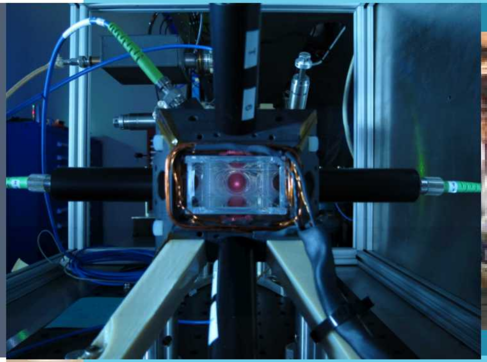
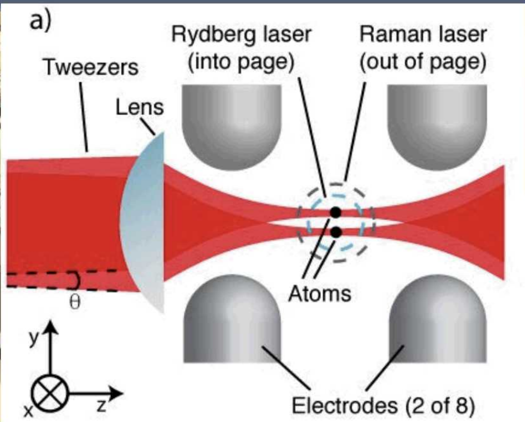
SAND2020-5366C

Entanglement Enhanced Matterwave Interferometry





PRESENTED BY Matthew Chow[1,2], Bethany Little[1], Lambert P. Parazzoli[1], Constantin Brif[1], Bandon Ruzic[1], and Grant Biedermann[1, 3]

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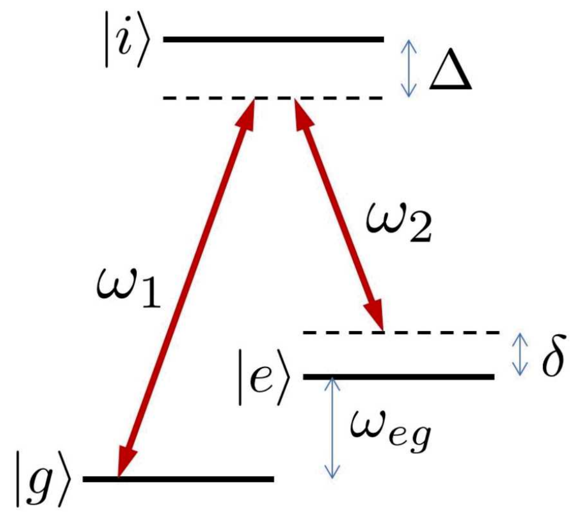
Light-pulse Atom Interferometry – Quick Review



Two counter-propagating laser beams drive Raman transitions

Large momentum kick

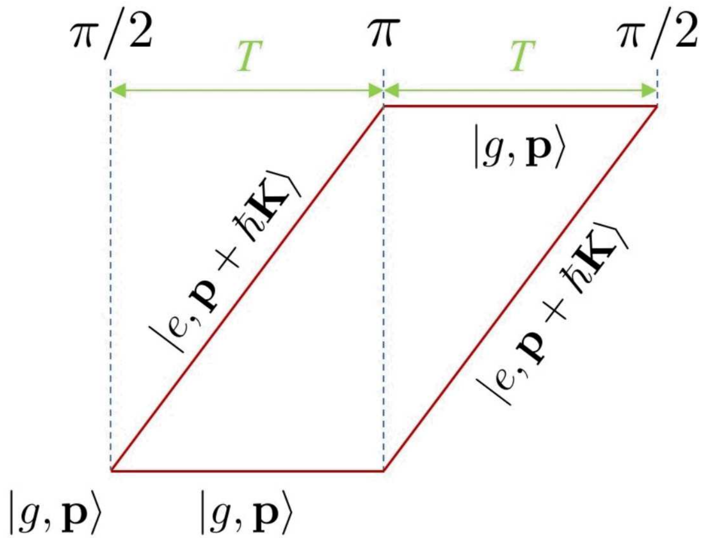
$$\mathbf{K} = \mathbf{k_1} - \mathbf{k_2} \approx 2\mathbf{k_1}$$

