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A singlet-triplet qubit coupled to the nuclear spin of a single phosphorus donor

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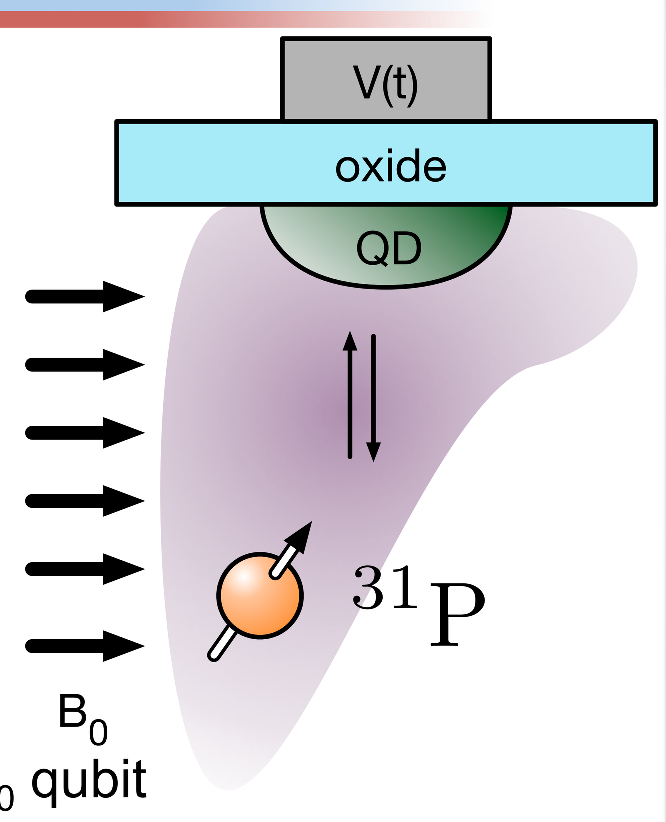
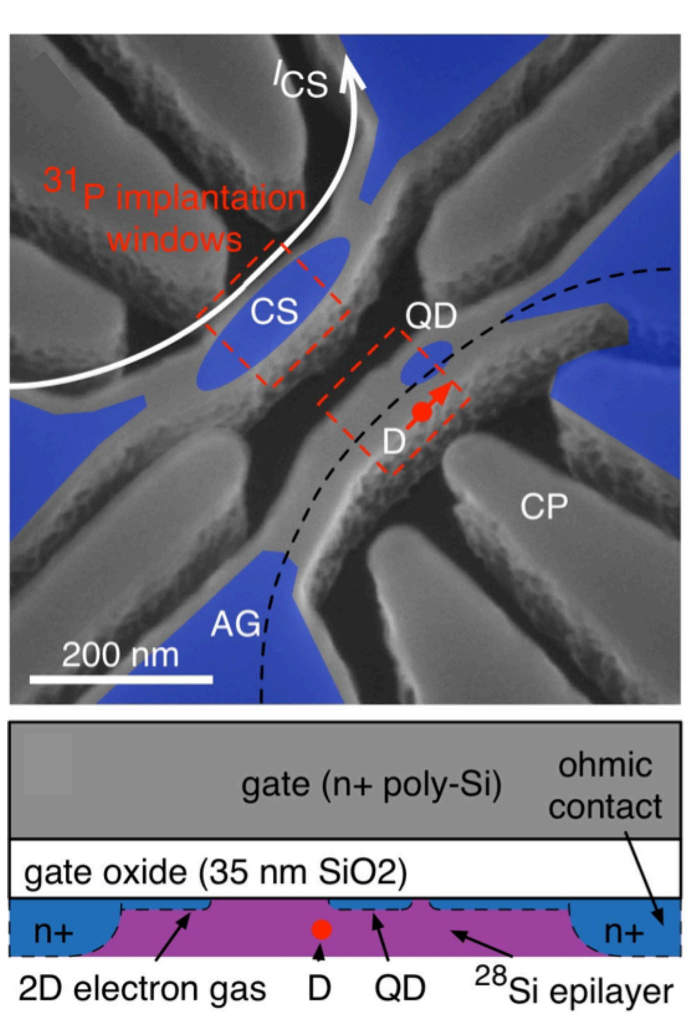
Introduction

