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Quantum fluctuations in the presence of thin metallic films and anisotropic materials

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Abstract

We present our most recent results seeking to understand the dependence of quantum fluctuations of the electromagnetic field on the dielectric properties of two boundary surfaces. In the first section, we provide a detailed description of our measurement of the skin-depth effect of the Casimir–Lifshitz force. The second section is devoted to the torque induced by quantum fluctuations on two birefringent plates.

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1. Introduction

Casimir–Lifshitz (CL) force experiments give scientists the opportunity to investigate the behaviour of electromagnetic quantum fluctuations in the presence of external conditions. It is thus worth asking whether suitably designed experimental configurations could provide new insights on the way in which boundaries affect the quantum vacuum and whether these experiments might have any impact on the development of future technologies. The most direct way to access this information is to exploit the dependence of the CL interaction between two juxtaposed objects on the dielectric functions of their surfaces. A few years ago, for example, we reported a measurement of the CL force between hydrogen switchable mirrors, metallic layers that become transparent when exposed to a hydrogen-rich atmosphere [1, 2]. Our experiment sheds light on a counterintuitive aspect of the Lifshitz theory.

In this paper, we present an updated description of our most recent efforts along the research line described above. First, we will discuss the role of the skin-depth effect on the

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CL force between metallized dielectric surfaces. Performing comparative measurements of the CL 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 modes that mostly contribute to the interaction, the force is significantly smaller than that measured with a thick bulk-like film. In the second part of this paper, we will present a discussion of the torque induced by quantum fluctuations on two parallel birefringent plates. After reviewing the theory, we will describe an experimental technique that should allow us to observe the phenomenon.

2. *Skin-depth* effect on the Casimir–Lifshitz force

The reflectivity of a metallic film strongly depends on its thickness. Thick metallic films behave like bulk metal, with a reflection coefficient close to 1 over a wide range of frequencies. Thin metallic films, in contrast, can be remarkably transparent: if the layer is much thinner than the skin-depth, most of the light passes through the film without interacting with the electrons of the metal. The use of thin metallic films in CL force experiments should thus reveal an interesting phenomenon [3]. At sub-micron distances, the CL attraction critically depends on the reflectivity of the interacting surfaces for wavelengths in the ultraviolet to far-infrared [1, 4]. 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. Therefore, the CL force between metallic films should be significantly reduced when their thickness is less than the skin-depth at ultraviolet to infrared wavelengths. For most common metals, this condition is reached when the thickness of the layer is $\simeq$100 Å.

Motivated by these considerations, we have measured the CL force between a thick metal and a dielectric sphere covered with a $\simeq$100 Å metallic film. The results were then compared to those obtained after evaporating a thicker layer of metal ($\simeq$2000 Å) onto the same sphere. Our experiment shows that the CL attraction is significantly smaller when the sphere is coated with the thin film. The experimental result is confirmed by calculations [3].

Our experimental set-up [1–3] resembles the one originally developed by one of us (FC), Chan and his collaborators [5]. The measurement is carried out by positioning a sphere on top of a micro-machined torsional balance (MTB) and measuring the rotation angle of the balance induced by the CL 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 (spring constant $\simeq 10^{-8}$ N m) keep a gold-coated polysilicon plate (500 μm × 500 μm) suspended over the substrate. When an external force F is applied to the top plate, the MTB rotates by an angle θ that is proportional to F. A capacitance bridge allows measurements of θ with a sensitivity on the order of 10^{-7} rad, which corresponds to a force of $\simeq$10 pN in our experiment [1, 3].

The MTB is mounted inside a chamber that can be pumped down to $\simeq 10^{-3}$ mTorr. A 100 μm radius polystyrene sphere, mounted at 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 figure 1) [1, 3].

To measure the CL force as a function of distance, we have followed the method described in [1, 3]. We refer the reader to those articles for further details. Here we only want to stress that the technique allows us to simultaneously carry out: (i) the calibration of the instrument, (ii) the indirect measurement of the distance between the two surfaces, (iii) the measurement of the residual potential at all separations and (iv) the measurement of the CL force.

