Measuring the Casimir Force with Atomic Force Microscope

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Topics

Lecture 1: Precision Normal Casimir force Experiments with Deflection Mode AFM

Lecture 2: Experiments Measuring the Lateral Casimir force with corrugated surfaces

Lecture 3: Normal Casimir force measurements using the Amplitude Shift & Frequency Shift techniques.
Normal Casimir Force Measurements
(Metallic Surfaces)


Many more investigations with AFM: Iannuzzi et al 2009; Capasso et al 2008,
Proximity force approximation (PFA)

If $R \gg z$ or $\beta < 0.5$

$$E_{pp}^C(z) = -\frac{\pi^3 \hbar c}{720} \frac{1}{z^3}$$

$$F_{sp}^C(z) = \left( -\frac{\pi^2 \hbar c R}{360} \right) \frac{1}{z^3}$$

Problems with Parallelization
Use Sphere-Plate Instead
200 micron Polystyrene Sphere on AFM Cantilever

Sphere Diameter ~ 200 μm
Larger spheres rougher
Diameter measured with SEM
Gold coating ~ 100 nm

Cantilever and Sphere uniformly coated with Au 10 nm Cr and 10-20 nm Al for adhesion and stress relief.
Allows electrical contact, uniform potential precise electrostatic calibration,

Rugar ca 1995’s – Magnetic Particles on cantilever
Using AFM for van der Waals force → Atmospheric pressure, dielectric samples, capillary forces
Force Measurements Using Atomic Force Microscope

1. Static Cantilever Deflection

\[ F = -k\Delta x \]

2. Change in Cantilever Oscillation (Amplitude, Phase, Frequency)
Improvements in Precision

Harris, Chen, U.M, PRA, 2000; Chen, U.M et al. PRA 2004

Random error = 5.8 pN @ 95% Confidence
Systematic error = 2.7 pN
Separation distance error = ± 1 nm
Total Error = 8.5 pN @ 95% confidence

Chang, et al PRL 2011

Random error = 0.55 pN @ 95% Confidence
Systematic error = 2.1-1.1 pN
Separation distance = ± 0.4 nm
Total Error = 2.5-1.5 pN @ 95% Confidence

How to achieve x3-4 reduction in error in 10 yrs?
How to get $x^{3-4}$ improvement in precision in 10 years?

C.C. Chang, Banishev, Klimchitskaya, Mostepanenko, UM, PRL, 090403 (2011)
Motivation to measure Casimir force with Indium Tin Oxide (ITO)

- Use Transparent Electrodes to Reduce the Casimir Force
- Manipulation of the Casimir Force using UV Light
- Explore same puzzles in the Lifshitz Theory with dielectrics

C.C.Chang et. al PRL, 090403 (2011)
De Mann et al, PRL, 103,040402 (2009)
**Transparent Electrodes to Reduce Casimir Force**

**Rationale:**
Reduce Casimir Force by Reducing Boundary Reflectivity at characteristic frequency (~c/2z)

In devices z~ 1μm
Gold Electrodes have ~100% Reflectivity

Use electrodes which are transparent around 1μm to reduce reflectivity and reduce Casimir force

De Mann et al, PRL, 103,040402 (2009)
UV treatment to Reduce Casimir Force

**Rationale:**
UV treatment known to change mobility of Charge Carriers in ITO

C.N. Li et al, Appl Phys. , 80,301 (2005)
EXPERIMENT

Compare the Casimir force using Au & ITO Plates (with and without UV Treatment)

Experiment:
i. Measure Casimir force between Au Sphere and Au plate
ii. Replace Au plate with ITO plate \(\rightarrow\) Compare
iii. UV Treat ITO plate and Measure Casimir Force \(\rightarrow\) Compare

Results:
1. Casimir force reduces by \(x\ 2\) with ITO
2. Casimir Force reduces additional \(~35\%)\ with UV treatment
Force Measurements Using Cantilever Deflection

Plate : Au or ITO

Radius of Au coated Sphere = 101.23±0.25 µm

Smooth Au coating of 105±1 nm
10 nm Cr followed by 20 nm of Al then Au coating
Au Coating done at 3.75 Å/min
Experimental set-up scheme for contact mode

