Experimental AMO meets Model Building: Part I

(Precision Atom Interferometry)
Interference of Rb atoms

Chiow, et. al, PRL, 2011
Young’s double slit with atoms

One of the first experiments to demonstrate de Broglie wave interference with atoms, 1991 (Mlynek, PRL, 1991)
(Light-pulse) atom interferometry

Resonant optical interaction

Momentum conservation between atom and laser light field (recoil effects) leads to spatial separation of atomic wavepackets.

Recoil diagram

Resonant traveling wave optical excitation, (wavelength $\lambda$)
Three contributions to interferometer phase shift:

\[ \Delta \phi_{\text{total}} = \Delta \phi_{\text{prop}} + \Delta \phi_{\text{laser}} + \Delta \phi_{\text{sep}} \]

**Propagation shift:**

\[ \frac{S_{\text{cl,B}} - S_{\text{cl,A}}}{\hbar} \]

**Laser fields (Raman interaction):**

\[ k(z_c - z_b + z_d - z_a) + \phi_I - 2\phi_{II} + \phi_{III} \]

**Wavepacket separation at detection:**

\[ \vec{p} \cdot \Delta \vec{r}/\hbar \]

Differential accelerometer

Applications in precision navigation, geodesy and precision gravitational physics
Laser cooling techniques are used to achieve the required velocity (wavelength) control for the atom source.

**Laser cooling:** Laser light is used to cool atomic vapors to temperatures of \( \sim 10^{-6} \) deg K.

Image source: www.nobel.se/physics

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The Nobel Prize in Physics 1997

"for development of methods to cool and trap atoms with laser light"

- **Steven Chu**
  - USA
  - Stanford University, Stanford, CA, USA
  - 1948 -

- **Claude Cohen-Tannoudji**
  - France
  - Collège de France and École Normale Supérieure, Paris, France
  - 1933 -

- **William D. Phillips**
  - USA
  - National Institute of Standards and Technology, Gaithersburg, Maryland, USA
  - 1940 -
Gravity gradiometer

Demonstrated accelerometer resolution: \( \sim 1 \times 10^{-11} \text{ g} \).
Measurement of $G$

Systematic error sources dominated by initial position/velocity of atomic clouds. $\delta G/G \sim 0.3\%$.

Next Generation: $<1e^{-4}$, exp’t in progress at AOSense, Inc. in collaboration with LLNL.

<table>
<thead>
<tr>
<th>Systematic</th>
<th>$\delta G/G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Atom Velocity</td>
<td>$1.88 \times 10^{-3}$</td>
</tr>
<tr>
<td>Initial Atom Position</td>
<td>$1.85 \times 10^{-3}$</td>
</tr>
<tr>
<td>Pb Magnetic Field Gradients</td>
<td>$1.00 \times 10^{-3}$</td>
</tr>
<tr>
<td>Rotations</td>
<td>$0.98 \times 10^{-3}$</td>
</tr>
<tr>
<td>Source Positioning</td>
<td>$0.82 \times 10^{-3}$</td>
</tr>
<tr>
<td>Source Mass Density</td>
<td>$0.36 \times 10^{-3}$</td>
</tr>
<tr>
<td>Source Mass Dimensions</td>
<td>$0.34 \times 10^{-3}$</td>
</tr>
<tr>
<td>Gravimeter Separation</td>
<td>$0.19 \times 10^{-3}$</td>
</tr>
<tr>
<td>Source Mass Density inhomogeneity</td>
<td>$0.16 \times 10^{-3}$</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$3.15 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Gravity gradiometer/mass tomography

Sample mass configurations:

Data:

Gravity gradient

AOSense

408-735-9500
AOSense.com
Sunnyvale, CA
Test Newton’s Inverse Square Law

Using new sensors, we anticipate \( \delta G/G < 10^{-4} \).

This will also test for deviations from the inverse square law at distances from \( \lambda \sim 1 \text{ mm} \) to 10 cm.

\[
V(r) = -G \frac{m_1 m_2}{r} \left[ 1 + \alpha e^{-r/\lambda} \right]
\]

(J. Wacker)
Physical sensitivity limits (10 m apparatus)

Quantum limited accelerometer resolution: $\sim 7 \times 10^{-20}$ g

Assumptions:
1) Wavepackets (Rb) separated by $z = 10$ m, for $T = 1$ sec. For 1 g acceleration: $\Delta \phi \sim mgz/\hbar \sim 1.3 \times 10^{11}$ rad
2) Signal-to-noise for read-out: SNR $\sim 10^5:1$ per second.
3) Resolution to changes in g per shot: $\delta g \sim 1/(\Delta \phi \text{ SNR}) \sim 7 \times 10^{-17}$ g
4) $10^6$ seconds data collection

We will exploit this sensitivity for:

Gravity wave detection, tests of General Relativity, new atom charge neutrality tests, tests of QED (photon recoil measurements), searches for anomalous forces...
Equivalence Principle

Co-falling $^{85}$Rb and $^{87}$Rb ensembles

Evaporatively cool to $< 1 \mu$K to enforce tight control over kinematic degrees of freedom

Statistical sensitivity

$\delta g \sim 10^{-15}$ g with 1 month data collection

Systematic uncertainty

$\delta g \sim 10^{-16}$ limited by magnetic field inhomogeneities and gravity anomalies.

