

Observation of the skin-depth effect on the Casimir force between metallic surfaces

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We have performed measurements of the Casimir force between a metallic plate and a transparent sphere coated with metallic films of different thicknesses. We have observed that, if the thickness of the coating is less than the skin-depth of the electromagnetic modes that mostly contribute to the interaction, the force is significantly smaller than that measured with a thick bulk-like film. Our results provide direct evidence of the skin-depth effect on the Casimir force between metallic surfaces.

Casimir effect | microelectromechanical systems | vacuum fluctuations | zero point energy

In 1948, H. B. G. Casimir showed that two electrically neutral, ideally metallic plates kept parallel in vacuum should mutually attract under the influence of a purely quantum force (1, 2). The plates define a cavity that supports only electromagnetic modes with nodes on the boundaries. The electromagnetic energy associated with each of these modes is given by $E_i = \hbar\omega_i(n_i + \frac{1}{2})$, where \hbar is the reduced Planck constant, ω_i is the angular frequency, and n_i is the number of real photons at that frequency. Because the plates are in vacuum, where there are no real sources, n_i is equal to zero at all frequencies. However, the energy associated with each mode does not vanish: quantum fluctuations of the electromagnetic field give rise to a non-null contribution even in vacuum. The electromagnetic energy is thus given by $E = \frac{1}{2}\sum_i \hbar\omega_i$, where the sum runs over the modes allowed between the plates. The Casimir force arises from the fact that the set of frequencies that the cavity supports, and, thus, the electromagnetic energy associated with the fluctuations of the electromagnetic field, depend on the distance between the plates d . The derivative of E with respect to d is always negative: the force is thus attractive.

A few years after Casimir's paper, E. M. Lifshitz generalized Casimir's theory to dielectrics (3). At very short distances, Lifshitz's theory provides a complete description of the nonretarded van der Waals force. At larger separations, retardation effects give rise to a long-range interaction that in the case of two ideal metals in vacuum reduces to Casimir's result.

The Casimir effect has witnessed renewed experimental interest since the precision measurements by S. K. Lamoreaux (4). All recent Casimir force experiments have been performed by using surfaces covered with a thick metallic layer (4–11). In this case, the dielectric function of the film can be considered equal to the tabulated value for the corresponding bulk metal, and the expected force can be calculated with high accuracy. The comparison of the theoretical predictions with experimental results has allowed new limits to be set on the existence of extragravitational forces at short distances and has contributed to discussions concerning temperature corrections to the Casimir effect (see, for example, refs. 12–14).

On the other hand, the use of much thinner metallic coatings over transparent dielectrics should reveal an interesting phenomenon. At sub- μm distances, the Casimir force critically depends on the reflectivity of the interacting surfaces for wavelengths in the UV to far-infrared (3, 15). The attraction between transparent materials is expected to be smaller than that between highly reflective mirrors as a result of a less effective confinement of electromagnetic modes inside the optical cavity

defined by the surfaces. A thin metallic film can be transparent to electromagnetic waves that would otherwise be reflected by bulk metal. In fact, when its thickness is much less than the skin-depth, most of the light passes through the film. Consequently, the Casimir force between metallic films should be significantly reduced when its thickness is less than the skin-depth at UV to infrared wavelengths. For most common metals, this condition is reached when the thickness of the layer is $\approx 100 \text{ \AA}$.

In this article, we present direct evidence of the skin-depth effect on the Casimir force between two dielectrics coated with metallic thin films. We have measured the Casimir force between a thick metal and a polystyrene sphere covered with a $\approx 100\text{-\AA}$ metallic film. The results are compared with those obtained after evaporating a thicker layer of metal ($\approx 2,000 \text{ \AA}$) onto the same sphere. Our experiment shows that the Casimir attraction is significantly smaller when the sphere is coated with the thin film. This finding is confirmed by calculations.