Oil Free vacuum at $10^{-7}$ Torr
Temperature 2 °C
Vibration Isolation
\[ F = 2\pi \varepsilon_0 \left( V - V_0 \right)^2 \sum_{n=1}^{\infty} \text{csch} n \alpha \left( \coth \alpha - n \coth n \alpha \right) \]

Where \( \alpha = \cosh^{-1}(1+z/R) \)

\( V \) = voltage on plate
\( V_0 \) = Residual sphere-plate voltage difference
Experimental Procedure

Cantilever deflection signal:

$$S_{def} = \frac{F_{Cas}}{k'} + \frac{F_e}{k'} = \frac{F_{Cas}}{k'} + \frac{X(z)}{k'} \cdot (V - V_0)^2$$

Sphere Plate Distance:

$$z = z_0 + z_{piezo} - S_{def} \cdot m$$

- $z_0 = \text{Surface separation on contact}$
- $Z_{piezo} = \text{piezo movement interferometrically calibrated}$
- $m = \text{cantilever deflection per signal unit}$

Precise determination of $m$ needs interpolation of contact

Parameters defined from parabolas:

- Use sphere-plate electrostatic formula

$$V_0 - \text{residual potential difference between the sphere and the plate}$$

$$\frac{X(z)}{k'} = \beta - \text{Curvature}$$

$m$ from

![Graph showing cantilever deflection (V) against Au sphere-ITO plate relative separations (nm) for different applied voltages (mV)]
Raw data from one force scan

![Graph showing photodiode difference signal vs distance moved by the plate.](image)

- Photodiode difference signal (signal units) vs Distance moved by the plate (nm)
- Region 1 and Region 2
- Plate and piezo components in the diagram
Raw data from one force scan

Region 1

Region 2

Photodiode difference signal (signal units)

Distance moved by the plate (nm)
**Raw data from one force scan**

**Apply to horizontal axis:**

\[ z = z_0 + z_{\text{piezo}} - S_{\text{def}} \times m \]

1. \( z_0 \) = Surface separation on contact
2. \( m \) = rate of change in distance due to cantilever tilt

**Apply to vertical axis**

\[ F_{\text{casimir}} = F_{\text{measured}} - F_{\text{electrostatic}} \]
Method: Measured Total Force (Electrostatic+Casimir) between Au Sphere and ITO Plate

Cantilever deflection signal:

\[ S_{def} = \frac{F_{Cas}}{k'} + \frac{F_{electric}}{k'} = \frac{F_{Cas}}{k'} + \frac{X(z)}{k'} \cdot (V - V_0)^2 \]

10 Different Voltages V
\( V_o \) = Residual Potential
\( X(z) \sim \) Capacitance
\( k' = \) cantilever spring constant

Parabolas Drawn at each Separation
Residual Electrostatic Potential between Au Sphere and ITO Plate

\[ \langle V_0 \rangle = -196.8 \pm 1.5 \text{ mV} \]

Residual Voltage independent of Au Sphere-ITO plate separation
This allows easy subtraction of the electrostatic force
Experimental Procedure

**Cantilever deflection signal:**

\[
S_{def} = \frac{F_{Cas}}{k'} + \frac{F}{k'} = \frac{F_{Cas}}{k'} + \frac{X(z)}{k'} \cdot (V - V_0)^2
\]

\[z = z_0 + z_{\text{piezo}} - S_{\text{photodiode signal}} \cdot m\]

**Parameters defined from parabolas:**

Use sphere-plate electrostatic formula

\[
V_0 \quad - \text{residual potential difference between the sphere and the plate}
\]

\[
\frac{X(z)}{k'} = \beta \quad - \text{Curvature}
\]

\[
z_0 \quad \Rightarrow k'
\]

**z_0 = Surface separation on contact**

**m = cantilever deflection per signal unit**

**Precise determination of m needs interpolation of contact**
Determination of contact separation $z_o$ & cantilever spring constant $k$

