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Sandia National Laboratories

Characterizing Errors in Entangled-Atom Interferometry

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LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

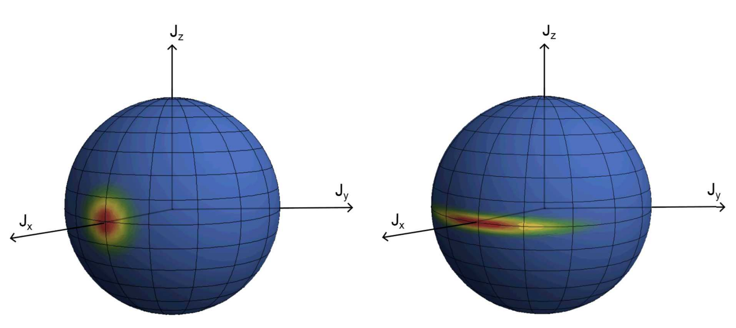
Entangled-Atom Interferometry

Recent progress in generating entanglement between neutral atoms provides opportunities to advance quantum sensing technology. In particular, entanglement can enhance the performance of accelerometers and gravimeters based on light-pulse atom interferometry. We study the effects of error sources that may limit the sensitivity of such devices, including errors in the preparation of the initial entangled state, spread of the initial atomic wave packet, and imperfections in the laser pulses. Based on the performed analysis, entanglement-enhanced atom interferometry appears to be feasible with existing experimental capabilities.

Few-Atom Entanglement vs. Spin Squeezing

Spin squeezing:

- Working technology:
  - ✓Atom clocks (10 dB beyond SQL)
    O. Hosten et al., Nature 529, 505 (2016)
  - ✓Magnetometers (5 dB beyond SQL)
    Sewell et al. (2012); Muessel et al. (2014)
- Advantage: Large number of atoms (up to 10^6)
- Drawback: Low fidelity of entanglement (0.1% of all atoms are entangled)



Coherent spin state — Entangled state

Adapted from O. Hosten et al., Nature 529, 505 (2016)

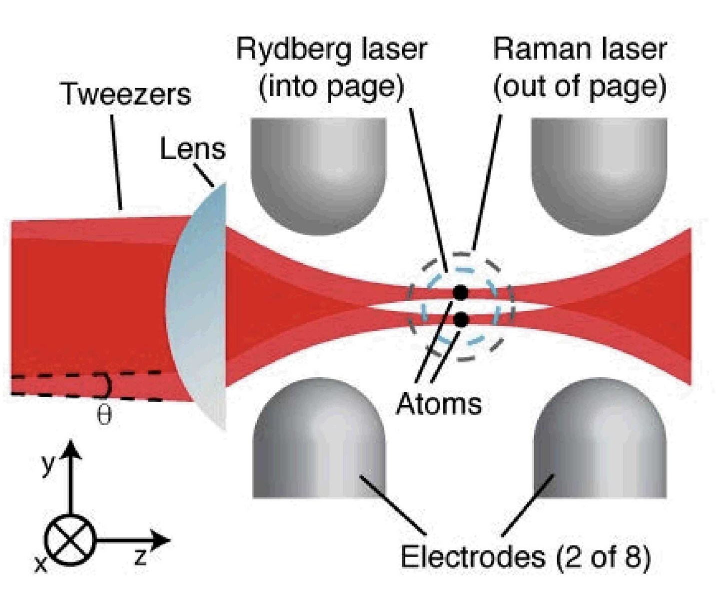
Few-atom Entanglement:

