A silicon quantum-dot-coupled nuclear spin qubit

Hensen B., Huang W. W., Yang C.-H., Chan K. W., Yoneda J., Tanttu T., Hudson F. E., Laucht A., Itoh K. M., Ladd T. D., Morello A., Dzurak A. S.

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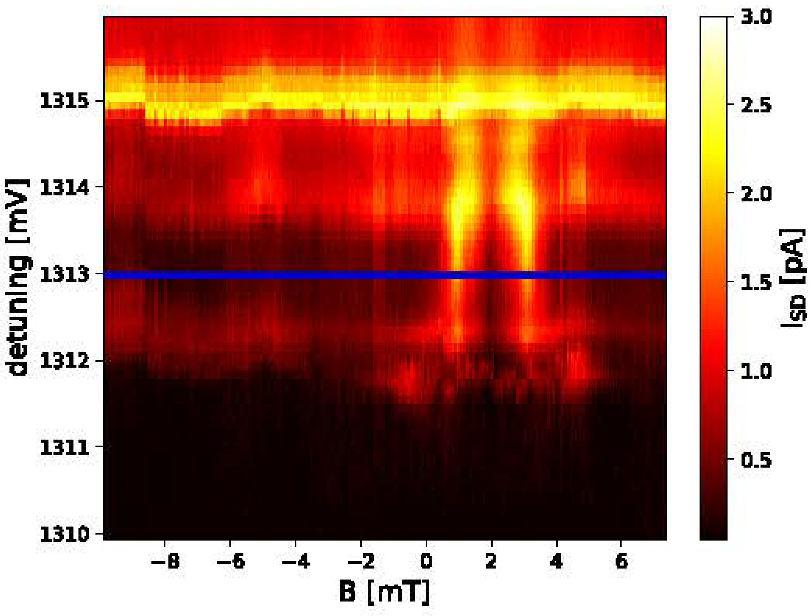
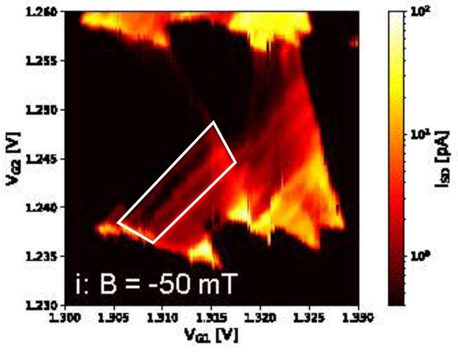
Outline

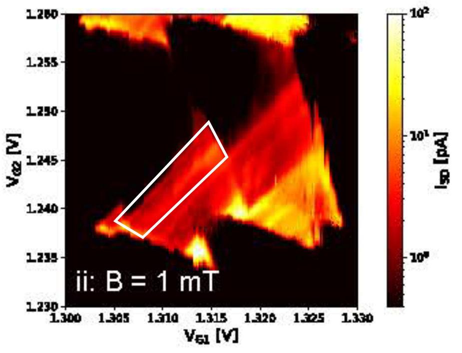
- Nuclear spins in silicon
- The device
- Hyperfine coupling to individual nuclear spin
- ^{29}Si nuclear spin qubit
- Qubit characterisation
- Electron & nuclear spin entanglement
- Spin coherence during electron transfer
- Conclusion

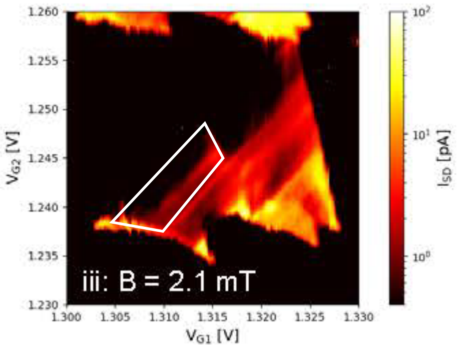
Nuclear spins in silicon

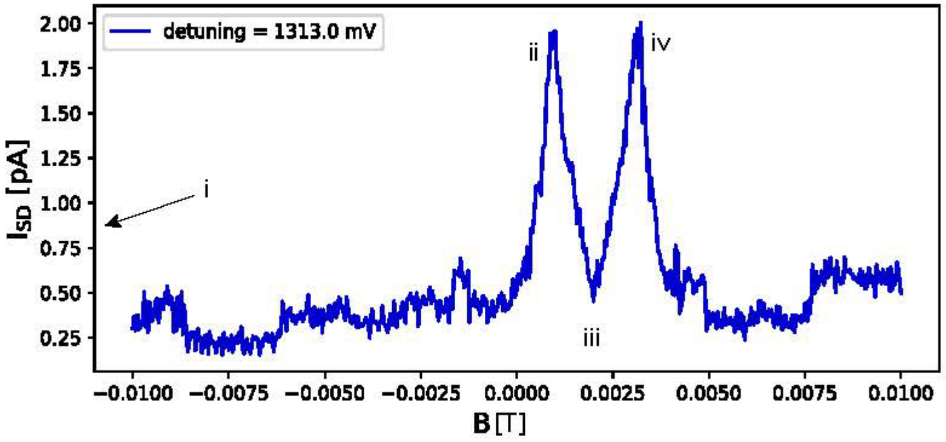
- ~5% of natural Si atoms are ^{29}Si with spin ½
- Approximation for finFET QDs:
  - Dot of size ~5*5*10 nm^3 contains ~584 ^{29}Si nuclei
- Hyperfine interaction observed:
  - i.e. lifting-mechanism of spin blockade