Small transition energy

$$\omega_{eg} = \omega_1 - \omega_2$$

Pulses drive Rabi oscillations $|g\rangle \, , |e\rangle$

pulse area $A = \Omega\tau$



Two paths acquire a phase difference

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

Alkali atoms

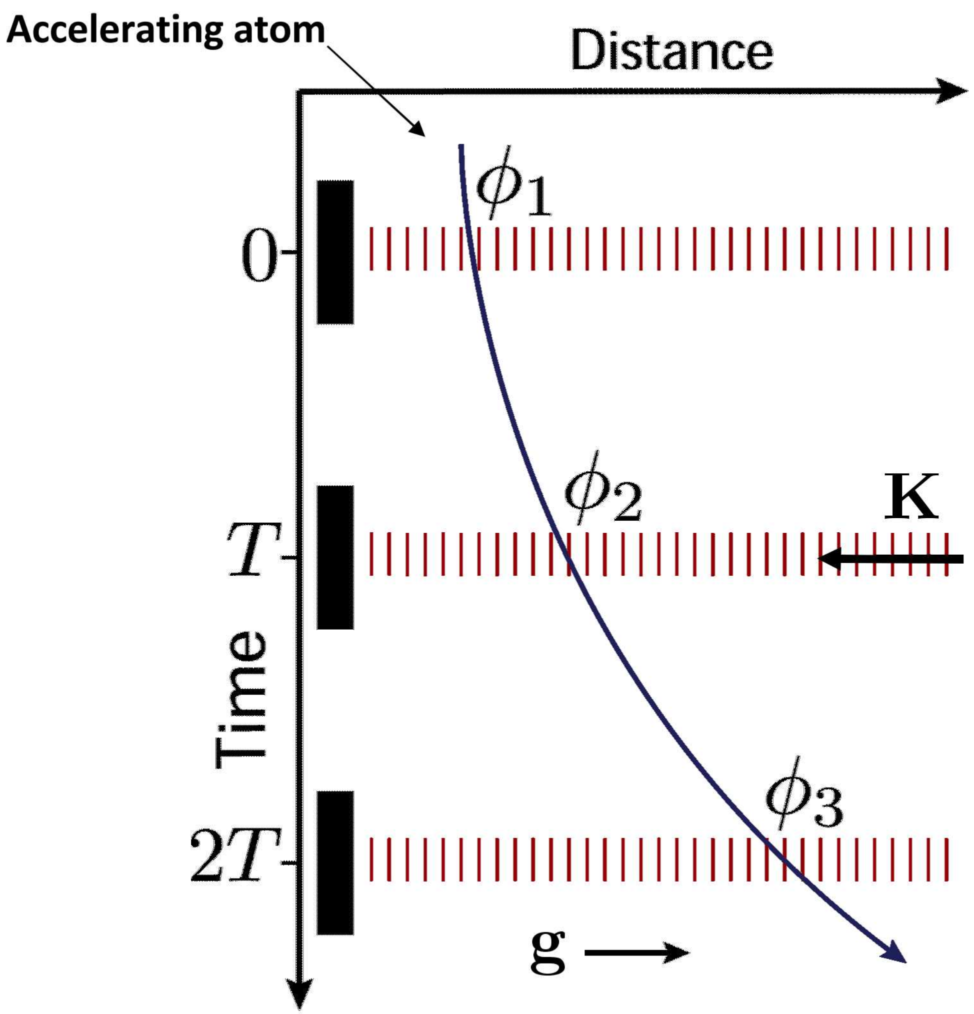
$|e\rangle \, , |g\rangle = |F, m_F\rangle$ long coherence time

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

Light-pulse Atom Interferometry

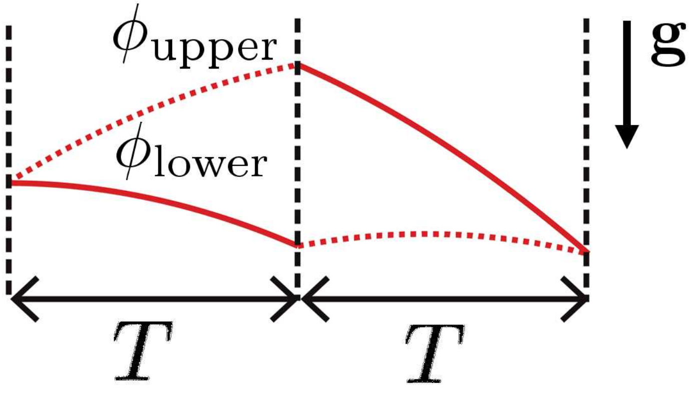
Kasevich, and Chu, Phys. Rev. Lett. 67, 181–184 (1991)

Laser ranging technique



Why is this an interferometer?

Single atom trajectory



Upper path acquires more phase because it has more curvature

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

Measure this phase difference to measure acceleration

Sensitivity and Scaling

Phase (acceleration) uncertainty for N *independent* measurements

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

$$P_{|F=3\rangle} = \frac{1}{2}(1 - \cos\phi)$$

Parity: $$\langle \Pi \rangle = \cos^N \phi$$

$$\Pi = \bigotimes_{\alpha=1}^{N} \sigma_z^{(\alpha)} = \bigotimes_{\alpha=1}^{N} (|g\rangle\langle g| - |e\rangle\langle e|)_{(\alpha)}$$

Phase Uncertainty

$$\Delta\phi = \frac{\Delta\Pi}{|\partial\langle\Pi\rangle/\partial\phi|} = \Delta a\, |K| \cos(\theta) T^2$$

$$\Delta\phi \geq \frac{1}{\sqrt{N}}$$ Standard Quantum Limit (Poisson shot noise)

However, interferometry with entangled states can lead to lower uncertainty. Two types of commonly sought states with potential metrological value:

Highly Entangled state[1,2]

✗Smaller N
✓High fidelity
✗Fragile, but achievable[1,2]

Spin-squeezed state[3]

✓Large N
✗Low fidelity

[1] Y.-Y. Jau, G.B., I.D., *et al.*, Nat Phys. **12** (2016) ; [2] A. Omran, M.D. Lukin *et al.*, Science **365** (2019); *[3] Wineland, et al., PRA 46 (1992)*

