Quantum sensing using single atoms in solid neon

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Abstract

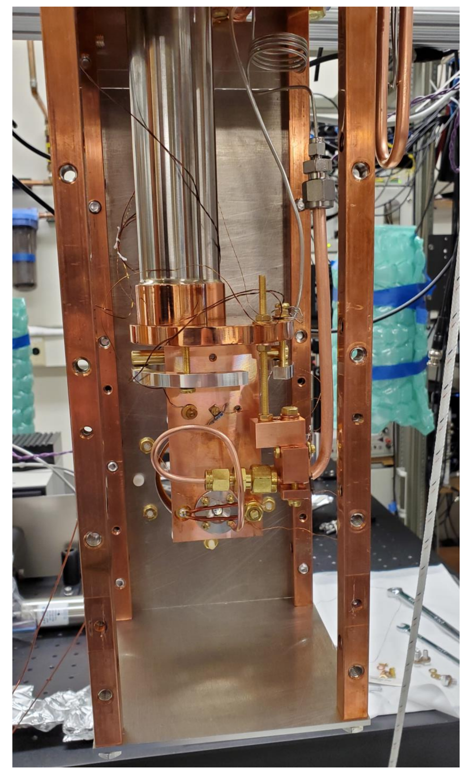
Rubidium atoms trapped in a solid neon matrix have demonstrated sufficiently long electron-spin coherence times to enable sensing single nuclei using NMR spectroscopy. This poster will present optical control and measurement of the spin state of a single Rb atom, progress toward single-atom NMR, and a comparison of different NMR sensing protocols.

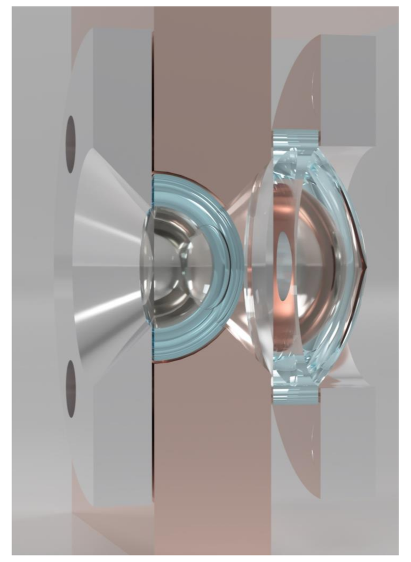
Background

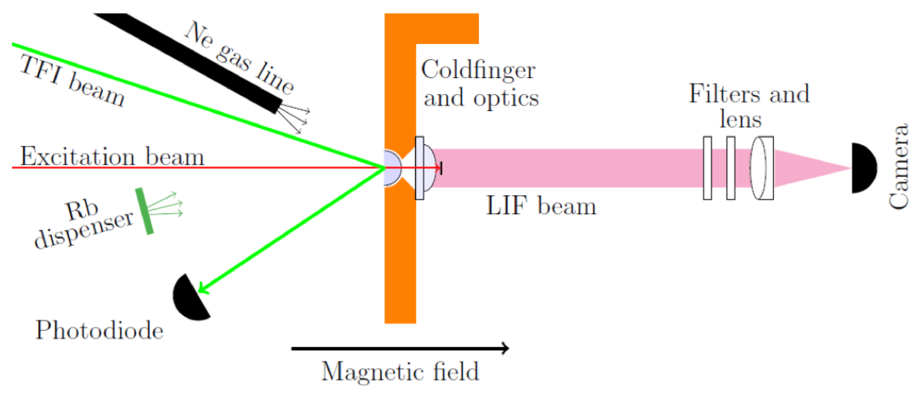
- Single-atom quantum sensing
  - Active area of research, with particular goal on performing MRI on nano-scale objects
    - Nat. Nanotechnol. **7**, 657 (2012); Phys. Rev. Lett. **109**, 137601 (2012); Nature **576**, 411-415 (2019)
  - Leading NV center systems sensitive enough to image individual ^{13}C impurities in diamond bulk
    - Nature **576**, 411–415 (2019)
  - However, also have surface noise issues that limit sensing capability
    - Phys. Rev. Lett. **114**, 017601 (2015); Phys. Rev. B **104**, 085425 (2021)
- Matrix Isolation technique
  - Trap atoms/molecules in inert solid, typically a rare gas
    - Atoms retain similar characteristics to gas-phase counterparts
  - Promising for sensing by providing good localization and high densities
    - Would circumvent surface issues, as target and sensor are in same bulk solid
  - Previous work looking at alkali atoms in argon and para-hydrogen
    - Phys. Rev. A **88**, 063404 (2013) , Phys. Rev. Lett. **117**, 175301 (2016); Phys. Rev. Lett. **125**, 043601 (2020)
  - Currently working with Rb-Ne, promising as sensing candidate
    - Optical characteristics: redshifted LIF, strong LIF emission, weak susceptibility to bleaching
      - D. M. Lancaster, U. Dargyte, S. Upadhyay, and J. D. Weinstein, Phys. Rev. A **103**, 052614 (2021)
    - Magnetic characteristics: good capacity for spin-state control (comparing to other solid-state systems), long T1, T2
      - U. Dargyte, D. M. Lancaster, and J. D. Weinstein, Phys. Rev. A **104**, 032611 (2021)

