Measurement at the Quantum Frontier

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Opportunities for AMO/quantum physics

Probe fundamental physics & emerging phenomena with “clock” precision and control

Search for dark matter

Spin manybody Table-top search for new physics

Lecture outlines

Lecture I

• Simple atomic physics
• Basic quantum physics
• Basic laser science

The ingredients for control & measurement of quantum coherence

Lecture II

• Atomic interactions
• Spin Hamiltonians
• Emergence of complexity from simple ingredients

A new frontier: quantum metrology & many-body physics
Lecture outlines

Lecture III

• Broad scientific motivations for cold molecules
• Technology developments
• Quantum degenerate gas of polar molecules

→ A new playground for quantum physics and chemistry
Probes for fundamental physics


Unruly spiral galaxies

Network of clocks ($10^{-21}$): long baseline interferometry

Dark matter halo

Space-time ripples
Time Scales

- **Quantum pendulum period:** $10^{-15}$ s
  - 0.000,000,000,000,001 seconds
- **The geometric mean:** $\sim 30$ s
- **Sr atoms:**
  - $^1S_0 \leftrightarrow ^3P_0$ (160 s)
  - $Q \sim 10^{17}$
- **Life of the Universe:** 15 billion years ($10^{18}$ s)
  - 1,000,000,000,000,000,000,000,000 seconds
Quantum Certainty & Uncertainty

\[ \frac{1}{\sqrt{2}} (|e\rangle + |g\rangle) \]

Quantized transition frequency
Standard quantum limit

Quantum Phase Noise of Atoms

Classical Phase Noise of Probe Laser

\[ \Delta \phi_{\text{SQL}} = \frac{1}{\sqrt{N}} \text{ rad} \]
Recipe for a good spectroscopy signal

Large desired effect

Large count rate
(split resonance by $\sqrt{N}$)

Long coherence time
(narrow resonance)

\[
\sigma_{\text{QPN}}(\tau) = \frac{1}{\omega T \sqrt{N}} \sqrt{\frac{T + T_d}{\tau}}
\]
Sync the laser to the atom
Laser is the Central Ruler of Time & Space

“The METER is the length of the path travelled by light in vacuum during a time interval of 1/299792458 seconds.”

Time/Frequency is the most accurately measureable quantity.

Length is linked to Time via $c$. 
Optical cavity length

Cavity length $L \sim 1 \text{ m} \rightarrow \Delta L \sim 10^{-16} \text{ m}$ (size of a nucleus: $10^{-14} \text{ m}$)

- Vibration noise: symmetric mounting
- Pressure noise $\Delta n/n$: vacuum $\sim 10^{-7}$ torr
- Spurious optical interference, etc
Laser is the Central Ruler of Time & Space

Cavity length $L \sim 1 \text{ m} \rightarrow \Delta L \sim 10^{-16} \text{ m}$ (size of a nucleus: $10^{-14} \text{ m}$)

Complex (lossy) Young’s modulus: $E = E_0 [1 + \frac{i}{Q} (\omega)]$

$$\frac{\Delta L}{L} \sim \sqrt{\frac{k_BT}{E_0 Q}}$$

Bishof et al., PRL 111, 093604 (2013).
Thermal Noise: a challenge for all!

- The best interferometers (at all scales) are thermal noise limited
- Many scientific communities attempting to make similar advances
Pushing optical coherence to ~ 1 minute

PTB - JILA
2007 - present

Stability: \(4 \times 10^{-17}\)
From one optical frequency to many

Laser Cavity

Single mode cw laser
From one optical frequency to many

2 modes
From one optical frequency to many

3 modes
From one optical frequency to many

Laser Cavity

Interference among many cavity modes

Phase locked

Intensity vs Time (ns)

1 mode
2 modes
3 modes
Time – frequency correspondence
(from one optical frequency to many)

- Temporal pulse width ↔ Spectrum bandwidth
- Train of pulses ↔ comb of frequencies
Control of light — DIGITAL synthesis of electromagnetic spectrum

A stable laser delivers phase coherence anywhere from IR to UV.


Hänsch & Hall: Optical frequency comb

Visible Light

Radio  $10^4$  $10^2$
Microwave  1
Infrared  $10^{-2}$
Visible  $10^{-5}$
Ultraviolet  $10^{-6}$
X-ray  $10^{-8}$
Gamma Ray  $10^{-10}$  $10^{-12}$

Wavelength in centimeters

About the size of...