Our experimental apparatus (see Fig. 1), which resembles the one described in ref. 9, is designed to measure the force between a sphere and a plate at sub- μm distances with a force sensitivity on the order of 10 pN. The measurement is carried out by positioning the sphere on top of a micromachined torsional balance (MTB), and measuring the rotation angle of the balance induced by the Casimir attraction with the sphere as a function of the separation of the surfaces.

The MTB is similar to a microscopic seesaw. Two thin torsional rods keep a gold-coated polysilicon plate ($500 \mu\text{m} \times 500 \mu\text{m}$) suspended over two polysilicon electrodes symmetrically located on each side of the pivot axis. The capacitance between the top plate and each bottom electrode depends on the tilting angle θ . When an external force F induces a rotation of the top plate, one of the two capacitances increases by $\delta C \propto \theta \propto F$, while the other decreases by the same amount. An electronic circuit allows measurements of δC with a sensitivity on the order of 10^{-6} pF, corresponding to $\theta \approx 10^{-7}$ rad. Because the spring constant of the seesaw k_s is $\approx 10^{-8}$ Nm/rad, the sensitivity in the torque measurement is approximately equal to $k_s\theta \approx 10^{-15}$ Nm, which corresponds to a force of 10 pN in our experiment (15).

The MTB is glued to a chip package and mounted inside a chamber that can be pumped down to $\approx 10^{-3}$ mTorr. A 100- μm radius polystyrene sphere, mounted on the end of a rigid support and coated with a metallic layer, is clamped to a manipulator that can bring the sphere close to the top plate of the MTB and controls the distance between the two surfaces. The manipulator consists of a triaxial stage for rough positioning and a piezoelectric translator (calibrated with an optical profiler) for fine tuning of the distance (see Fig. 1).

To measure the Casimir force as a function of distance, we have followed the method described in ref. 15. After the chamber

Abbreviation: MTB, micromachined torsional balance.

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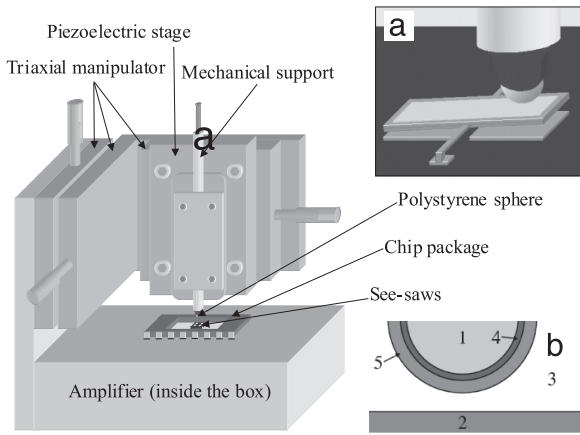


Fig. 1. Sketch of the experimental set-up (not to scale). (Inset a) Sketch of the working principle of the micromachined torsional device. (Inset b) Layout of our experimental configuration. 1, the polystyrene sphere; 2, the gold-coated top plate of the micromachined torsional device; 3, vacuum; 4, the titanium adhesion layer; 5, the palladium film.

is evacuated, the piezoelectric stage is extended toward the MTB to reduce the separation between the sphere and the plate until the distance is only a few nanometers larger than the jump-to-contact point (i.e., the distance at which the restoring torque of the seesaw is not sufficient to overcome the external torque induced by the Casimir force, causing the plate to come into contact with the sphere). The output of the capacitance bridge A is then recorded as a function of the voltage applied to the sphere V_{bias} , which is scanned a few hundred millivolts around the so-called residual voltage V_0 (≈ 200 mV), i.e., the electrostatic potential drop arising from the difference of the work functions of the two films (16) plus the potential difference generated by the metallic contacts of the electronics (4). The read-out system is designed so that A is proportional to δC and, therefore, to F :

$$A = c_1 F = c_1 \epsilon_0 \pi R \left(\frac{V_{\text{bias}} + V_0}{d_0 - d_{\text{pz}}} \right)^2 + c_1 |F_C|, \quad [1]$$

