Perspectives to measure forces between macroscopic flat parallel plates

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Proposal

We propose to measure the forces between two massive bodies in the 1-10 μm range

Why? Fundamental physics implications
1. Thermal Casimir corrections (Geyer et al 2010)
2. Many specific theoretical predictions of modifications to gravity (Lamoreaux review 2010)
3. Yukawa-like interactions (Kapner et al 2007)
4. Rule out chameleon field theories (Upadhye et al 2012)

How?
1. Using a torsion pendulum
2. Using two “macroscopic” flat parallel plates
3. Via a dynamic measurement
The Casimir effect is the attraction between a pair of neutral, parallel conducting plates, resulting from the modification of the electromagnetic vacuum by the boundaries. It is a purely quantum effect.

Between two perfectly conductive plates of area $A$ at a distance $d$ at temperature $T=0$ the attractive force is

$$F_{C \parallel}^{(T=0)}(d) = \frac{\pi^2 \hbar c}{240} \frac{A}{d^4}$$
Surface reflection properties depend on frequency-dependent dielectric permittivity $\varepsilon(\omega)$

- *Have the zero frequency transverse electrical mode to be included in the finite temperature force calculation?*
- *Drude model or plasma model for $\varepsilon(\omega)$?*

Force with dissipative Drude model of $\varepsilon$ is $\sim \frac{1}{2}$ force with non dissipative Plasma model of $\varepsilon$ (at large distances)
Gravitational and Yukawa forces

\[ V(d) = -G \frac{m_t m_a}{d} \left( 1 + \alpha e^{-d/\lambda} \right) \]

where \( \alpha \) is the strength of a possible new interaction relative to standard gravity and \( \lambda \) is the range.

In the simplest case of semispace (attractor) and plate (test) case

\[ F_N = 2\pi G \sigma_a m_t \]

\( \sigma_a \) attractor surface density and \( m_t \) the test mass

\[ F_Y(d) = 2\pi \alpha G \rho_t \rho_a \lambda^2 A_t \left( 1 - e^{-t_a/\lambda} \right) \left( 1 - e^{-t/\lambda} \right) e^{-d/\lambda} \]

\( t \) is the thickness and \( \rho \) the density
Patch potential effects

The surface of a conductor is not equipotential
Work functions differences due to:
  polycrystalline structure, stress, chemical contamination

\[ F_{\text{elect}} = \frac{1}{2} \frac{\partial C(d)}{\partial d} V^2 = \frac{1}{2} \varepsilon_0 \frac{S}{d^2} \left[ V_{\text{rms}}^2 + (V - V_m)^2 \right] \]

C(d) is the capacitance
\( V_m \) is the contact potential and \( V \) a potential applied to null \( V_m \)
\( V_{\text{rms}} \) is the patch potential
Gold-niobium on alumina (p-to-p 10 mV)

DLC on beryllia (p-to-p 22 mV)

Indium tin oxide on titanium (p-to-p 6 mV)

Gold-niobium on alumina (p-to-p 13 mV)

Titanium carbide on titanium (p-to-p 6 mV)

Titanium carbide on alumina (p-to-p 6 mV)

Contact potential difference in volts over 10 mm by 10 mm area (400 data points) with offset removed (from N. Robertson)
Why plate-plate

“The original Casimir configuration of two parallel plates is the only one where the comparison of experiment with theory does not require either the Proximity Force Approximation or more sophisticated exact computational methods which can be effectively used so far solely in some restricted ranges of parameters.” (Geyer et al 2010)

“Flat-flat is the best geometry to put constraints on long range forces” (Mostepanenko et al 1993)

Flat-flat allows to increase S/N giving better chance to measure Casimir thermal corrections

Compared to sphere-plate, in the flat-flat geometry the patch effect dominates at larger distances
Comparison p-p vs p-s

\[ F_{Cps}^{(T=0)} = \frac{2\pi^3 \hbar c}{720} \frac{R}{d^3} \]

Plate-Plate

- Sparnaay 1958
- Bressi et al. 2002
- Antonini 2008 (attempt)

@ 1 \( \mu \) m the ratio is \( \sim 5 \times 10^3 \); @ 10 \( \mu \) m is \( 5 \times 10^2 \)
Patch voltage 3mV rms compared with Casimir force

With P-P patch force dominates at larger (2x) distances
Plate-Plate configuration issues

• Absolute distance

requirements

\[
\frac{\left| \delta F \right|}{F} = n \frac{\left| \delta d \right|}{d}
\]

Where n is the index in distance power dependency (for Casimir n=4).

A 1% accuracy force measurement requires a 0.25% accuracy in minimum distance i.e. 25 nm for \(d_{\text{min}} = 10 \ \mu \text{m}\)

• Parallelism

For a 5 cm diameter plate, control on tilt angle better than

\[ \theta < 5 \times 10^{-7} \text{ rad (over measurement time)} \]
Apparatus cartoon parallelism control

- Tungsten wire
- Torsion pendulum
- Shadow sensor blades
- Test mass
- Attractor
- Optical lever

Shadow sensor sensitivity $\sim 10^{-8}$ m $\rightarrow 10^{-7}$ rad
Apparatus cartoon
absolute distance calibration

Measure independently three capacitances (~ 1 pF at 0.1%)
Semispace-plate (gold)

For Yukawa: $\lambda=1\times10^{-5}$ and $\alpha$ such that $F_N = F_Y$ at $10^{-5}$ m
For Yukawa: $\lambda=1e^{-5}$ and $\alpha$ such that $F_N = F_Y$ at $10^{-5}$ m
Performance of the double torsion pendulum (see talk L. Di Fiore) in the gravitational Napoli’s lab: $3 \times 10^{-14}$ Nm/$\sqrt{\text{Hz}}$ @ 4 mHz
Dynamical measurement

A dynamic measurement allows to reach high S/N by choosing a proper modulation frequency and integrating for enough time. The force at the first harmonic is given by

\[ F = \beta \times \frac{d_0 \sqrt{d_{\text{min}} (d_{\text{min}} + 2d_0)(4d_{\text{min}}^2 + 8d_{\text{min}}d_0 + 5d_0^2)}}{[d_{\text{min}} (d_{\text{min}} + 2d_0)]^4} \]

For a given \( d_{\text{min}} \) there is an amplitude that maximize the force:

\[ d_0 \sim 0.445d_{\text{min}} \]
(Grado et al PRD 1998)
Distance modulation

Given $d_{\text{min}}$ there is an amplitude that maximize the signal

Example for $d_{\text{min}} = 8 \ \mu\text{m}$
Using info from harmonics we can disentangle patch from Casimir force.
Constraints on Yukawa forces

Measuring the Casimir force at 10 μm (10% accuracy)
Conclusion

- We want to measure forces in the 10 μm range between massive flat bodies
- Using a torsion pendulum
- Using optical and electrostatic systems to control parallelism and determine the absolute distance
- Using a synchronous detection we plan to disentangle the various forces contributions
- We can measure the Casimir force at large distances where thermal and real metal corrections are important
- We can put constraints on Yukawa forces on scales 1 – 10 μm
- Others physics ........
THANKS