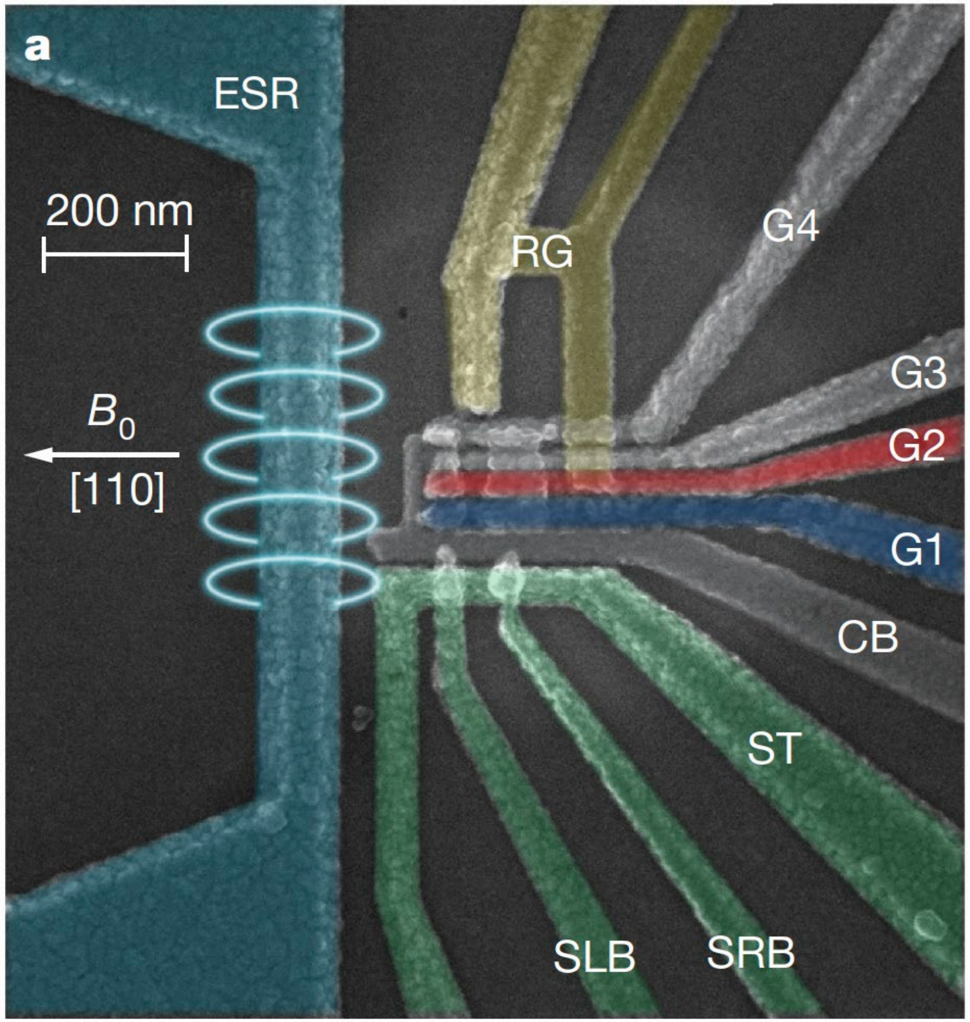
- Early proposal for nuclear spin based quantum computer

Kane B. (1998) doi.org/10.1038/30156

The device

- "Known" from other papers/journal clubs
- Accumulation of double dot by G1/G2
- Confinement by CB/G3/G4
- Loading through reservoir RG
- Charge sensing with SET, ST/SLB/SRB
- ESR antenna
- $B_{ext} = (1.42 \pm 0.04)T$

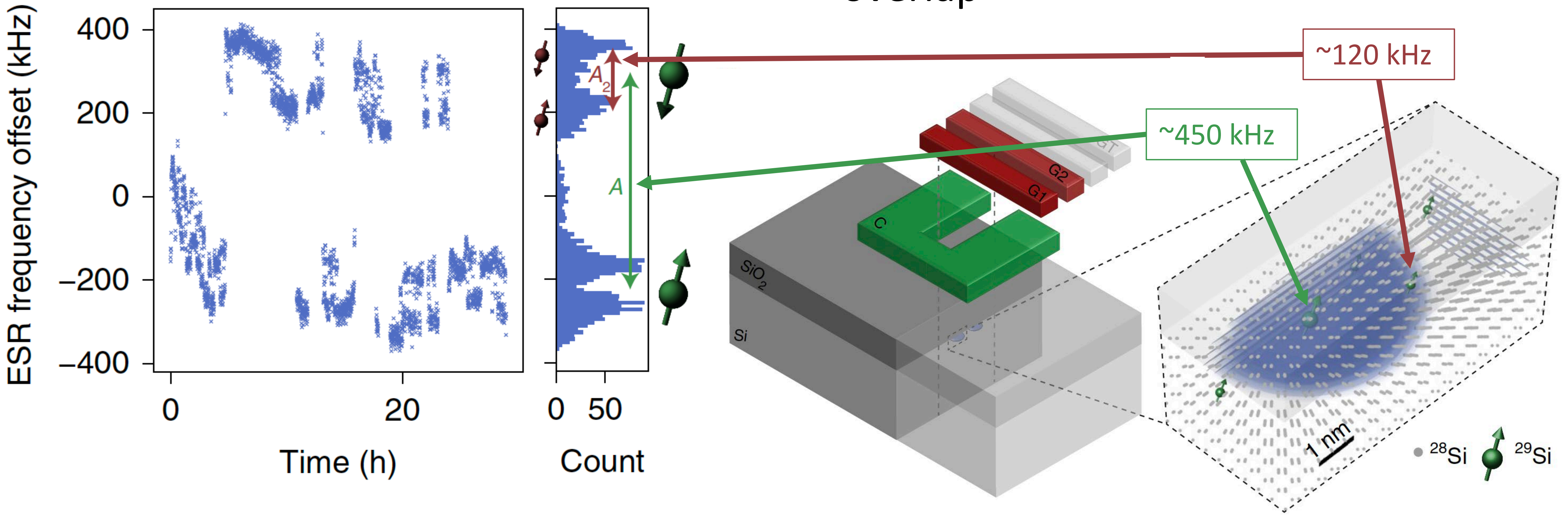
- Chip substrate:
  - isotopically purified Si (800 ppm ^{29}Si)
  - Expect ~2 ^{29}Si nuclei in an 8 nm dot



