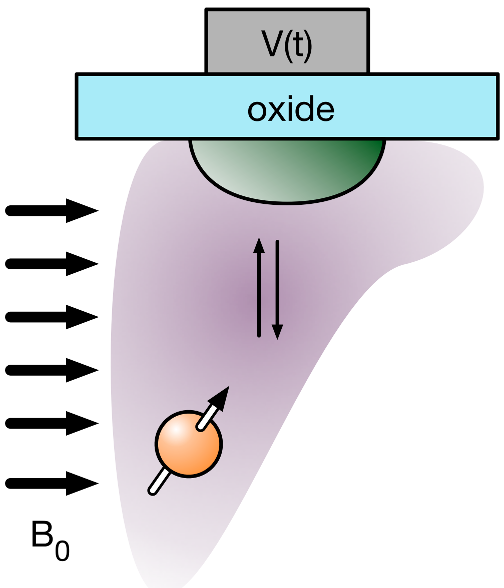
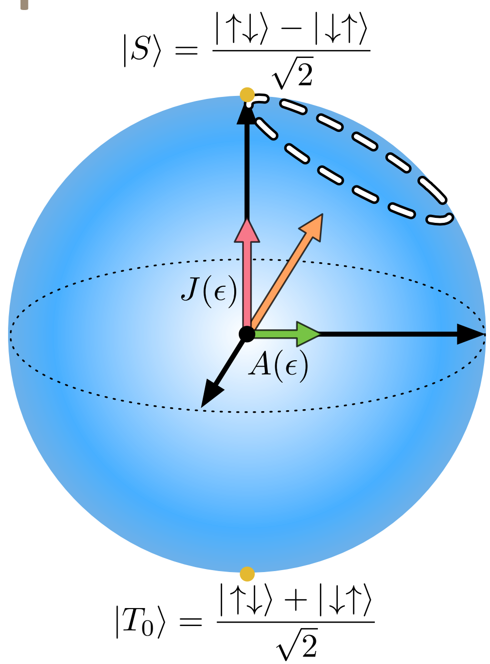
SAND2016-1999C

All-electrical control of a singlet/triplet qubit coupled to a single nuclear spin





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CENTER FOR COMPUTING RESEARCH

Collaborators:

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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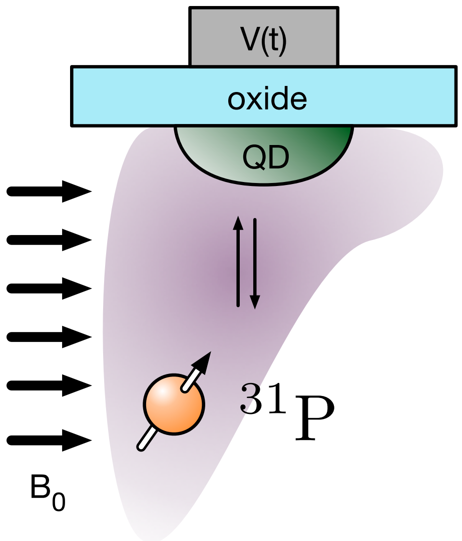
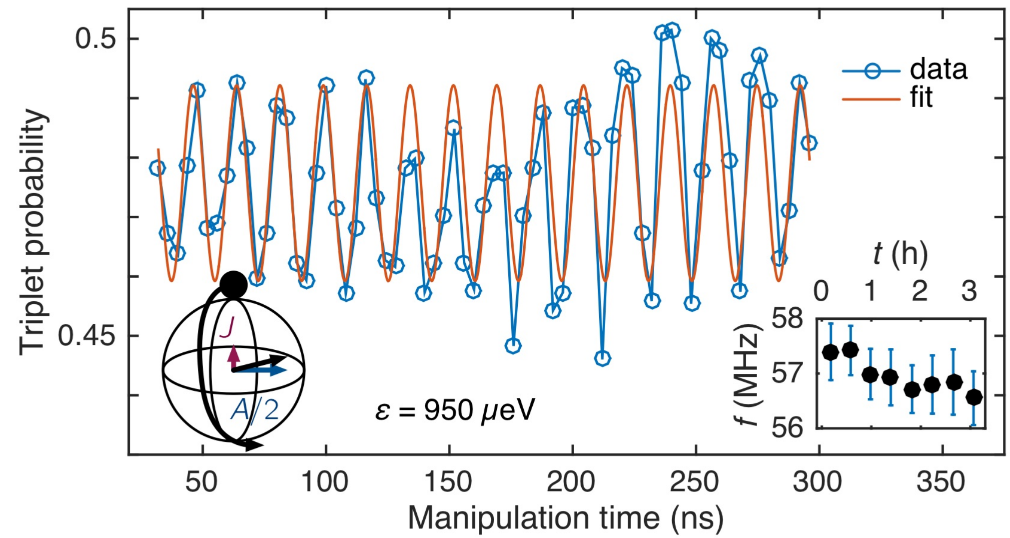
A singlet/triplet qubit in a donor + dot system