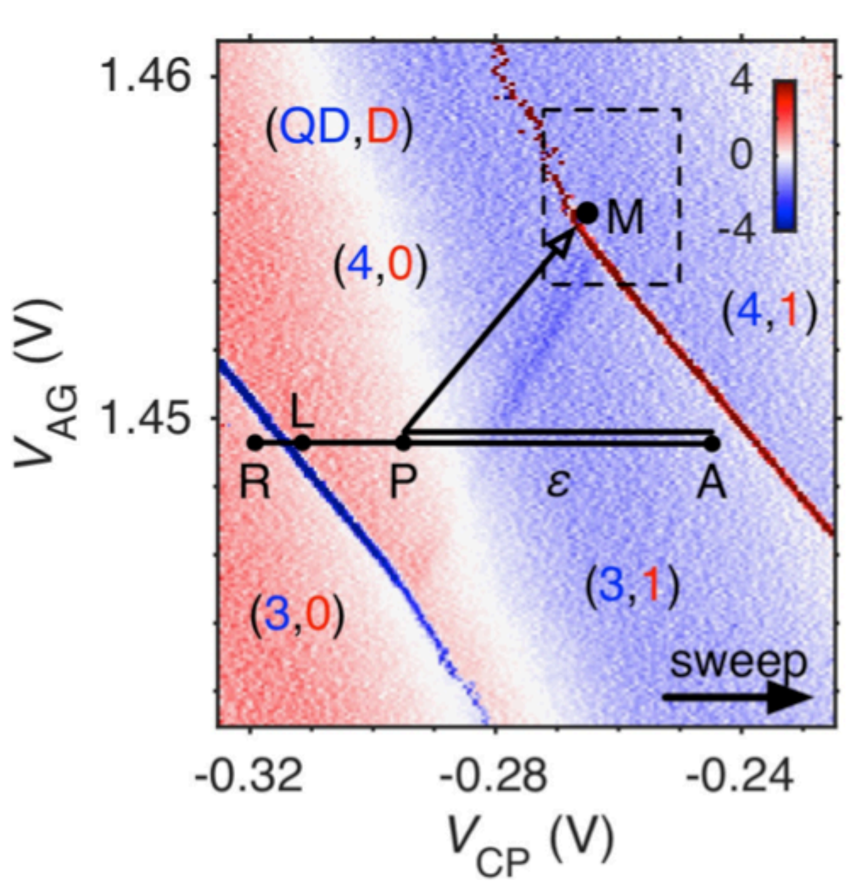
We've demonstrated[1] a singlet/triplet (S/T_0) electron spin qubit defined by a pair of electrons bound to a quantum dot with a nearby ^{31}P donor in ^{28}Si. The electron-nuclear hyperfine (HF) interaction generates an effective B-field gradient conditioned on the nuclear spin state.

