Testing Gravity at the Micron Scale with a Superconducting Torsion Balance

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Outline of talk

• Motivation for testing gravity at short ranges: Signals of new physics associated with Dark Energy or Dark Matter.

• Experimental techniques for measuring gravity at short ranges

• The Inverse Square Law (ISL) project
  - Aims of the experiment.
  - Test-mass design
  - Overall design of apparatus
  - The levitation system
    - Modelling dynamics; Design and construction

• Current status, and future plans
Cosmological constant problem

- Standard Model: Vacuum energy density $\sim (10^{19} \text{ GeV})^4$.
- SUSY (broken at TeV scale): Vacuum energy density $\sim (10^3 \text{ GeV})^4$.
- Observed: Vacuum energy density $\sim (10^{-3} \text{ eV})^4$.
- Unbroken SUSY: Vacuum energy density zero.

Supersymmetric Large Extra Dimensions: SUSY broken on the Standard Model brane, unbroken in the bulk. Energy density coupled to gravitational field set by size, $r$, of extra dimensions, $\sim hc/r$. For the observed cosmological constant, we expect $r \sim 14 \mu\text{m}$.

Current limits on Yukawa-like modification to gravity at short ranges. Sensitivity to $\alpha = 1$ lost below $\lambda = 56 \, \mu m$.


Cantilever experiments:
Very small effective mass for measuring gravity. Low sensitivity.

Torsion balance experiments: large mass and high sensitivity, but alignment of large areas limits minimum range to about 0.1 mm.
ISL Project

- New superconducting torsion balance design to maximise short-range gravity signal.
- Flat, gold-coated source- and test-masses to eliminate parasitic torques.
- Interferometric readout to reduce readout noise.
- Can eventually be operated continuously in low-noise, magnetically shielded cryocooler.
Test- and source-masses comprise identical radial spoke pattern, 80 mm diameter, 15 μm thick. Positioned ~10 μm apart.

Gravitational torque from density difference of Au and Cu stripes. Gold shield layer should eliminate electrostatic forces.

Actual pattern has 2048 pairs of spokes, average pitch 92 μm.
Overall Experiment Design

Cryocooled chamber, \(~4.2\) K

6 DOF Micro-positioning system for source mass

Angle interferometer (ILIAD) to measure rotation of levitated test-mass.

Source- and test-masses comprising radial stripes of density-modulated material. Separation 10 \(\mu\)m, controlled by 5 DOF capacitance measurement

Equilateral triangular prism, levitated by superconducting magnetic bearing, supports test-mass
Mass foils produced by EuminaFAB European collaboration, involving Philips in Eindhoven and Karlsruhe Institute of Technology.

Gold spoke pattern produced lithographically on silicon substrate. In-filled with copper and cut to size.

Silicon removed with hot KOH to leave free foil.
One foil mounted on float..

..and one on micropositioner system.
Superconducting bearing

- Produced by CNC machining aluminium substrate, which is anodised, then coated with ~ 100 nm gold.
- 0.25 mm Pb wire wound into groove.
- Levitates 40 g copper float with 9 A current.
- Each of 12 coils can be independently addressed by electronics. A different persistent current can be stored in each.
- Each coil faces the lead-lined inner surface of the float, and acts as a tunable spring.
Rotation about z-axis with electronically tunable stiffness; can move oscillation period to minimum of seismic noise. 10 second period requires current tuning to \(~1\%\) (1mA) accuracy.
Centre Of Mass (COM) tuning

Currents can mimic the effect of a centre of mass offset.

1 μA current precision gives ~ 1 μm tuning. Used to cancel the mechanical COM offset.
‘ILIAD’ Homodyne angular interferometer reduces readout noise

Common-mode rejection of tilt and displacement of float. Low frequency electronic stability through chopper-stabilised amplifiers. Noise level $< 10^{-9}$ Rad Hz$^{-1/2}$ at 0.05 Hz.
What it actually looks like.
Expected sensitivity to Yukawa force

However, due to small spacing between source- and test-mass, signal enhanced to give SNR of 1 in 1 day for \( r = 14 \) m LEDs.
Our experiment would be in near field of $r = 14$ micron extra dimensions. Yukawa approximation no longer valid.
Current and future work

• Transfer of mass foils for science run onto source mass and test mass support structures.
• Measurement of flatness of masses using capacitance measurements. Also using white light interferometry, and scanning with EUCLID linear homodyne interferometer.
• Commissioning and calibrating refurbished levitation system.
• Measurement of other short-range forces: Casimir Force, forces between metamaterials, superconductors. Possible search for chameleons, symmetrons, Axion-like-particles (ALPs).
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