Both $z_o$ & $k$ independent of separation
Critical for precision measurement

$<z_o> = 29.5 \pm 0.4 \text{ nm}$

$<k> = 0.0139 \pm 0.0001 \text{ N/m}$
Correction for Sphere or Plate Movement during Measurement

Will lead to Dependence of $V_0$ on Separation Distance (Anamalous Behaviour Due to Skewed Parabola)

Force vs. Separation Curves for Same Applied Voltage Shifted due to Sphere/Plate Movement

Precise Correction for drift is easier with Deflection mode due to contact
1. Find Precise Sphere Plate Contact Point- Extrapolate

2. Repeat Electrostatic Force Measurement for same applied V and look at change in contact point.
Errors due to Sphere-Plate Separation Drift

Corrected

Uncorrected

\[ \langle V_0 \rangle = -196.8 \pm 1.5 \text{ mV} \]

\[ \langle z_0 \rangle = 29.5 \pm 0.4 \text{ nm} \]
Measured Casimir Force from Au Sphere-ITO Plate

Subtract Electric Force from Total Force

\[ F_{Casimir} = F_{Total} - F_{Electric} = F_{Total} - X(z) \cdot (V - V_0)^2 \]

100 Voltages Applied to Plate

\[ \text{Casimir Force (pN)} \]
\[ \text{Au sphere-ITO plate separations (nm)} \]

Random Error Reduced with Number of Repetitions
Measured Casimir Force

Comparison of Au plate to ITO plate

Number of voltages $V = 10$
Number of repetitions = 10

<table>
<thead>
<tr>
<th>$z$ (nm)</th>
<th>$F_{Cas}$ (pN)</th>
<th>ITO/Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>-123.42</td>
<td>0.57</td>
</tr>
<tr>
<td>100</td>
<td>-81.62</td>
<td>0.61</td>
</tr>
<tr>
<td>120</td>
<td>-50.1</td>
<td>0.59</td>
</tr>
</tbody>
</table>

40% Reduction in Casimir Force with ITO
UV Treatment of ITO Plate

• Penray Hg Lamp 9.0 inch long and 0.375 inch diameter
• $\lambda=254$ nm $\rightarrow$ 5.4 mWatt/cm$^2$ at 1.9 cm
• $\lambda=365$ nm $\rightarrow$ 0.2 mWatt/cm$^2$ at 1.9 cm
• 12 hr
• Cleaned as before (Acetone, Methanol, Ethanol, water rinse and Nitrogen dry)
Insert UV Treated ITO Plate & Repeat Measurement
Measured Total Force (Electrostatic + Casimir) between Au Sphere and ITO Plate

Cantilever deflection signal:

\[ S_{def} = \frac{F_{Cas}}{k'} + \frac{F_{electric}}{k'} = \frac{F_{Cas}}{k'} + \frac{X(z)}{k'} \cdot (V - V_0)^2 \]

Electric Force

10 Different Voltages V on plate
\( V_0 = \) Residual Potential
\( X(z) = \) Capacitance
\( k' = \) cantilever spring constant

Use sphere-plate electrostatic formula

\[ V_0 \quad \text{- residual potential difference between the sphere and the plate} \]

\[ \frac{X(z)}{k'} = \beta \quad \text{Parabola Curvature} \]
Check Stability of Measurements of Au Sphere and ITO Plate (after UV treatment)

**Fit Electrostatic Force Curve**

1. Distance independence of residual potential $V_o$
2. Distance independence of contact separation $z_o$
3. Distance independence of Spring constant

$\langle V_o \rangle = 65 \pm 2 \text{ mV}$

$\langle z_o \rangle = 29 \pm 0.6 \text{ nm}$

$\langle k \rangle = 0.0138 \pm 0.0001 \text{ N/m}$
Repeat Casimir Force between Au Sphere and ITO Plate (after UV treatment)

Subtract Electric Force from Total Force

\[ F_{\text{Casimir}} = F_{\text{Total}} - F_{\text{Electric}} = F_{\text{Total}} - X(z) \cdot (V - V_0)^2 \]