Buildings  Humans  Honey Bee  Pinhead  Protozoans  Molecules  Atoms  Atomic Nuclei
Time is relative - Motion is “bad”

\[ \frac{\Delta \omega}{\omega} = -\frac{1}{2} \frac{v^2}{c^2} \]
Cooling atoms with light

Chu, Cohen-Tannoudji, Phillips
**Atomic Fountain Clock**

First realization (Stanford 1989):

- Coherence time: 0.25 s
- Accuracy: $10^{-9}$

Big improvements ahead
Surfing the waves

microwave wavelength

= $10^5 \times$ optical wavelength
Sr atoms - A tale of twin electrons

\[ \begin{align*}
\text{461 nm (32 MHz)} & \quad \text{689 nm (7.4 kHz)} \\
\text{698 nm (1 mHz)} & \end{align*} \]

Temperature \( \sim 220 \text{ nK} \)

Loftus et al., PRL 93, 073003 (2004).
Nuclear spin-1/2 Landé g-factor differences

Differential Landé $g$-factor

$I = 9/2$

$\pm 9/2$

$1S_0$ $3P_0$

$\pm 9/2$

$1S_0$ $3P_0$

Photon recoil

No recoils

|1>

|2>

error

|1>

|2>
Holding atoms with light

See, Dalibard & Cohen-Tannoudji, 1985
Holding atoms in a magic light bowl


Incident laser

Standing wave

Laser beam

$^{87}\text{Sr}$

$^3\text{P}_0$

$^1\text{S}_0$

698 nm
Sr energy levels

\[ 5snp^1P_1 \]
\[ 5snp^3S_1 \]
\[ 5s5p^1P_1 \]
\[ 5s6s^3S_1 \]
\[ 5s5d^3D_{1,2,3} \]
\[ 5p^{23}P_{0,1,2} \]
\[ 5s4d^3D_{1,2,3} \]
\[ 5s5p^3P_{0,1,2} \]

\[ \lambda_{\text{trap}} \approx 460 \text{ nm} \]
\[ \lambda_{\text{trap}} \approx 680 \text{ nm} \]
\[ \lambda_{\text{trap}} \approx 490 \text{ nm} \]
\[ \lambda_{\text{trap}} \approx 480 \text{ nm} \]
\[ \lambda_{\text{trap}} \approx 2.7 \mu\text{m} \]

Crossing of polarizabilities

\[
\frac{\alpha}{4\pi \varepsilon_0 a_0^3} \text{ (a. u.)}
\]

Optical trap wavelength (\(\mu\text{m}\))
Quantum state control

- Doppler, recoil, trap shifts = 0
- Precision improvement by $N^{1/2}$

- At $10^{-18}$ accuracy, atomic interactions can be controlled
- Opportunity to harness quantum many-body science for precision gains

Haroche, Wineland, 2012
$\sim 10^{-17}$
Putting all ingredients together

Ultrastable laser

optical frequency comb

atoms

Counter

Oscillator
Reaching the Cs primary standard


JILA, Tokyo, SYRTE, PTB, Firenze, INRIM, NICT, NIM, NPL, NRC


Optical “Second”

Campbell et al., Metrologia 2008

Recommended for “practical realization of the metre and secondary representations of the (SI) second” (2008)
Local Lorentz Invariance

Fundamental constants & gravitational potential

S. Blatt et al.,
A new frontier for clock stability & accuracy


Two independent Sr clocks (1000 atoms each)

3.4 × 10^{-16} \tau

Cs clock

NIST Yb clock (2013), RIKEN Sr clock (2015)

Optical Lattice Clock

JILA Sr Clock II :

2.1 x 10^{-18}

Bloom et al.,

Huntemann et al.,
PRL 116, 063001 (2016).

Nicholson et al.,
Nature Comm. 6 (2015).
State-of-the-art clock comparison

Sr/Yb frequency ratio statistics: $1 \times 10^{-18}$
Collision between identical Fermions

- Ultracold $\rightarrow$ lowest possible angular momentum collision channel
- Fermions $\rightarrow$ $l = 1\hbar$, $p$-wave collisions

$$|\psi_0\rangle|\psi_1\rangle - |\psi_1\rangle|\psi_0\rangle$$

$p$-wave collisions

(suppressed as $E^2$, as $E \rightarrow 0$)

Dalibard Fermi School 1998
Precision metrology meets many-body physics

Pauli Exclusion Principle

$\left| \psi_0 \right\rangle \left| \psi_1 \right\rangle - \left| \psi_1 \right\rangle \left| \psi_0 \right\rangle$

Ultracold Fermions