Apparatus

- Cryogenic vacuum chamber
  - 300 K exterior, 50 K radiation shield, 3 K interior
- Create samples on sapphire hemisphere
  - Co-deposit Ne and Rb vapors
    - Deposition rate of Ne monitored with TFI
      - Typically ≈ 0.24 μm/min
    - Rb produced by dispenser outside 50 K shield
  - Samples typically about 4 μm thick
  - Substrate temperature during growth ≈ 3.1 K
- Measure atom properties using LIF
  - Use of in-vacuum optics helps to achieve CE ≈ 0.18
  - Combination of physical beam block and longpass optical filters reject resonant scatter
  - LIF imaged with cooled sCMOS camera
  - Optical resolution of system is approximately 3 μm
  - Pairs of external permanent magnets create bias field
    - Nonlinear Zeeman levels are used as two-level systems for quantum sensing

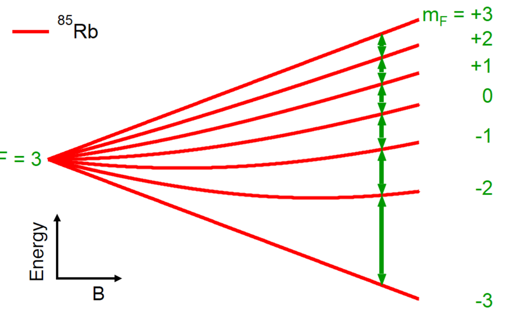


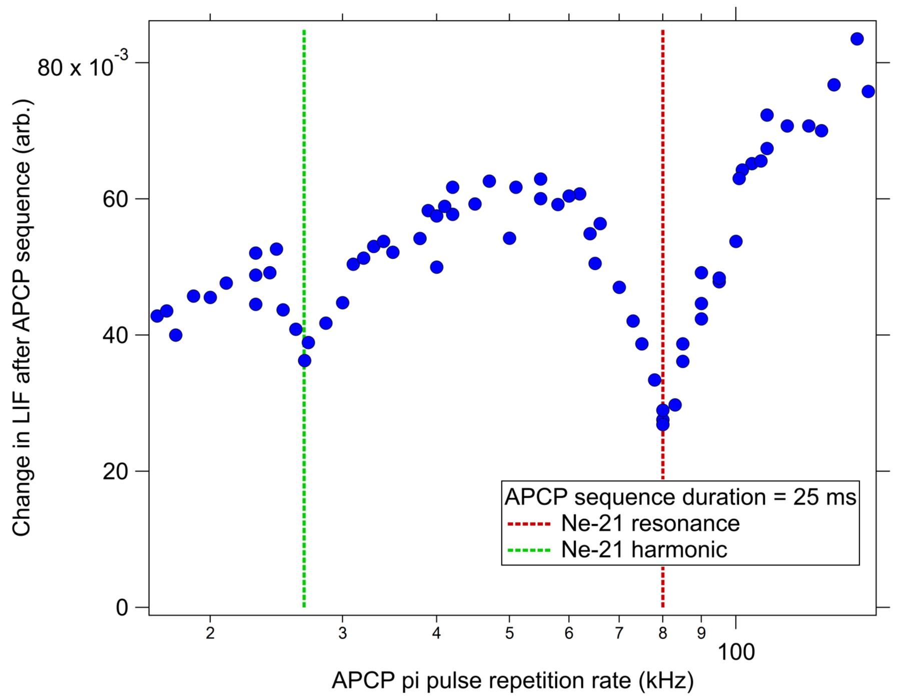




Experimental Results