Huang W. et al. (2019) doi.org/10.1038/s41586-019-1197-0
Seedhouse A. et al. (2020) arxiv.org/pdf/2004.07078.pdf

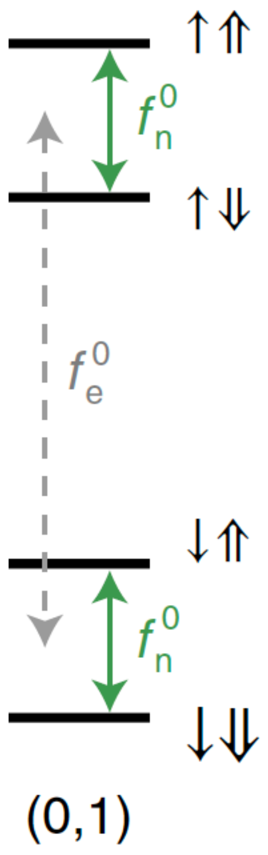
Initial observation

- Rabi frequency switches over time
  - Pattern of four different frequencies
  - hour-timescale
- Histogram reveals four peaks
- Explanation: 2 nuclear spins overlap with electron wavefunction
- Different couplings from different overlap



Hyperfine coupling to individual nuclear spin

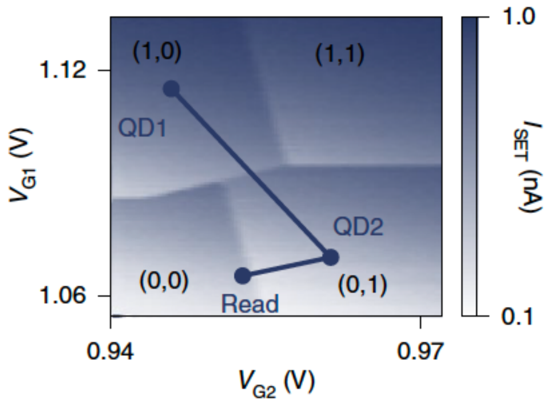
- What does this proposal imply?
- Only consider strongly coupled nuclear spin: 4-level system



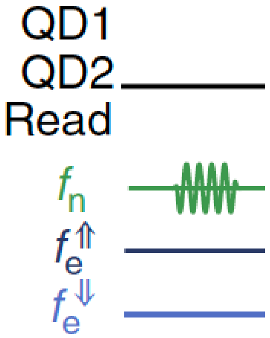
$$H = -B_{ext}(\gamma_e S_z + \gamma_{Si} I_z)$$

- Overlap is zero if the electron (↑) is not on the same dot as the nucleus (⇑):
  - Electron rabi frequency $f_e^0 = 39\ GHz$
  - Nuclear spin rabi frequency f_n^0
- Hyperfine if e⁻ is on the same dot as nucleus:
  - Eigenstates are displaced by $\pm\frac{A}{4}$
  - Sign depends on parallel/antiparallel spins
- Four transitions: $f_e^{\Uparrow}, f_e^{\Downarrow}, f_n^{\uparrow}, f_n^{\downarrow}$

