Gravitation at small distances

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Introduction and motivations
Issues for measuring forces in the micrometer range
Update on cylinder-plane configuration
Conclusions

Moriond Workshop, La Thuile, 17/3/2007
Modifications to the Newton’s gravitational law

They seem required by any reasonable unification of gravity to the other forces

\[ V = V_N + V_Y \]

\[ \frac{V_Y}{V_N} = \alpha e^{\frac{r}{\lambda}} \]

\[ \lambda < 10^{-3} m \] ...short distances

\[ \lambda > 10^{16} m \] ...long distances
\[ P_c = \frac{K_c}{d^4} \]

\[ K_c = \frac{\pi \hbar c}{240} = 1.3 \times 10^{-27} \text{Nm}^2 \]

(130nN/cm\(^2\) @ d = 1\(\mu\)m \(\rightarrow\) 10\(\mu\)Torr)
## Experimental configurations

<table>
<thead>
<tr>
<th>Parallel plates</th>
<th>Sphere-plane</th>
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</thead>
<tbody>
<tr>
<td><strong>Original configuration</strong></td>
<td><strong>No sum of modes approach, theoretical interpretation relies on the proximity force approximation, under control at the &lt;1 % level</strong></td>
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<tr>
<td>proposed by Casimir, “textbook” geometry, clean theoretical predictions based on sum of modes</td>
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<tr>
<td><strong>Parallelism is difficult to achieve, dust is a problem</strong></td>
<td><strong>No parallelism issues, dust is not an issue</strong></td>
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<tr>
<td><strong>Large signal (nN)</strong></td>
<td><strong>Smaller signal (pN)</strong></td>
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Status: a second generation of Casimir force experiments
(after the pioneers: Sparnaay, van Blokland, Overbeek, et al.)

Now a third generation of experiments is ongoing
- Casimir effects are macroscopic manifestations of quantum vacuum
  - Many macroscopic manifestations of quantum mechanics (black-body, specific heats, superfluidity and superconductivity), very few of quantum vacuum
  - Open window on renormalization issues in QED

- Casimir forces are a background to other (hypothetical) forces in the micrometer range

- We need to understand the role of quantum fluctuations in the acceleration of the universe

- Interplay between quantum fluctuations and relativity of motion (“dynamical” Casimir effect)
Non-relativistic deviations from Newton’s law

Casimir forces are the dominant background for neutral and nonmagnetic objects in a distance range between nanometers and micrometers

At larger distances experiments with modulated torsional balances

Apart from ultracold neutrons, no alternative experiment seems competitive in the nanometer to micrometer range


Control of the Casimir force at the highest accuracy level is crucial

The current bottleneck is the understanding of thermal/conductivity corrections
Cylinder-plane configuration

In between a plane-plane and a sphere-plane: cylinder-plane geometry

The cylinder-plane case has intermediate advantages and drawbacks

• With respect to the parallel plane configuration, it has less parallelism and dust issues, but less signal

• With respect to the sphere-plane configuration, it has an 1D issue of parallelism, but more signal, and it shares the proximity force approximation

[D. A. R. Dalvit et al., Europhys. Lett. 67, 517 (2004)]
Combined conductivity and thermal corrections
The combined conductivity-temperature corrections are larger than in the parallel-plane situation for at least two different models, the plasma model (a) and a model without the TE0 mode (b). The predictions of the two models differ by almost a factor 2 around 3-4 micrometers for all geometries.

Cylinder-plane is in between the two other configurations
Slightly eccentric cylinders has the softest dependence
The expression for the Casimir force in a cylinder-plane configuration is

\[ F_{cp} \approx \frac{\pi^3 \hbar c}{384\sqrt{2}} \frac{La^{1/2}}{d^{7/2}} \]

Signal linear in the cylinder length (if \( L \gg d, L \gg a \))

Compare to the forces in sphere-plane and parallel plane

\[ F_{sp} \approx \frac{\pi^3 \hbar c}{360} \frac{R}{d^3} \]

\[ F_{pp} = \frac{\pi^2 \hbar c}{240} \frac{A}{d^4} \]
Top micrometer (coarse) and PZT (fine) for optical fiber-resonator distance

