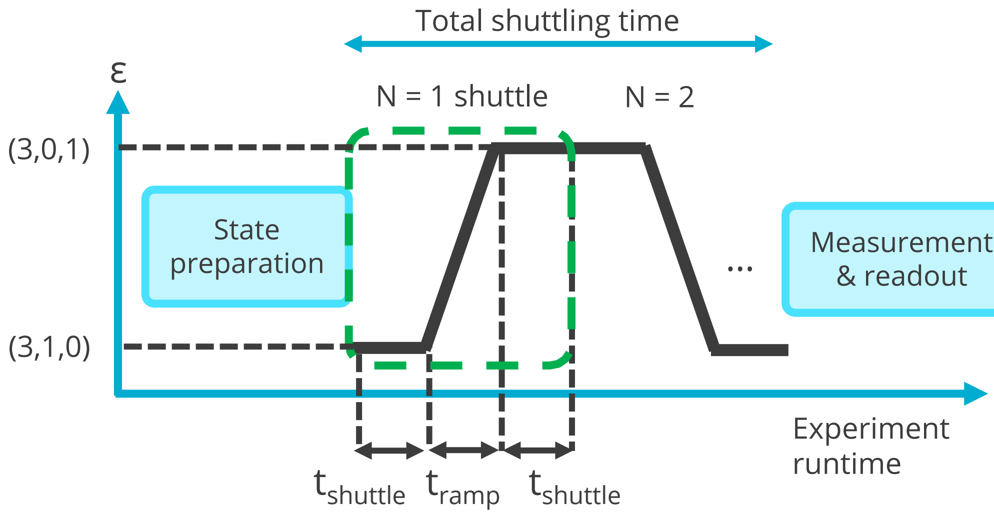


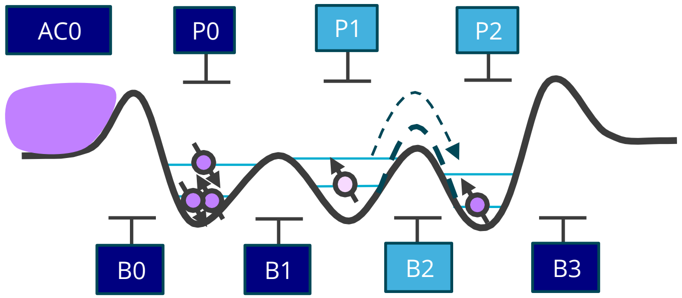
T_2* measurement

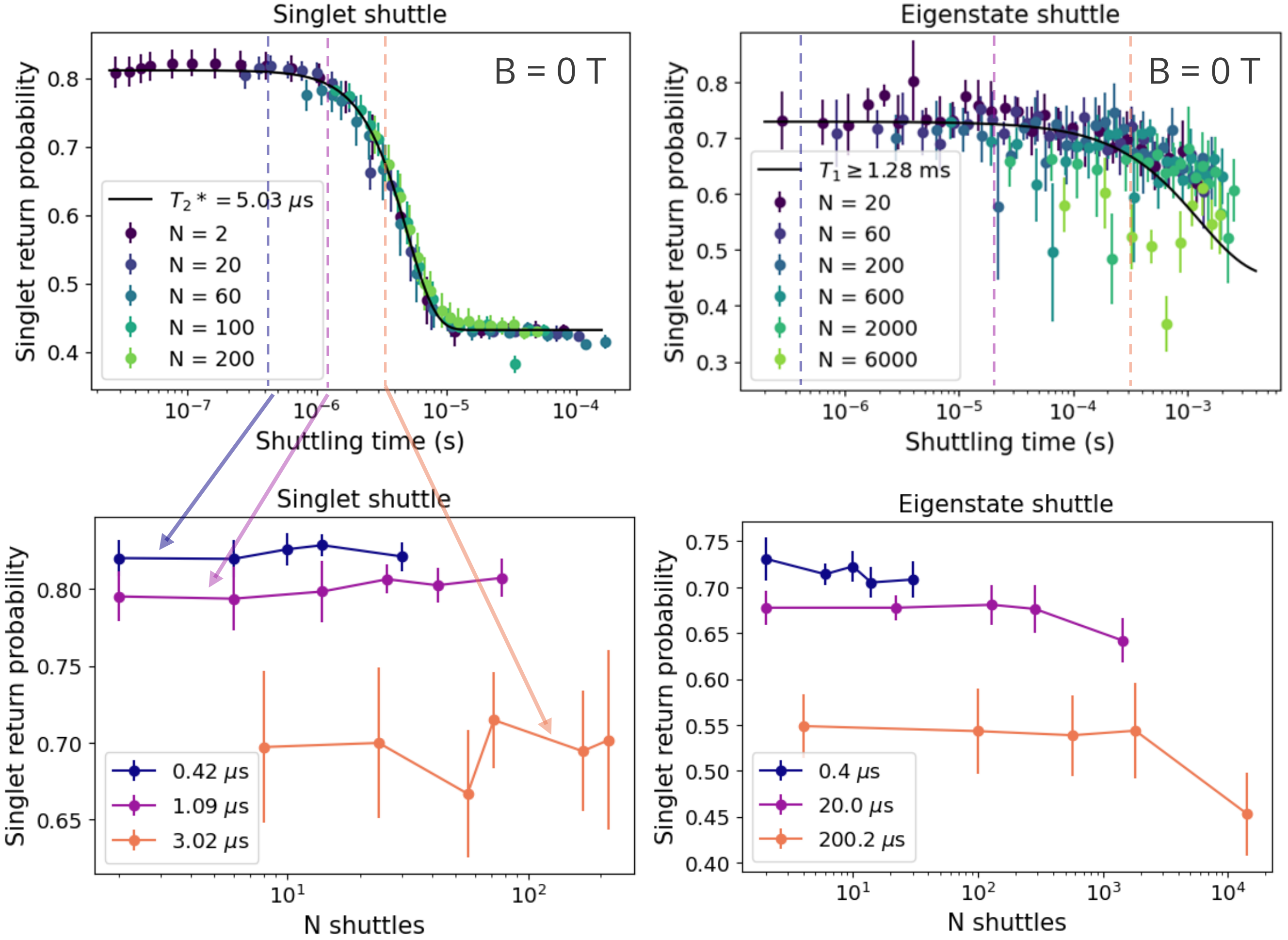
- Spin decay due to background nuclei
- Singlet-triplet rotations driven by local QD differences in *g*-factor
- Anticrossing is sensitive to charge noise