- We've implemented a few-electron **quantum dot in ^{28}Si** coupled to a single **^{31}P donor**
- Device analogous to a DQD singlet/triplet (S/T) qubit where one of the "dots" is actually a donor
- We've observed rotations between electronic singlet/triplet states driven by hyperfine (HF) coupling to a single nucleus:



[Harvey-Collard, et al. arXiv:1512.01606]

Features:

- Stable HF coupling (bath of one)
- Potential to use nuclear spin as a quantum memory (next talk)
- Fast electronic-nuclear entangling operations (~10 ns)

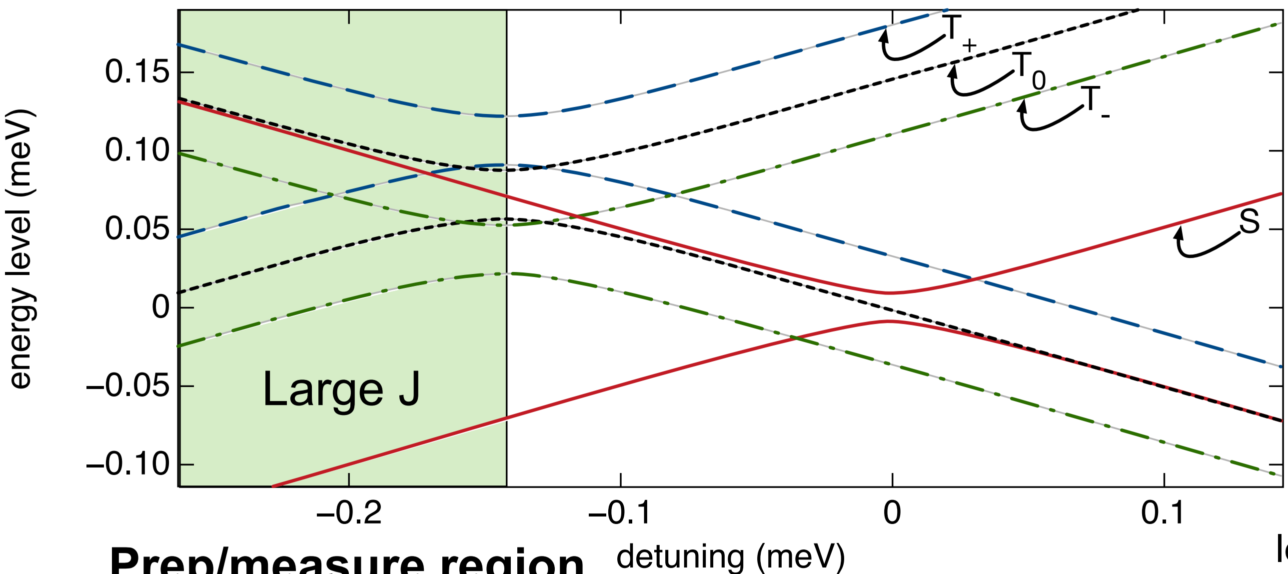
Model

Relevant states: $\underset{\text{charge}^*}{\{(2,0),(1,1)\}} \otimes \underset{\text{electron spin}}{\{|S\rangle, |T_{-,0,+}\rangle\}} \otimes \underset{\text{nuclear spin}}{\{|\Uparrow\rangle, |\Downarrow\rangle\}}$

