Precision atom interferometry for fundamental physics

Undergraduate Summer Research Seminar

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Atom interference

Light interferometer

Atom interferometer

http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html
Atom optics using light

(1) Light absorption:

\[ \hbar k \longrightarrow \begin{array}{c}
\hbar k \\
\end{array} \]

\[ v = \frac{\hbar k}{m} \]

(2) Stimulated emission:

\[ \hbar k \longrightarrow \begin{array}{c}
\hbar k \\
\end{array} \]

\[ \begin{array}{c}
\hbar k \\
\end{array} \longrightarrow \begin{array}{c}
\hbar k \\
\end{array} \]
Atom optics using light

(1) Light absorption:
\[ \hbar k \rightarrow \nu = \frac{\hbar k}{m} \]

(2) Stimulated emission:
\[ \hbar k \rightarrow |1,p\rangle \]
\[ \hbar k \rightarrow |2,p+\hbar k\rangle \]

In practice, typically 2-photon Raman or Bragg transitions

Rabi oscillations

Time \( [\Omega_{\text{Rabi}}^{-1}] \)
\[ |\text{atom}\rangle = |p\rangle \]

\( \frac{1}{\sqrt{2}} \left( |p\rangle + e^{i\Delta \phi} |p + k\rangle \right) \)

\( \frac{1}{\sqrt{2}} \left( |p + k\rangle + e^{i\Delta \phi} |p\rangle \right) \)

\[ \frac{1}{2} \left( (1 + e^{i\Delta \phi}) |p\rangle + ((1 - e^{i\Delta \phi}) |p + k\rangle \right) \]

Probability in State \( |p\rangle = \cos^2 \left( \frac{\Delta \phi}{2} \right) \)

Probability in State \( |p + k\rangle = \sin^2 \left( \frac{\Delta \phi}{2} \right) \)
Light Pulse Atom Interferometry

- Long duration
- Large wavepacket separation
Interference at long interrogation time

\[ 2T = 2.3 \text{ seconds} \]
\[ 1.4 \text{ cm wavepacket separation} \]

Interference (3 nK cloud)

Large space-time area atom interferometry

Long duration (2 seconds), large separation (>0.5 meter) matter wave interferometer

90 photons worth of momentum

World record wavepacket separation due to multiple laser pulses of momentum

Kovachy et al., Nature 2015
Large space-time area atom interferometry

Robust interference observed at macroscopic time and length scales

Kovachy et al., Nature 2015
Phase shift from spacetime curvature

Spacetime curvature across a single particle's wavefunction

General relativity: gravity = curvature (tidal forces)

Curvature-induced phase shifts have been described as first *true manifestation* of gravitation in a quantum system
Gravity Gradiometer

Gradiometer baseline defined by atom recoil:

\[ L = \left( \frac{N_1 \hbar k}{m} \right) \tau \]

(Insensitive to initial source position)

Gradiometer interference fringes

\[ \Delta z = 4 \text{ cm} \quad 10 \hbar k \]

\[ \Delta z = 12 \text{ cm} \quad 30 \hbar k \]

P. Asenbaum et al., PRL 2017.
Phase shift from tidal force

Gradiometer response to 84 kg lead test mass

Upper interferometer

Lower interferometer

(a)

(b)

(c)

$L = 10 \text{ cm}, n = 30, \text{ and } T = 900 \text{ ms} (\Delta z = 16 \text{ cm})$

Asenbaum et al., PRL 118, 183602 (2017)
Equivalence Principle

\[ mg = ma \]

Bodies fall at the same rate, independent of composition

\[ \eta = \frac{\Delta a}{\bar{a}} \]

**Why test the EP?**
- Foundation of General Relativity
- Quantum theory of gravity (?)
- Search for new forces, dark matter
Lunar laser ranging: \[ \eta(M, E) = (-1.0 \pm 1.4) \times 10^{-13} \]
*Williams et al, PRL 2004*

Torsion pendula: \[ \eta(Be, Ti) = (0.3 \pm 1.8) \times 10^{-13} \]
*Schlamminger et al, PRL 2008*

MICROSCOPE satellite: \[ \eta(Ti, Pt) = (-0.1 \pm 1.3) \times 10^{-14} \]
*Touboul et al, PRL 2017*
Simultaneous dual species interferometers

Suppresses time varying effects (mirror motion, laser phase, etc.)

