Searching for non-Newtonian forces with optically levitated microspheres

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Introduction

• Searches for new short range forces can probe a variety of models of new physics that are difficult to test with other techniques
• Typically parameterize resulting non-Newtonian potential with Yukawa form:

\[
V(r) = -\frac{Gm_1m_2}{r} \left( 1 + \alpha e^{-r/\lambda} \right)
\]

Current experimental constraints on non-Newtonian forces:

- Strong limits from terrestrial and astrophysical tests exist at large distance
- For short length scales, constraints are much weaker: \( \alpha \lesssim 10^{10} \) for \( \lambda = 1 \mu m \)
- May be possible to significantly improve sensitivity at micron length scales
Introduction

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Current experimental constraints on non-Newtonian forces:

- Laboratory: Lunar laser ranging
- Planetary: Terrestrial and satellites
- Terrestrial: Decca et al., PRL 94, 240401 (2005)
- Terrestrial: Sushkov et al., PRL 107, 171101 (2011)
- Terrestrial: Geraci et al., PRD 78, 022002 (2008)
- Terrestrial: Kapner et al., PRL 98, 021101 (2007)

For short length scales, constraints are much weaker:

- May be possible to significantly improve constraints at micron length scales

Optical levitation

- Previous measurements at short distance have used mechanical springs as force sensors (e.g. torsion pendulums, micromachined cantilevers)
- Suspending test mass with an “optical spring” offers several advantages:
  - Thermal and vibrational noise from mechanical support minimized
  - At high vacuum, test mass can be isolated from surroundings and cooled optically (without cryogenics)
  - Test mass position can be controlled and measured precisely with optics
  - Control of optical potential and motion in all 3 DOF allows powerful differential measurements
  - Dielectric spheres with a wide range of sizes (~10 nm – 10 μm) can be used
  - Extremely low dissipation is possible: \( Q \sim 10^{12} \) at \( 10^{-10} \) mbar

_Schematic of optical levitation technique:_

*Geraci et al., PRL 105, 101101 (2010)*
Experimental setup

- Developed setup capable of levitating SiO₂ microspheres with $r = 0.5$-$5 \mu m$
- Microspheres are levitated in UHV chamber with $\lambda = 1064$ nm, ~few mW trapping laser
- Imaged by additional $\lambda = 650$ nm beams
- Have stably trapped a single microsphere at $\sim 10^{-7}$ mbar for >100 hrs

Photograph of trapped microsphere:

Simplified optical schematic:
Microsphere cooling

- Below ~1 mbar, active feedback cooling is needed to maintain stable trapping
- Monitor position of microsphere and apply feedback by modulating amplitude and pointing of the trapping beam (using FPGA and AOD)
- Can cool center of mass motion to <50 mK in all 3 DOF

Mechanism for laser heating:

Microsphere position spectrum with cooling:

- Minimal feedback, $T_{eff} \approx 300$ K
- Typical feedback, $T_{eff} \approx 50$ mK

$p = 10^{-6}$ mbar
Microsphere neutralization

- Electromagnetic backgrounds can overwhelm signal from new short-range forces
- Microsphere can be discharged by flashing with UV light from Xe flash lamp
- Have demonstrated controlled discharging with single e precision
- Once neutral, microspheres have not spontaneously charged in total integration time of more than $5 \times 10^5$ s

**Example of discharging process:**

- $V_{\text{peak}} = 10$ V
- $V_{\text{peak}} = 500$ V

![Diagram of electrode configuration](image)
Force sensitivity

- Can also use observed single $e$ steps to perform absolute calibration of force sensitivity for each microsphere *in situ*
- At high pressure, sensitivity limited by residual gas damping
- Below $10^{-3}$ mbar, force sensitivity limited to $\sigma_F = 5 \times 10^{-17} \text{ N Hz}^{-1/2}$
- Current sensitivity limited by non-fundamental sources of noise (imaging and laser jitter)
- Significant improvement possible – pressure limited sensitivity at $10^{-9}$ mbar $\sim 10^{-20} \text{ N Hz}^{-1/2}$
Search for millicharged particles

- As a first application of this force sensing technique, we have performed a search for millicharged particles ($|q| \ll 1e$) bound in the microspheres.
- Sensitive to single fractional charges as small as $5 \times 10^{-5} e$.
- Current sensitivity (<1 aN) limited by residual response due to microsphere inhomogeneities that couple to E-field gradients.