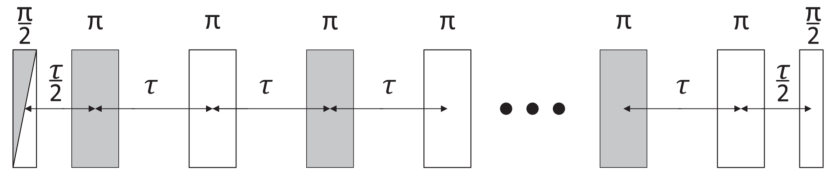
Ensemble NMR Quantum Sensing



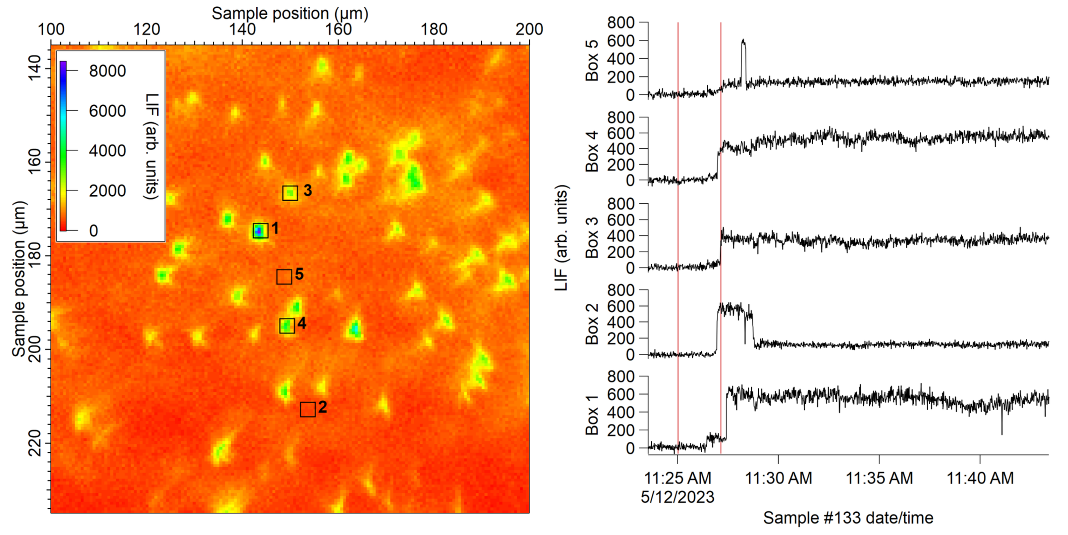


- Optical pumping of ^{85}Rb places atoms in F = 3, m_F = -3 ground-level quantum state
- Manipulate quantum state by using pulsed radiofrequency (RF) magnetic fields
  - Measure long $T_2 \approx 0.15$ s using APCP sequence at 300 kHz repetition rate
- APCP decouples the atoms from static fields, and makes them sensitive to AC fields at frequencies controlled by the repetition rate of the sequence
- Can detect the NMR of ^{21}Ne impurities in the solid
  - Dotted lines indicate the calculated precession frequency and first harmonic we expect to be sensitive to
  - The ^{21}Ne nuclei are unpolarized, bias field insufficient
  - Atoms sensing single nearby nuclei
    - Demonstrates sufficient sensitivity for single-nucleus NMR

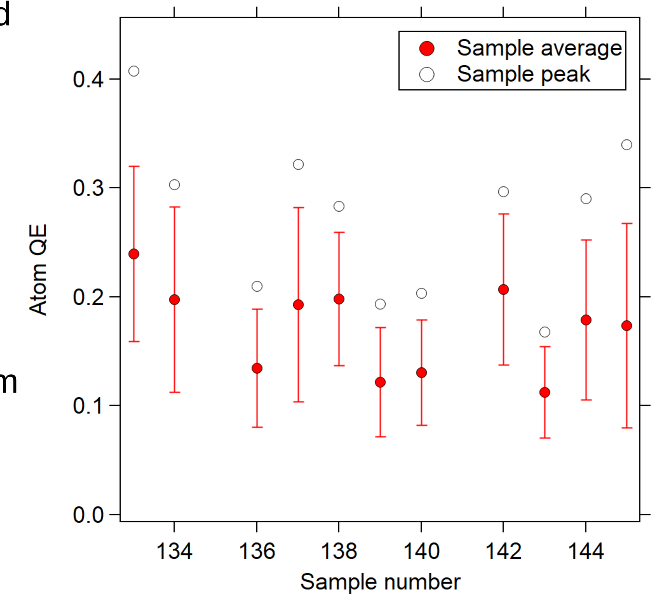
Alternating-phase Carr-Purcell (APCP) pulse sequence