100 Voltages Applied to Plate

Grey Bars represent the complete range of data every 5 nm
Casimir Force between Au Sphere and ITO Plate
(Before and After UV comparison)

21-35% Reduction with UV treatment
21% at 60 nm and 35% at 130 nm

<table>
<thead>
<tr>
<th>z (nm)</th>
<th>After UV/Before UV</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>0.72</td>
</tr>
<tr>
<td>100</td>
<td>0.68</td>
</tr>
<tr>
<td>120</td>
<td>0.66</td>
</tr>
</tbody>
</table>
Histograms of the Experimental Data- Check for Gaussian Distribution

- No Overlap

<table>
<thead>
<tr>
<th>Layer</th>
<th>Histograms</th>
<th>Casimir Force (pN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITO Before UV</td>
<td><img src="image1.png" alt="Histogram 60 nm" /></td>
<td>60 nm</td>
</tr>
<tr>
<td>ITO After UV</td>
<td><img src="image2.png" alt="Histogram 60 nm" /></td>
<td>80 nm</td>
</tr>
<tr>
<td>ITO Before UV</td>
<td><img src="image3.png" alt="Histogram 60 nm" /></td>
<td>100 nm</td>
</tr>
<tr>
<td>ITO After UV</td>
<td><img src="image4.png" alt="Histogram 60 nm" /></td>
<td>100 nm</td>
</tr>
</tbody>
</table>
Experimental Errors at 95% Confidence Level

Error due to use of Proximity Force Approx <0.3%
Radius of Sphere = 101.2±0.5 μm
Comparison with Lifshitz Theory
Lifshitz Formula

\[ F_c(z) = K_B TR \sum_{l=0}^{\infty} (1 - \frac{1}{2} \delta_{l0}) \int_{0}^{\infty} K_{\perp} dK_{\perp} \left\{ \ln[1 - r_{\parallel}^{(1)}(\xi_i, K_{\perp})] r_{\parallel}^{(2)}(\xi_i, K_{\perp}) e^{-2q_i z}] + \ln[1 - r_{\perp}^{(1)}(\xi_i, K_{\perp})] r_{\perp}^{(2)}(\xi_i, K_{\perp}) e^{-2q_i z}] \right\} \]

Reflection Coeffs:

\[ r_{\parallel}^{(k)}(\xi_i, K_{\perp}) = \frac{\varepsilon_{l}^{(k)} q_{l} - K_l^{(k)}}{\varepsilon_{l}^{(k)} q_{l} + K_l^{(k)}}, \quad r_{\perp}^{(k)}(\xi_i, K_{\perp}) = \frac{K_l^{(k)} - q_{l}}{K_l^{(k)} + q_{l}} \]

Matsubara Freqs.

\[ \xi_l = \frac{2\pi k_B T_l}{\hbar} \quad \text{At } l=0, \xi=0 \]

\[ q_l = \left( \frac{\xi_l^2}{c^2} + K_{\perp}^2 \right)^{1/2}, \quad K_{l}^{(k)} = [\varepsilon^{(k)}(i \xi_l) \frac{\xi_l^2}{c^2} + K_{\perp}^2]^{1/2} \]
Measure Permittivity
Ellipsometry Measurements

VUV-VASE

Spectral range 0.14 – 1.7 μm;
Angle of incidence is computer controlled from 10° to 90°;

IR-VASE

Spectral range 1.7–33 μm;
Angle of incidence is computer controlled from 30° to 90°.

J.A. Woollam Co., Inc.
Comparison with Theory:
Casimir Force between Au Sphere and ITO Plate

Dielectric Permittivity Measured by Ellipsometry from 0.04 eV to 8.47 eV. Fit to Lorentz oscillators and Drude type free electron behavior

\[
\varepsilon_{\text{Osc}} = \frac{a_A \cdot g_0 \cdot x_W}{(x_W^2 - w_0^2)^2 + g_0^2 \cdot x_W^2}
\]

\[a_A = 111.52; w_0 = 8.0 \text{ eV}, g_0 = 4.0 \text{ eV}\]

Extrapolated to lower Frequency with Drude Model \([\omega_p = 1.5 \text{ eV}, \gamma = 0.128 \text{ eV}]\)
Dielectric Permittivity in Imaginary Frequency