Evaporatively cooled atom source

10 m drop tower
Status update

Image of cold atom cloud launched in 10 m fountain.
Light-pulse interferometer phase shifts for Schwarzschild metric:

- Geodesic propagation for atoms and light.
- Path integral formulation to obtain quantum phases.
- Atom-field interaction at intersection of laser and atom geodesics.

Tests of General Relativity

Schwartzchild metric, PPN expansion:
\[ ds^2 = (1 + 2\phi + 2\beta\phi^2)dt^2 - (1 - 2\gamma\phi)dr^2 - r^2d\Omega^2 \]
\[ \frac{d\hat{v}}{dt} = -\nabla[\phi + (\beta + \gamma)\phi^2] + \gamma[3(\hat{v} \cdot \hat{r})^2 - 2\hat{v}^2]\nabla \phi \]
\[ + 2\hat{v}(\hat{v} \cdot \nabla \phi). \]

Corresponding AI phase shifts:

<table>
<thead>
<tr>
<th>Phase Shift</th>
<th>Size (rad)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-k_{\text{eff}}gT^2)</td>
<td>(3 \times 10^8)</td>
<td>gravity</td>
</tr>
<tr>
<td>(-k_{\text{eff}}(\partial rg)T^3v_L)</td>
<td>(-2 \times 10^3)</td>
<td>1st gradient</td>
</tr>
<tr>
<td>(-3k_{\text{eff}}T^2v_L)</td>
<td>(4 \times 10^1)</td>
<td>Doppler shift</td>
</tr>
<tr>
<td>((2 - 2\beta - \gamma)k_{\text{eff}}g\phi T^2)</td>
<td>(2 \times 10^{-1})</td>
<td>GR</td>
</tr>
<tr>
<td>(-\frac{7}{12}k_{\text{eff}}(\partial r^2)gT^4v_L^2)</td>
<td>(8 \times 10^{-3})</td>
<td>2nd gradient</td>
</tr>
<tr>
<td>(-5k_{\text{eff}}T^2v_L^2)</td>
<td>(3 \times 10^{-6})</td>
<td>GR</td>
</tr>
<tr>
<td>((2 - 2\beta - \gamma)k_{\text{eff}}\partial_r(g\phi)T^3v_L)</td>
<td>(2 \times 10^{-6})</td>
<td>GR 1st grad</td>
</tr>
<tr>
<td>(-12k_{\text{eff}}g^2T^3v_L)</td>
<td>(-6 \times 10^{-7})</td>
<td>GR</td>
</tr>
</tbody>
</table>

Projected experimental limits:

<table>
<thead>
<tr>
<th>Tested Effect</th>
<th>current limit</th>
<th>AI initial</th>
<th>upgrade</th>
<th>future</th>
<th>future</th>
<th>future</th>
</tr>
</thead>
<tbody>
<tr>
<td>PoE</td>
<td>(3 \times 10^{-13})</td>
<td>(10^{-15})</td>
<td>(10^{-16})</td>
<td>(10^{-17})</td>
<td>(10^{-19})</td>
<td></td>
</tr>
<tr>
<td>PPN ((\beta, \gamma))</td>
<td>(10^{-4})</td>
<td>(10^{-5})</td>
<td>(10^{-1})</td>
<td>(10^{-2})</td>
<td>(10^{-4})</td>
<td>(10^{-6})</td>
</tr>
</tbody>
</table>

Steady path of apparatus improvements include:
- Improved atom optics
- Longer baseline
- Sub-shot noise interference read-out

(Dimopoulos, et al., PRL 2007; PRD 2008)
Atom charge neutrality

- Apparatus will support >1 m wavepacket separation
- Enables ultra-sensitive search for atom charge neutrality through scalar Aharonov-Bohm effect.

\[ \varepsilon = \delta e/e \sim 10^{-26} \] for mature experiment using scalar Aharonov-Bohm effect

Current limit: \[ \delta e/e \sim 10^{-20} \] (Unnikrishnan et al., Metrologia 41, 2004)

Impact of a possible observed imbalance currently under investigation.

Theory collaborators:
Gravity waves

Atoms provide inertially decoupled references

Gravity wave phase shift through propagation of optical fields

Evades quantum measurement noise (photon scattering regularized by non-linear atom/photon interaction; prepare fresh atom ensemble each shot)


Possible satellite configuration
Possible sensitivity

(2012) Laser frequency noise insensitive detector

Use single photon transitions to suppress laser frequency noise.

Dramatically eases experimental requirements.

Fundamentally new GW detection paradigm.

(Graham, Hogan, Kasevich, Rajendran, in preparation)
Can sensitivity be improved with new classes of atom optics?

Can precision atom interferometric methods be extended to massive particles?

Can quantum metrology approaches be used to improve interferometer sensitivity?
~100 atom solitons produced by forced evaporation of (attractively interacting) \(^7\)Li

Under appropriate conditions solitons behave as single particles. In principle, 100x improved sensitivity for interferometers...
Soliton lifetime \( \sim 10 \text{ s} \). Enables precise force sensing applications.
Soliton center-of-mass wavefunction dynamics

Sequence of images of solitons (100 atoms in each) suddenly released from a tight optical trap.

Histogram of observed soliton positions at a 60 msec time of flight following release from the trap.

Center-mass-wavefunction spreading for single solitons released from tight traps.

Dashed: Expected behavior from Heisenberg uncertainty principle.

Control: soliton adiabatically released from trap.

…. Precursor to soliton interferometry experiments
THANKS SAVAS!