Optical Characteristics of Single Atoms

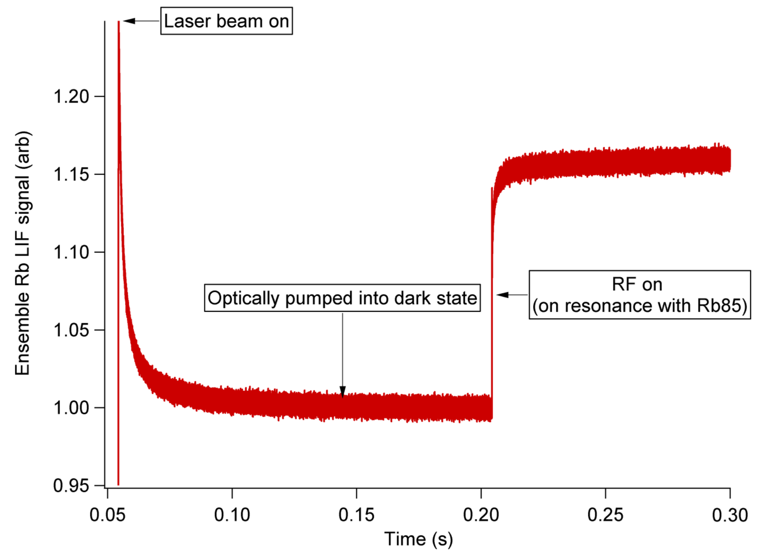


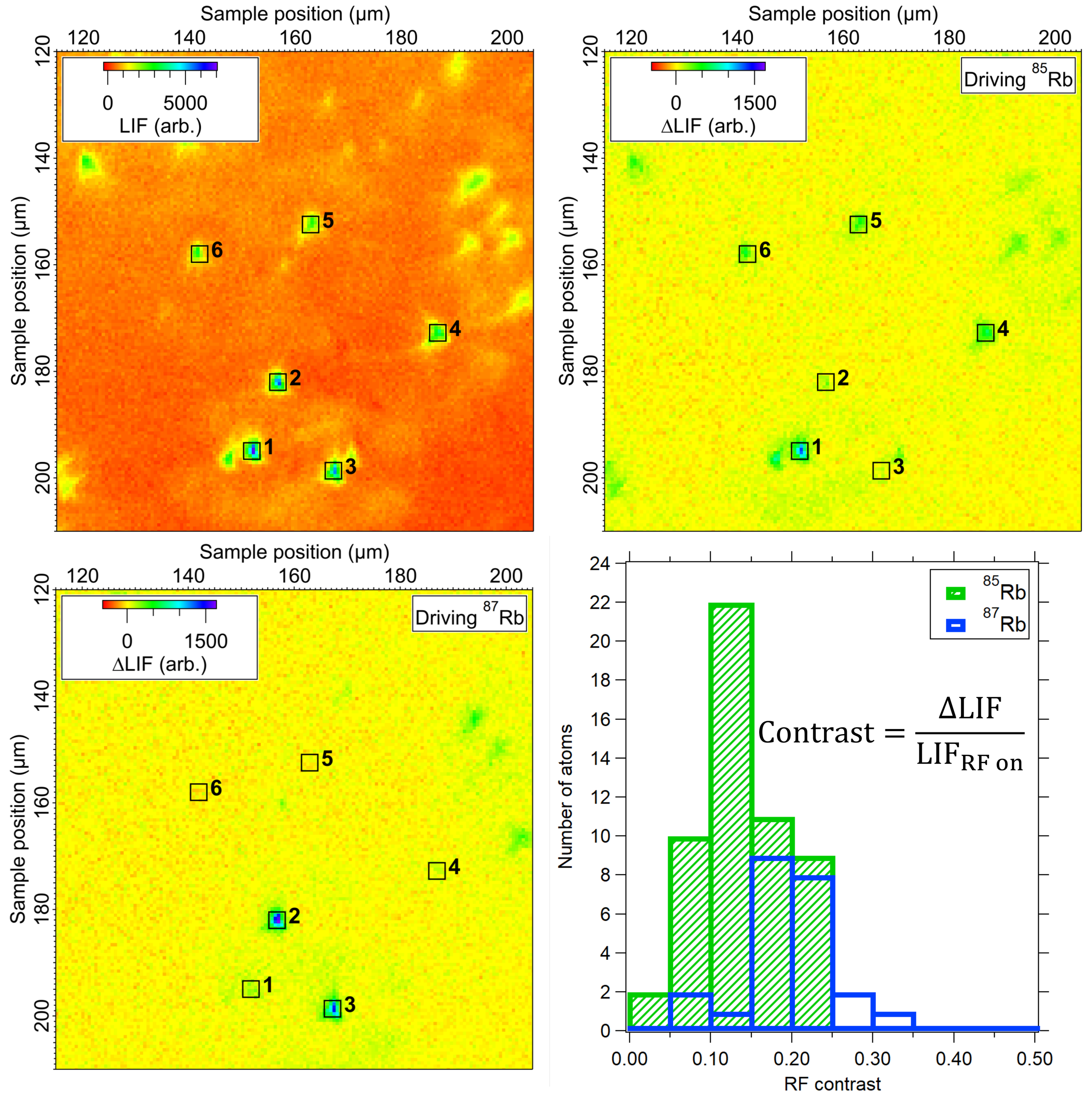
- Sharp increase in LIF when atom is captured by matrix
- LIF signal from single atoms comparable to background signal
  - Background subtracted off in all data shown here
- Atoms captured after dispenser turned off
- To determine quantum efficiency, compare the LIF in a 9 μm² area on the sample to the level we expect to capture from a single atom
  - Average QE for 77 atoms = 0.17
    - Peak QE > 0.4
  - LIF outside of this region, so QE is an underestimate