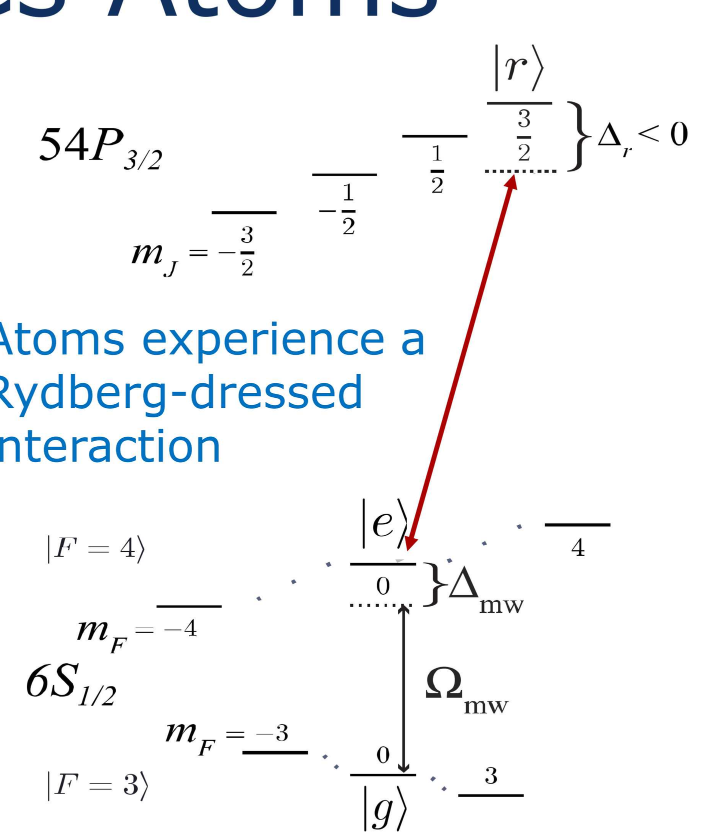
- Advantage: High fidelity of entanglement (81% published and close to 89% in our current experiment at Sandia)
- Drawback: Small number of atoms (currently only 2)
- Bonus: It may be easier to discover the fundamental limitations on the performance of an AI operated with entangled atoms.

Entangling Two Cs Atoms

Experiment at Sandia

^{133}Cs atoms in optical tweezers



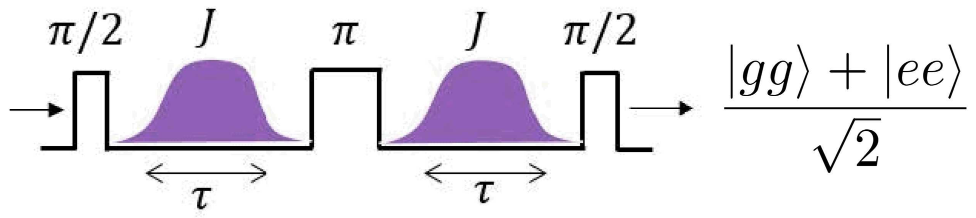


Atoms experience a Rydberg-dressed interaction

Qubit stored in clock states with a 100 ms coherence time

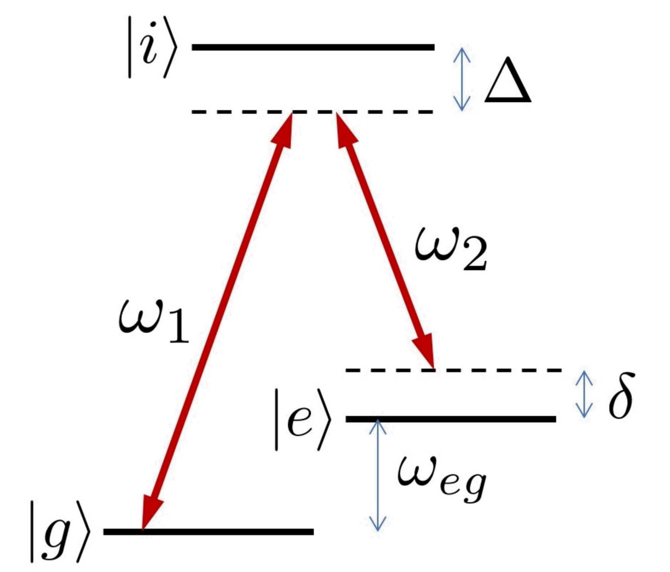
Pulse sequence

Input state $|gg\rangle$ → $\frac{|gg\rangle + |ee\rangle}{\sqrt{2}}$ Entangled output state



Light-Pulse Atom Interferometry

Two counter-propagating laser beams drive Raman transitions

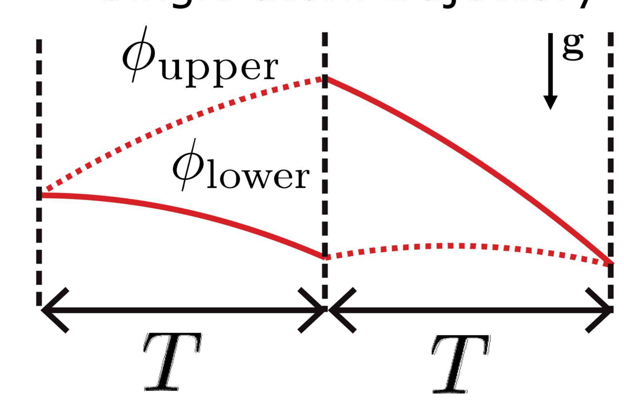


Large momentum kick $\mathbf{K} = \mathbf{k_1} - \mathbf{k_2} \approx 2\mathbf{k_1}$