where ϵ_0 is the permittivity of vacuum, R is the radius of the sphere, d_{pz} is the extension of the piezoelectric stage, d_0 is the distance between the sphere and the plate when the piezoelectric stage is not extended, and F_C is the Casimir force. The distance d between the sphere and the plate is given by $d_0 - d_{\text{pz}}$; although the calibration of the piezoelectric stage provides d_{pz} with a precision of < 1 nm, d_0 is *a priori* unknown and must be determined independently for an accurate comparison of experiment with theory (17). In addition, it is worth stressing that c_1 is also unknown at this point, because the MTB has not yet been calibrated.

The measurement of A as a function of V_{bias} is then repeated for different values of d , which is changed by sequentially retracting the piezoelectric stage by a few nanometers.

For each value of d , data are interpolated with a generic quadratic equation $y = \alpha(x + x_0)^2 + \beta$, where α , β , and x_0 are free parameters. Note that

$$\alpha = c_1 \frac{\epsilon_0 \pi R}{(d_0 - d_{\text{pz}})}. \quad [2]$$

By fitting α as a function of d_{pz} , it is thus possible to determine d_0 and c_1 . Once c_1 is known, F_C can be calculated by means of

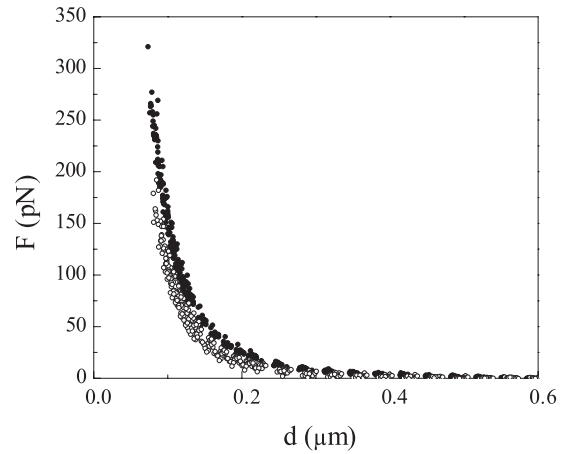


Fig. 2. Experimental results of the measurement of the force as a function of the separation between the interacting surfaces. Filled circles indicate data obtained with a metallic thick film; open circles indicate those obtained with a thin film on the same sphere.

$$|F_C| = \frac{\beta}{c_1}. \quad [3]$$

Because d_0 has also been determined, one can finally plot F_C as a function of the distance between the sphere and the plate, $d = d_0 - d_{\text{pz}}$.

Demonstrating the skin-depth effect requires careful control of the thickness and surface roughness of the films. The sphere was glued to its support and subsequently coated with a 29 ± 2 Å titanium adhesion layer and a 92 ± 3 Å film of palladium. The thickness of the titanium layer and of the palladium film was measured by Rutherford back scattering on a silicon slice that was evaporated in close proximity to the sphere. After evaporation, the sphere was imaged with an optical profiler to determine its roughness, and mounted inside our experimental apparatus. After completion of the Casimir force measurements, the sphere was removed from the experimental apparatus, coated with an additional 2,000 Å of palladium, analyzed with the optical profiler, and mounted back inside the vacuum chamber for another set of measurements. It is important to stress that the surface roughness measured before and after the deposition of the thicker palladium layer was the same within a few percent.

In Fig. 2, we compare the results of the thin film measurements with those obtained after the evaporation of the thick layer of palladium. We repeated the measurement 20 times for both the thin and thick films.

Our results clearly demonstrate the skin-depth effect on the Casimir force. The force measured with the thin film of palladium is in fact smaller than that observed after the evaporation of the thicker film. Measurements were repeated with a similar sphere: the results confirmed the skin-depth effect. To rule out possible spurious effects, we have compared our data with a theoretical calculation.