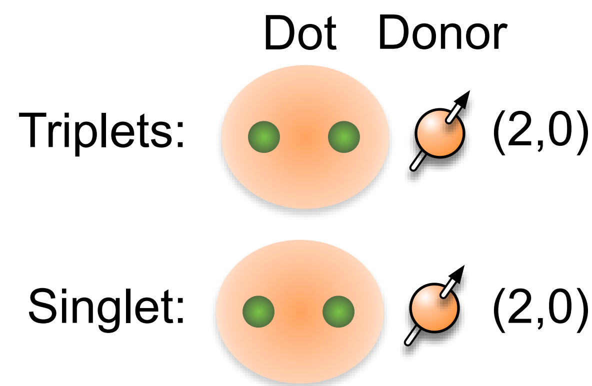
*may opt for (4,0),(3,1) charge sectors (Si valley physics)

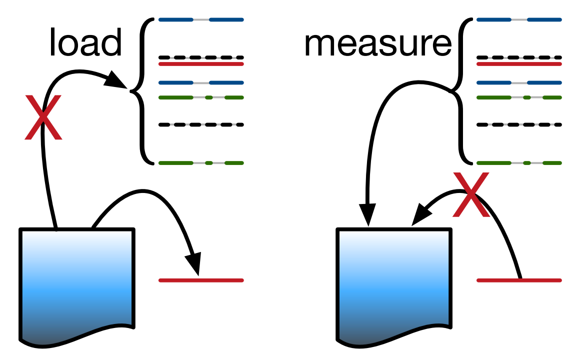
Control knob:

Bias between (2,0) and (1,1) charge sectors (detuning)



Prep/measure region



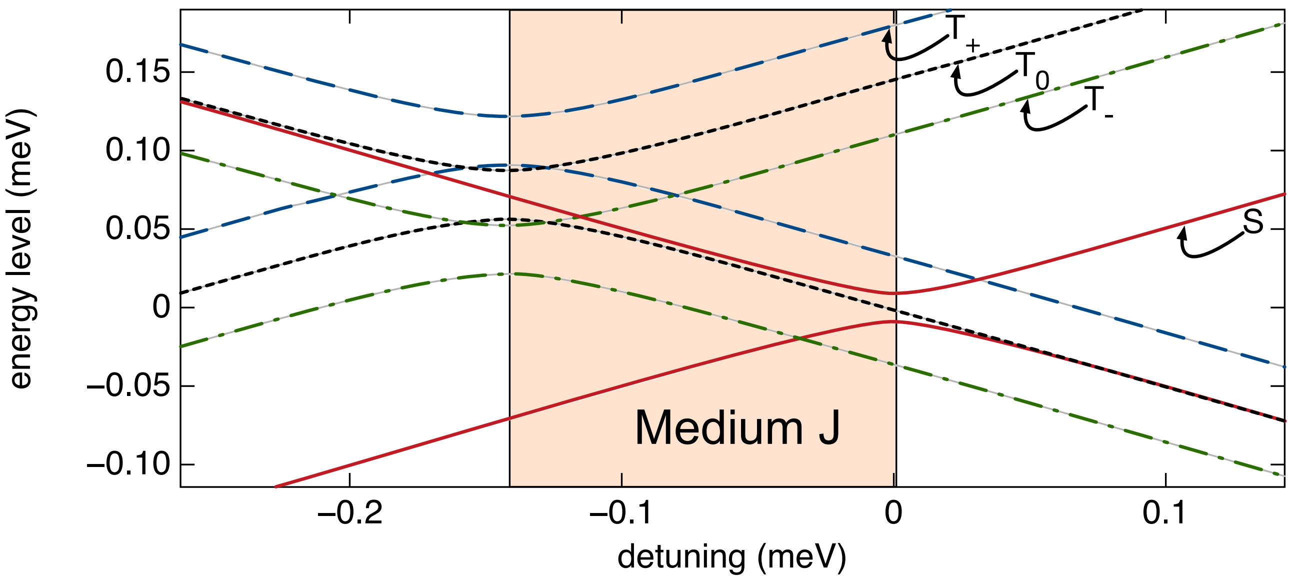


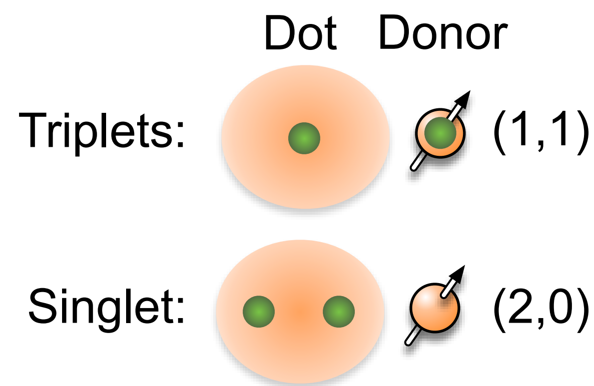
Model

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

*may opt for (4,0),(3,1) charge sectors (Si valley physics)