T_2* = 3.5 – 5 μs is timescale for magnetic noise dephasing

Repeated spin shuttling



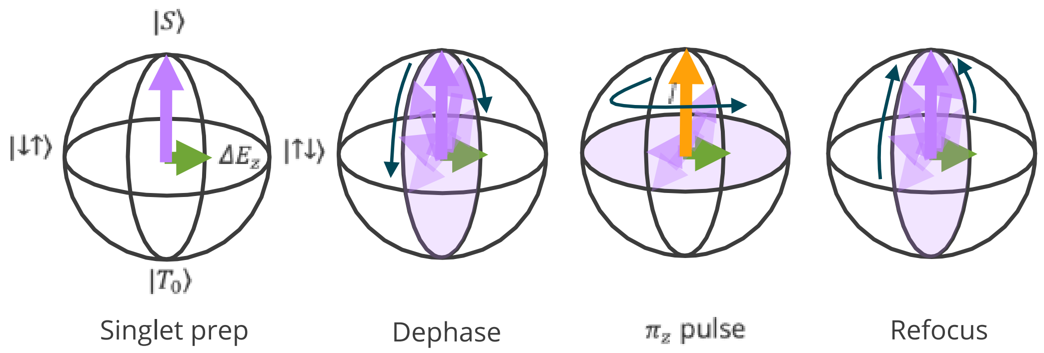


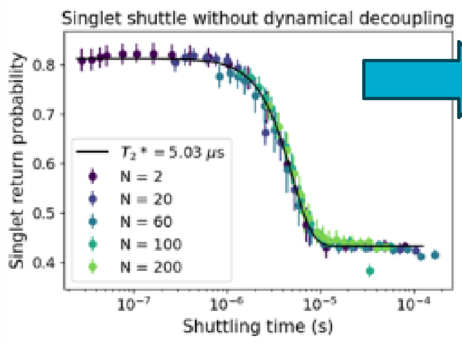


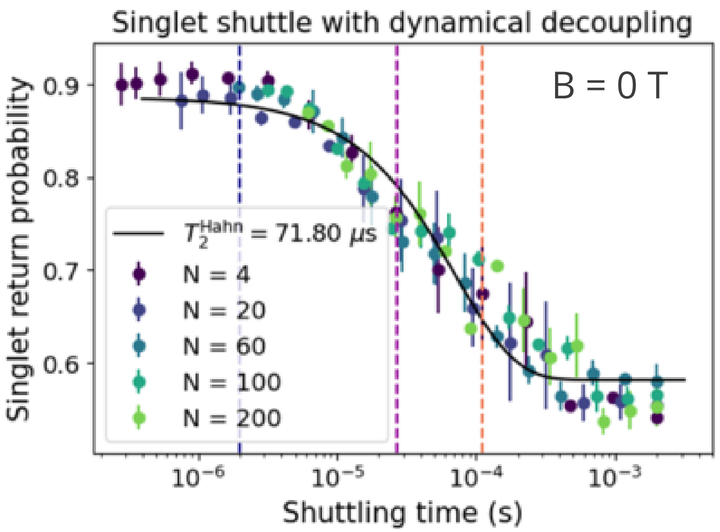
- Coherent $|S\rangle$ shuttling limited by hyperfine background, not shuttling itself
- $|\uparrow\downarrow\rangle$ spin lifetimes are longer and allow more shuttles

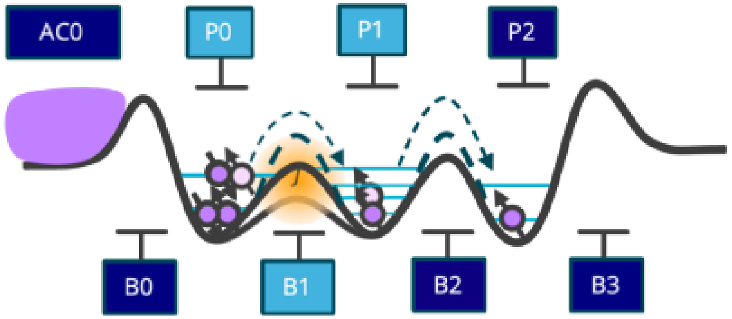
Coherent shuttle dephasing dominated by magnetic noise; Adding more shuttles does not increase error