Measured residual response:

<table>
<thead>
<tr>
<th>Angle of response relative to field</th>
<th>X component of residual response [$10^{-6} e$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1</td>
</tr>
<tr>
<td>45°</td>
<td>10</td>
</tr>
<tr>
<td>90°</td>
<td>100</td>
</tr>
<tr>
<td>135°</td>
<td>1000</td>
</tr>
</tbody>
</table>

Limits on abundance of millicharged particles:


Kim et al., PRL 99 161804 (2007)
Attractor design

- Short-range force measurements require gravitational attractor that can be positioned near microsphere.
- Attractor with spatially varying density allows reduction of many backgrounds.
- Have begun fabrication of Au and Si test mass arrays.
- Au shielding layer screens electromagnetic backgrounds that vary with composition.

Images of preliminary fabrication tests:

- Top view:
  - Au, \( \rho \approx 20 \text{ g/cm}^3 \)
  - Si, \( \rho \approx 2 \text{ g/cm}^3 \)

- Side view:
  - \( s \approx 0.2 - 5 \mu m \)
  - \( t \approx 0.5 - 3 \mu m \)
  - \( r_b \approx 5 \mu m \)
Microsphere positioning

• The position of the microsphere can be precisely controlled via the optical potential
• Acousto-optic deflector (AOD) is used to position microsphere with ~μm separations from attractor mass
• Microsphere can be moved along the attractor face to produce an oscillation in density near the microsphere at up to ~200 Hz

Side view of microsphere near attractor:

Top view of microsphere near attractor:
Expected backgrounds (Casimir)

• If unscreened, differential Casimir force between Au and Si can present dominant background
• Coating attractor with Au shield layer (0.5 to 3 μm thick) can sufficiently suppress this background
• Differential Casimir force modulates with the same spatial frequency as the expected signal
• Calculation assumes proximity force approximation (PFA)
• Full calculation without PFA for realistic 3D geometry is in progress

![Diagram of the expected backgrounds](image)

**Calculation of differential Casimir force:**

\[ F(s) = \frac{A}{s^2} \]

- \( F(s) \) is the differential Casimir force
- \( A \) is a constant depending on the material and separation
- \( s \) is the separation between the surfaces

Current force sensitivity:
- Pressure limited, \( 10^{-3} \) mbar
- \( 1/r^2 \) gravity

- \( s = 0.2 \) μm
- \( s = 0.5 \) μm
- \( s = 1.0 \) μm
- \( s = 2.0 \) μm
Expected backgrounds (Patch potentials)

• Deposited metal films typically have potential variations ~10–100 mV over 10 nm–1 μm surface regions due to crystalline grains or impurities
• Such “patch potentials” have been studied extensively since they provide a significant background in Casimir force experiments
• Estimated background using recent patch measurements of Au films (only small component will be at same spatial frequency as attractor mass)

Topography and surface potential for sputtered Au film:

Calculation of force due to patch potentials:
Expected sensitivity

- Have calculated expected sensitivity to Yukawa strength parameter, $\alpha$, as a function of length scale, $\lambda$
- Assume face-to-face separation of $s = 0.2 \, \mu m$ (dashed) or $2 \, \mu m$ (solid)
- Plot sensitivity for demonstrated $\sigma_F = 5 \times 10^{-17} \, N \, Hz^{-1/2}$ (blue) and for pressure limited $\sigma_F$ at $10^{-9} \, mbar$ (red)
- Assume Au shielding layer of sufficient thickness to make Casimir background negligible
- Improvement in sensitivity by several orders of magnitude over existing limits at $0.5$–$10 \, \mu m$ is possible
- Hatched regions, lines show selection of theoretical models from PRD 68 124021 (2003)
Summary

• Have developed apparatus to optically levitate micron sized dielectric spheres in vacuum
• Force sensitivity $\ll 10^{-18}$ N and our ability to precisely manipulate the microspheres near the attractor surface can enable unprecedented sensitivity to non-Newtonian forces at micron distances
• Have demonstrated force sensing technique in search for millicharged particles bound in the microspheres (sensitive to $q > 5 \times 10^{-5} e$)
• Currently fabricating spatially varying attractor masses that are needed for searches for short-range forces
• Sensitivity projections indicate that several orders of magnitude improvement is possible over existing constraints at 0.5-10 $\mu$m