Quantum many-body states for precision measurement

James K. Thompson, NIST, JILA & Dept. of Physics at Univ. of Colorado
Precision Measurements: Things you can do with many quantum objects, that you can’t do with one.

- Spin squeezed states
- Steady-state superradiant lasers
Reducing Quantum Noise

Atoms cancel each other’s noise

World record entanglement for quantum sensors
Making Sharper Optical Rulers

Hide laser information in collective state of atoms

100x reduction in laser linewidth for frequency, length, and gravity metrology
Both Impact Wide Array of Measurements

To go where nobody has gone before

Force, pressure, temp.

Magnetic & electric field

Rotation, Acceleration

Gravity field

Realization & distribution of SI Base Units
## A Lineage of Quantum Control Freaks

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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</thead>
<tbody>
<tr>
<td>1989</td>
<td>Control of Internal Atomic States</td>
</tr>
<tr>
<td></td>
<td>Single Ion/Electron Trapping</td>
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<tr>
<td>1997</td>
<td>Laser Cooling &amp; Trapping</td>
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<tr>
<td>2001</td>
<td>Bose Einstein Condensation</td>
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<tr>
<td>2005</td>
<td>Coherent Optical Control</td>
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<tr>
<td>2012</td>
<td>Single-System Quantum Control</td>
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</table>
Nearly Complete Control of Single Atoms

What’s next!?
Parallel Control of Independent Atoms

credit: Nobel
Ultra-Precise
Atomic Clocks

0.000 000 000 000 000 000 000 003
World’s most precise absolute measurement of any kind
Matterwave Interferometers

Use pulses of light to spatially split the atomic wave function

$\phi_1 \pi \phi_2 \pi/2$

Einstein’s equivalence principle
Determine gravitational constant $G$
Detect gravity waves

GPS free navigation
Gyroscopes
Accelerometers
Gravimetry
Fundamental constants of nature
Tests of QED
Test atomic charge neutrality

Credit: A. Peters group
Parallel Control of Independent Atoms

credit: Nobel

But what’s next?!
Vision for New Frontier of Precision Measurements

Can we move beyond the single atom paradigm?
Precision Measurements: Things you can do with many quantum objects, that you can’t do with one

- Core NIST mission
- Critical advances in measurement science
Two Complex Experimental Systems: Rb, Sr
Canceling Quantum Fuzziness with Entanglement

JG Bohnet, KC Cox, MA Norcia, JM Weiner, Z Chen, JKT
Nature Photonics 8, 731-736 (2014)
Why Use Atoms/Molecules? Accuracy

Quantum Certainty Principle:
all atoms are identical
Quantum Mechanics Giveth and Taketh...

Quantum Certainty

Quantum Fuzziness

Energy

Fundamental limit for all quantum sensors
Squeezing Quantum Noise

- Fuzzy state of independent atoms
- Measure pointing
- Cavity enables collective measurement
- Squeezed fuzziness of entangled atoms
Surpassing the Standard Quantum Limit

Precision Measurements: Things you can do with many quantum objects, that you can’t do with one?

Entangled atoms cancel each other’s quantum noise
World Record Entanglement

Directly observed enhancement over SQL with no background subtractions
Technology: Matterwave Interferometers

Use pulses of light to spatially split the atomic wave function

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Determine gravitational constant $G$
Detect gravity waves?

GPS free navigation
Gyroscopes
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Credit: A. Peters group
Technology: Optical Lattice Clocks

- Extended to our strontium system
- Improved optical lattice clocks of Ye, Ludlow et al


Many Key Advantages of Optical Approach
- Very fast: 40 μs
- Avoids inaccuracies
- Non-destructive for higher bandwidth
Superradiant Lasers: Ultraprecise Rulers of Time and Space

Collective Synchronization

Atoms collectively store information inside laser
Laser is *the* Central Ruler of **Time** & **Space**

**Optical Atomic Clock**
- Quantum atoms
- Classical probe laser

**Optical frequency comb**
- Laser
- $10^6 : 1$ Reduction Gear
- Microwave

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*Visible Light*

- *name of wave*: Radio waves, Microwaves, Infrared, Ultra Violet, X-rays, Gamma
- *wavelength (meters)*: $10^2$, $10^1$, $10^{-1}$, $10^{-2}$, $10^{-3}$, $10^{-4}$, $10^{-5}$, $10^{-6}$, $10^{-7}$, $10^{-8}$, $10^{-9}$, $10^{-10}$, $10^{-11}$, $10^{-12}$
- *length of wavelength*: football field, human, bee, pin head, cell, bacteria, virus, atom, nuclei
IMS: Two Innovative Paths
Thompson, Ye, Jin, Holland, Rey, Gorshkov

Ye Lab: New Optical Materials

Thompson Lab: Superradiant Laser

Goal: x 100 improvement
Radically different approach
Quiet laser lab not needed
Lasing on ultranarrow atomic transitions

Strontium

Lifetime 150 seconds

\[ ^3P_0 \]

\[ ^1S_0 \]

>10,000 x less sensitive to cavity noise

\(~1\) mHz quantum linewidth, \(Q \sim 10^{18}\)

Stepping Stone: Lasing on 7.5 kHz \(^3P_1\) transition

Meiser, Ye, Carlson, Holland, *PRL* 102, 163601 (2009)

Gravity’s Impact on Time

~ 30 cm in 1 day

Proposed IMS work: ~1 cm in 1 second!
Vision for New Frontier of Precision Measurements

Can we move beyond the single atom paradigm?
Thanks to the Team:

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- Joshua Weiner
- Zilong Chen (Data Storage Inst.)
- Graham Greve
- Jiayan Dai, Shannon Sankar

**Strontium**
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- Karl Mayer
- Matthew Winchester

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- Steven Moses (JILA)
- Katherine McAlpine (UW)
- Elissa Picozzi (Whitman College)
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