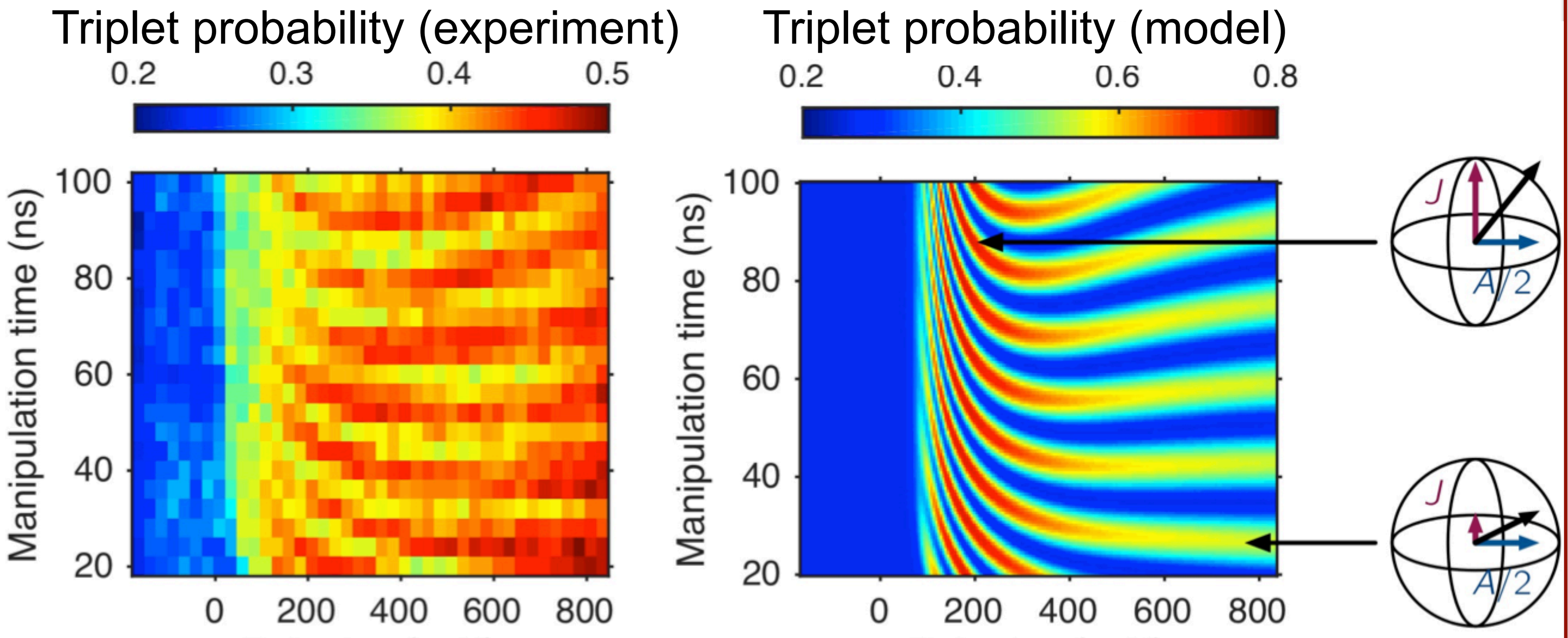


Features:

- Operationally analogous to a DQD S/T_0 qubit
- Z rotations: Generated by electrically tunable triplet-singlet exchange energy splitting, $J(\epsilon) \sim 0-100\ \mu\mathrm{eV}$
- X rotations: Effective B-field gradient generated by electrically tunable contact HF interaction with the nuclear spin, $A(\epsilon)$
- Fast timescale for X_π rotation: ~10 ns for P, even faster if other donor species used (e.g. ~0.7 ns for Bi)
- Exceptionally stable HF coupling. Spin bath of one nucleus, with effectively static HF coupling as compared with Overhauser field fluctuations in GaAs. Compact alternative to micro magnets
- Fast (~10 ns) entangling operations w/ nuclear spin, if desired
- Two-qubit interactions may be possible through capacitive coupling, a la Yacoby group[2]
- With NMR, nuclear spin may also be operated as a qubit (see poster by Andrew Baczewski)