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We use a GHZ state:

$$|\psi\rangle_{in} = \frac{1}{\sqrt{2}}\left[\bigotimes_{\alpha=1}^{N}|g,\mathbf{p}_\alpha\rangle_\alpha + \bigotimes_{\alpha=1}^{N}|e,\mathbf{p}_\alpha+\hbar\mathbf{K}\rangle_\alpha\right]$$

$$\langle\Pi\rangle = \cos(N\phi)$$

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

Heisenberg Limit

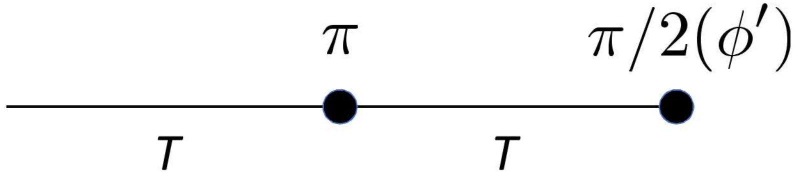
[1] Y.-Y. Jau, G.B., I.D., *et al.*, Nat Phys. **12** (2016) ; [2] A. Omran, M.D. Lukin *et al.*, Science **365** (2019); *[3] Wineland, et al., PRA 46 (1992)*

The Ideal Entangled Atom Interferometer

N entangled atoms

$$\frac{|g\dots g\rangle + |e\dots e\rangle}{\sqrt{2}}$$

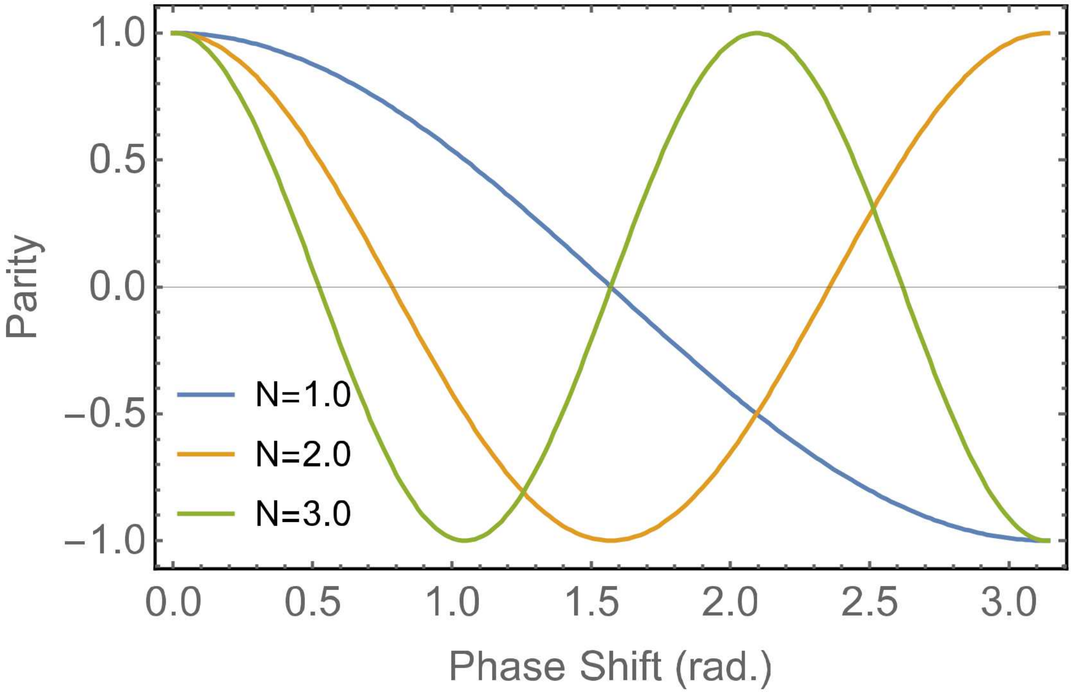
Pulse sequence



Measure Parity

$$\Pi = \bigotimes_{\alpha=1}^{N} \sigma_z^{(\alpha)}$$

For 2 atoms $\langle \Pi \rangle = P_{ee} + P_{gg} - P_{eg} - P_{ge}$



As N grows:

Parity oscillates faster

$$\langle \Pi \rangle = \cos \Theta_N$$
$$\Theta_N = N\mathbf{K} \cdot \mathbf{a}T^2 = N\phi$$

Phase uncertainty decreases

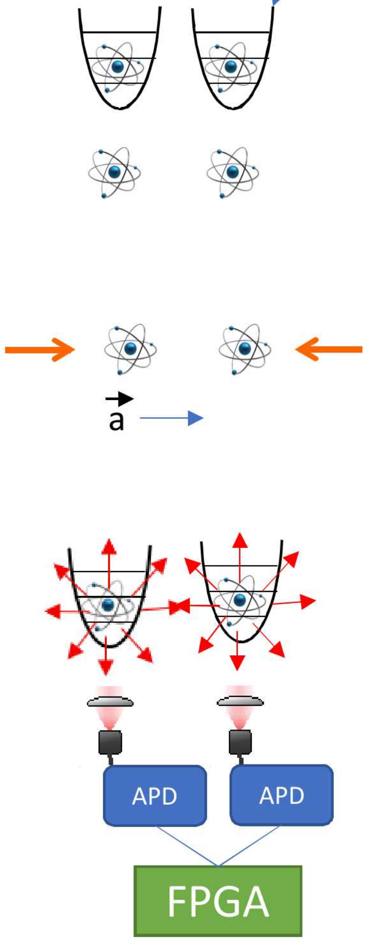
$$\Delta\phi = \frac{\Delta\Pi}{\left|\frac{\partial\langle\Pi\rangle}{\partial\phi}\right|}$$