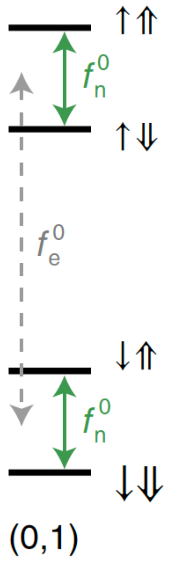
Nuclear spin readout scheme



- Measure electron spin rabi frequency
- Gives nuclear spin state

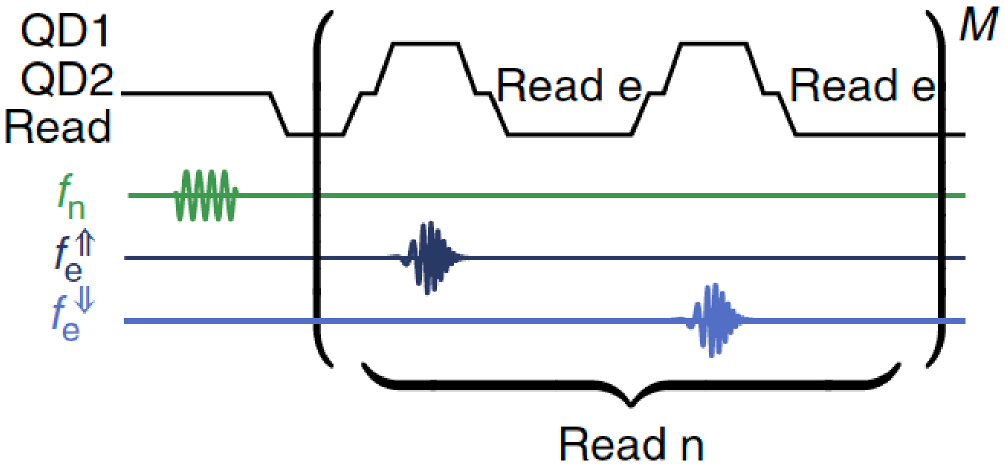


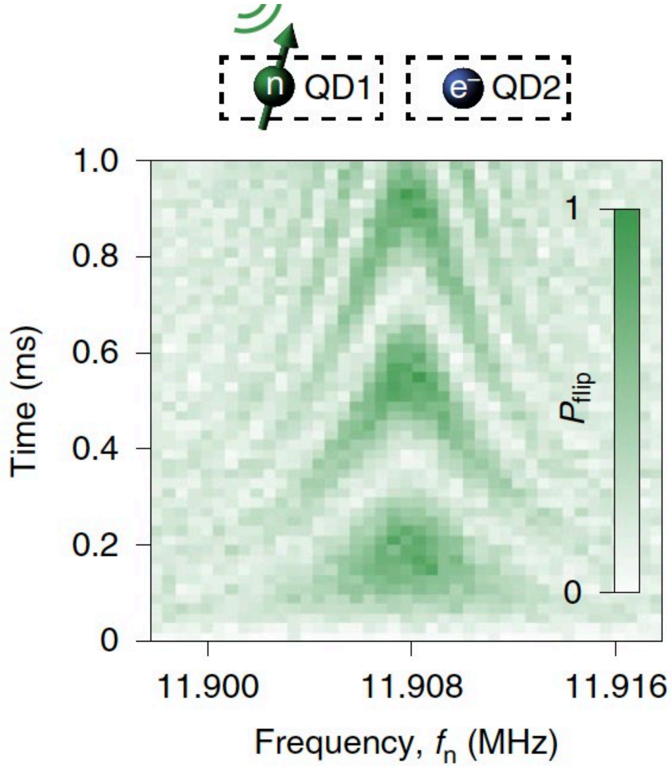
- Pulse in (0,1) charge state ($A = 0$)
- Apply pulse at f_n^0
- Pulse in (1,0) state
- π-Pulses at $f_e^{\Uparrow}$and $f_e^{\Downarrow}$
- Electron spin readout: Elzermann + SET
- Only one of the two pulses will drive electron spin



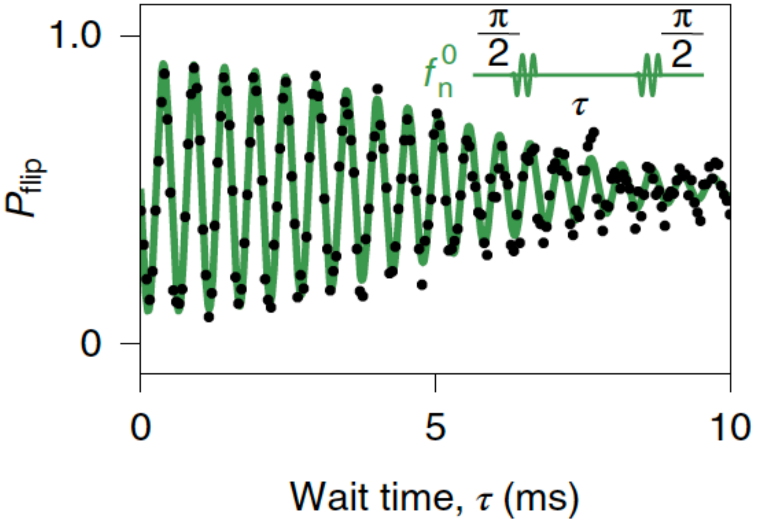
^{29}Si nuclear spin qubit

- Rabi-Chevron of the nuclear spin
- Ramsey and Hahn-Echo measurements
- Quantum non-demolition readout

