Entanglement-Enhanced Interferometry with Neutral Atoms

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Abstract

Precision measurement and inertial sensing applications have relied on neutral atoms for decades. Recent advancements in utilizing Rydberg dressing to mediate strong, tunable, interactions between neutral alkali atoms suggest they now also provide a promising platform for quantum sensing. We report on development of an entanglement-enhanced atom interferometer, whereby the measurement precision follows Heisenberg scaling rather than the standard quantum limit. Our apparatus can scale to many entangled atoms. We discuss the effects of various error sources on the fidelity and progress on overcoming critical experimental challenges, as we work towards making advanced quantum sensing with neutral atoms a reality.

Why Quantum Sensing?

- Neutral Atoms As Sensors
  - Atom Clocks: Cesium defines the second
  - Magnetometers
  - Atom interferometers measure acceleration and rotation:
    - Gravimetry
    - Inertial Navigation
- The Quantum Advantage

  Sensitivity: ability to measure the phase shift

  $$\phi = \mathbf{K} \cdot \mathbf{a} T^2$$

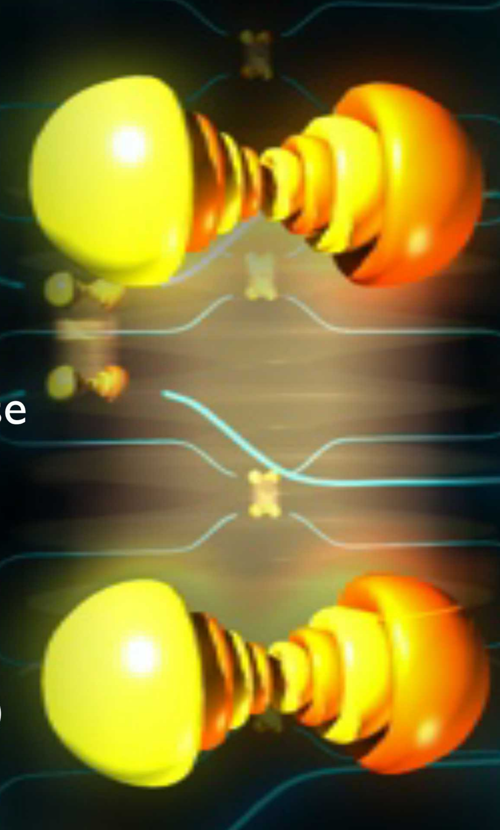
  Standard Quantum Limit (SQL):

  $$\Delta\phi \geq \Delta\phi_{SQL} = \frac{1}{\sqrt{N}}$$

  Using Entangled Atoms: (beyond SQL)

  $$\Delta\phi \geq \frac{1}{N}$$

- Few-atom entanglement (few atoms, high fidelity) is an alternative to spin squeezing (many atoms, low fidelity)
- ***Our Goal:*** *Demonstrate entanglement-enabled gain in an inertially-sensitive atom interferometer*

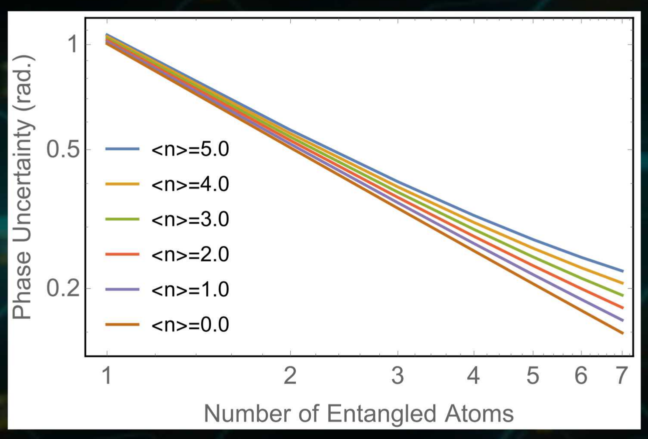


Multi-Atom Entanglement

1. Create side-by-side dipole traps
2. Generate a strong, tunable, interaction via Rydberg Dressing
3. Use Rydberg-dressing mediated interaction to generate entanglement
4. Measure enhanced interferometer signal

Theory: Predictions & Error Modeling[6]