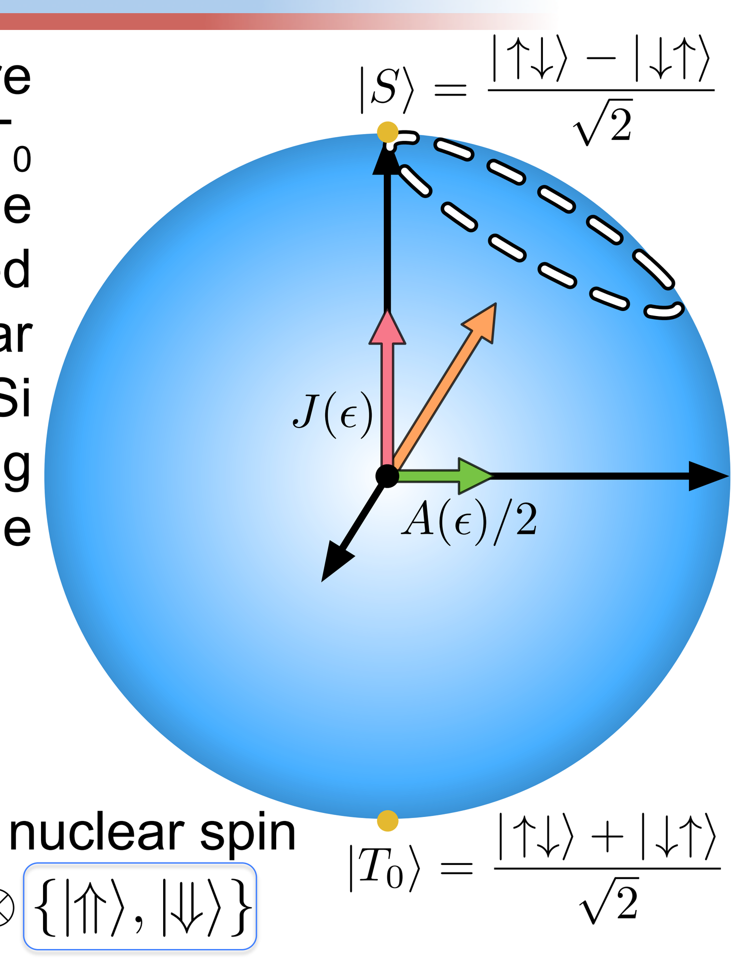




T_2^* ~ 1 μs in ensemble-averaged measurements, primarily due to quasi-static charge noise (~9 μeV)

Model

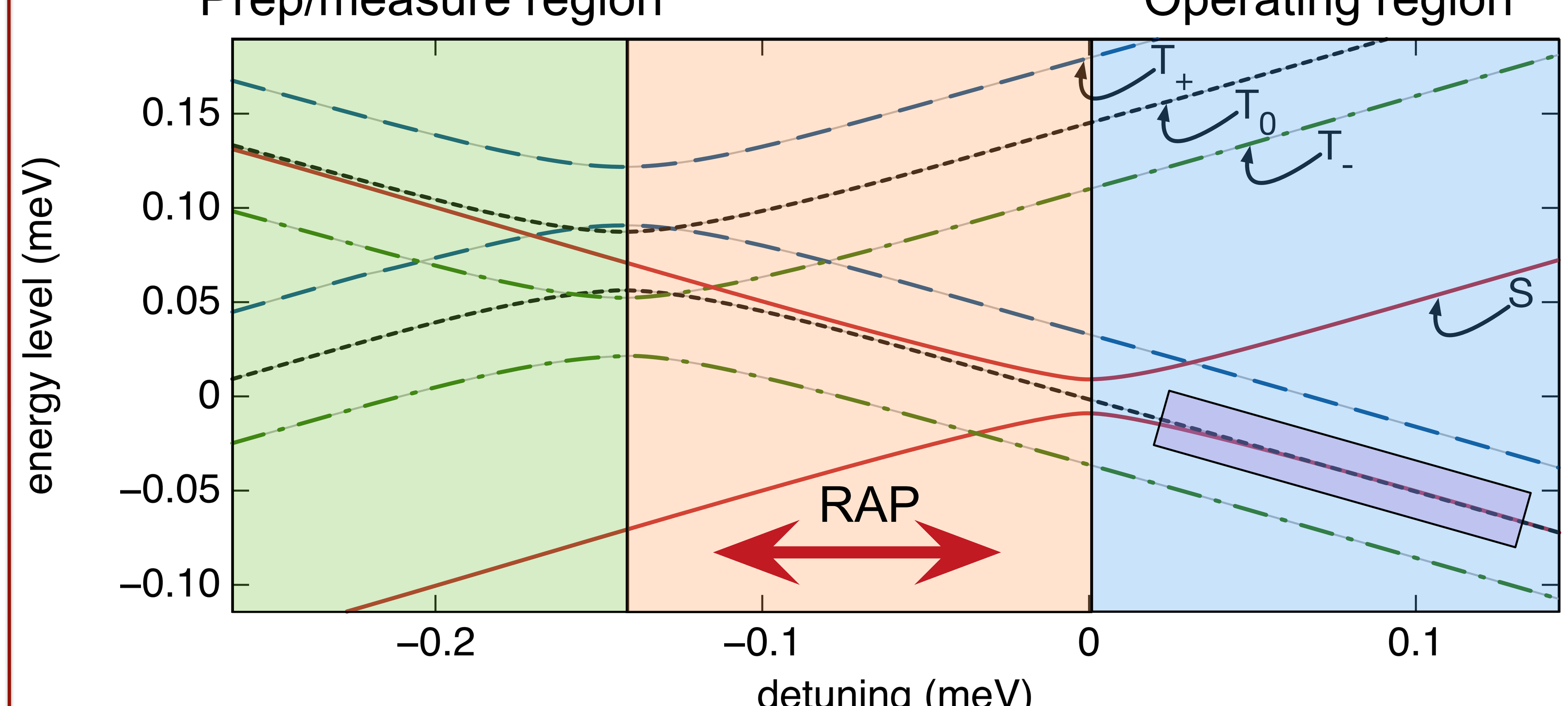
Electronic degrees of freedom are essentially those of standard DQD S/T_0 qubits, with the addition of a single nuclear spin that may be manipulated through NMR and/or dynamic nuclear spin polarization (DNP). Due to Si valley physics (shell filling), operating within (4,0), (3,1) electronic charge sectors may be advantageous.



