Precise Measurements of the Casimir Force: Experimental Details

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Motivation

- Precise measurements of the Casimir force
  - Background for hypothetical forces
  - Allows for comparison with theory
  - Temperature dependence and effects on nanosystems
Outline

• Experimental setup, sample preparation, and characterization

• Measurement of the interaction

• Measurement of the separation dependence

• Comparison with theory

• Proposed measurements to see the effects of geometry

• Summary
Experimental setup

\[ z_{metal} = z_i - z_o - z_g - b \theta \]

In our last measurements we have changed the setup, the sphere is on the oscillator, the plate is on top.

- Larger sample, requires different deposition.
- Measurements done in vacuum at room temperature, in an oil-free chamber.

MEMS plate: 500 µm x 500 µm
Plate thickness: 3.5 µm
Spring lengths: 500 µm
Sphere radii: 10 µm – 150 µm
Resonance frequency ~ 1000 Hz
Quality factor ~ 10000 (@ 10^{-6} Torr)
Sample preparation and characterization

-Au on the sapphire sphere is deposited by thermal evaporation.

-Au on the oscillator is also deposited by thermal evaporation

-In new, larger samples it is deposited by electroplating (on Si[111])

-Samples are characterized by measuring resistance as a function of temperature, AFM measurements and also ellipsometry in the electrodeposited sample.

-The sample is mounted into the system, baked to ~ 60 °C for ½ hour.

\[
(10 \times 10 \, \mu m^2) \\
\sim 20 \, nm_{pp}
\]
AFM measurements
Resistivity and spectroscopic ellipsometry

- R vs T and spectroscopic ellipsometry (190 nm to 830 nm) used to determine $\omega_p$.

Both methods indicate a rather good Au sample

$$\rho(T) = \frac{4\pi}{\omega_p^2 \cdot \tau(T)} \propto \frac{T}{\omega_p^{3/2}}$$

$$\omega_p = (8.9 \pm 0.1)\text{eV}$$
Resistivity and spectroscopic ellipsometry

- Measured real and imaginary parts of the dielectric functions (red circles) are similar to published values (Palik, black squares)

- It was checked that either can be used, giving similar results. Palik values are used on the rest of this presentation.
Pressure measurements

\[ \omega_r^2 = \omega_o^2 \left( 1 - \frac{b^2}{I \omega_o^2} \frac{\partial F_C}{\partial z} \right) \]

\[ F_C = 2\pi R \times E_C \Rightarrow \frac{\partial F_C}{\partial z} = 2\pi R \times P_C \]
Pressure determination

\[ \omega_r^2 = \omega_0^2 \left( 1 - \frac{b^2}{I \omega_0^2} \frac{\partial F_C}{\partial z} \right) \]

\[ F_C = 2\pi R \times E_C \Rightarrow \frac{\partial F_C}{\partial z} = 2\pi R \times P_C \]

Determined by:
- Looking into the response of the oscillator in the thermal bath
- Inducing a time dependent separation between the plate and the sphere

z = 550 nm
f₀ = 713.250 Hz

New Frontiers in Casimir Force Control
Santa Fe, New Mexico, September 28, 2009
Pressure measurements

\[
\omega_r^2 = \omega_o^2 \left( 1 - \frac{b^2}{I \omega_o^2} \frac{\partial F_C}{\partial z} \right)
\]

\[
F_C = 2\pi R \times E_C \Rightarrow \frac{\partial F_C}{\partial z} = 2\pi R \times P_C
\]

<table>
<thead>
<tr>
<th>Errors</th>
<th>Minimum values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency:</td>
<td>6 mHz</td>
</tr>
<tr>
<td>R:</td>
<td>0.2 (\mu)m</td>
</tr>
<tr>
<td>b(^2)/I:</td>
<td>0.0005 (\mu g^{-1})</td>
</tr>
</tbody>
</table>

Errors:

- Random: 0.46 mPa (162 nm)
- 0.11 mPa (300 nm)

Systematic: 2.12 mPa (162 nm)

0.44 mPa (300 nm)
Separation measurement

\[ z_o \text{ is determined using a known interaction} \]

\[ z_i, \Theta \text{ are measured for each position} \]

\[ z_g = (2172.8 \pm 0.1) \text{ nm, interferometer} \]

\[ z_i = ~(12000.0 \pm 0.2) \text{ absolute interferometer} \]

\[ z_o = (8162.3 \pm 0.5) \text{ nm, electrostatic calibration} \]

\[ b = (207 \pm 2) \mu\text{m, optical microscope} \]

\[ \Theta = ~(1.000 \pm 0.001) \mu\text{rad} \]
Separation measurement

Electrostatic force calibration

\[ F_e = -2\pi\varepsilon_0 (V - V_{Au})^2 \sum_{n} \frac{\coth u - n\coth nu}{\sinh nu} \sim \]

\[ -2\pi\varepsilon_0 (V - V_{Au})^2 \sum_{n} \frac{R}{(z_{metal} + z)}^{1+i} \]

\[ u = 1 + \frac{(z_{metal} + z)}{R} \]

\[
\begin{align*}
\Delta V &= 0.35 \text{ V} \\
\Delta V &= 0.27 \text{ V}
\end{align*}
\]

\[
\begin{align*}
F_e (\text{pN}) &\quad z = 3 \text{ } \mu \text{m} \\
F_e (\text{pN}) &\quad z = 5 \text{ } \mu \text{m}
\end{align*}
\]
Separation measurement

