Lecture #1

Light-Pulse Atom Optics and Interferometry

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Young’s double slit interferometer with atoms

Mlynek, PRL, 1991
Young's double slit interference fringes

Mlynek, PRL, 1991
1991 Light-pulse atom interferometer

6 mm at 2% contrast

See Borde, 1989
Pulses of light are used to coherently manipulate atom de Broglie waves:

Kasevich and Chu, PRL, 1991
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:
\[ \vec{p} \cdot \Delta \vec{r}/\hbar \]


Graham lectures
Lagrangian

Action evaluation includes rotations (Coriolis, centrifugal), gravity, and gravity gradient terms:

\[
L(\vec{r}, \vec{v}) = m \left( \frac{v^2}{2} + \vec{g} \cdot \vec{r} + \frac{1}{2} \vec{r} \cdot T_{gg} \cdot \vec{r}^t + \vec{\Omega} \cdot \left( (\vec{r} + \vec{R}) \times \vec{v} \right) \right. \\
\left. + \frac{1}{2} \left( \vec{\Omega} \times (\vec{r} + \vec{R}) \right)^2 \right)
\]

Trajectory evaluation contains gravity and rotations; Integrate above expression over trajectories determined by:

\[
\tilde{L}(\vec{r}, \vec{v}) = m \left( \frac{v^2}{2} + \vec{g} \cdot \vec{r} + \vec{\Omega} \cdot \left( (\vec{r} + \vec{R}) \times \vec{v} \right) \right. \\
\left. + \frac{1}{2} \left( \vec{\Omega} \times (\vec{r} + \vec{R}) \right)^2 \right)
\]

Accelometer phase shifts in long T fountain

<table>
<thead>
<tr>
<th>Term</th>
<th>Phase Shift</th>
<th>Size (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$k_{\text{eff}} g T^2$</td>
<td>$2.1 \times 10^8$</td>
</tr>
<tr>
<td>2</td>
<td>$2k_{\text{eff}} \cdot (\Omega \times v) T^2$</td>
<td>5.1</td>
</tr>
<tr>
<td>3</td>
<td>$k_{\text{eff}} v_z \delta T$</td>
<td>3.5</td>
</tr>
<tr>
<td>4</td>
<td>$\frac{hk_{\text{eff}}^2}{2m} T_{zz} T^2$</td>
<td>0.44</td>
</tr>
<tr>
<td>5</td>
<td>$k_{\text{eff}} T_{zi} (x_i + v_i T) T^2$</td>
<td>0.18</td>
</tr>
<tr>
<td>6</td>
<td>$\frac{1}{2} k_{\text{eff}} \alpha (v_x^2 + v_y^2) T^2$</td>
<td>0.04</td>
</tr>
</tbody>
</table>

($T_{ij}$, gravity gradient; $vi$, velocity; $xi$, initial position; $\alpha$, wavefront curvature; $g$, acceleration; $T$, interrogation time; $keff$, effective propagation vector)

$T = 1.15$ s in 10 m fountain.

Quantum corrections: Dubetsky, PRA (2006)
Reference frames and paths for uniform acceleration

In reference frame co-falling with atoms:

*Phase shift due to relative motion of atom with respect to optical phase fronts*

In reference frame anchored to optical fields:

*Phase shift due to relative motion of atom with respect to optical phase fronts*

* Path kinetic term cancels optical shift; has been interpreted as redshift measurement (Mueller)

In reference frame anchored to optical fields, integration over unperturbed trajectories (Storey and CCT, 1994):

*Phase shift from path phase*
Questions

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?

How can improved sensitivity be exploited for technology and fundamental science?
Physical sensitivity limits (10 m apparatus)

Quantum limited accelerometer resolution: \( \sim 7 \times 10^{-20} \, \text{g} \)

Assumptions:

1) Wavepackets (Rb) separated by \( z = 10 \, \text{m} \), for \( T = 1 \, \text{sec} \). For 1 g acceleration:
   \[ \Delta \phi \sim \frac{mgzT}{\hbar} \sim 1.3 \times 10^{11} \, \text{rad} \]

2) Signal-to-noise for read-out: \( \text{SNR} \sim 10^5:1 \) per second.

3) Resolution to changes in g per shot:
   \[ \delta g \sim \frac{1}{(\Delta \phi \, \text{SNR})} \sim 7 \times 10^{-17} \, \text{g} \]

4) 106 seconds data collection

Applications?