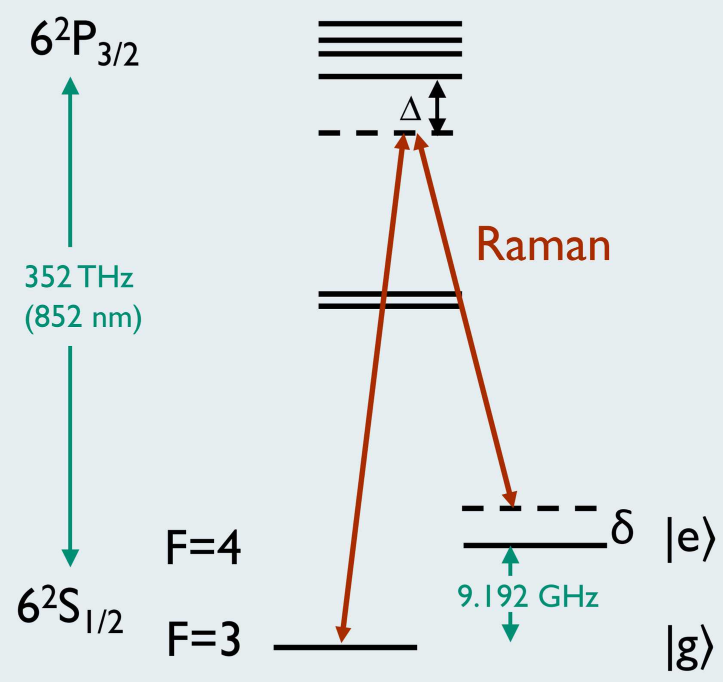
- The interferometer phase uncertainty can be written in terms of the parity of the joint (entangled) state. As the number of entangled atoms increases, the phase uncertainty decreases.
- Entangled input (GHZ state): $|\psi\rangle = \frac{1}{\sqrt{2}}\left[\bigotimes_{\alpha=1}^{N} |g, \mathbf{p}_\alpha\rangle_\alpha + \bigotimes_{\alpha=1}^{N} |e, \mathbf{p}_\alpha + \hbar\mathbf{K}\rangle_\alpha\right]$
- Limiting Error Analysis:
  - *State prep*: $\Delta\phi \approx 1/[(1-\epsilon)N]$; ε =.11 ($\mathcal{F}$=.89)
  - *Imperfections in the laser pulses:* deviation from the Heisenberg scaling is insignificant for N $\lesssim$ 10
  - Initial atomic wave packet spread: the most significant source of error.
  - Heisenberg scaling for tens of entangled atoms



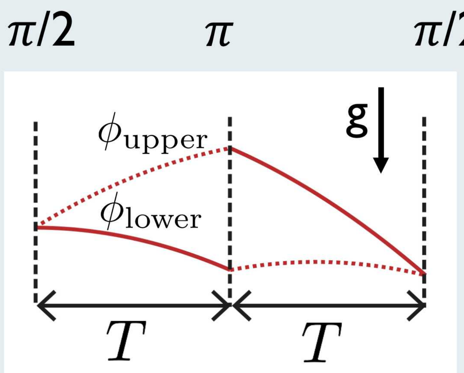
Numerical calculations of the minimum phase uncertainty Δϕ when the error associated with the initial momentum spread of the atoms is included, for average trap excitation levels <n>. [6]

Single-Atom Control

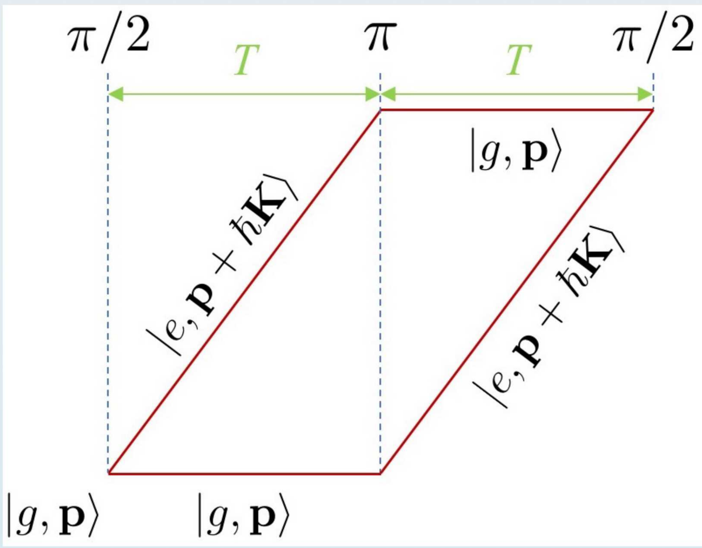
- Raman lasers flip the atom state between |g⟩ and |e⟩ (π pulse)
- A "half" ($\pi/2$) pulse puts the atom into a superposition of |g⟩ and |e⟩
- The atom interferes with itself