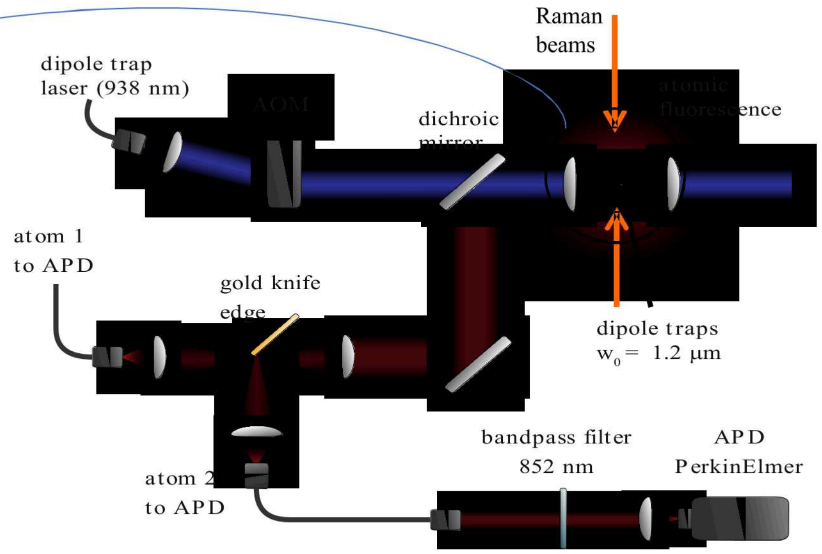
$$\Delta\Pi = \sqrt{1 - \langle\Pi\rangle^2}$$

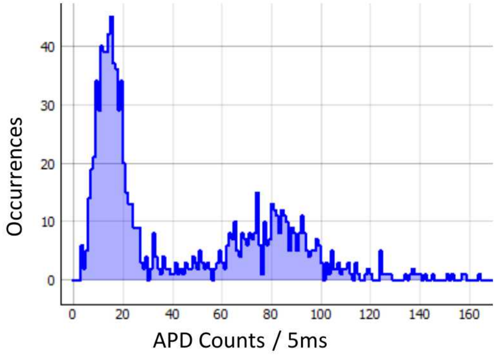
How it works

- Trap atoms individually in tweezers
- Extinguish traps
- Apply pulses to run (entangled) interferometer
    - Atoms fall a few microns. Information encoded in phase
- Recapture atoms in traps and perform state readout

Repeat experiment until atoms are lost

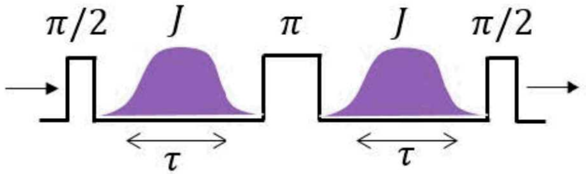






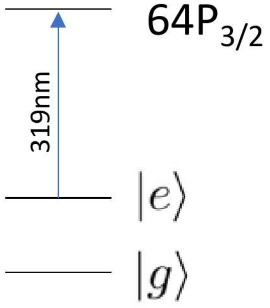
Entanglement and Interferometer Protocols

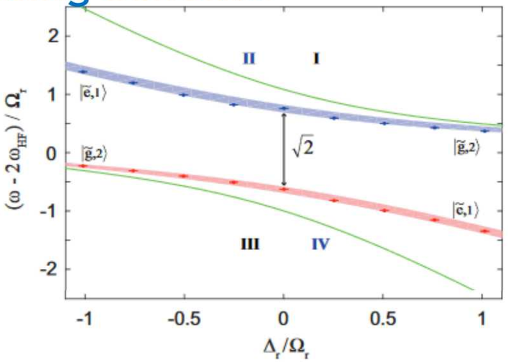
Molmer-Sorenson(MS) Gate[1] Input state $|gg\rangle$



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

Adiabatic Rydberg Dressing Scheme[2]