Single Atom State-Selective Detection

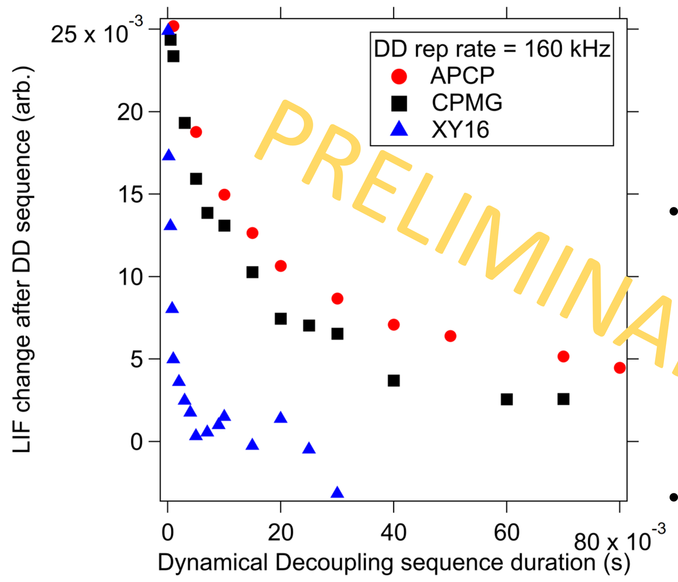
- Circularly-polarized laser optically pumps atoms into dark state
  - LIF level decreases
- Applying RF magnetic field on resonance with Zeeman transition(s) moves atoms out of dark state
  - LIF level increases
- ^{85}Rb and ^{87}Rb have different gyromagnetic ratios
  - Can be driven separately
- Subtract level with RF on from level with RF off to get ΔLIF