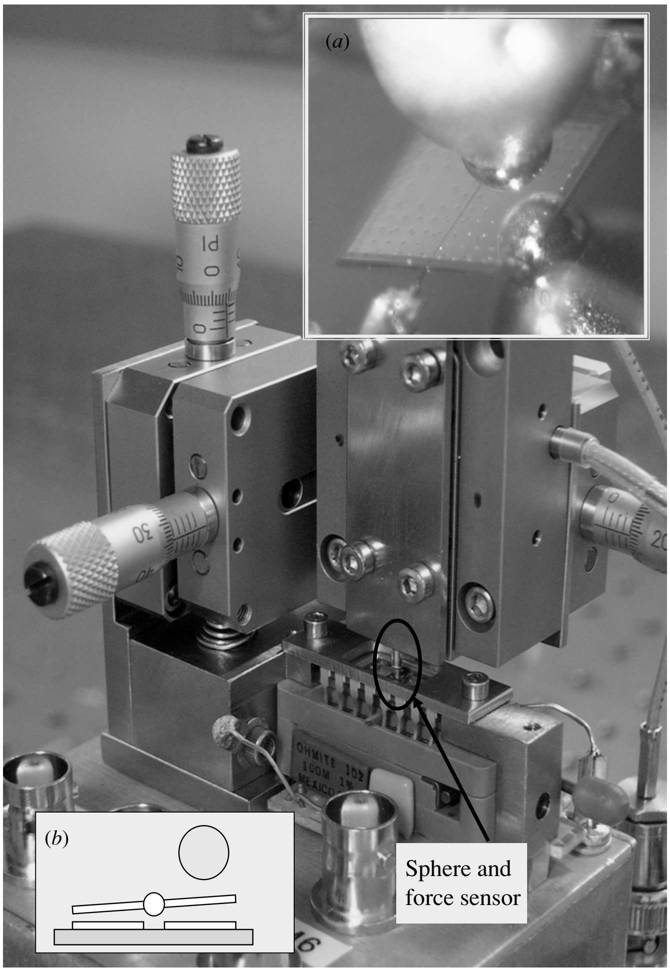

Figure 1. Experimental set-up for measurements of the Casimir–Lifshitz force between a sphere and a plate. Insets: (*a*) an image of a metallized sphere above the top plate of the microtorsional balance; (*b*) schematic view of the micro-machined torsional device (not to scale).

In order to demonstrate the effect, it is necessary to compare data obtained with spheres having identical radii and comparable surface roughness. To address this issue, a sphere was attached to its support, coated with a thin metallic film, imaged with an optical profiler and finally mounted inside our experimental apparatus. After completion of the CL force measurements, the sphere was removed from the experimental apparatus, coated with an additional thick metallic layer, analysed again with the optical profiler and mounted back inside the vacuum chamber for another set of measurements. Optical profiler images were used to establish whether surface roughnesses of the thin film and of the thick film were comparable.

The experiment was performed with a sphere coated with a 29 ± 2 Å titanium layer and a 92 ± 3 Å film of palladium. Thicknesses were measured by Rutherford back scattering on a silicon slice that was positioned in close proximity to the sphere during the deposition process. For the thick film, an additional 2000 Å of palladium was evaporated on top of the sphere. As far as surface roughness is concerned, we analysed $10 \times 10\ \mu\text{m}^2$ images of the

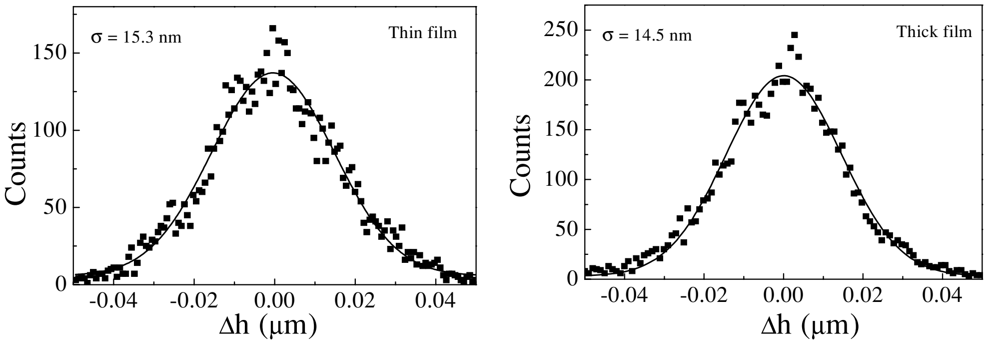

Figure 2. Measurement of the surface roughness of the metallic layers used in our experiment. Dots represent the number of pixels of an optical profiler image in which the height of the sphere was vertically displaced by an amount δh with respect to the ideally smooth surface. Continuous curves were obtained by fitting the data with a Gaussian function. σ indicates the rms surface roughness obtained from the fit.