Small transition energy $\omega_{eg} = \omega_1 - \omega_2$

Gravimeter

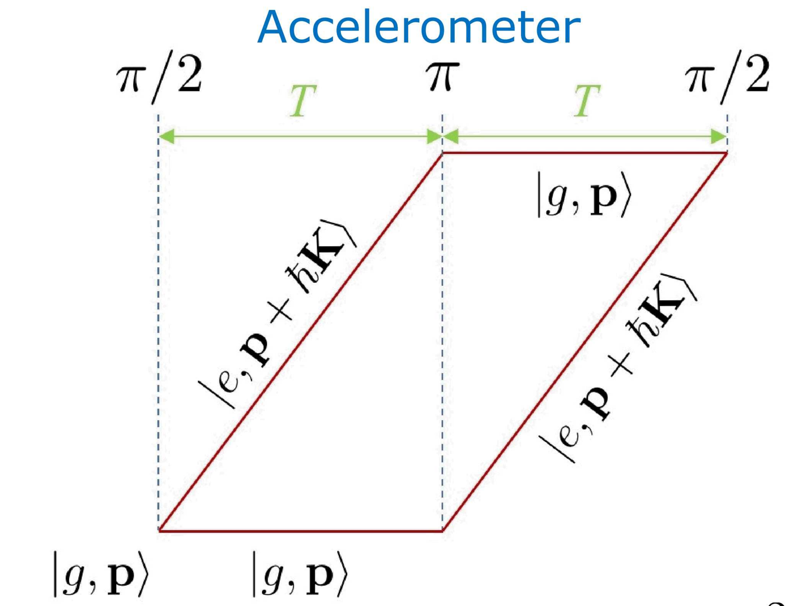
Single atom trajectory



Upper path acquires more phase

$\phi_{\text{lower}} - \phi_{\text{upper}} = \mathbf{K} \cdot \mathbf{g} T^2$

Accelerometer



Two paths acquire $\phi = \mathbf{K} \cdot \mathbf{a}\, T^2$

Alkali Atoms

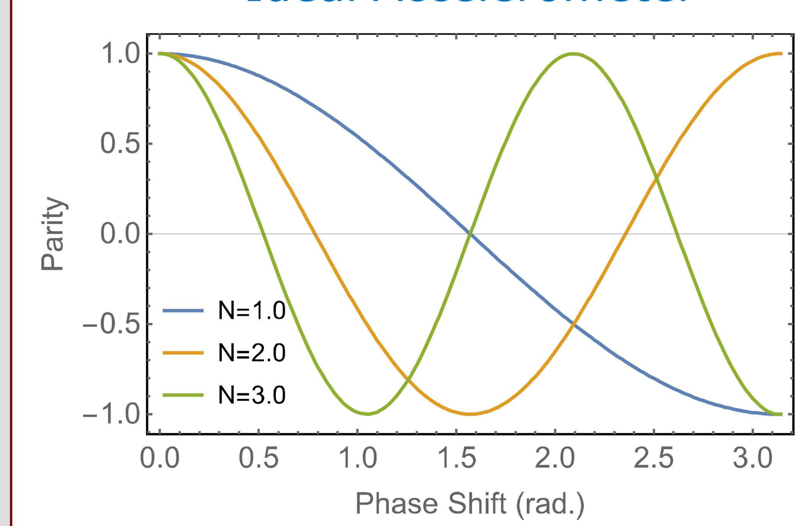
$|e\rangle, |g\rangle = |F, m_F\rangle$

Large K amplifies signal $|\mathbf{K}| \approx 10^7$ rad./m

Long coherence time $T \approx 100$ ms

Characterizing Error Sources

Ideal Accelerometer



Frequency proportional to N

$$\langle \Pi \rangle = \cos \Theta_N$$

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

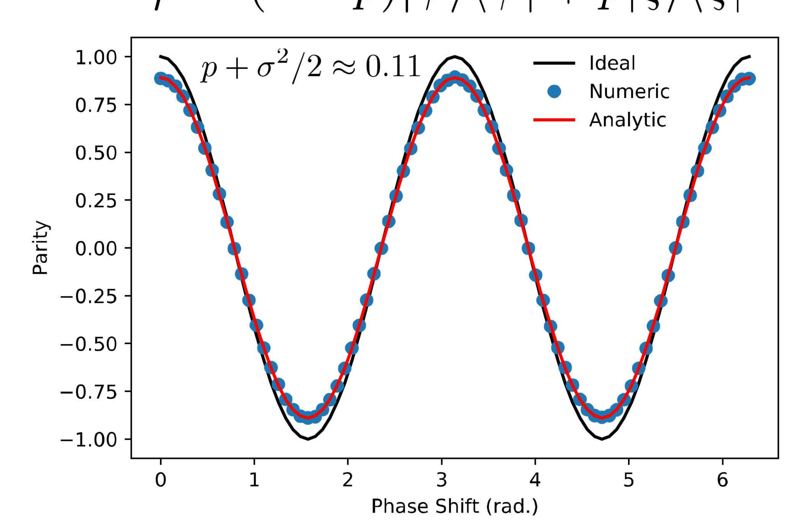
Uncertainty at Heisenberg limit

$$\Delta\phi = \Delta\Pi \left| \frac{\partial \langle \Pi \rangle}{\partial \phi} \right|^{-1} = 1/N$$