Gravity wave detection, tests of General Relativity, new atom charge neutrality tests, tests of QED (photon recoil measurements), searches for anomalous forces, geodesy ...
Large momentum transfer (LMT) at long T

6 photon recoil beamsplitter (sequential Raman)

$2T = 2.3 \text{ s}$

Wavepacket separation $\sim 4 \text{ cm}$

Inferred acceleration sensitivity $\delta g \sim 4e-12 \text{ g/shot}$

Dickerson, Hogan, Kovachy, Sugarbaker, unpublished
LMT atom optics

102 photon recoil atom optics

Chiow, Kovachy, PRL, 2011
Sequential Bragg LMT atom optics

Employ sequences of multi-photon Bragg pulses to obtain large momentum recoil

Sample interferometer pulse sequence

(LMT sequences of Raman pulses, McGuirk, PRL, 2000)
Multi-photon Bragg transitions

The frequencies of two far-detuned counter-propagating beams are tuned to drive multi-photon transitions between two momentum eigenstates.

We have driven transitions ranging from 6 and 30 photon recoils.

Initially demonstrated by S.A. Lee in 90’s.

Where does overall sequence efficiency optimize as function of number of recoils in each Bragg pulse?

Experiment: 6 photon recoils (!)
Sequential Bragg beamsplitter and mirror

30 photon recoil momenta (20 cm/s) beam splitter and mirror pulses.

5 sequential 6 photon recoil Bragg pulses

Wavepacket separation of ~1 mm

Wavepackets in coherent superposition state
High contrast LMT atom interferometers

30 photon recoil

102 photon recoil

70% contrast

18% contrast
Interferometer output phase distributions

Interferometer phase fluctuates due to phase noise on the Bragg lasers.

($\lambda/100$ fluctuations lead to 1 rad phase shifts)

Distribution of observed shifts has expected behavior.

18% contrast for 102 $\hbar k$
Comments

• Ultra-cold source required for high diffraction efficiency.
  – 4 nK temperatures used in this work
  – >99%/h\hbar k achieved

• Effective optical phase grating periodicity is \( \lambda/102 \) ~ 8 nm.
  – effective x-ray photon
  – stringent demands placed on optical wavefronts

• With improved laser source/optics, 1000 \( \hbar k \) appears feasible.
Differential accelerometer

Simultaneous, vertically displaced interferometers

Despite fluctuations in the phase shift of each individual interferometer, differential phase shift between two interferometers is constant.

Such cancellation is crucial to advanced sensors (e.g., gravity gradiometers).

False color images of interferometer outputs, 30 photon recoil

20 µm
Dual interferometer correlated phase outputs

The two interferometers display the expected (anti-) correlated phase shifts.
Use frequency chirped/amplitude shaped pulses to overcome the limited velocity acceptance of multi-photon Bragg pulses.

 Appropriately designed pulses can have 2 photon recoil velocity acceptance (max. allowed).

Kovachy, et al., PRA 2012
Interferometer pulse efficiency

\[ \pi \text{ pulse} \]

\[ \pi/2 \text{ pulse} \]
Pulse efficiency

Left: +30 $\hbar k$ (12 msec drift time)

Right: +50 $\hbar k$ followed by -50 $\hbar k$

99.7% transfer efficiency per photon recoil
Interferometer contrast and phase

2T = 10 msec
interferometer contrast:

Interferometer phase as a function of pulse detuning:
Optical lattice interferometry

Optical lattice manipulations are thought to enable very large area atom interferometry


Schematic illustration of lattice atom beam splitter
Lattice interferometry proof-of-concept

Implemented pulse sequence with third order Bragg pulses and lattice hold; atom wave packet separated by 20 microns, held apart in lattice for times of 7 and 10 ms, and subsequently recombined:

$$\frac{\pi}{2} - \frac{\pi}{2} - \text{lattice hold} - \frac{\pi}{2} - \frac{\pi}{2}$$

Kovachy, Chiow, 2010 unpublished. Poor contrast for longer hold times.
2296 photon recoil lattice manipulation

Image of atom cloud after 8.5 m launch.

1 cm

Coherent lattice launch.
Momentum transfer quantized in $2\hbar k$ increments.

Lattice beam configuration

99.995% / $\hbar k$ pulse efficiency.
No observable heating.

Enables meter-scale wavepacket separation which combined with a beamsplitter pulse?

105 atoms
3 nK (evaporatively cooled)
2.64 sec drift time
$m=0$ state prep
2296 photon recoil launch
(150 g accel. on launch)
**Atomic solitons as massive quasi-particles for AI**

Forced evaporation produces stable, ~100 atom, single solitons

**(Medley, submitted)**
Soliton center-of-mass wavefunction dynamics (1)

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

Histogram of observed soliton positions at a 60 msec time of flight following sudden 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
Soliton collisions

Sequence of images illustrating a collision between two solitons.

The initial soliton phase is not controlled between shots.
Multiple collisions

Images after 7 collisions.

~50% of experimental trials result in single (merged) solitons.

Possibly illustrates phase depended collision dynamics.