No UV

After UV

Drude Model Parameters

\[ \omega_p = 1.5 \text{ eV}, \gamma = 0.128 \text{ eV (No UV)}, \gamma = 0.132 \text{ eV (UV)} \]

\[ \varepsilon_{osc} = \frac{a_A \cdot g_0 \cdot x_W}{(x_W^2 - w_0^2)^2 + g_0^2 \cdot x_W^2} \]

\[ a_A = 111.52; w_0 = 8.0 \text{ eV}, g_0 = 4.0 \text{ eV}; \]

\[ a_A = 240.54, w_0 = 9.0 \text{ eV}, g_0 = 8.5 \text{ eV}. \]

Very Little Difference between Before and After UV in imaginary frequency
Fractions $v_i$ of the surface area covered by roughness with heights $h_i$

<table>
<thead>
<tr>
<th>$h_i$, nm</th>
<th>$v_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.097</td>
<td>4.40E-04</td>
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<tr>
<td>0.483</td>
<td>1.50E-04</td>
</tr>
<tr>
<td>0.87</td>
<td>0.00102</td>
</tr>
<tr>
<td>1.257</td>
<td>0.0016</td>
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<tr>
<td>1.644</td>
<td>8.70E-04</td>
</tr>
<tr>
<td>2.03</td>
<td>0.00262</td>
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<tr>
<td>2.417</td>
<td>0.00189</td>
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<td>2.804</td>
<td>0.00277</td>
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<td>3.191</td>
<td>0.00408</td>
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<td>3.577</td>
<td>0.00452</td>
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<tr>
<td>3.964</td>
<td>0.00335</td>
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<td>4.351</td>
<td>0.0051</td>
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<td>4.738</td>
<td>0.00641</td>
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<tr>
<td>5.124</td>
<td>0.0083</td>
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<tr>
<td>5.898</td>
<td>0.01049</td>
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<td>6.355</td>
<td>0.01321</td>
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<td>6.671</td>
<td>0.01734</td>
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<td>7.058</td>
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<td>7.445</td>
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<td>7.832</td>
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<td>0.05041</td>
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<td>9.379</td>
<td>0.05522</td>
</tr>
<tr>
<td>9.765</td>
<td>0.06148</td>
</tr>
</tbody>
</table>

**Roughness effect**

- <0.5 % for >116 nm
- <1% for > 90 nm
- <2.2% at 60 nm

**RMS Roughness=2.04 nm**
Carrier Density Measurement

\[ V_H = \frac{-IB}{dne} \]

Slope = \( \frac{B}{dne} \) is same

Same Carrier Density = \( 7 \times 10^{20} \) /cc
Comparison with Theory: Casimir Force between Au Sphere and ITO Plate Before UV

ITO Before UV  DC Conductivity Included – Good Agreement
Comparison with Theory:
Casimir Force between Au Sphere and ITO Plate After UV

Effect of inclusion of DC Conductivity
ITO After UV   No Agreement if we include Free Carriers
Comparison with Theory: Casimir Force between Au Sphere and ITO Plate After UV

DC Conductivity Not Included

Good Agreement only if we drop the DC conductivity of ITO After UV
Assume it to be a perfect dielectric

C.C. Chang et al, PRL, 090403 (2011)
Conclusions

1. Advantages of Static Deflection Mode AFM: Ease of use, Ease in measuring and confirming separation distance due to contact


3. Necessary consistency checks for Precision Measurements:
   (a) No Anomalous distance dependence of the Compensating Voltage.
   (a) No Anomalous distance dependences of calibration constants.

4. Sample Experiment using UV treated ITO was discussed.
   (i) 21-35% reduction of Casimir force by UV treatment even though there is not much change in \( \varepsilon(i\xi) \)
   (ii) Inclusion of DC conductivity in the Lifshitz formula for the ITO after UV leads to disagreement with the experimental results.
   (iii) A Study of the Temperature Dependence of the Carrier Mobility might shed light on the discrepancy.
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G.L. Klimchitskaya

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