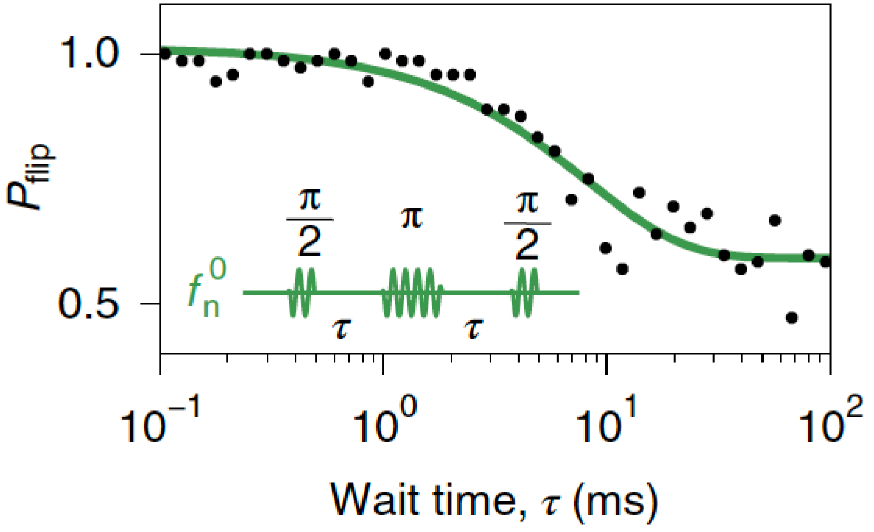




$f_n^0 = 11.9078\ MHz$



$T_2^* = (6.5 \pm 0.3)\ ms$

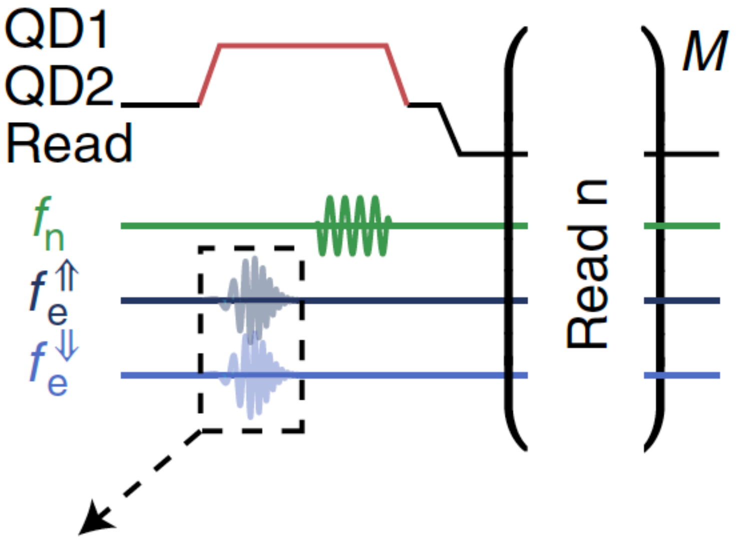


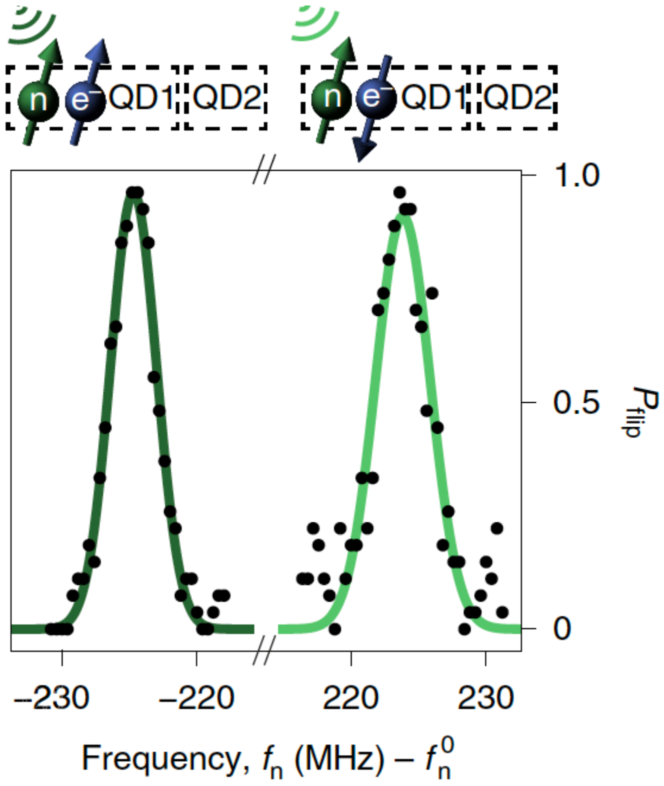
$T_2^{Hahn} = (16 \pm 2)\ ms$

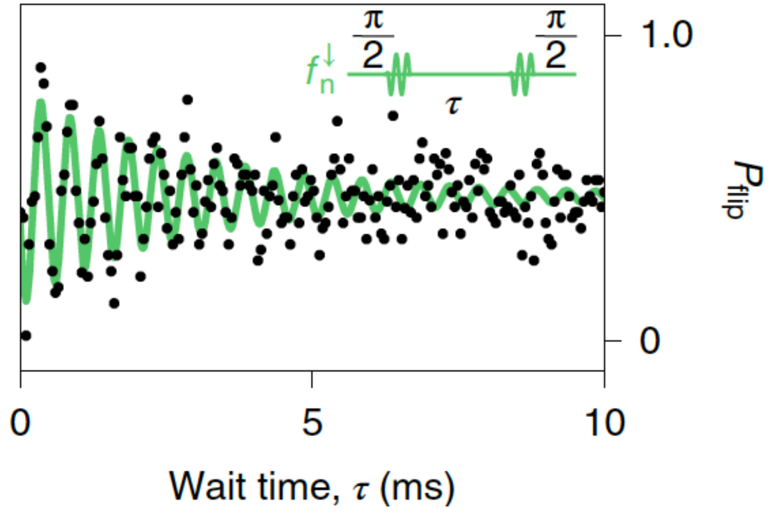
Comparison for electron in same device: $T_2^{*,e} \approx 15\ \mu s$

^{29}Si nuclear spin qubit

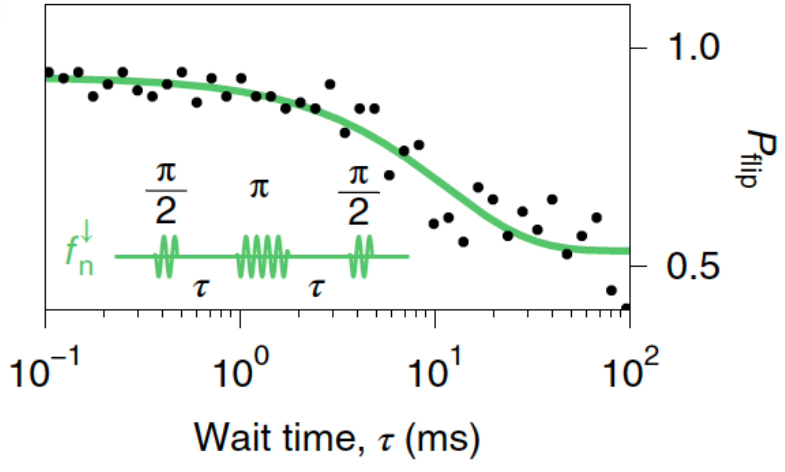
- Alternative measurement:
  - Pulses while electron in same dot as nucleus
  - Electron spin set to up/down
- Resonances at $f_n^0 \pm 225\ kHz$