Extending coherence using dynamical decoupling

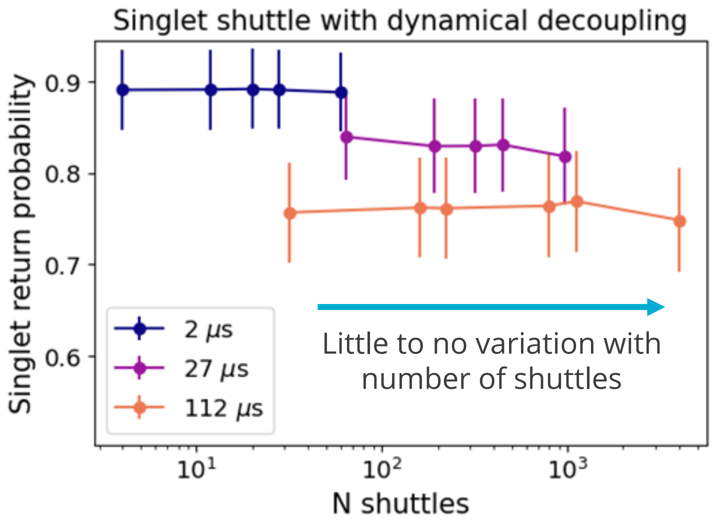


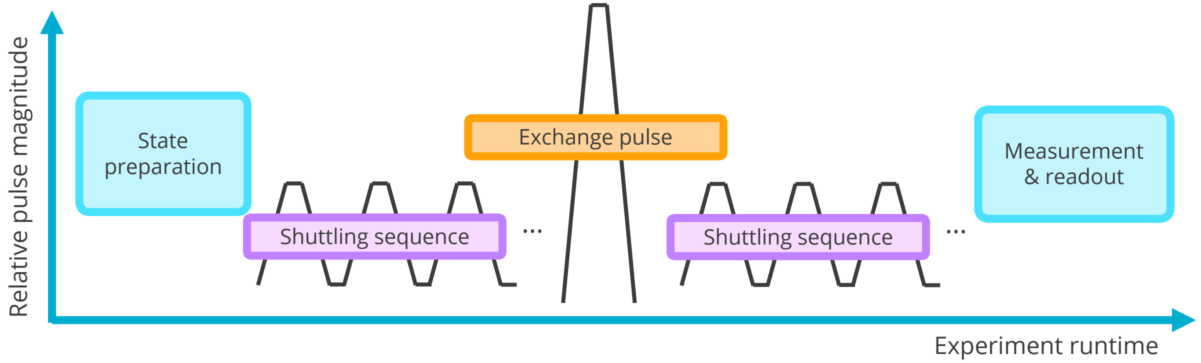






Dynamical decoupling enabled by exchange interaction between P0 and P1,P2

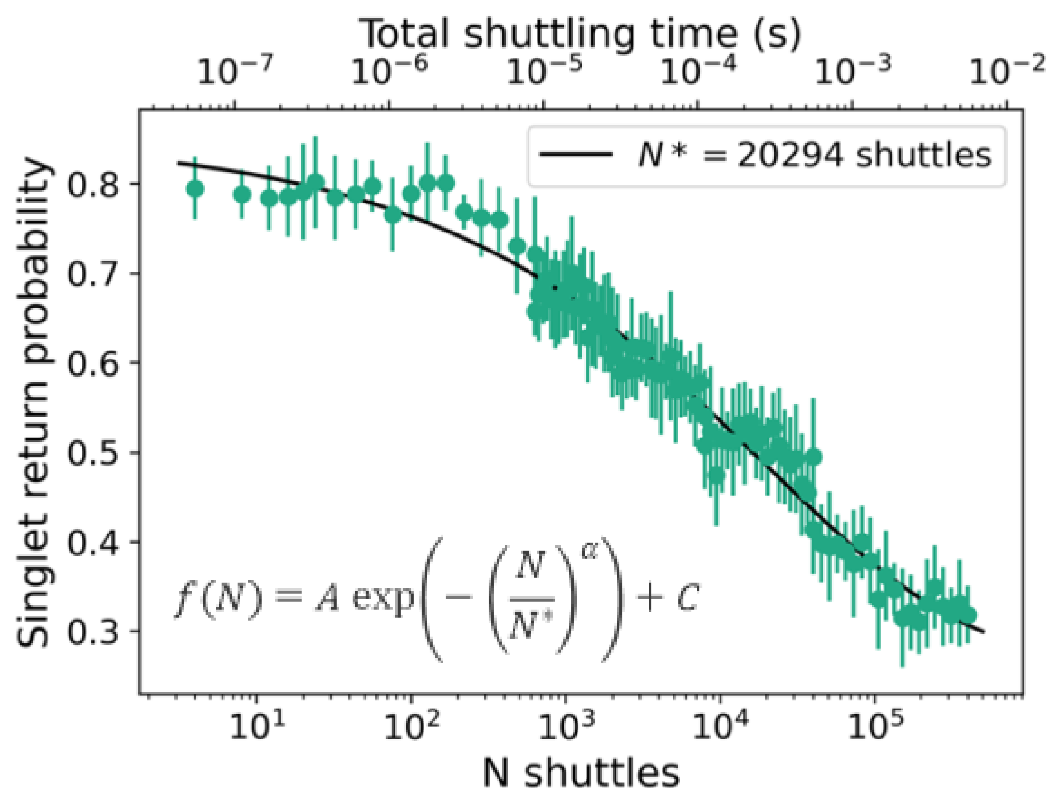




Coherent shuttling time extended by 65 μs with near N invariance

Coherent shuttling performance

Measurement:
Repeated shuttles with dynamical decoupling at minimum wait time of 4 ns



- Coherent shuttles completed within $1/e$ decay = **20k**
- Coherence loss per shuttle ~= **.0031%**
- Shuttle distance **1.2 mm** can be achieved with 10k shuttles and ~25% $|S\rangle$ error