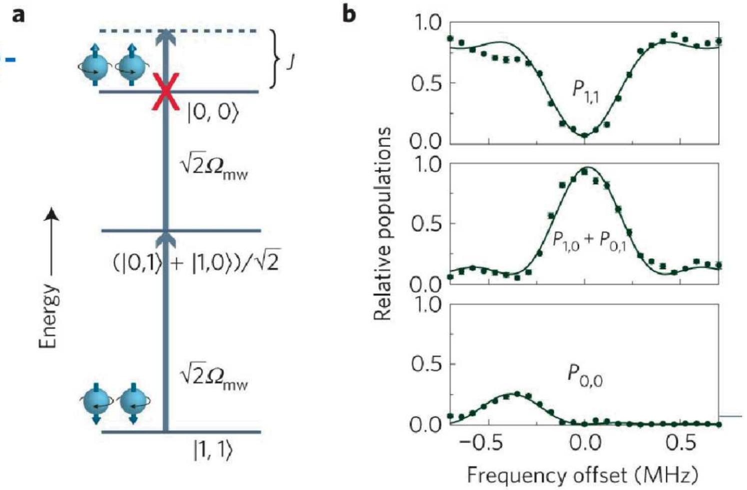




1. Use MS Gate with *Doppler-sensitive* global rotations to prepare GHZ state input to interferometer

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left[\bigotimes_{\alpha=1}^{N} |g, \mathbf{p}_\alpha\rangle_\alpha + \bigotimes_{\alpha=1}^{N} |e, \mathbf{p}_\alpha + \hbar\mathbf{K}\rangle_\alpha\right]$$

Electric dipole-dipole interaction blockades double excitation [3]



2. Apply single atom "mirror" and final "beamsplitter" pulses

$$U = \bigotimes_{\alpha=1}^{N} U_\alpha$$

3. Add a phase difference

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

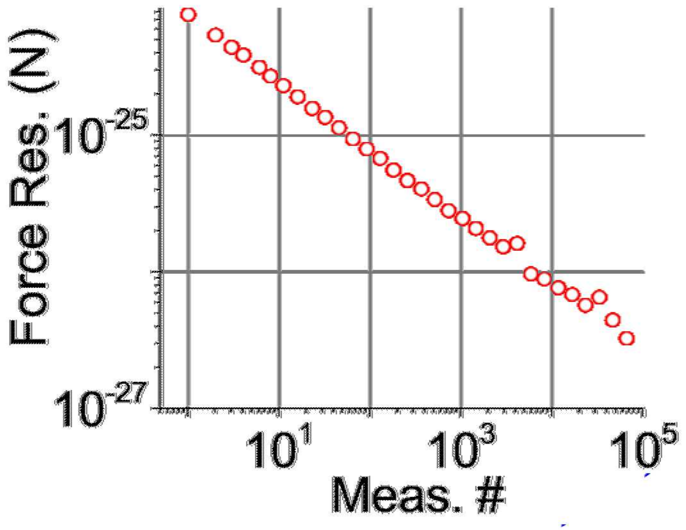
4. Measure parity

$$\Pi = \bigotimes_{\alpha=1}^{N} \sigma_z^{(\alpha)}$$

[1] Mitra, Anupam et al. "Robust Mølmer-Sørensen Gate for Neutral Atoms Using Rapid Adiabatic Rydberg Dressing." Physical Review A 101.3 (2020).
[2] Lee, et al. Physical Review A. 95. 10.1103/PhysRevA.95.041801.
[3] Y.-Y. Jau, G.B., I.D., *et al.*, Nat Phys. **12** (2016)

Experimental Progress at Sandia

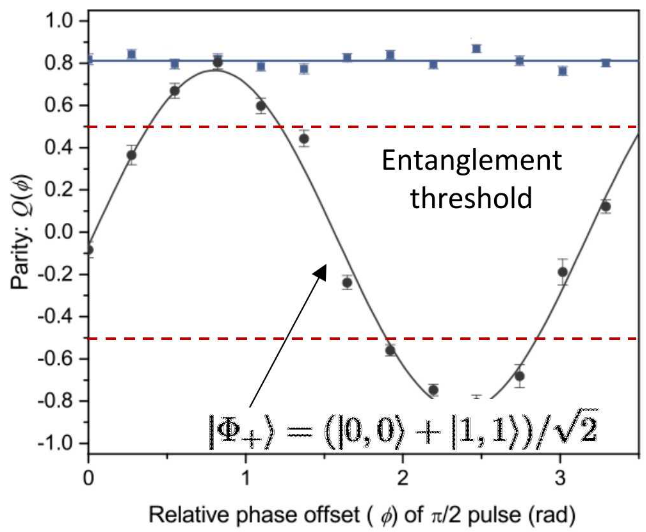
Single Atom Gravimeter



Parazzoli, *et al.*, Phys. Rev. Lett. **109**, 230401 (2012)

+

2 entangled Cs atoms with 81% fidelity



Jau, Y., *et al. Nature Phys* **12,** 71–74 (2016)

Steps towards sensitivity beyond SQL:

- Study sources of error to determine feasibility of demonstration
- Demonstrate sufficient state readout
- Move Raman beams to measure g
- Construct infrastructure for larger arrays
- Improve global rotations with counter-propagating Raman beams
- Improve GHZ state fidelity