Control knob:
Bias between (2,0) and (1,1) charge sectors (detuning)





Rapid adiabatic passage (RAP) to operating point

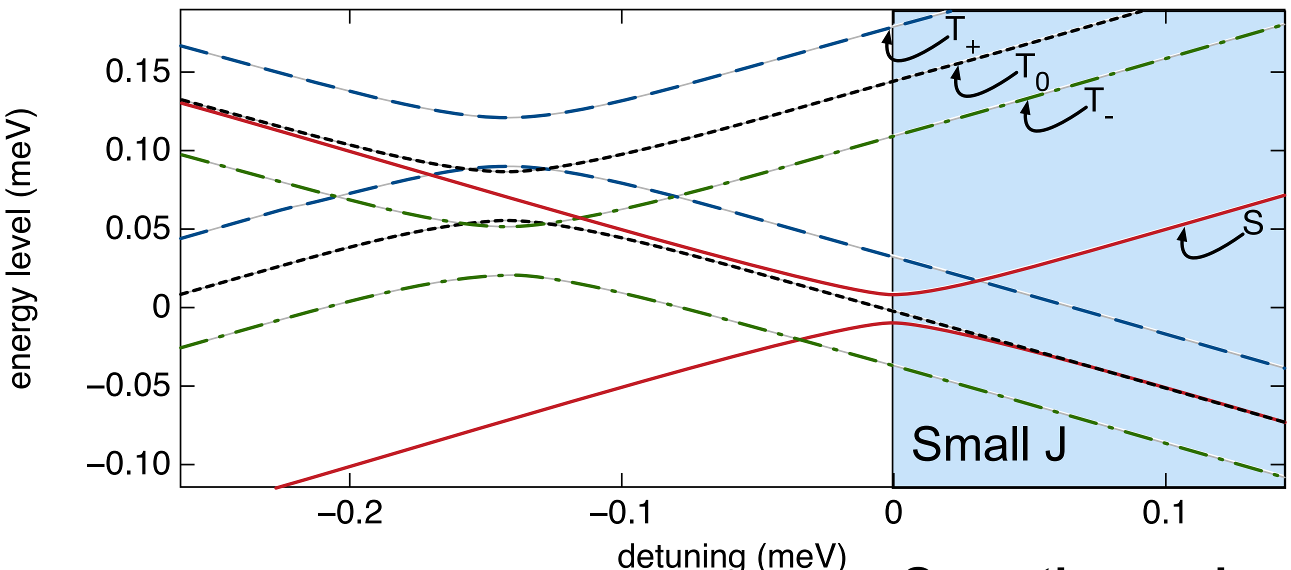
Model

Relevant states: $\underbrace{\{(2,0),(1,1)\}}_{}$ ⊗ $\{|S\rangle, |T_{-,0,+}\rangle\}$ ⊗ $\{|\Uparrow\rangle, |\Downarrow\rangle\}$

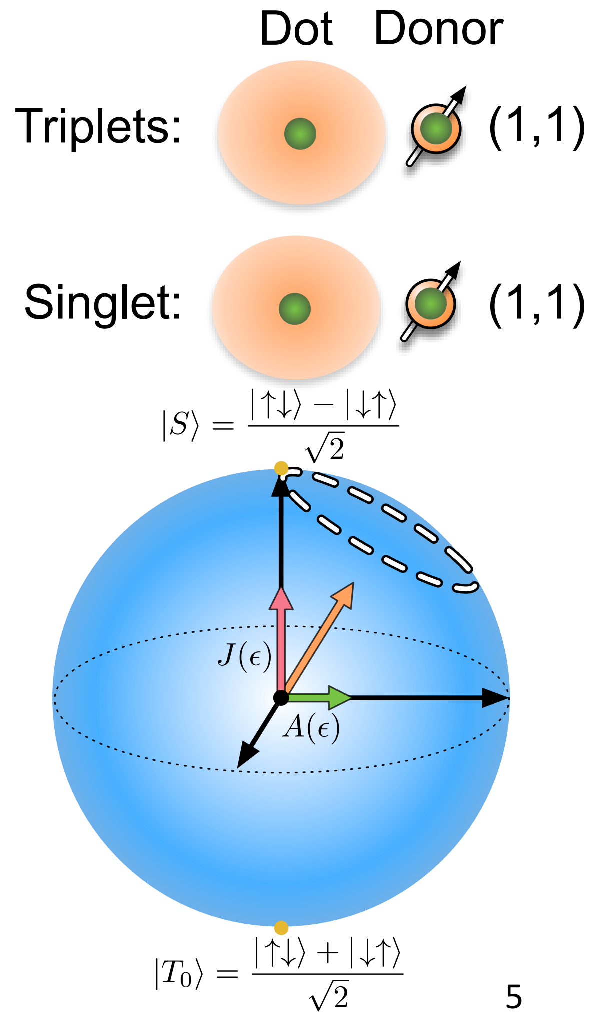
charge*	electron spin	nuclear spin
$\{(2,0),(1,1)\}$	$\{\lvert S\rangle, \lvert T_{-,0,+}\rangle\}$	$\{\lvert\Uparrow\rangle, \lvert\Downarrow\rangle\}$