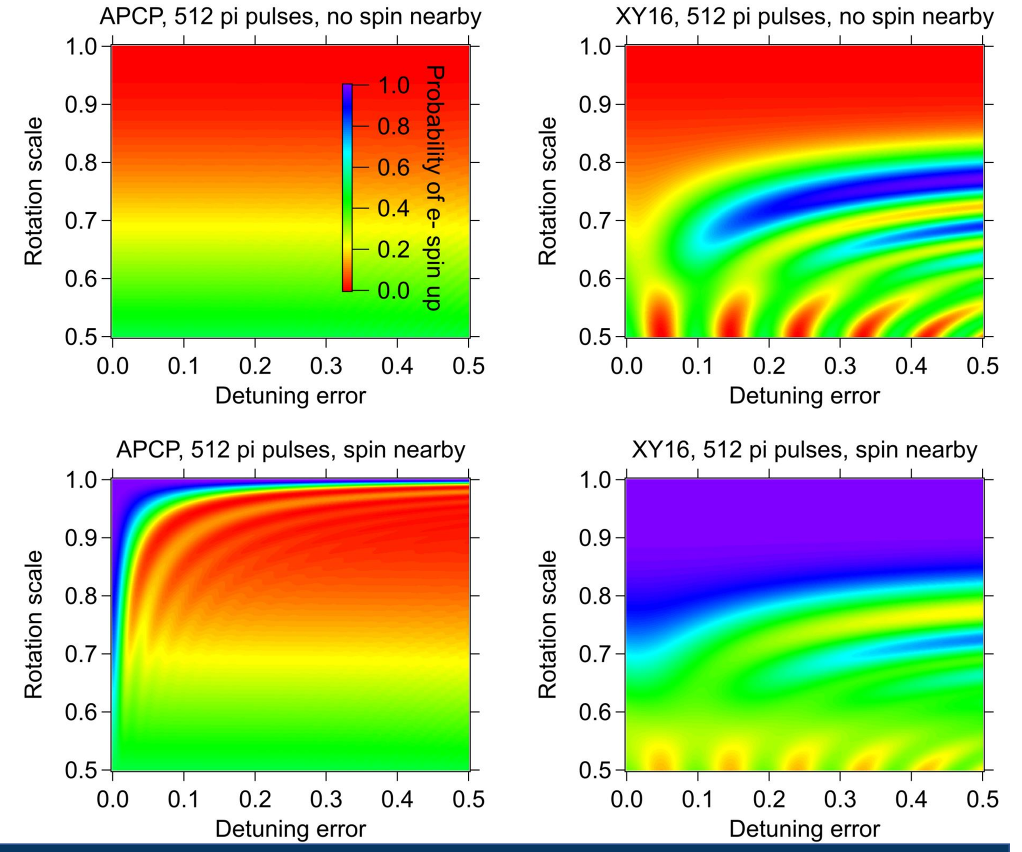
- Contrast for ^{87}Rb, F = 2 higher than ^{85}Rb, F = 3 on average:
  - ^{87}Rb average contrast → 0.196
  - ^{85}Rb average contrast → 0.138
- Highest contrasts seen for each isotope:
  - ^{87}Rb peak contrast → 0.313
  - ^{85}Rb peak contrast → 0.248
- These contrasts are slightly lower than reported for NV ensembles and near surface NV's
  - Much lower than single NVs in bulk
- Long averaging time to collect data, suggesting poor readout fidelity
  - Still workable for a sensing system
  - Leads to additional complication due to ambient magnetic field drift
    - From ensemble experiments, see the field drift by several kHz every few hours

Sensing Protocols: Error Tolerance



- Measure T_2 spin coherence time using APCP, CPMG, and XY sequences:
  - Look at ensembles of atoms
  - Use F = 2, m_F = -2 ↔ -1 transition in ^{87}Rb
    - Inhomogeneous broadening ~200 kHz FWHM; Rabi frequency = 167 kHz
- T_2 results from above data:
  - APCP = 21 ms
  - CPMG = 13 ms
  - XY16 = 0.4 ms
    - XY8 and XY4 even shorter
  - Good for sensing ≠ good for spin coherence?
- Further T_2 measurements on other m_F transitions and Rb isotope in progress
  - Also checking NMR sensing performance

- Perform simulation of numerous DD protocols used for sensing nearby spin-1/2 nucleus
  - Modeled using delta-function rotation pulses
  - Several variants of Carr-Purcell, with different relative pi-pulse phases



Conclusion & future work

- Rubidium atoms trapped in cryogenic neon solids show strong promise for nanoscale AC magnetic field sensing
  - System has shown capability of detecting NMR from nearby ^{21}Ne nuclei
- Progress toward using single Rb atoms to perform sensing:
  - Can image individual atoms in the solid
  - After optical pumping, can determine RF contrast
    - Different atoms show contrast signal depending on what Rb isotope is being driven by RF; ^{87}Rb performs better on average
  - Long averaging times provide issues, but calculations suggest other dynamical decoupling protocols may provide more stability
- Future steps:
  - Implement a confocal microscope for illumination and imaging
  - Measure ^{21}Ne NMR using a single atom
  - Implant simple molecule at high density, detect NMR from the different nuclei

References

- D. M. Lancaster, U. Dargyte, S. Upadhyay, and J. D. Weinstein, Phys. Rev. A **103**, 052614 (2021)
- U. Dargyte, D. M. Lancaster, and J. D. Weinstein, Phys. Rev. A **104**, 032611 (2021)
- D. M. Lancaster, U. Dargyte, and J. D. Weinstein, Phys. Rev. Research **6**, L012048 (2024)