Imperfect Initial State Preparation

We mix in random $|\zeta\rangle$ with probability p and we give $|\psi\rangle$ a random phase with a standard deviation σ

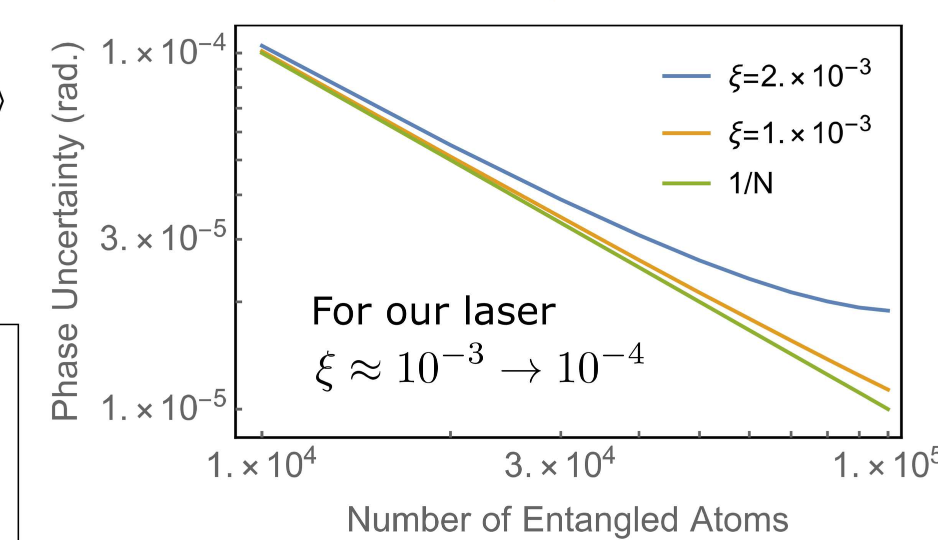
$$\rho = (1-p)|\psi\rangle\langle\psi| + p|\zeta\rangle\langle\zeta|$$



The noise reduces the visibility

$$\Delta\phi \approx 1/N(1 - p - \sigma^2/2)$$

Laser Intensity Fluctuations



We average over random changes in pulse area with a standard deviation

$$\sigma = \xi A_0$$

Error term is proportional to N

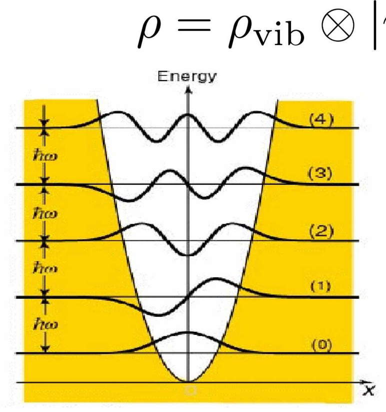
$$\Delta\phi \approx 1/N(1 - \frac{3\pi^2}{8} N \xi^2)$$

Dominant Error and Mitigation Strategy

Initial Momentum Spread Can Easily Dominate All Other Error Sources

Atoms begin in optical tweezers

$$\rho = \rho_{\text{vib}} \otimes |\psi_{\text{spin}}\rangle \langle\psi_{\text{spin}}|$$