*may opt for (4,0),(3,1) charge sectors (Si valley physics)

Control knob:
Bias between (2,0) and (1,1) charge sectors (detuning)



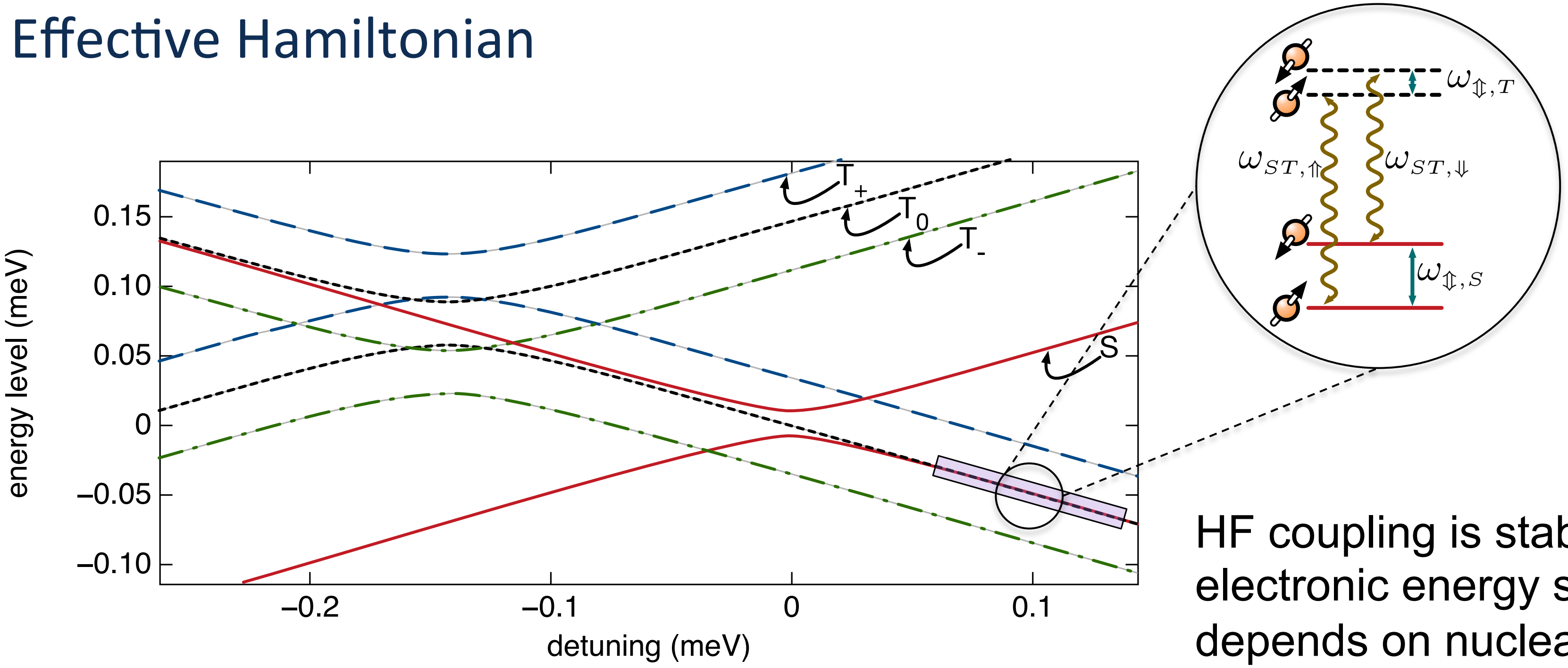
Operating region



Dominant decoherence mechanisms expected:

- Charge (exchange) noise
- Uncertain nuclear spin

Effective Hamiltonian



HF coupling is stable, but electronic energy splitting depends on nuclear spin

Difference in rotation rates: < 1 MHz for typical parameters (suppressed by B-field)

Polarize nucleus to eliminate uncertainty in nuclear spin state and entanglement between electronic and nuclear degrees of freedom

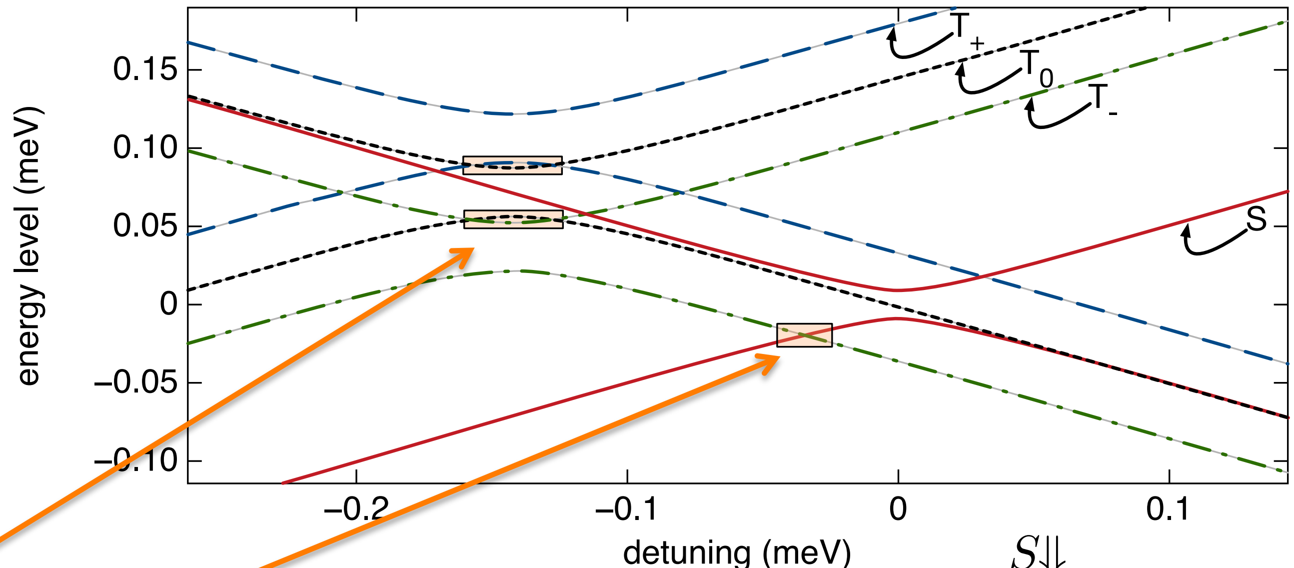
To do this, we can use *dynamic nuclear polarization (DNP)*

Dynamic nuclear polarization (DNP)

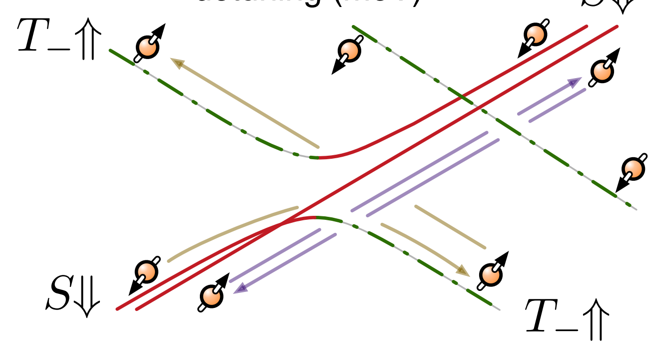
Nuclear spin pumping (a la [Foletti, et al. Nat. Phys. **5**, 903 (2009)]):

- Asymmetric drive through a spin-exchanging avoided crossing
- Pump entropy into environment via unload/reload of electronic state
- Fixed point of pumping process is a well-polarized nuclear spin