Coherent shuttling distance possible on order of millimeters

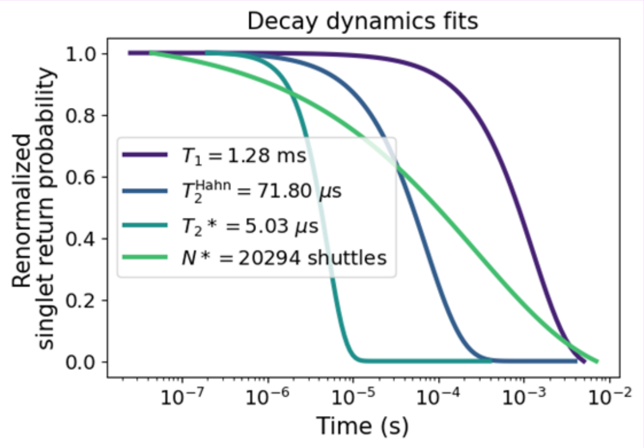
Summary

Demonstrated versatile device control

- **Coherent shuttling of an entangled spin state**
- Two-axis Bloch sphere control

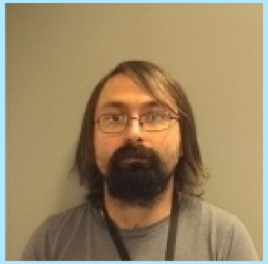
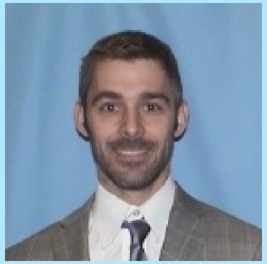
Achieved >20k shuttles

- Error per shuttle ~0.0031%
- Shuttling distance ~1.2 mm with 25% coherence loss
- Limited by residual magnetic dephasing



Acknowledgments

Sandia National Laboratories team

Natalie Foster | Jacob Henshaw | Martin Rudolph | Dwight Luhman | Ryan Jock

intel team

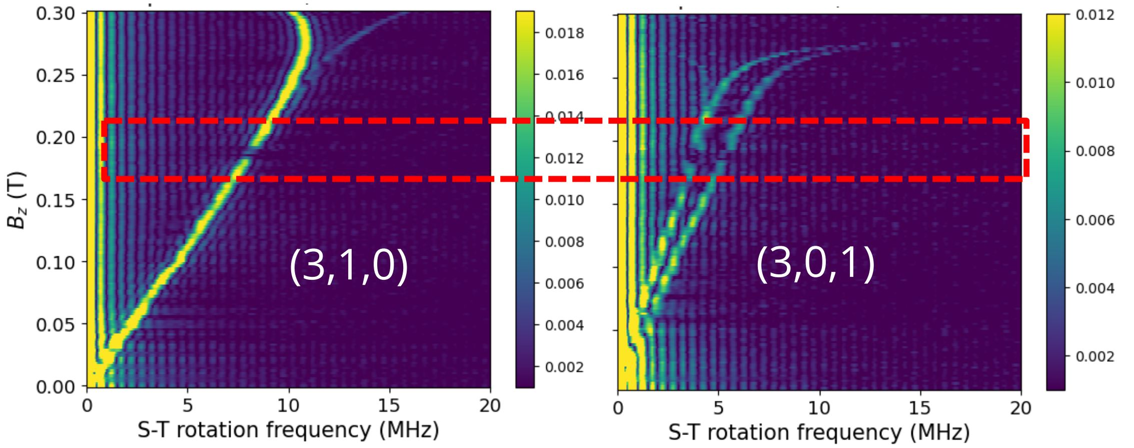

Matt Curry | Lester Lampert

Future work

- Understand decay dynamics and loss mechanisms
- Expand to more QD

supplementary

Same spin-valley hotspot = ST qubit shares dot P0 ✓



Fit parameters for $f(N) = A\exp\left(-\left(\frac{N}{N^*}\right)^{\alpha}\right) + C$

- A = 0.582
- N* = 20294
- Alpha = 0.33985
- C = 0.2698