$T_2^{*,loaded} = (2.9 \pm 0.7)\ ms$



$T_2^{Hahn,loaded} = (23 \pm 4)\ ms$

Qubit characterisation

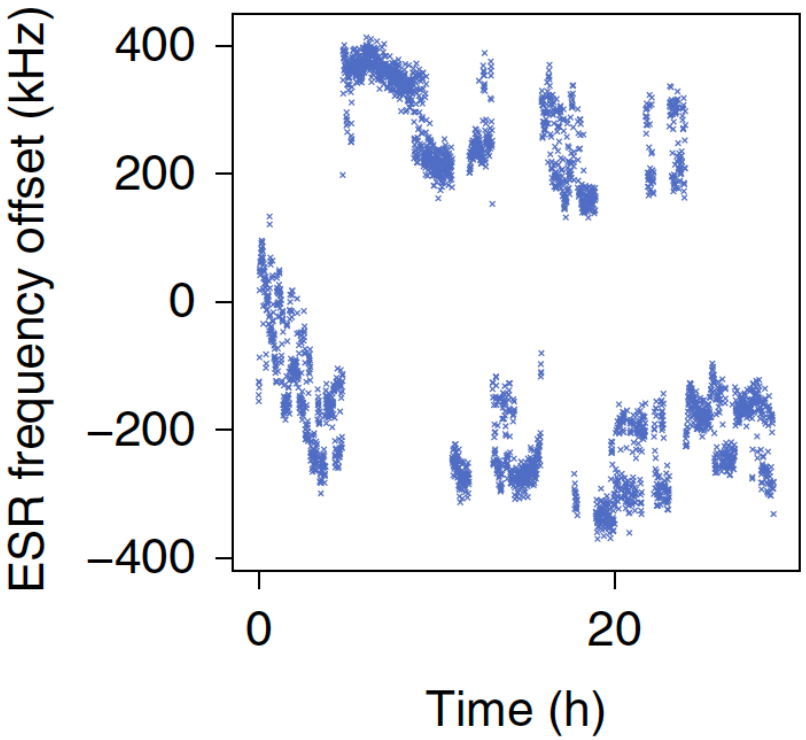
- From intervals between switches:

$$T_1^{450kHz} = (1.0 \pm 0.5)\ h$$

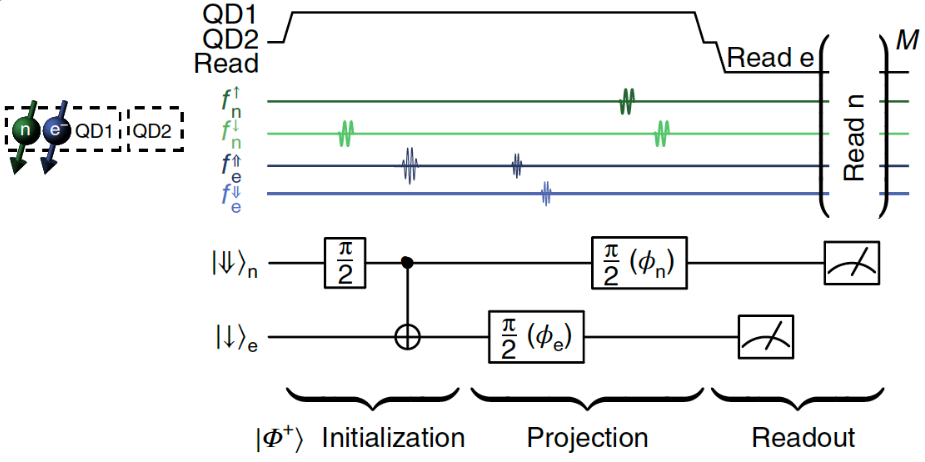
$$T_1^{120kHz} = (10.0 \pm 0.6)\ min$$

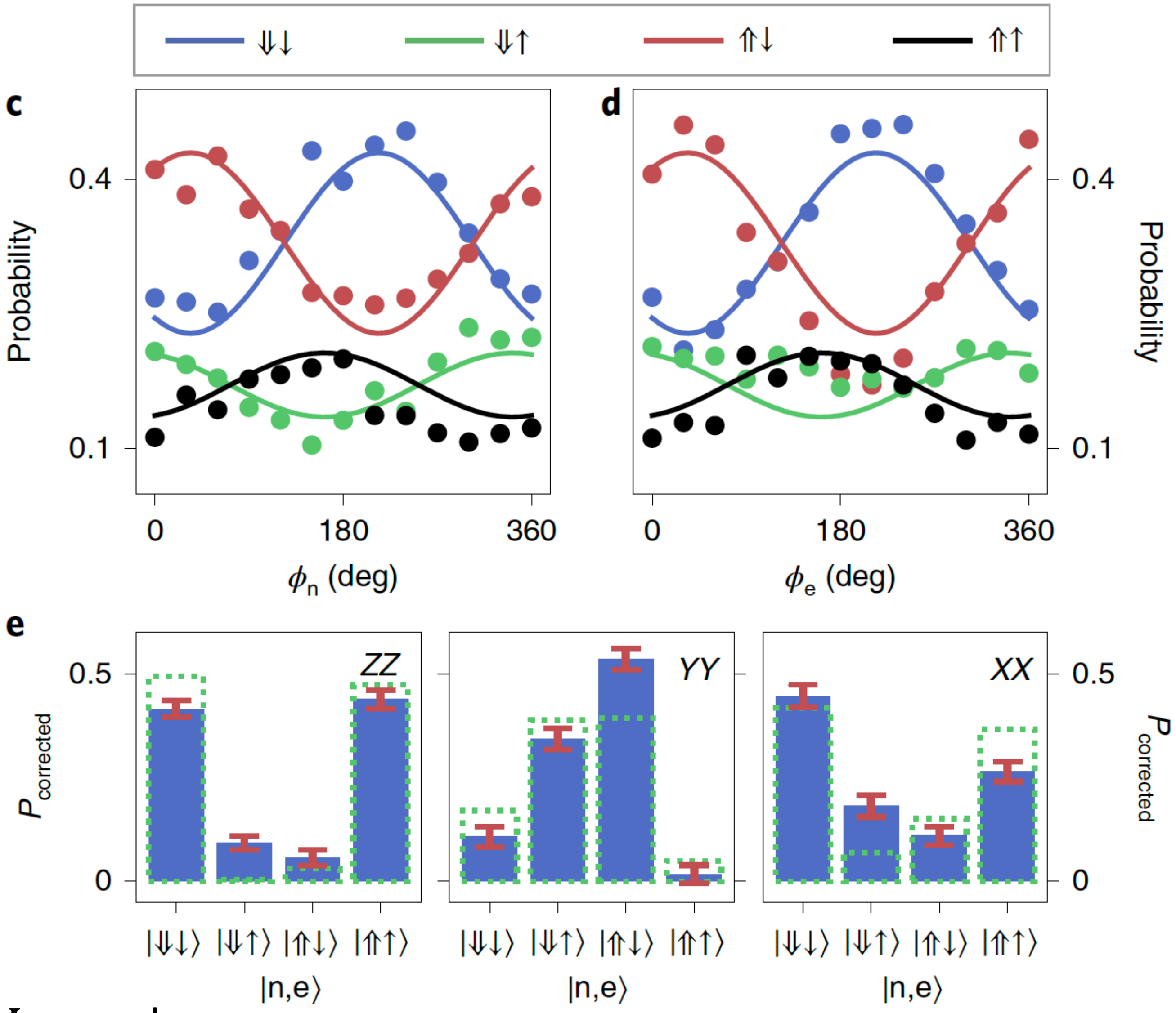
- Simulation of multiple readouts:
  - $\sim 8 \frac{ms}{measurement}$
  - Spin readout visibility: $\sim 76\%$
  - Optimal nuclear spin readout for 26 cycles
  - Expect 99.99% nuclear spin readout fidelity

- Here: 20 cycles, fidelity of 99.8% reported



Electron & nuclear spin entanglement





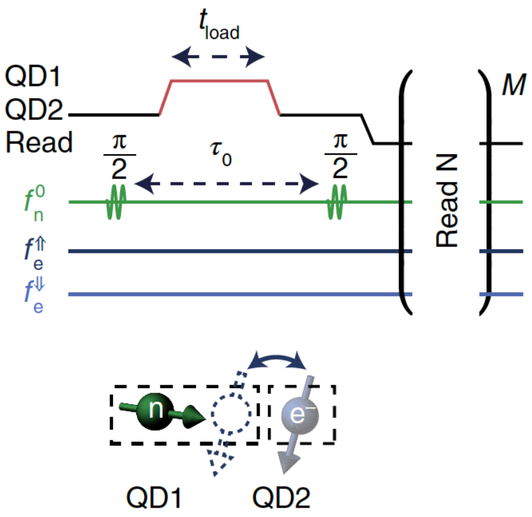
- Initialize bell state:

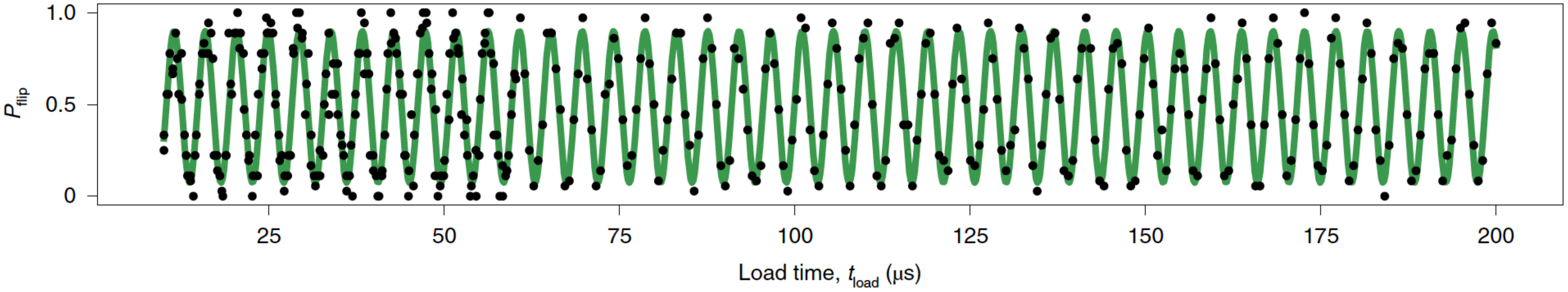
$$|\phi^+\rangle = \frac{|\Uparrow\uparrow\rangle + |\Downarrow\downarrow\rangle}{\sqrt{2}}$$

- State tomography reveals:
  - Preparation fidelity $(73 \pm 1.9)\%$
  - $\langle XX \rangle$ and $\langle YY \rangle$ with projection
  - Error sources: $T_2^{*,e}$, uncontrolled 120 kHz nucleus etc.