The Casimir force between a sphere and a plate can be calculated according to the well known Lifshitz equation (3):

$$F_C^{(L)}(d) = \frac{\hbar}{2\pi c^2} R \int_0^\infty d\xi \int_1^\infty dp \epsilon_3 p \xi^2 \left\{ \log \left[1 - \Delta_{31}^{(1)} \Delta_{32}^{(1)} e^{-x} \right] + \log \left[1 - \Delta_{31}^{(2)} \Delta_{32}^{(2)} e^{-x} \right] \right\} \quad [4]$$

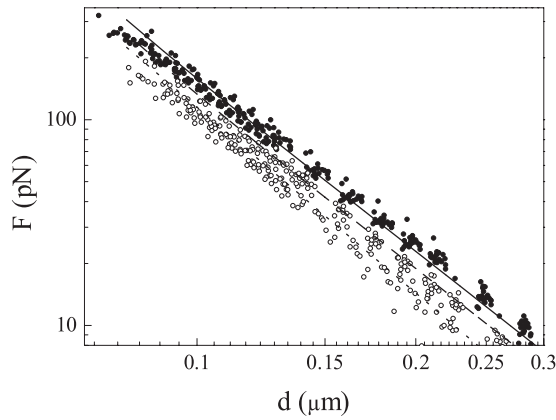


Fig. 3. Comparison between experimental data and theory. Filled circles indicate data obtained with a thick film; open circles indicate those obtained with a thin film. Continuous and dashed lines represent theoretical predictions for thick and thin films, respectively. The dotted line corresponds to the best fit of thin film data obtained by using equation $y = C/d^3$, where C is an adjustable parameter.

$$\Delta_{jk}^{(1)} = \frac{s_k \varepsilon_j - s_j \varepsilon_k}{s_k \varepsilon_j + s_j \varepsilon_k} \quad \Delta_{jk}^{(2)} = \frac{s_k - s_j}{s_k + s_j} \quad [5]$$

$$x = \frac{2d \sqrt{\varepsilon_3 \xi p}}{c} \quad s_k = \sqrt{p^2 - 1 + \frac{\varepsilon_k}{\varepsilon_3}} \quad [6]$$

where \hbar and c are the usual fundamental constants, and ε_1 , ε_2 , ε_3 are the dielectric functions of the sphere, the plate, and the intervening medium, respectively, evaluated at imaginary frequencies $i\xi$

$$\varepsilon_k(i\xi) = 1 + \frac{2}{\pi} \int_0^\infty \frac{x \operatorname{Im} \varepsilon_k(x)}{x^2 + \xi^2} dx. \quad [7]$$

If the sphere is covered with an adhesion layer of thickness t_4 plus a coating film of thickness t_5 , the force is still given by Eq. 4, with $\Delta_{31}^{(1,2)}$ replaced with (18):

$$\Delta_{31}^{(1,2)} \rightarrow \frac{\Delta_{35}^{(1,2)} + \Delta_{51}^{(1,2)} e^{-\frac{xt_{55}}{pd}}}{1 + \Delta_{35}^{(1,2)} \Delta_{51}^{(1,2)} e^{-\frac{xt_{55}}{pd}}} \quad [8]$$

$$\Delta_{51}^{(1,2)} = \frac{\Delta_{54}^{(1,2)} + \Delta_{41}^{(1,2)} e^{-\frac{xt_{45}}{pd}}}{1 + \Delta_{54}^{(1,2)} \Delta_{41}^{(1,2)} e^{-\frac{xt_{45}}{pd}}} \quad [9]$$

where the subscripts 4 and 5 refer to the adhesion layer and to the coating film, respectively, as shown in Fig. 1. Surface roughness further modifies the Casimir force. This correction can be calculated according to (19):

$$F_C^{(L,\rho)}(d) = \sum_{i,j} v_i^{(sp)} v_j^{(pl)} F_C^{(L)}(d - (\delta_i^{(sp)} + \delta_j^{(pl)})), \quad [10]$$

where v_i is the probability that the surface of the sphere (superscript sp) or of the plate (superscript pl) is displaced by an amount δ_i with respect to the ideally smooth surface.