Electrostatic force calibration

![Graph showing separation measurement and electrostatic force calibration](image)

- Graph (a): Shows the relationship between $|dF_z/dV|$ (a.u.) and $V_{DC}$ (mV) for $z = 3.5$ μm.
- Graph (b): Shows the distribution of $V_o$ (mV) and $z$ (nm) with distinct markers for different values of $z$.
Separation measurement

Electrostatic force calibration

\[ V_0 \text{ must be constant as a function of separation...} \]

Otherwise, \( V_0 \) needs to be determined at each point

\[ 10 \times 10 \text{ grid, } 5 \, \mu\text{m pitch} \]
Separation measurement

Electrostatic force calibration

\[ F_e = -2\pi \varepsilon_0 (V - V_{Au})^2 \sum_n \frac{\coth u - n \coth nu}{\sinh nu} \]

\[ \approx -2\pi \varepsilon_0 (V - V_{Au})^2 \sum_0^7 A_i \left( \frac{R}{(z_{metal} + z)} \right)^{1-i} \]

\[ u = 1 + \frac{(z_{metal} + z)}{R} \]

- After measuring the deflection (expressed as force here), we adjust for the unknown separation.
- The figure shows the \( \Delta F_e \) for the optimal and one off by 1.5 nm.
- The error in the force associated with the error in \( V_o \) is < 1 fN.
Equivalent $P_C$ measurement

New sample (September 2009)  Old data (2005)
Comparison with theory

Roughness corrections

\[ F_C = \sum_i \nu_i F_{CS}(z) \]

\( \nu_i \): Fraction of the sample at separation \( z_i \)

Roughness corrections are \( \sim 0.5\% \) to the Casimir force at 160 nm
Comparison with theory

Finite conductivity and finite temperature

\[ P(z) = -\frac{k_B T}{\pi} \sum_{l=0}^{\infty} \int_0^\infty k_\perp \, dk_\parallel \, q_l \]

\[ \times \left\{ r_{||}^{-2}(\zeta_l, k_\perp) e^{2q_l z} - 1 \right\}^{-1} + \left\{ r_{\perp}^{-2}(\zeta_l, k_\perp) e^{2q_l z} - 1 \right\}^{-1} \]

\[ r_{||,L}^{-2}(\zeta_l, k_\perp) = \frac{[k_l + \varepsilon(i\zeta_l)q_l]}{[k_l - \varepsilon(i\zeta_l)q_l]} \]

\[ r_{\perp,L}^{-2}(\zeta_l, k_\perp) = \left[ \frac{k_l + q_l}{k_l - q_l} \right]^2 \]

\[ q_l^2 = k_\perp^2 + \left( \frac{4\pi^2 k_B T l}{\hbar c} \right)^2 \]

\[ \varepsilon(i\zeta) = 1 + \frac{2}{\pi} \int_0^\infty \frac{\omega \text{Im}\varepsilon(\omega)}{\omega^2 + \zeta^2} \, d\omega \]

\[ k_l^2 = k_\perp^2 + \varepsilon(i\zeta_l) \zeta_l^2 / c^2 \]
Comparison with theory

\[ \varepsilon(i\xi) = 1 + \frac{2}{\pi} \int_{0}^{\infty} \frac{\omega \text{Im} \varepsilon(\omega)}{\omega^2 + \xi^2} \, d\omega \]

\[ \varepsilon(\omega) = 1 - \frac{\omega_p}{\omega(\omega + i\gamma)} \]

\[ \varepsilon(\omega) = 1 - \frac{\omega_p}{\omega^2} \]

There is a significant issue: Drude does not agree with the data
-Experimental problem?
-Theoretical problem?
-Theory not applied to the right experiment?

Theoretical errors:
-Sample dependence: 0.5%
-Separation dependence: 1.5% (162 nm)
  0.32% (750 nm)

~19 mPa @162 nm (Exp: ~2.5 mPa @162 nm)
Geometrical effects

“Role of surface plasmons in the Casimir effect”, F. Intravaia et al., PRA 76 (2007)

Real-time manipulation

Dynamically deformable nanostructure
- Integration of nanostructure with MEMS
- Displacement ~ 500nm
- Precise control of motion (± 1nm)
- Shielded surfaces (fringe fields)
Geometrical effects

Metallic nanostructures

• Electroplating process
• HSQ molds (highest resolution resist)
• 100keV electron beam lithography tool
  • pattern thick resist (1 µm)
  • large depth of focus
  • small electron scattering
Geometrical effects

• “Role of surface plasmons in the Casimir effect”, F. Intravaia et al., PRA 76 (2007)
• Metallic nanowire (w < λ_p) close to a flat metallic surface

Net contribution from the first 5 plasmonic modes is repulsive for d ≥ 200nm

Dimension < 100nm
Aspect ratio > 5:1
Summary

• Precise experiments of the Casimir force between Au-Au surfaces

• Good agreement with plasma model
  Differences with Drude model cannot be explained as a problem in the separation measurement, or the Au layer properties. It appears that any model with a finite relaxation time will give discrepancies when comparing with the Casimir force. Why do Casimir modes decouple from the dissipative part?

• Geometrical effects
  An innovative MEMS that allows to modify the geometry in situ is being designed and tested. This system will be used to investigate the plasmonic contributions to the Casimir effect.