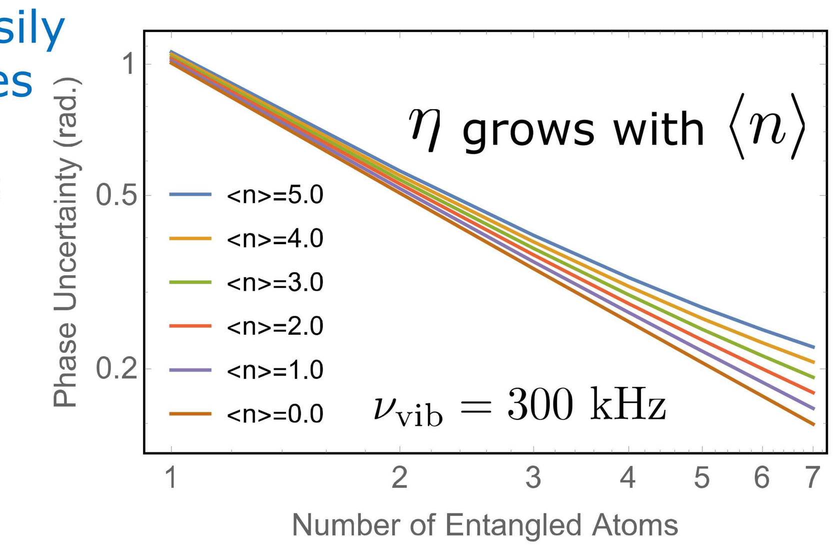
$$\rho_{\text{vib}} = \sum_{n=0}^{\infty} P_n |n\rangle\langle n|$$

$$P_n = \frac{\langle n \rangle^n}{(1 + \langle n \rangle)^{n+1}}$$

$$\langle n \rangle = [\exp(\hbar\omega_{\text{vib}}/k_B T) - 1]^{-1}$$

The initial momentum spread leads to a detuning error in the pulses

$$\delta = -\hbar p K / m$$



Error term is proportional to N

$$\Delta\phi \approx \frac{1}{N(1 - \eta N)}$$

Error is significant at $N^* \equiv 0.1/\eta$

$\langle n \rangle = 0$ $\nu_{\text{vib}} = 300$ kHz $N^* \approx 16$

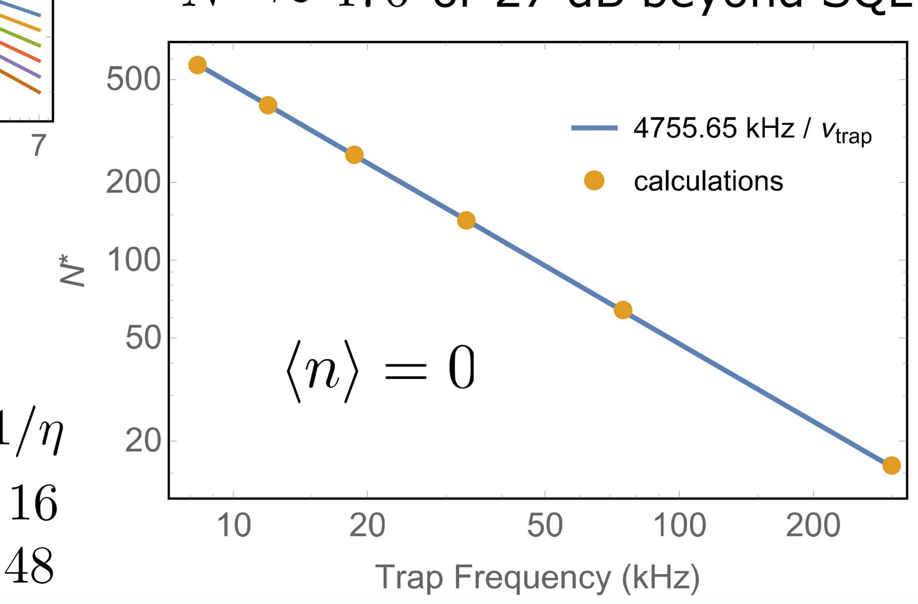
$\nu_{\text{vib}} = 100$ kHz $N^* \approx 48$

We Can Mitigate Momentum Spread Error by Lowering the Trap Frequency

$$N^* \approx 4755.86 \text{ kHz}/\nu_{\text{trap}}$$

A trap frequency of 10 kHz is feasible

$N^* \approx 476$ or 27 dB beyond SQL



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