Effects of Small Errors

$$\langle\Pi\rangle = \Pi_0 \cos(N\phi), \quad \Delta\phi = \frac{1}{\Pi_0 N}$$

Type of error	Error parameter(s)	Π_0 for small error	Parameter value(s)
Imperfect state preparation	p — weight of random noisy state $\lvert\zeta\rangle$ σ_β^2 — variance of random phase β	$1-(p+\sigma_\beta^2/2)$	Π_0 ranges from 0.89 to 0.97 for $N=2$ $\Pi_0 \approx 0.70$ for $N=4$ $\Pi_0 \approx 0.49$ for $N=8$
Laser intensity fluctuations	$\sigma_A^2 = \xi^2 A_0$ — variance of random pulse area error δA	$1-N\xi^2\pi/2$	$\xi \sim 10^{-3}$ to 10^{-4}
Laser phase noise	σ_ϑ^2 — variance of random relative phase error ϑ r — correlation parameter	$1-N^2\sigma_\vartheta^2 r/2$	σ_θ is very small but actual value is unknown $1 \le r \le 5$
Initial momentum spread	η — empirical scaling parameter, $\eta = f(\nu_{\text{trap}}, \langle n\rangle)$	$1-N\eta$	$\eta \approx \dfrac{\nu_{\text{trap}}}{1204.62\ \text{kHz}}$ for $\langle n\rangle = 0$
Measurement error	q — probability of erroneous state detection for one atom	$1-Nq$	$\Pi_0 \approx 0.877$ for $N=10$ at q=0.987[1] $\Pi_0 \approx 0.94$ for $N=100$ at q=0.9994[2]

Paper on error modeling to be submitted to PRX by C. Brif and Brandon Ruzic!

1 Fidelity reported by Saffman group, 2017

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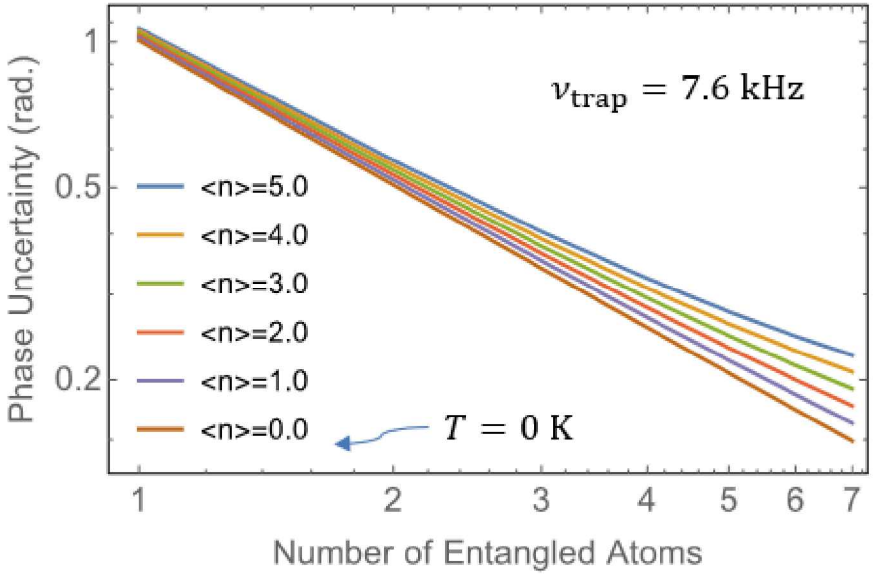
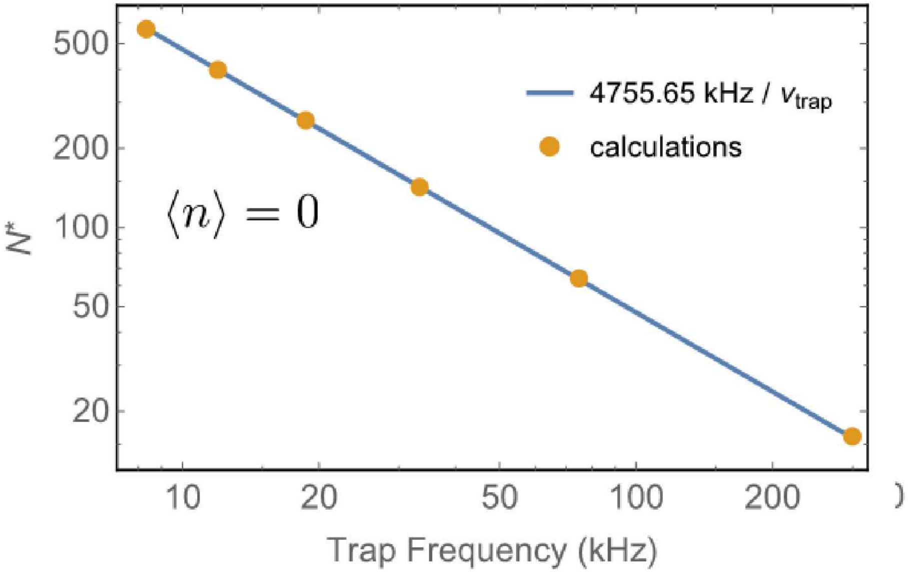
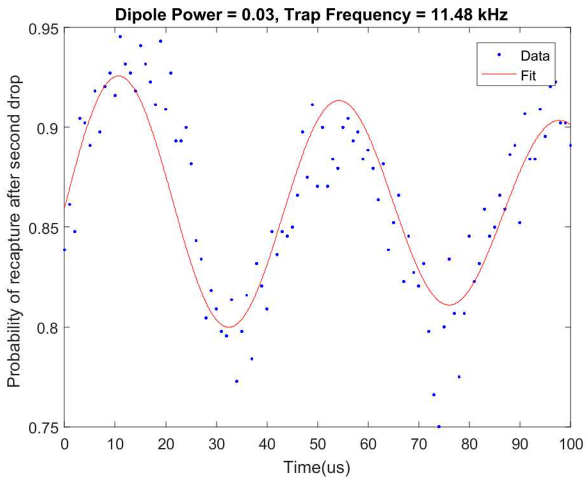
Initial Velocity Distribution

Reasonable trap frequency : ~10 kHz







N* is the approximate point of breakdown for Heisenberg scaling.