**Bragg Interferometer**
- Common Bragg laser beams
- Common velocity selection
- AC stark shift compensation

**Phase shear readout**
Measure phase + contrast in one shot
(Sugarbaker et al, PRL 2013)
10 \hbar k Dual Species Run

Rb-85 and Rb-87 are in phase

2T = 1.8 s
Gravitational waves science:

- **New carrier for astronomy**: Generated by moving mass instead of electric charge
- **Tests of gravity**: Extreme systems (e.g., black hole binaries) test general relativity
- **Cosmology**: Can see to the earliest times in the universe
Laser Interferometer Detectors

Ground-based detectors: LIGO, VIRGO, GEO (> 10 Hz)

Space-based detector concept: LISA (1 mHz – 100 mHz)
There is a gap between the LIGO and LISA detectors (0.1 Hz – 10 Hz).

Moore et al., CQG 32, 015014 (2014)
**Mid-band discovery potential**
Historically every new band/modality has led to discovery
Observe LIGO sources when they are younger

**Optimal for sky localization**
Predict *when* and *where* events will occur (before they reach LIGO band)
Observe run-up to coalescence using electromagnetic telescopes

**Astrophysics and Cosmology**
Black hole, neutron star, and white dwarf binaries
Ultralight scalar dark matter discovery potential
Early universe stochastic sources? (cosmic GW background)
Sky localization precision:

\[ \sqrt{\Omega_s} \sim \left( \text{SNR} \cdot \frac{R}{\lambda} \right)^{-1} \]

**Mid-band advantages**
- Small wavelength \(\lambda\)
- Long source lifetime (~months) maximizes effective \(R\)

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>(\sqrt{\Omega_s} ) [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW150914</td>
<td>0.16</td>
</tr>
<tr>
<td>GW151226</td>
<td>0.20</td>
</tr>
<tr>
<td>NS-NS (140 Mpc)</td>
<td>0.19</td>
</tr>
</tbody>
</table>
Measurement Concept

**Essential Features**

1. Light propagates across the baseline at a constant speed
2. Atoms are good clocks

\[ L (1 + h \sin(\omega t)) \]
Simple Example: Two Atomic Clocks

\[ |e\rangle \]
\[ |g\rangle \]

Phase evolved by atom after time \( T \)

\[ \frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega_a T} \]

\[ \frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega_a T} \]

Stanford University
Simple Example: Two Atomic Clocks

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

\[ \frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega_a T} \]

GW changes light travel time

\[ \Delta T \sim \frac{hL}{c} \]

\[ \frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega_a (T+\Delta T)} \]

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

Time

Atom clock

Atom clock
Gradiometer sensor design

- Compare two (or more) atom ensembles separated by a **large baseline**
- Science signal is **differential phase** between interferometers
- Differential measurement suppresses many sources of common noise and systematic errors

*Science signal strength is proportional to baseline length (DM, GWs).*
Clock Gradiometer

(a) $s_2$

(b)

\[
\begin{aligned}
L & \quad T + \frac{L}{c} & \quad 2T + \frac{L}{c} \\
\frac{L}{c} & \quad T & \quad T + \frac{2L}{c} \\
0 & \quad T & \quad 2T + \frac{2L}{c}
\end{aligned}
\]

Atoms

Position

Time
Projected gravitational wave sensitivity

Dots indicate remaining lifetimes of 10 years, 1 year, 0.1 years, and 0.01 years.
MAGIS-100 detector at Fermilab

**Matter wave Atomic Gradiometer Interferometric Sensor**

- MINOS, MINERvA, NOvA experiments use NuMI beam
- 100 meter access shaft – 100 meter atom interferometer
- Search for dark matter coupling in the Hz range
- Intermediate step to full-scale detector for GWs
Stanford MAGIS prototype

Sr gradiometer CAD
(atom source detail)

Trapped Sr atom cloud
(Blue MOT)

Two assembled Sr atom sources

Atom optics laser
(M Squared SolsTiS)
Collaborators

**Rb Atom Interferometry**
- Mark Kasevich
- Tim Kovachy
- Chris Overstreet
- Peter Asenbaum
- Remy Notermans

**Sr Atom Interferometry**
- TJ Wilkason
- Hunter Swan
- Jan Rudolph
- Yijun Jiang
- Ben Garber
- Benjamin Spar
- Connor Holland

**MAGIS-100:**
- Joseph Lykken (Fermilab)
- Robert Plunkett (Fermilab)
- Swapan Chattopadhyay (Fermilab/NIU)
- Jeremiah Mitchell (Fermilab)
- Roni Harnik (Fermilab)
- Phil Adamson (Fermilab)
- Steve Geer (Fermilab)
- Jonathon Coleman (Liverpool)

**Theory:**
- Peter Graham
- Savas Dimopoulos
- Surjeet Rajendran
- Asimina Arvanitaki
- Ken Van Van Tilburg