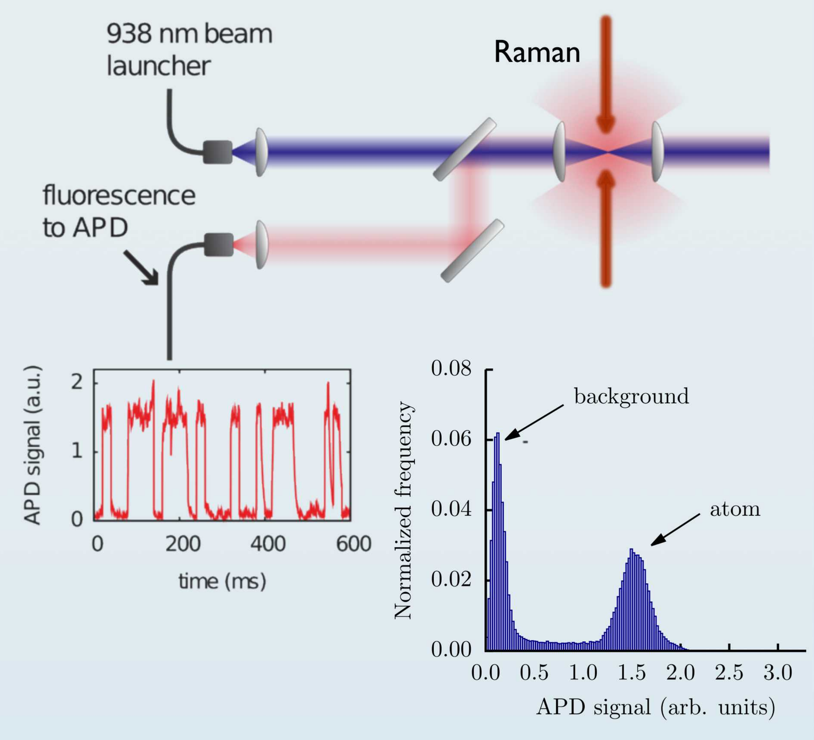
^{133}Cs energy levels for interferometry



Wave packet trajectory: the upper path acquires more phase because it has more curvature. [1]

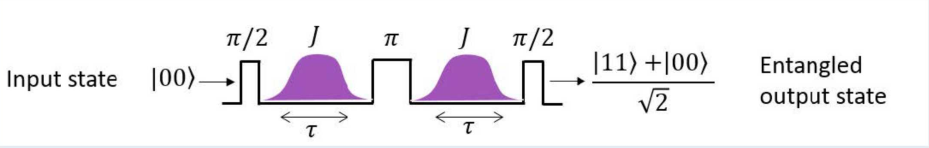


Single atom interferometer scheme

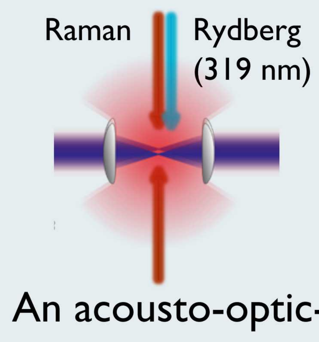


Cesium atoms are confined in a dipole trap. An APD measures fluorescence. Atom $\mathcal{F}$=95% [3]

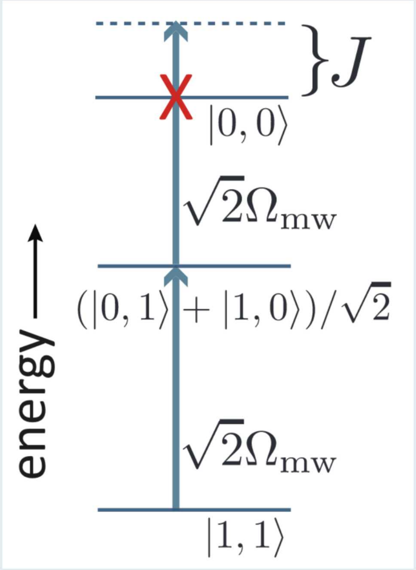
Multi-Atom Entangled Interferometer



- A 319 nm laser interacts strongly with the $6S_{1/2}$, F=4 to $64P_{3/2}$ transition
- In this dressed Rydberg state, one atom is highly sensitive to the field of the other, with interaction strength *J*; *J* is tuned to create an entangled state
- Bell state fidelity ≥ 81% [4]
- A GHZ input state gives optimal Mach-Zender enhancement.



An acousto-optic-modulator creates multiple trap sites



Rydberg interaction mechanism [4]

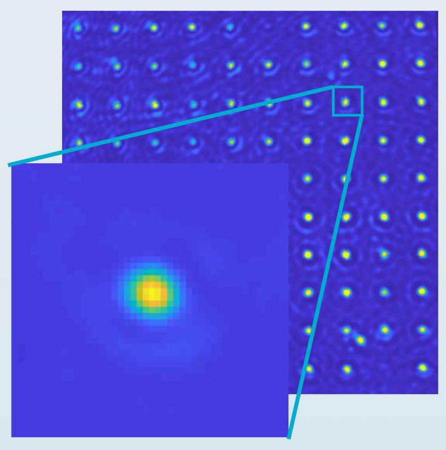
The Path Forward

Improvements to the Experiment

- Raman laser system has been improved by switching to a more stable laser and adding clean-up cavities
- Changing our trap configuration from an internal asphere to an external objective with corrective optics is expected increase stability and consequently to improve both our *data rate* and our state discrimination *fidelity*.
- New CCD to replace APDs
- New control software and hardware will be implemented early 2020, which will provide more room for future progress and scaling

Plans for Future Work

- Optimal control with deep learning



500 nm pinhole array used for qualifying new optics

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LDRD Laboratory Directed Research and Development

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