Bottom 2-PZT actuators for distance control (common mode) and for 1D parallelization (differential mode)

20 mm diameter cylindrical lens (220 nm gold coating)

Rectangular-shaped silicon resonator (around 870 Hz)

Optical microscope for assessment of cylinder-plane distance
Parallelism procedure

Deviations from parallelism can be detected by studying the dependence of the forces upon the “degree of parallelism” 

\[ \alpha = \frac{L \sin \theta}{2d} \]

\[ F_{np} \approx F_p \left[ 1 + \frac{5}{8} \alpha^2 + O(\alpha^4) \right] \]

Coulomb

\[ F_{np} \approx F_p \left[ 1 + \frac{21}{8} \alpha^2 + O(\alpha^4) \right] \]

Casimir

Minimization of the force for a constant distance allows to find the parallel configuration.
We now use a capacitance meter, getting a faster and more accurate procedure.

Before

Parallelization in the $10^{-5}$ range is feasible

After
**Electrostatic calibrations**

**Frequency shift technique**

\[ \Delta \nu^2 = \nu_{res}^2 - \nu^2 = - \frac{1}{4\pi^2} \frac{\partial F(d)}{\partial d} \]

The curvature of the frequency-shift directly depend on distance

\[ \Delta \nu^2 = - \frac{3\varepsilon_0}{16\sqrt{2\pi}} \frac{\sqrt{aL}}{md^{5/2}} V^2 = k_c V^2 \]
Locking the laser to Lithium line

- Buffer gas (Ar) for mitigating diffusion on the end windows
- Pump and probe beams scanned around the D2 line of the transition
- Lithium vapor cells require temperatures of the vapor of order 400°C
- Lockable signal for stabilizing diode lasers
Recent results (November ‘06-March ’07)

Cylinder-plane: new lens with 20.07 cm radius x 20 mm length
250 nm Au coating

Electrostatic calibration

Capacitance measurement

\[ a = -1.3344 \pm 0.22 \]
\[ b = -58571 \pm 4.2e+03 \]
\[ d0 = 97.541 \pm 0.507 \]

\[ a = 53.366 \pm 0.0899 \]
\[ b = 30.365 \pm 1.25 \]
\[ d0 = 126.17 \pm 1.78 \]
Examples of runs with no bias voltage: evidence for an attractive force at small distances

As usual, it is crucial to determine precisely the absolute gap
In order to better understand the apparatus and to freeze the parameters of the resonator/detection system we also *calibrate* the system with the sphere-plane Casimir force.

Gold-plated sphere of 30.9 cm radius of curvature, 250 nm Au coating. Also, very satisfactory electrostatic calibrations (0.05 % error on $d_0$ from fit).

![Graph 1](image1.png)

- $a = 5.9928 \pm 3.49$
- $b = -13770 \pm 366$
- $d_0 = 87.755 \pm 0.0398$
- $e = 2 \pm 0$

![Graph 2](image2.png)

- $a = 21.983 \pm 3.02$
- $b = -190.15 \pm 11.8$
- $d_0 = 87.76 \pm 0$
Force about a factor 2 smaller than the one expected w/o temperature/conductivity corrections

More data with spheres and cylinders of different radius of curvature

It is still not clear so far if the sensitivity will be enough to chase successfully the thermal corrections at larger (order of 1 micrometer) range

They should be definitely detectable with the Grenoble project using torsional balance (and similar, like the one under development by Steve Lamoreaux at Yale)
The collaboration

• Fernando Lombardo, Francisco Mazzitelli (Buenos Aires)
• Woo-Joong Kim, Michael Brown-Hayes, R. O. (Dartmouth)
• Valery Nesvizshevsky (ILL, Grenoble)
• Diego Dalvit (Los Alamos)
• Astrid Lambrecht, Serge Reynaud (LKB @ UPMC, Paris)
For an updated review: Special Issue on Casimir Forces,
New J. Phys. (October 2006)  www.njp.org  (free access)