In Fig. 3, we compare our data with the theoretical result. The dielectric function used in the calculation was obtained from refs.

20–23. The values of ν as a function of δ were extracted from $10 \mu\text{m} \times 10 \mu\text{m}$ images obtained with an optical profiler. At close distance (≤ 100 nm), our data are smaller than the prediction, both for the thin and for the thick film. This disagreement most likely lies in the fact that, in the analysis of the data, we have neglected the decrease of surface separation induced by the rotation of the top plate of the MTB (9): this rotation modifies Eq. 1, and, thus, Eq. 2. Furthermore, in equation Eq. 1, we have neglected the effect of surface roughness on the electrostatic force, which might induce errors in the determination of d_0 and c_1 . Finally, it is worth noting that the calculated force at short distances strongly depends on the roughness of the two surfaces (Eq. 10), with corrective factors that, in our case, are as large as $\approx 25\%$. These corrections might give rise to relevant errors in the calculations.[¶]

The experimental results obtained with the thin metallic film are systematically smaller than those expected by the theoretical calculation also at larger separations. To emphasize this behavior, we have fitted thin film experimental and theoretical data in the separation range from 100 nm to 300 nm, using equation $y = C/d^3$, where C is a fitting parameter. For the experimental data, the best unweighted fitting curve corresponds to $C_{\text{exp}}^{(\text{thin})} = 1.15 \times 10^{-31} \text{ Nm}^3$ (see Fig. 3). For the theoretical curve, the best unweighted fit is achieved for $C_{\text{th}}^{(\text{thin})} = 1.38 \times 10^{-31} \text{ Nm}^3$, corresponding to a discrepancy between theory and experiment of $\approx 17\%$. It is worth stressing that, for the case of the thick metallic film, theory and data are in better agreement in this separation range. With a similar analysis, in fact, one obtains $C_{\text{exp}}^{(\text{thick})} = 1.61 \times 10^{-31} \text{ Nm}^3$ and $C_{\text{th}}^{(\text{thick})} = 1.66 \times 10^{-31} \text{ Nm}^3$.

The discrepancy observed in the case of the thin metallic film is not surprising. The calculation of the force is based on two approximations: (i) the dielectric function for the metallic layers (both titanium and palladium) is assumed to be equal to the one tabulated for bulk-materials and is considered independent of the wave vector \mathbf{k} , and (ii) the model used to describe the dielectric function of polystyrene is limited to a simplified two-oscillator approximation (20). These assumptions might lead to significant errors in the estimated force (25).

It is clear, however, that our data represent a direct evidence of the skin-depth effect on the Casimir force. We have demonstrated that the Casimir attraction between a metallic plate and a metallized dielectric sphere depends on the thickness of the metal layer deposited on the sphere. In particular, if the coating is thinner than the skin-depth relative to the modes that mostly contribute to the interaction, the force is significantly smaller than what is expected for a thick, bulk-like film. This result might suggest interesting solutions for micro- and nanomachinery applications because it provides a technique to decrease the Casimir attraction between two DC-conductive surfaces kept at sub- μm distances.

[¶]It is important to stress that more accurate models to calculate surface roughness corrections to the Casimir force have been recently developed (see, for example, ref. 24).

^{||}Optical measurements do not allow us to distinguish topological details whose typical dimensions are smaller than ≈ 500 nm. We have thus imaged the surface of one of the spheres used for thick film measurement using an atomic force microscopy (AFM). The rms value obtained over a $1 \times 1 \mu\text{m}^2$ (≈ 12 nm) is slightly smaller than what was obtained with the optical profiler (≈ 15 nm) over a larger area. Therefore, ignoring topological details not accessible to optical profiler measurements does not affect the calculation of surface roughness corrections.

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