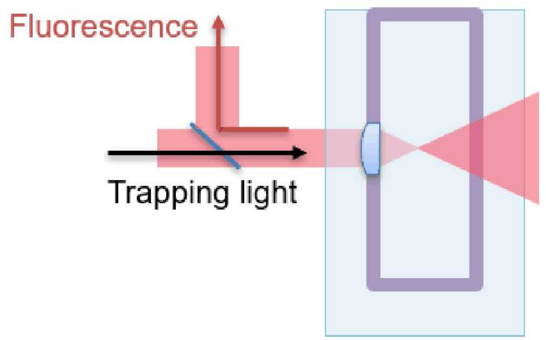
So for 10 kHz, we should be able to get metrological advantage for order 100’s of atoms.

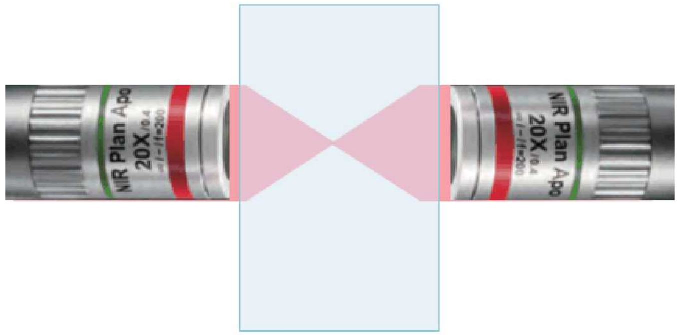
SPAM Error

State dependent detection fidelity: 95%

q = 0.05 -> $\Pi_0 \approx 0.9$ for N=2

For N>2, will need to improve.



