Testing the weak equivalence principle in the Stanford 10-meter tower

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Equivalence Principle

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 (?)

Torsion balance
(University of Washington)

Lunar Laser Ranging

C. Will, Living Reviews
New fundamental interactions

Yukawa type:

\[ V(r) = -\frac{GM_1 M_2}{r} \left( 1 + \alpha e^{-r/\lambda} \right) \]

New forces violate EP

Tests are sensitive to charge differences of new forces

Can also look for AC violations caused by proposed dark matter particle (P. Graham et al., arXiv:1512.06165).
Direct detection of dark matter

- Weakly coupled, light bosonic particles
- New fundamental interaction
- Acts like a classical field that exerts forces on matter:

\[ F \propto g \sqrt{\rho_{DM}} \cos(m_{DM}t) \]

Force is oscillatory and equivalence-principle violating

Example:
Reach of searches for $B$-$L$-coupled vector DM

P. Graham et al., arXiv:1512.06165
Atom interference

**Light interferometer**

![Diagram of light interferometer](http://scienceblogs.com/principles/2013/10/22/quantum-erasure/)

**Atom interferometer**

![Diagram of atom interferometer](http://www.cobolt.se/interferometry.html)
Light Pulse Atom Interferometry

- Long duration
- Large wavepacket separation
10 meter scale atomic fountain

Atom Optics & Lattice Beam
Delivery Enclosure

Upper Detection Region

3 Layer Magnetic Shield
(<1 mG on axis)

Lower Detection Region

2D MOT Loading 3D

Rotation Compensation System

< 3 nK

1 cm

$\alpha_{\text{87}}$ $\alpha_{\text{85}}$
Interference at long interrogation time

2T = 2.3 seconds
1.4 cm wavepacket separation

Wavepacket separation at apex (this data 50 nK)

Large momentum transfer demonstration

- Enhanced sensitivity
- Multiple pulses to transfer momentum
- Absolute AC Stark compensated Bragg pulses
- Long duration (>2 s)

Kovachy et al., Nature 2015
Interferometer ports

Interference causes population modulation between the ports

Kovachy et al., Nature 2015
Maximum observed contrast vs LMT order

- High contrast out to 90 $\hbar k$
- All data using $2T = 2.08$ s
- Limited by atom loss (inset)

Contrast metric corrects for technical noise in atom populations (using maximum likelihood analysis)

8 $\times 10^9$ rad/g for 90 $\hbar k$

Kovachy et al., *Nature* 2015
Gravity Gradiometer

Gradiometer baseline defined by atom recoil:

\[ L = \left( N_1 \hbar k/m \right) \tau \]

(Insensitive to initial source position)

Gradiometer interference fringes

\[ \Delta z = 4 \text{ cm} \]

10 \hbar k

\[ \Delta z = 12 \text{ cm} \]

30 \hbar k

P. Asenbaum et al., arXiv:1610.03832 (PRL, to appear)
Phase shift from tidal force

Gradiometer response to 84 kg lead test mass

First observation of “tidal” phase shift:

\[ \Delta \phi_{\text{tidal}} \approx \left( \frac{\hbar}{2m} \right) n^2 k^2 (\Delta T_{zz}) T^3 \]

Spacetime curvature across a single particle’s wavefunction

GR: gravity = curvature

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

P. Asenbaum et al., arXiv:1610.03832 (PRL, to appear)
Current Status

Dual species source, launched

\[ ^{85}\text{Rb} \quad F=3, \quad m_F=0 \]
\[ ^{87}\text{Rb} \quad F=2, \quad m_F=0 \]

10^5 atoms per launch, 40 nK radial

Initial operating parameters:

\[ 10 \, \hbar k \]
\[ \delta \phi = 3 \, \text{mrad/shot (shot noise } 10^5 \text{ atoms)} \]
\[ \sim 1000 \text{ shots/day} \]

Estimated initial sensitivity:

\[ \frac{\delta g}{g} \sim \frac{\delta \phi}{k_{\text{eff}} g T^2} \]

\[ \delta g < 10^{-13} \text{ g in a day} \]
Gravity gradient characterization

*Measured gravity gradient vs launch height*

$L = 10 \text{ cm baseline}$
$10 \text{ hk}$
$T = 500 \text{ ms}$

**Red:** Gravity Model = preliminary reference Earth + cylindrical pit + lab basement

Gradiometer resolution: $3E$ per shot
Magnetic Field Control

Three layer mu-metal magnetic shield

Welded together and annealed

Residual field < 1 mG rms

Coriolis phase shift control

Interference patterns for rotating platform:

Tip-tilt mirror for rotation compensation

Measurement of rotation rate near null rotation operating point.

Dickerson, et al., PRL 111, 083001 (2013)
Collaborators

*Rb Atom Interferometry*
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