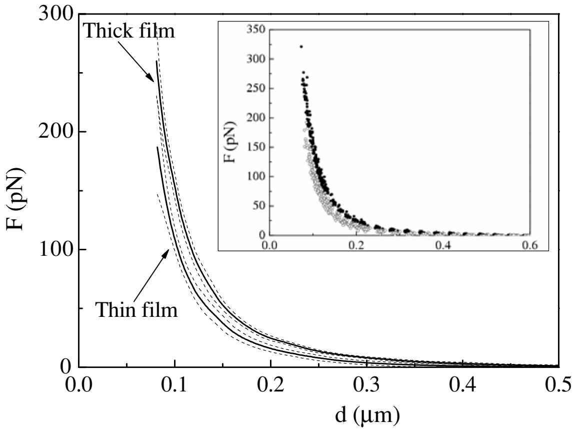

Figure 3. Experimental demonstration of the skin-depth effect on the Casimir–Lifshitz (CL) force. Each continuous line represents the average of 20 measurements of the CL force F between a metallized plate and a dielectric sphere coated with a thin or a thick metallic film as a function of separation d. Dotted lines represent the standard deviation associated with the averaging procedure (see the text for details). Inset: plot of the experimental data before averaging.

two surfaces. Graphs in figure 2 show the number of pixels in which the height of the sphere was vertically displaced by an amount δh with respect to the ideally smooth surface. Those data were interpolated with a Gaussian curve by means of an unweighted fit. The surface roughnesses rms obtained from the fit for the thin and the thick films are equal to 15.3 ± 0.2 nm and 14.5 ± 0.4 nm, respectively. CL force measurements (including calibration) were repeated 20 times for both the thin and the thick films. The results are reported in the inset of figure 3. One can immediately recognize that the force measured with the thin film is significantly smaller with respect to that of the thicker film.

We have interpolated each of the 40 data curves with cubic splines. These curves allow us to evaluate the force that we would have measured at any separation d as the average of the values of the splines at that separation. The results of this averaging procedure, both for the thin and the thick data, are reported in figure 3. Similar curves were obtained also with another sphere and another MTB.

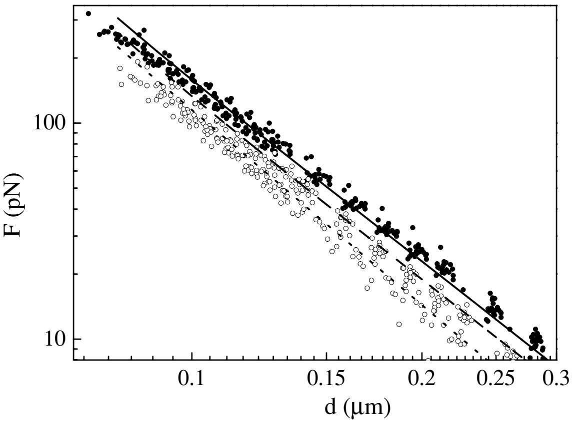

Figure 4. Comparison between experimental data and theory relative to the skin-depth experiment. Dots indicate data obtained with a thick film; open circles indicate those obtained with a thin film. Continuous and dashed lines represent theoretical predictions for thick and thin films, respectively. The dotted line corresponds to the best fit of thin film data obtained using the equation $y = \frac{C}{d^3}$, where C is an adjustable parameter.

Our experiment clearly demonstrates the skin-depth effect on the CL force. The force measured with the thin film of palladium is in fact smaller than that observed after the evaporation of the thicker film. To rule out possible spurious effects, we have compared our data with a theoretical calculation [3]. Results are reported in figure 4. Theoretical curves were obtained using the Lifshitz equation [4], implemented with the Parsegian–Ninham model for accounting for the multi-layered structure [3, 6]. Dielectric functions for gold, palladium and titanium were obtained from [7–9]. The dielectric function of polystyrene was obtained from [10]. Surface roughness corrections were calculated according to standard procedures [3, 11].

The experimental results obtained with the thin metallic film are systematically smaller than those expected from the theoretical calculation. To emphasize this behaviour, we have fitted thin film experimental and theoretical data in the separation range from 100 nm to 300 nm using the equation $y = \frac{C}{d^3}$, where C is a fitting parameter. For the experimental data, the best unweighted fitting curve corresponds to $C_{\text{exp}}^{(\text{thin})} = 1.15 \times 10^{-31}$ N m^3 (see figure 4). For the theoretical curve, the best unweighted fit is achieved for $C_{\text{th}}^{(\text{thin})} = 1.38 \times 10^{-31}$ N m^3, corresponding to a discrepancy between theory and experiment of $\simeq$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 $C_{\text{exp}}^{(\text{thick})} = 1.61 \times 10^{-31}$ N m^3 and $C_{\text{th}}^{(\text{thick})} = 1.66 \times 10^{-31}$ N m^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 (ii) the model used to describe the dielectric function of polystyrene is limited to a simplified two-oscillator approximation [10]. These assumptions might lead to significant errors in the estimated force.

It is interesting to note that we have neglected any possible dependence of the dielectric function of the interacting surfaces on the wave vector of the incident electromagnetic wave. A recent theoretical paper, however, has shown that differences between local and non-local calculations are not relevant for the configuration used in our experiment [12].

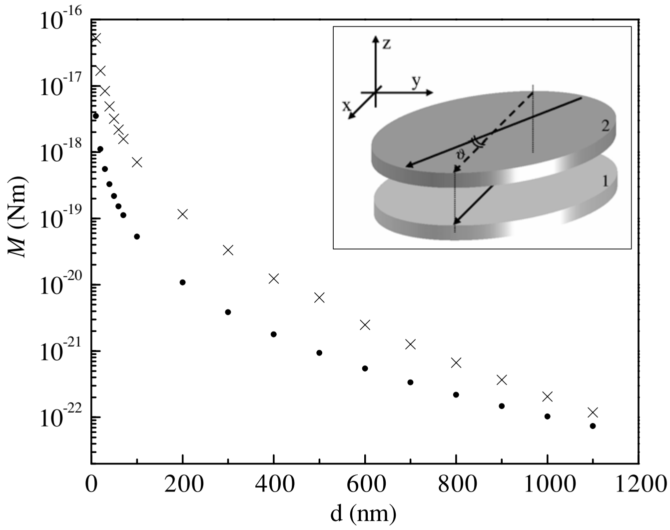

Figure 5. Maximum torque ($\theta = \frac{\pi}{4}$) that a 40 μm diameter calcite (×) or quartz (●) disc would experience when kept parallel to a barium titanate plate as a function of the distance between the disc and the plate.

In conclusion, our data represent a direct evidence of the skin-depth effect on the CL force. We have demonstrated that the CL 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.

3. Quantum-electrodynamical torque between birefringent plates

The experiment described above represents the more recent investigations of the CL force beyond the standard configuration of two bulk-like metals in vacuum or two dielectrics in a liquid[5]. Other groups are currently following a similar approach in the attempt to demonstrate new phenomena resulting from specific boundary conditions imposed on the vacuum. Mohideen and his collaborators are trying to demonstrate that the interaction between a silicon plate and a metallic sphere can be increased by shining a powerful light source on the silicon slab: incident photons should increase the number of carriers in the semiconductor, giving rise to an increase of its reflectivity and, therefore, of the force between the two surfaces [14, 15]. A new experimental approach for the investigation of the zero-point energy in a cavity containing a superconducting surface has also been recently proposed [16]. We refer the reader to the original paper for further details.

In all cases, the interacting surfaces are made out of materials with isotropic dielectric functions. Yet, during the 1970s, two papers [17, 18] pointed out that anisotropic dielectric functions should give rise to an interesting effect. Let us consider, for example, two parallel uniaxial birefringent slabs with the in-plane optical anisotropy (see the inset of figure 5),

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[5] Full lists of experimental works can be found in several review articles (see, e.g., [13]). These lists are limited to experiments performed with metallic surfaces in vacuum. A partial list of experiments with dielectrics in liquids can be found, for example, in [2].

immersed one on top of the other in an isotropic medium. Because of the optical anisotropy of the plates, the set of electromagnetic modes allowed inside the cavity depends on the angle between the two optical axes. An in-plane rotation of the top plate with respect to the bottom one will thus result in a modification of the zero-point energy. We are led to conclude that two parallel birefringent plates should experience a torque that causes them to spontaneously rotate towards configurations of smaller energy. This torque is solely generated by quantum fluctuations of the electromagnetic field.

The equations that describe the phenomenon discussed above are rather cumbersome [18] and will be omitted for the sake of brevity. Here, we will only discuss the results that we have obtained from calculations relative to a specific geometry of our interest [19].

Our calculations refer to the case of a 40 μm diameter, 20 μm thick disc, made of either calcite or quartz, kept parallel to a barium titanate plate [19]. The torque M is then given by

$$M(\theta, d) = H(d) \times A \times \sin(2\theta), \tag{1}$$

where A is the area of the disc, θ is the angle between the two optical axes, d is the distance between the disc and the plate and H is a monotonically decreasing function of d. It can be immediately recognized that, in order to measure the effect, it is necessary to keep large surfaces ($M \propto A$) at close distances ($M \propto H(d)$).

In figure 5, we plot the maximum torque (i.e. $\theta = \frac{\pi}{4}$) that the disc considered in our calculations would experience if it were kept at a distance d from the barium titanate plate. Because of the relatively small area of the disc, it is not feasible to design experiments in which the separation between the disc and the plate is larger than a few hundred nanometres. At larger distances, the torque would probably be too small to be measured.

Instead of designing complicated and maybe unfeasible torsional balances that could allow us to measure the effect, we have recently proposed a simpler approach [19]. The idea is to levitate the disc over the plate at $d \simeq 100$ nm by means of a repulsive CL force. According to the Lifshitz theory [4], two plates made out of the same material always attract, regardless of the choice of the intervening medium. However, for slabs of different materials the sign of the force depends on the dielectric properties of the medium in which they are immersed. In particular, the force between two plates with dielectric functions ϵ_1 and ϵ_2 immersed in a medium with a dielectric function ϵ_3 should be repulsive if, for imaginary frequencies, $\epsilon_1 < \epsilon_3 < \epsilon_2$ or $\epsilon_2 < \epsilon_3 < \epsilon_1$, and should be attractive in all other cases [20, 21]. It is then possible to show that the CL force between quartz or calcite and barium titanate in liquid ethanol is repulsive [19]. Therefore, if the two birefringent slabs considered above are immersed in liquid ethanol, the disc should float parallel to the plate at a distance where its weight is counterbalanced by the repulsive CL force. For the geometry that we have chosen, the equilibrium distance would be approximately equal to 100 nm [19]. The static friction between the two birefringent plates should be virtually zero, and the disc should be free to rotate suspended in bulk liquid. Further calculations of M as a function of d and θ show that the torque in liquid ethanol does not significantly change with respect to the case of vacuum. This approach should thus allow us to observe the rotation of the disc induced by the fluctuations of the electromagnetic field in a reasonably straightforward experiment.

It is interesting to stress that repulsive CL forces can be obtained with many other low-cost and easily micro-machinable materials (such as silicon or gold over Teflon or silica immersed in ethanol, bromobenzene or cyclohexane), and that this technique could be used to develop ultra-sensitive force and torque sensors (like, for example, a nano-compass sensitive to very small static magnetic fields) [22]. Because the surfaces never come into direct contact as a result of their mutual repulsion, these objects are free to rotate or translate relative to each other with virtually no static friction. Dynamical damping due to viscosity will put limits on

Table 1. Calculated value of the Hamaker constant relative to the interaction between two macroscopic objects (materials 1 and 2) immersed in a liquid (material 3). The negative sign corresponds to repulsive force.

Material combination			Hamaker constant
(1-3-2)			(10^{-20} J)
Gold	Ethanol	Silica	−2.46
Gold	Ethanol	Teflon AF	−6.23
Gold	Ethanol	Polystyrene	−1.88
Gold	Water	Teflon AF	−2.28
Aluminium	Ethanol	Silica	−1.57
Aluminium	Ethanol	Teflon AF	−7.78
Aluminium	Ethanol	Polystyrene	−1.04
Aluminium	Water	Teflon AF	−4.21

how quickly such a device can respond to changes in its surroundings; however, in principle even the smallest modifications can be detected on longer time scales. Hence, force and torque sensors could be developed that far surpass those currently used.

To give a more quantitative description of these repulsive forces, we have calculated the Hamaker constants for several material combinations. The Hamaker constant, A_{132}, can be used to describe the magnitude and sign of the van der Waals interaction between two objects (1 and 2) immersed in a third medium and depends on the dielectric functions of the materials involved [20, 23]. For instance, the non-retarded van der Waals force between a sphere and a plate immersed in a liquid is given by $F = -\frac{A_{132}R}{6d^2}$, where R is the radius of the sphere and d is the separation between the sphere and the plate. Using this convention, a negative Hamaker constant corresponds to a repulsive force. Table 1 shows the Hamaker constants for several commonly used materials configurations[6]. The dielectric functions of the interacting materials and of the intervening medium were obtained from [7, 24–27]. All the combinations listed in the table lead to a short range repulsive force. For a complete description of the force at all distances, the full Lifshitz equation must be solved; however, it suffices for our purpose to show that repulsive dispersion forces can exist for commonly used materials and suggest that this could be used to construct highly sensitive force and torque sensors or devices based on CL repulsion.

In figure 6, we show a schematic view of the experimental set-up that we are implementing in our laboratory for the demonstration of the quantum-electrodynamical torque [19]. A 40 μm diamater, 20 μm thick disc made out of either calcite or quartz is placed on top of a barium titanate plate immersed in ethanol. The optical axes of the birefringent crystals are oriented as shown in inset (*a*) of figure 6. A 100 mW polarized laser beam can be collimated onto the disc to rotate it by the transfer of angular momentum of light. A shutter can then block the beam to stop the light-induced rotation. The position of the disc can be monitored by means of a microscope objective coupled to a CCD-camera for imaging.

Using the laser, one can rotate the disc until $\theta = \frac{\pi}{4}$. Once the laser beam is shuttered, the disc is free to rotate back towards the configuration of minimum energy following the behaviour reported in the inset of figure 6 [19]. For the calcite disc, rotations should be easily measured within a few minutes after closing the laser beam shutter. The quartz disc should rotate much slower, and it is questionable whether its rotation can be detected.

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[6] It should be noted that there are small discrepancies between different references in evaluating the dielectric functions of the materials listed in table 1. This uncertainty leads to variations of the Hamaker constant that are typically smaller than 10% and are thus not significative in the context of our discussion.

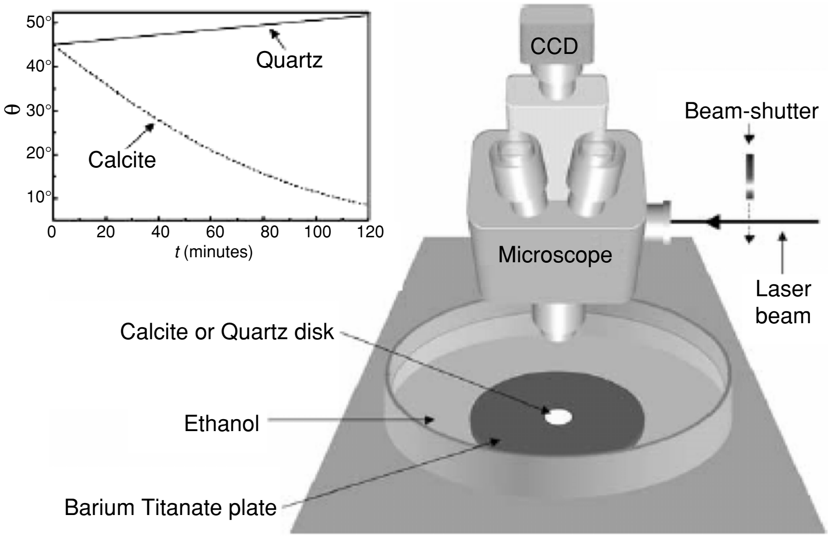

Figure 6. A sketch of the experimental set-up proposed for the observation of the torque between birefringent plates induced by zero-point fluctuations of the electromagnetic field. Inset: calculated value of the angle between the optical axes of the two birefringent crystals as a function of time.

In conclusion, our numerical calculations of the mechanical torque between a micromachined birefringent disc, made of quartz or calcite, and a barium titanate birefringent plate show that a demonstration of the effect could be readily obtained if the birefringent slabs were immersed in liquid ethanol. In this case the disc would float on top of the plate at a distance where the repulsive CL force balances gravity, giving rise to a mechanical bearing with virtually zero static friction. The disc, initially set in motion via transfer of angular momentum of light from a laser beam, would return to its equilibrium position solely driven by the torque arising from quantum fluctuations.

Acknowledgments

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