Unlike GaAs:
We need pump only a **single** spin-1/2 degree of freedom



Two options: **Triplet** and **singlet** schemes



(In GaAs: analogous anti-crossing is between $S\Uparrow$ and $T_+\Downarrow$)

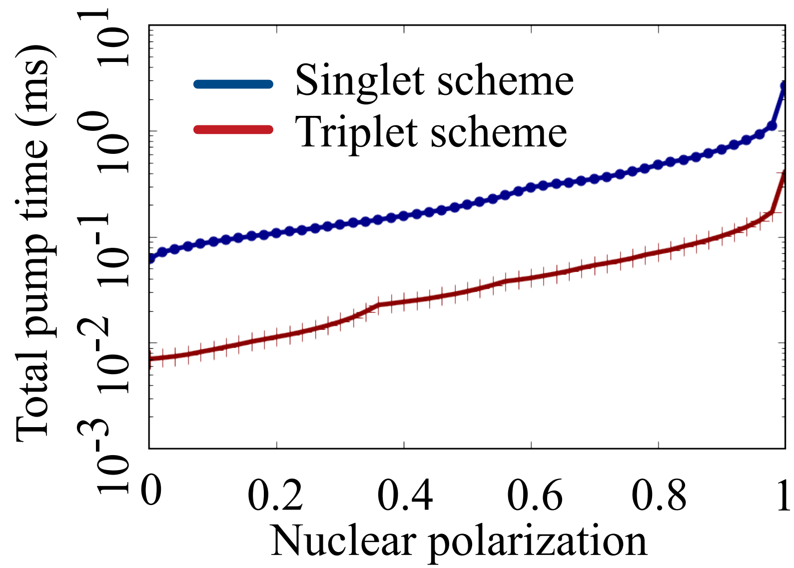
Dynamic nuclear polarization (DNP)

Two DNP schemes:

- Singlet — prep mostly singlet
- Triplet — prep mostly triplet

Pumping efficiency:

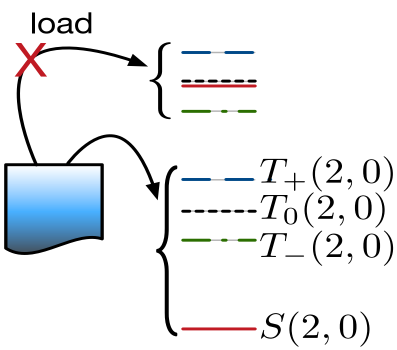
$$\eta_{\rm DNP} = \langle\Uparrow|\mathrm{tr}_{\rm e}\left[U_{\rm DNP}\,\rho_{\rm e}\otimes|\Downarrow\rangle\langle\Downarrow|U^{\dagger}_{\rm DNP}\right]|\Uparrow\rangle$$