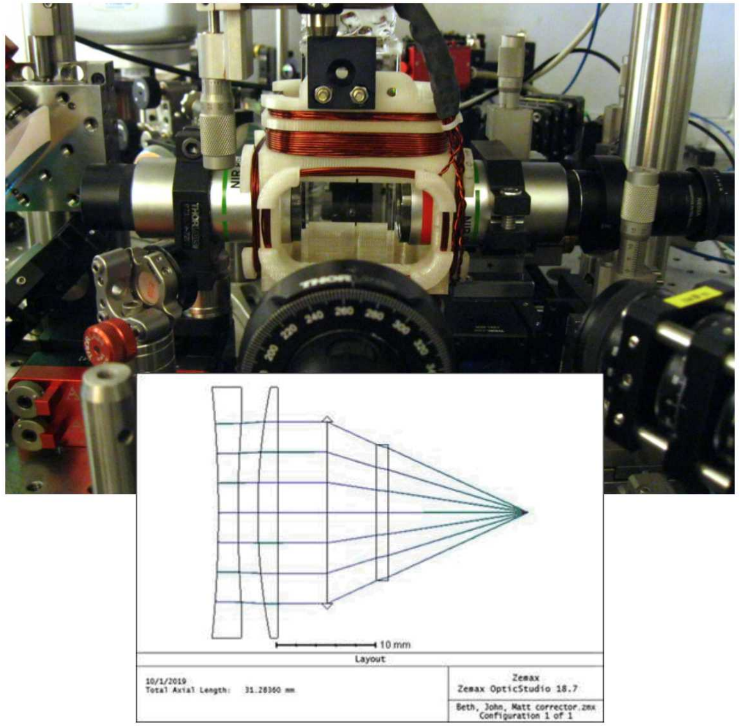


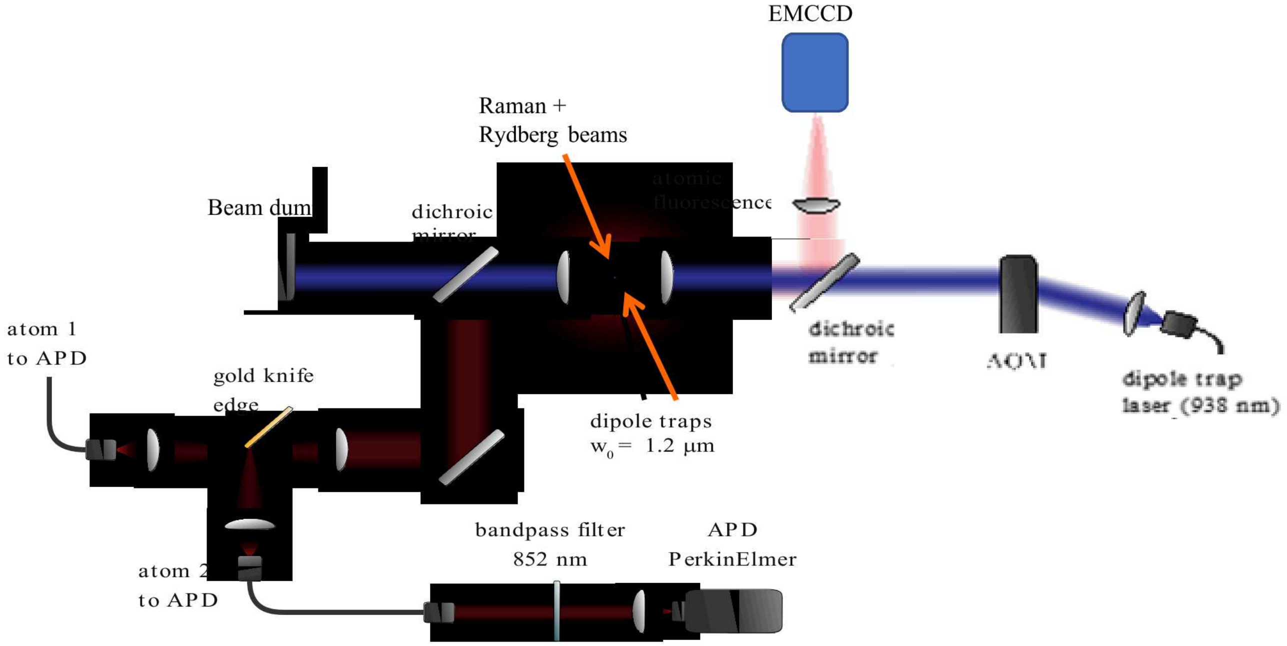
Before:
- Internal aspheric lens
- Expected efficiency ~1.13%
- Measured efficiency 0.15%

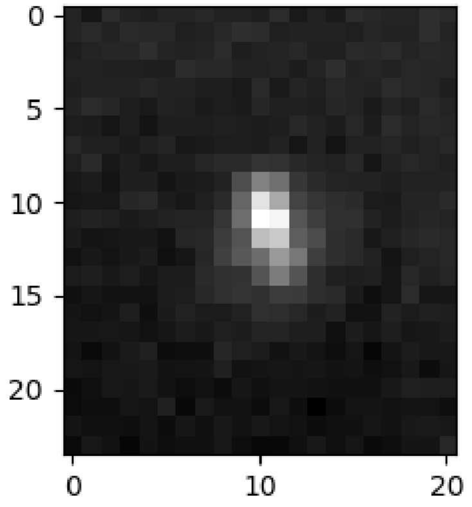
Now:
- External objective lens
- Expected efficiency ~0.52%
- Measured efficiency > 0.48%

Best DF Entangled State to date: 81% -> More to come on this

Ongoing Work



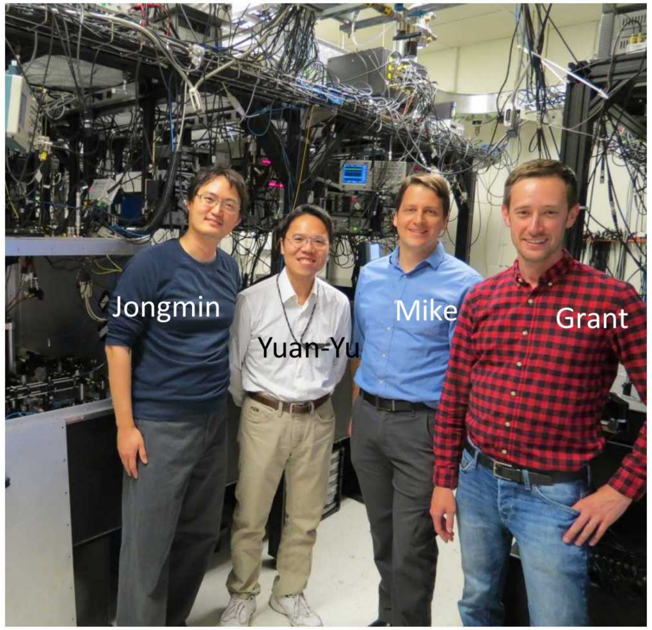




Steps towards sensitivity beyond SQL:

- ~~Study sources of error to determine feasibility of demonstration~~
- ~~Demonstrate sufficient state~~ readout (80%)
- ~~Move Raman beams to measure g~~
- ~~Construct infrastructure~~ for larger arrays (50%)
- **Improve global rotations with counter-propagating Raman beams**
- Improve GHZ state fidelity

Contributors



This has been a team effort over many years!

<u>Sandia Experiment:</u>
Bethany Little
Matthew Chow
Paul Parazzoli

<u>Sandia Theory:</u>
Brandon Ruzic
Constantin Brif

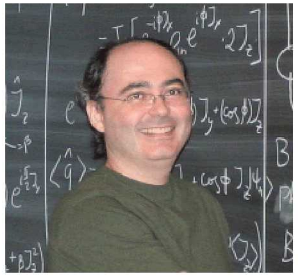
<u>Longtime Lead & Continuing Advisor/Collaborator:</u>
Grant Biedermann (OU)

<u>Collaborators:</u>
Jongmin Lee (SNL)
Yuan-Yu Jau (SNL)
Peter Schwindt (SNL)
Jonathan Bainbridge (SNL, UNM)
Ivan Deutsch (UNM)
Mike Martin (LANL)
Alberto Marino (OU)

John

Bethany

Paul



Constantin

Brandon

We welcome discussion & collaboration!