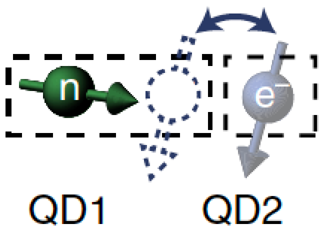
Spin coherence during electron transfer

- $t_c \approx 1\,GHz \gg |A| \gg \frac{1}{T_2^{*,e}}$
- Allows adiabatic movement of the electron across the dots
- Setting electron in (1,0) state changes nuclear phase evolution
- Phase accumulates for the time the electron spend in (1,0)
- Coherent nuclear spin oscillations in Ramsey-type experiment

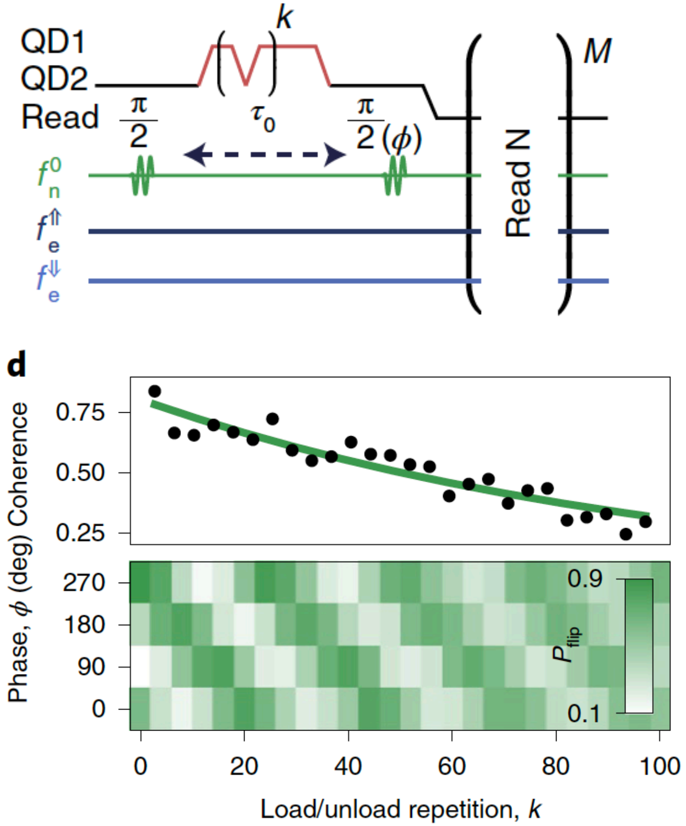


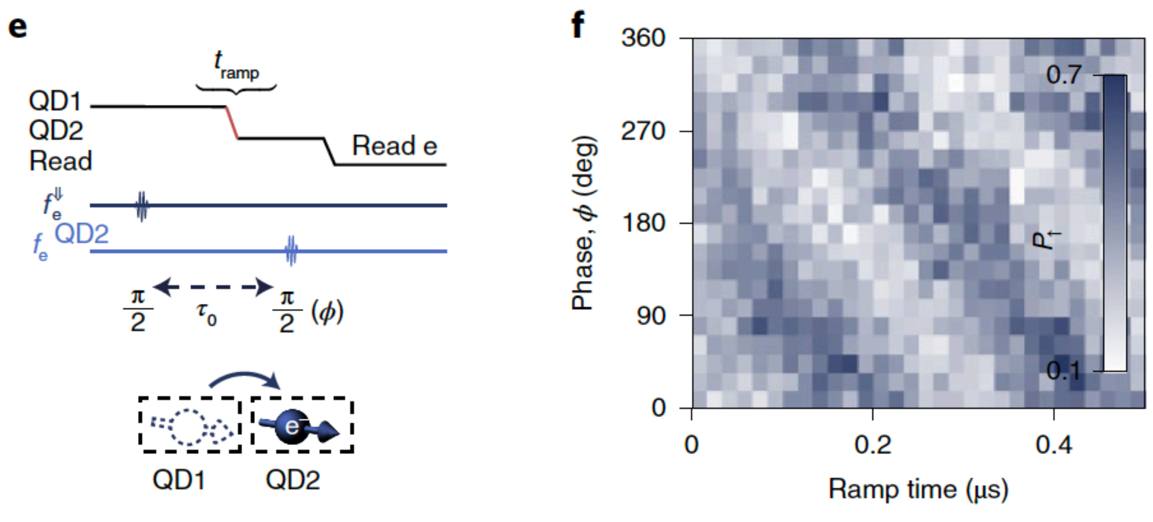


Spin coherence during electron transfer



- Does the shuttling across dots affect the nuclear spin coherence?
- Same experiment as before but with 2k shuttling events during pulse into (1,0) state
- Observe a decay in coherence:
- Error probability per cycle ≈ $(0.49 \pm 0.29)\%$





- Same experiment with electron spin
- Different ramp time for transition from (1,0) to (0,1)

Conclusion and Outlook

- Demonstrate coherent control of a single nuclear spin in silicon quantum dots
- Implementation of nuclear spin qubit without need for single atom doping
- Slow nuclear qubit for information storage, fast electron qubit for processing and information transmission
  - Quantum error correction
- Use nuclear spin as electron spin sensor
  - Conclude electron wavefunction $< 8\ nm$ due to existence of $450\ kHz$ nucleus

Challenges:

- Randomly distributed ^{29}Si nuclei
- Long control time for nucleus and effects of long NMR pulses on electron spin readout

Thank you for your attention!