$$H(\epsilon) = -\frac{1}{2}\left[J(\epsilon)\sigma_z \pm \frac{A(\epsilon)}{2}\sigma_x\right]$$

(± : ⇑ / ⇓)

charge: $\{(2,0),(1,1)\}$ ⊗ spin: $\{|S\rangle, |T_{-,0,+}\rangle\}$ ⊗ nuclear spin: $\{|\Uparrow\rangle, |\Downarrow\rangle\}$

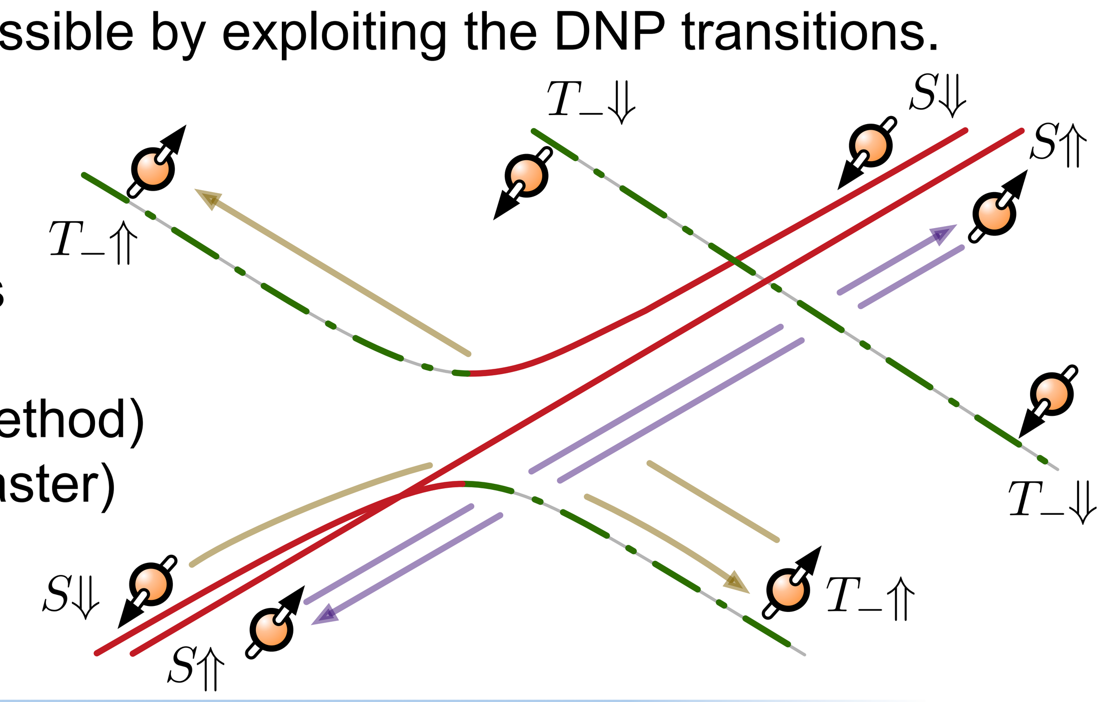


Nuclear initialization/readout

Fully electrical *preparation* of the nuclear spin state is feasible through DNP. This enables nuclear spin stabilization to suppress any slow nuclear spin flips and nuclear initialization for potential S/T_0+nuclear two-qubit operations. Electrical *measurement* of the nuclear spin is also possible by exploiting the DNP transitions.

Two avoided crossings available for DNP:

- Singlet (standard method)
- Triplet (potentially faster)



Summary

We've implemented a S/T_0 qubit in a ^{31}P donor coupled to a MOS quantum dot and demonstrated X rotations driven by electron-nuclear HF coupling. This platform provides a stable effective B-field gradient, along with the potential to utilize the donor nuclear spin as a second qubit or quantum memory.

References:

[1] P. Harvey-Collard, et al., arXiv:1512.01606 (2015)
[2] M.D. Shulman, et al., Science **336**, 202 (2012)

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