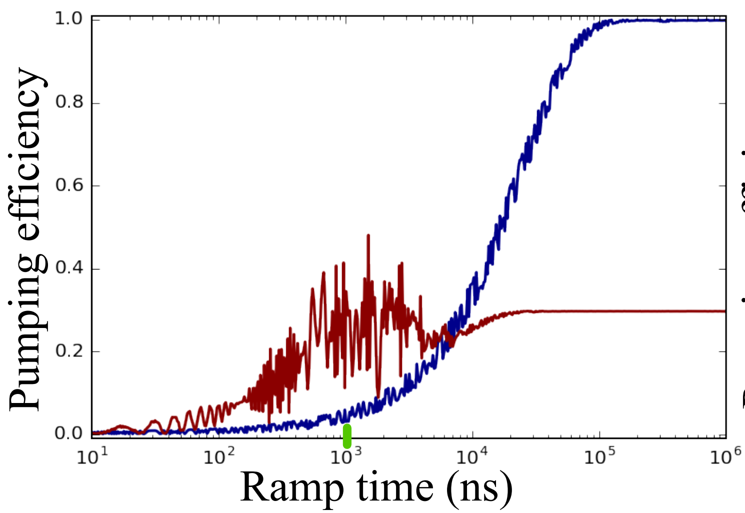


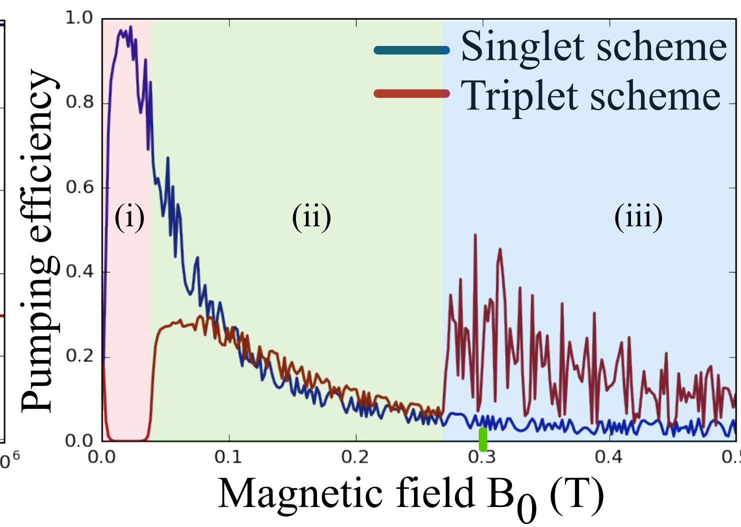
Load/unload rate:

Triplets: fast

Singlet: slow



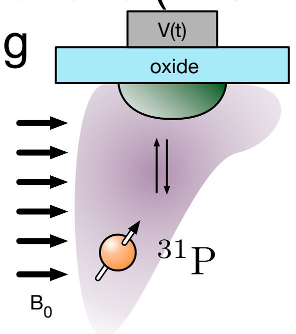




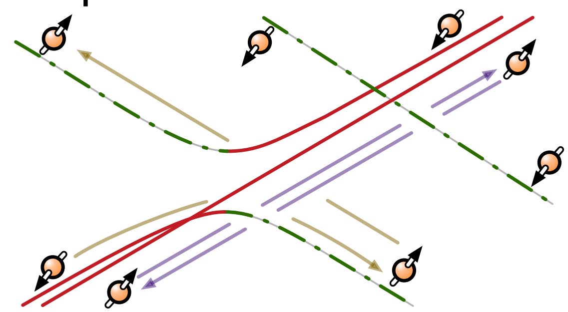
Summary

Donor + dot S/T qubit:

- Fast HF-driven rotations (~10 ns)
- Stable HF coupling

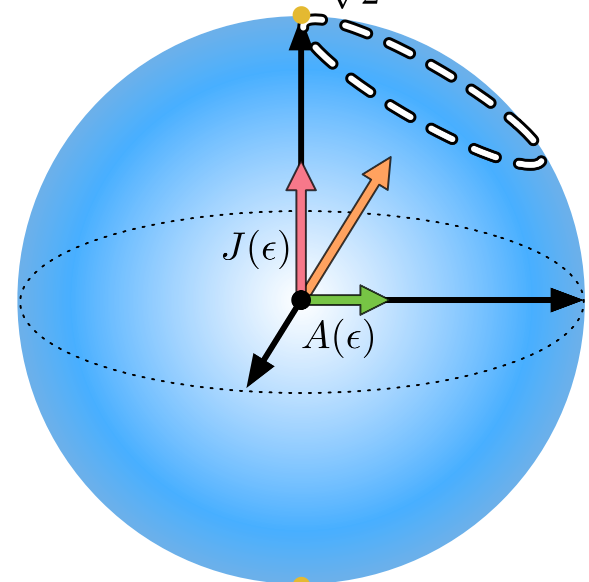


Prep nuclear state w/ DNP



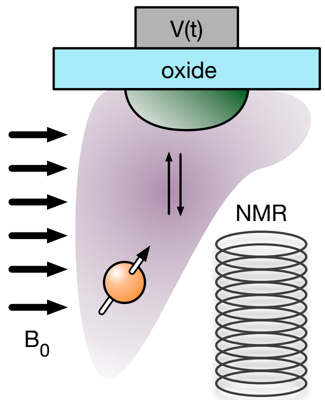
Faster DNP w/ triplet scheme

$$|S\rangle = \frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}$$



$$|T_0\rangle = \frac{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle}{\sqrt{2}}$$

Donor nuclear spin: a potential quantum memory (next talk)



Collaborators:
Patrick Harvey-Collard [P45.1 (Wed 2:30pm)],
Andrew Baczewski [P45.3 (Wed 2:54pm)], John K. Gamble,
Erik Nielsen, Rick Muller, Martin Rudolph, Malcolm Carroll

Thank you!

Backup slide

Triplet scheme: