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# Non parabolic capacitive coupling in an AFM based microsystem at the picoNewton level

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Capacitive coupling is most commonly used in NEMS/MEMS or in Scanning Probe Techniques to either induce a displacement or to detect an external interaction applied to the micro/nanosystem. A parabolic elastic deformation of the sensor signs a capacitive interaction as the applied voltage is varied. In this paper, we present detailed force measurements performed in the submicron range with a picoNewton sensitivity, and using a UHV AFM and a silicon microlever equipped with a metallized microsphere,. A complete treatment of the sensor sphere/plane geometry enables one to detect quantitatively a  $V^4$  departure from the parabolic behaviour. This shows that using this setup allows to detect the increased deformation of a lever much before the mechanical instability. More importantly, this effect must be carefully taken into account if sphere/plane absolute separations are to be quantitatively measured on the basis of electrostatic calibration. To our knowledge, this behaviour in AFM is reported for the first time. We believe that it is relevant for the description of NEMS/MEMS behaviour. Moreover, it provides a method to accurately measure the lever spring constant without any direct contact.

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## 1 Introduction

During the last years, the wide development in the technology of MEMS and NEMS (Micro and Nano Electro Mechanical Systems) allowed the fabrication of miniature movable structures on-chip. The applications of this new class of devices include for example nanosensors, actuators, nano-displacement engines and capacitive tunable resonators... [1-3]

Reduction of system sizes down to the sub-micrometer scale and even to the nanometer scale one makes the system sensitive to long range attractive forces which are too much weak to be relevant for larger systems.

A simple estimate of the van der Waals-Casimir force for a micrometer object shows that this force overcomes gravity as the distance separation becomes smaller than a micrometer [4]. This simple analysis shows that a distance separation of a micrometer appears a frontier for the relevance of attractive force interaction such

as the Van der Waals interaction. This estimate has been a strong motivation to investigate quantitatively the long range interaction between surfaces. The first part of the presented study is dedicated to the electrostatic coupling between micrometer size objects with a nanometer distance separation measured by AFM techniques. We quantitatively investigated how the MEMS and NEMS's behaviours could depend upon the dominant interactions at the nanoscale. We specifically focused our studies on electrostatic, van der Waals and Casimir forces, as the importance of these interactions at the micro/nanoscale can play a major role in various configurations where NEMS/MEMS are involved.

Indeed, they can be used to:

- for actuate micro/nanodevices [5-6]
- to detect weak forces using a capacitive coupling between a mechanical oscillator and an electrical oscillator [7] at the expense of a significant back action effect.

- Besides a classical AFM cantilever, to open new opportunities to quantitatively measure non contact weak forces using NEMS and MEMS.[8-9]

Secondly, these long range and rapidly varying interactions can present strong spatial gradients. MEMS or NEMS usually present a restoring force that can be modeled by a spring constant. As the force gradient of these attractive forces exceed the MEMS/NEMS spring constant, mechanical instability occurs: the two interacting surfaces irreversibly stick together. A typical spring constant can be estimated to 1 N/m for a standard silicon cantilever. For microscale interacting surfaces ( $S=100\mu\text{m}^2$ ), the Van der Waals gradient overcome the restoring force at a distance of 10 nm. This behaviour can then be a real nuisance for real MEMS system. [10]

Then, in this paper, we focus on the importance of electrostatic forces in the non contact interaction of two surfaces. We do not address the problem of capillarity although it is well known that it introduces a very strong short scale interaction and that the water layer efficiently screens the electrostatic interaction (for water,  $\epsilon_r$  is roughly close to 80).

Therefore, a central objective of this paper is to provide quantitative measurements of the measured electrostatic force versus the distance between the two surfaces on a range as large as possible (here from 100 nm up to a micrometer) and for voltage in the commonly used range (between 0 and 1 volt).

## 2 Experiments

### 2.a Range of probed distances.

Within these AFM force measurements, we start with the identification of experimental limits and sources of errors. In particular, we identify in the case of interacting surfaces of large areas, the domain of accessible distances. That is clearly very different from AFM measurements that are based on nanotips with an area of interacting surfaces smaller by about five or six orders of magnitude. At short scale, the achievable distance range achievable is limited by the

mechanical instability and at large scale by the measuring system sensibility. These two limits are not independent. This behaviour can be rationalised and based on characteristics figures. A reasonable cantilever would present a spring constant of  $k=0.1$  N/m, a fundamental resonance frequency of 10 kHz and a quality factor  $Q$  (characteristic factor of the resonance peak width) of 1000. The force detection relies on the surface coupling with a sphere of radius  $R=10-100\mu\text{m}$ . In the van der Waals limit, the force between two surfaces is:

$$F_{vdw} = -\frac{HR}{6D^2}. \text{ This leads to } \frac{\partial F_{vdw}}{\partial D} = \frac{HR}{3D^3}$$

and a mechanical instability given

$$\text{by: } \frac{\partial F_{vdw}}{\partial D} = \frac{HR}{3D^3} = k. \text{ Quantitatively for a}$$

typical Hamaker constant,  $H= 5,46 \times 10^{-19} \text{ J}$

$$\text{this gives } D = \sqrt[3]{\frac{HR}{3k}}$$

- In the usual AFM behaviour with  $R \approx 10 \text{ nm}$ , we find  $D \approx 2,6 \text{ nm}$ . This is routinely observed in approach-retract curves under vacuum.
- For a sphere radius  $R \approx 50 \mu\text{m}$ , this distance increases up to  $D=50 \text{ nm}$ .

This provides the low limit separation between the surfaces that we can possibly achieve.

The upper limit is fixed by the noise level intensity. In our measurements, the thermal noise is observed in the measured spectral density and is a dominant factor at room temperature. In any case, the analysis of the noise influence, based on the Brownian motion enables us to show how using a large sphere allows to extend the measurable range of distances. The average displacement of the

$$\text{sphere is determined by } \langle X^2 \rangle = \frac{k_B T}{k} \text{ and}$$

then transformed in a fluctuating force  $F_{noise} = \sqrt{k_B T k}$ , equal to 20pN at room temperature. Such a noise floor limit enables one to measure, in force measurement and using static cantilever deflection detection, the retarded Van der Waals interaction up to a separation of 189 nm, taking into account a sphere radius of 50 $\mu\text{m}$ . As a reference and to

better show the relevance of this estimate, we can establish this upper limit for the classical AFM setup. One finds  $D=7\text{nm}$ . One immediately notices that the distance range for which the Van der Waals interaction can be measured using a classical AFM set up is limited by the mechanical instability for the lower limit,  $D=2.7\text{ nm}$  and by the noise floor at larger distances,  $D=7\text{ nm}$ . This is indeed what is observed using a vacuum AFM: this measurement is hardly possible.

The use of large spheres largely broadens this measurable distance range from a few nanometers up to more than 100nm.

Using a stiffer cantilever spring enables one to measure closer to the surface. This is of course at the expense of a reduced sensibility and therefore to a limited range of large separations investigations. On the contrary, a soft cantilever favours force measurements at large separations between surfaces and prevents force measurements at small separations. It leads to the use of very stiff tuning forks ( $k=1000\text{-}10000\text{N/m}$ ) [11-13] to obtain true atomic resolution with very short scale interactions between a tip and a surface. On the opposite, the development of ultra soft cantilevers allow the measurement of very weak interactions as for instance magnetic interactions between a tip and a single spin [14-15]

Nanometer scale control, high sensitivity in the measurements of nano displacements and increased availability of specific MEMS beside AFM cantilever have largely motivated investigations in weak forces measurements. Two strategies are basically used:

- Measurement of static deflections
- Measurement of oscillator perturbations.

In this last technique based on the use of narrow bandwidth detections, force sensitivity often reaches a few  $fN/\sqrt{\text{Hz}}$  [6, 8, 16]. Thanks to this higher sensitivity, major improvements in weak force and long range force measurements have been achieved [8, 14, 15, 17, 18]. A classical set up of Atomic Force Microscope (AFM) is a very stable and powerful tool to measure non contact forces. For example, the nanotip approach and retract curves technique is a very well adapted tool to measure and identify interactions between a tip and a surface for

distances smaller than few tens of nanometers. [19, 20]. In [19], a clear separation between a longer range electrostatic force and a shorter range van der Waals could be experimentally achieved at the nanometer scale surface separation using a nanotip.

Using large sphere to drastically increase the interaction area, the capability of an AFM to measure, on the basis of static deflection, long range and weak interactions between a surface and a micrometer size object has been demonstrated [17,18]. These measurements have opened an avenue in the use of AFM systems to measure long range and non contact interactions for micrometers objects.

In this context, we present in this paper results based on high precision AFM measurements of the capacitive interaction between a micrometer sphere and a flat surface. We essentially focus on the quantitative acquisition and analysis of experimental curves. A detailed description of the quantitative determination of the experimental parameters (i.e. Force constant of the lever, absolute distance) will be done. We shall show that this objective requires taking into account effects that are usually neglected and put emphasis on limiting factors in both measurement and analysis.

## 2.b Experimental Set Up

A schematic representation of the experiment is shown in figure 1.

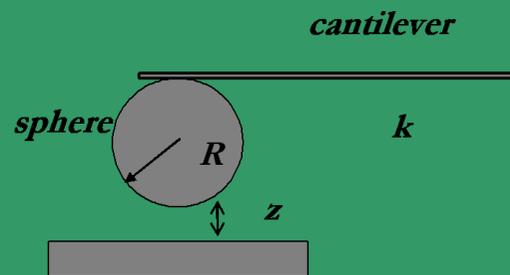


Figure1. Schematic representation of the experiment. (At this scale,  $z/R$  is such that no long range interaction can be measured)

Experiments were performed under ultra high vacuum with a pressure in the range of  $10^{-10}$  Torr and at room temperature with an Omicron UHV AFM. In this system the sample is mechanically

fixed (i.e. immobile) and electrically grounded. The displacement and the applied voltage are imposed to the cantilever.

In order to investigate capacitive interaction in the 0.1 to 0.5  $\mu\text{m}$  range, a polystyrene sphere with a radius of 42 $\mu\text{m}$  was mounted on a cantilever. Nominal geometrical characteristics of the cantilever are (350  $\mu\text{m}$  x35  $\mu\text{m}$  x1  $\mu\text{m}$ ).The sphere was glued onto the cantilever using a micromanipulator following this method:

- The first step, consists in manually depositing glue on the cantilever. The amount of deposited glue must be large enough to insure a good mechanical maintains. On the other side, depositing too much glue can severely degrade the reflectivity of the lever or deteriorate the electrical contact between the lever and the sphere. For these reasons, the gluing process constitutes a crucial step. Bad gluing prevents the use of the final system.
- The second step consists in approaching the lever towards the sphere until contact using a micromanipulator. After gluing the lever is retracted.

All these manipulations are performed under an optical microscope.

The sphere is then metallized by evaporating thin gold layer of about 300 nm thick. Before the gold deposition, a 2 nm thick layer of titanium is evaporated to insure the strong adhesion of the gold layer. The coating thickness is sufficient to consider the properties of an infinitely thick metal. In our experiments, the voltage being applied to the cantilever, this metallization establishes the electrical continuity between the lever and the coated sphere. In the case of a bad electrical continuity, time scale to reach electrical equilibrium of more than one minute has been observed. On the other side, for good metallization this equilibrium time was much below the measuring time. Figure 2 shows a picture of a sphere mounted onto the cantilever after metallization.



Figure 2 Picture of a sphere glued on the cantilever after metallization obtained by Optical microscopy.

The surface used is a Au (111) prepared under Ultra High Vacuum by ion sputtering and annealing. Use of a gold surface suppresses the problem of static surface charges by screening. In the case of oxidized surfaces, this may be a central problem.

The experiment consists in measuring the displacement of the laser back reflected on the cantilever into a photodiode. This is the classical AFM measurement. In this method, the displacement of the laser spot in the photodiode as a consequence of the cantilever's deflection is directly proportional to the force acting between the sphere and the plate. There is, a priori, no reason to question this statement but its failure would appear in the subsequent measurement and analysis. The cantilever is chosen with a very low force constant to be as sensitive as possible. The value of the force constant is supposed to be around 0.01 N/m as indicated by the supplier. The precise determination of this spring constant through departure from the classical  $V^2$  capacitive force is an issue in this work.

### 3 Measurement methods

Quantitative measurements of non contact force with an AFM require a precise determination of the following parameters: the absolute distance, the stiffness of the cantilever and the shape of the tip. Short range forces in non contact AFM usual configuration are locally measured thanks to the nanosize of the tip apex and to the fact that the tip cone contribution is negligible. Quantitative force measurements with no adjustable parameters are usually based on the electrostatic force measurements. However due to the tip-cantilever geometry and to the very long range of the unscreened electrostatic

interaction, a precise determination of the capacitance is not easily reached. In our case, the capacitance is, on the contrary, precisely determined by the sphere-plane geometry and the ex situ measurement of the sphere radius. It then becomes possible to independently determine the absolute values of the gap and of the cantilever stiffness by varying the applied voltage between the tip and the surface.

We then determine the absolute distance between the sphere and the surface and the cantilever stiffness. This enables us to make an absolute measurement of the sphere-plane force versus the distance.

The capacitive force between a sphere and a plate is exactly [21]:

$$F_{cap} = 2\pi\epsilon_0 V^2 \sum_{n=1}^{\infty} \operatorname{csch} n\alpha (\coth \alpha - n \coth n\alpha) \quad (3.1)$$

with  $\alpha = \cosh^{-1} \left(1 + \frac{z}{R}\right)$

and where  $\epsilon_0$  is the vacuum permittivity,  $Z$  the distance separation and  $R$  the radius of the sphere.

In our geometry, the radius of the sphere is much larger than the distance investigated. The capacitive force given by (3.1) can be approximated by:

$$F_{app} = \pi\epsilon_0 V^2 \frac{R}{z} \quad (3.2)$$

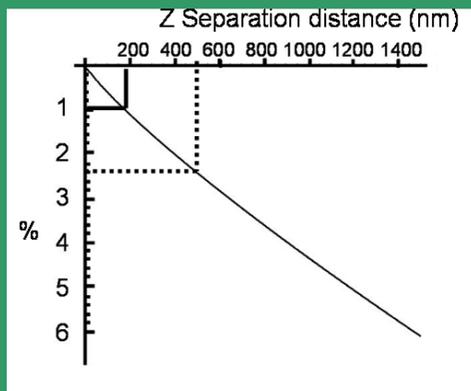


Figure 3 Comparison between the approximate and exact formula of a sphere plane capacitance force. The error introduced by the utilisation of the approximate formula is smaller than 2.5% for distances smaller than 500 nm.

The validity of this approximation is shown in figure3. For a sphere radius  $R=40\mu\text{m}$ , and a separation distance smaller than 200 nm, the error is smaller than 1%. In this paper we shall restrict our quantitative analysis by the use of this approximation with no apparent effect in the conclusion. As the sensitivity is increased, this approximation may become a significant limitation. Future measurements may require for each distance separation at least a partial resummation of expression 3.1.

Measurement method: as the relative voltage between the sphere and the plate is varied, the cantilever deflection is measured through the laser deflection. A set of sphere-plane separations is used. During the measurement, as we forbid direct contact between surface and sphere, the absolute gap between the sphere and the plane remains unknown. It has to be determined.

The relative  $z$  displacement is directly controlled by the applied voltage to  $z$ -piezoactuator. At this stage, the  $z$ -piezoactuator calibration is given by the measurement of known atomic step height. The estimated precision of this calibration is as usual of a few percents. We shall question the precision of this calibration at the end of this paper.

Absolute gap separation can be measured through deflection measurement as the relative sphere-plane voltage is varied. The usual AFM analysis supposes a constant gap separation as the voltage is varied. This is a good approximation in an AFM context.

Due to the very low cantilever stiffness and due to the required experimental precision, it is here necessary to include the deflection of the cantilever as the sphere-plane distance is to be determined. We shall see that this otherwise negligible contribution in classical AFM measurement here becomes significant, as the cantilever's deflection is not small enough compared to the sphere plane distance. Including this deflection, the capacitive force is now given by:

$$F_{app}^{def} = \pi \epsilon_0 V^2 \frac{R}{(z + \Delta z_{def})} \quad (3.3)$$

$$\text{with } \Delta z_{def} = \frac{1}{2} \left( z - \sqrt{z^2 + \frac{4\pi\epsilon_0 R V^2}{k}} \right)$$

where  $\Delta z_{def}$  represents the lever deflection effect.

We shall use this result to analyze our data. The high level of precision for the quantitative comparison between the experience and the model which includes the lever deflection is a central result of this paper.

## 4 Results

### 4.a Determination of the absolute distance between the sphere and the surface, calibration of the photodiode signal and determination of the cantilever stiffness.

Figure 4 shows experimental curves obtained by measuring the deflection of the lever varying the difference voltage between the sphere and the surface. Each curve is an average of 6 different measurements. Typical measuring time of a single curve is of the order of a few seconds. The curve minimum has been adjusted to  $V=0$  and to  $F_{interaction}=0$ .

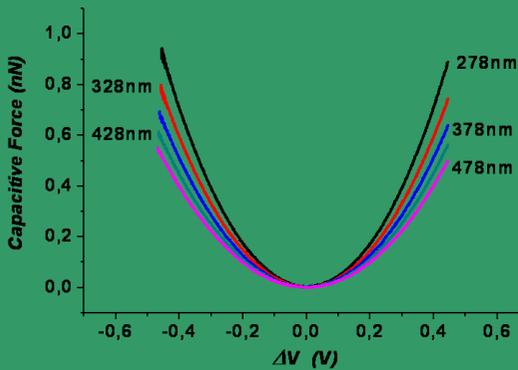


Figure 4 Variation of the capacitive force versus the gap voltage between the sphere and the plate for different separations.

Figure 5 shows the correction  $\Delta V$  applied to adjust the curve minimum to zero for different distances. The linear variation of  $\Delta V$  versus  $z$  is clear. We have not identified the origin of this variation although it is clear and reproducible.

We suspect that it might be due to the stray electric field from the z-piezo. Indeed changing the  $z$  distance, requires a change in the piezo polarization that results in a change of the electrostatic environment.

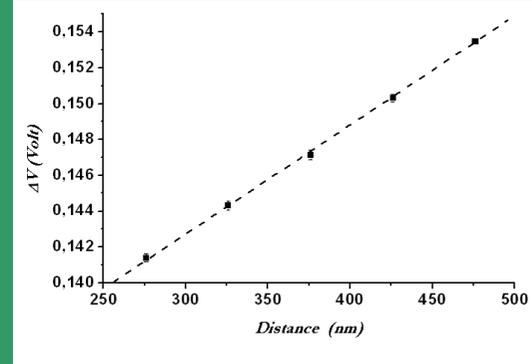


Figure 5 Evolution of the gap voltage between the sphere and the plate versus the distance separation. A linear variation is clearly observed.

Here the radius of the sphere, the applied voltage and finally the relative distances between each measurement are known. At this step of the analysis, the absolute distance, the calibration in force unit of the photodiode signal and the stiffness of the cantilever remain unknown. The knowledge of these three parameters is crucial to compare quantitatively and precisely experimental data with theoretical predictions. They have been determined according to the method described hereafter.

For measurements shown in the figure 4, the relative distance between each curve is known. Those different distances are directly given by the applied voltages on the  $z$  piezo, but only if the deflection of the cantilever is negligible. We consider that this condition is verified for low voltage difference between the sphere and the plate. For low applied voltage, we can directly determine the absolute distance from the experimental curves by calculating the ratio between each of those experimental curves. As given by equation 3.2, this corresponds to the ratio between the distances of each curve. By this method and for the smallest separation, the determined absolute distance is  $Z=278 \pm 2$  nm. Once again, this value corresponds to the distance between the sphere and the plate without considering distances variation induced by the cantilever deflection under the interaction

between the two surfaces. As we shall see, the quantitative determination of the deflection is crucial for a precise quantitative comparison between theory and experiments. In order to quantify the deflection it is necessary to know the stiffness of the cantilever. Before determining this stiffness we need to calibrate the photodiode signal in force unit.

For this, knowing the absolute distance and once again for low applied voltages, we can calculate the ratio between the measured photodiode signal and the theoretical capacitive force given by equation 3.2. This ratio gives us directly the calibration of the photodiode in force unit. Finally, we can calculate the cantilever stiffness in the spring constant unit (ie: N/m) by considering the slope of an approach curve after contact equal to 1. For this, we assume a priori that the stiffness of the gold surface and the polystyrene sphere are, a priori, much larger than the stiffness of the lever. We then found a cantilever stiffness of  $k=0.046 \pm 0.002$  N/m.

For such a low cantilever stiffness, an interaction of 1nN induces a cantilever deflection and therefore a decrease in the sphere-surface distance of 21.5 nm.

The variation of the capacitive force between the sphere and the plane versus the potential difference does not strictly follow a parabola. This is quantitatively described by equation 3.3. In our experimental setup (in strong contrast with usual AFM conditions where such an effect has never been investigated to our knowledge) this deviation from the parabola is then not negligible. The sphere-surface distance is not only given by the piezoelectric displacement. It is necessary to take into account this correction due to this deflection in quantitative force measurements.

Figure 6 shows the deviation to the parabola of experimental curve due to this deflection. These curves are obtained by subtraction between the experimental curves (shown in Fig4) and theoretical values given by equation 3.2. This correction is compared directly to the theoretical deviation given by the difference between  $F_{app}^{def}$  from equation 3.3 and  $F_{app}$  from equation 3.2 for two different distances. The two curves were artificially shifted from zero along the Y-axis for a better visibility.

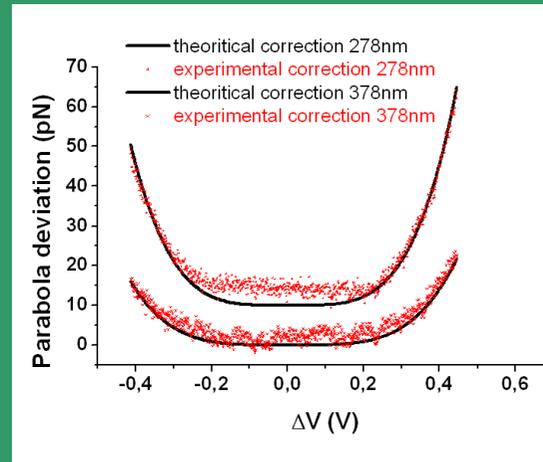


Figure 6 Correction to the parabola due to the cantilever deflection. The dotted line corresponds to the difference between theoretical formula without deflection and theoretical formula taking in account the deflection. The solid line corresponds to the difference between theoretical formula without deflection and experimental curve.

Figure 6 asks for several comments:

- For a given voltage, the deviation is larger in the regime of short distance separation. This is no surprise.
- This deviation is concentrated in the high voltage regime. The parabola even for this large sphere diameter remains a very good approximation at low voltage from 0 to  $\pm 0,2$  V. This validates our approximation in the determination of the absolute gap distance using the central part of curves.
- This flat part can be easily analysed through the comparison of equations 3.2 and 3.3. This force difference is at the first order proportional to  $V^4$ , which explains the very flat part at low voltage.
- The determination of the cantilever stiffness from the slope of an approach curve after contact allowed us to verify without any fitting parameters the good agreement between our experimental data and theoretical predictions. However, contact between the sphere and the surface especially for a contact between two gold surfaces in UHV generates a strong increase of the roughness of the two surfaces being able to reach a loss of the well defined geometry necessary to these measurements. Direct contact should then be avoided. Comparison made in figure 6 then provides an alternative and original method to measure the

spring constant in a non contact static interaction. This measurement is then a non destructive method allowing the determination of the cantilever spring constant without any contact.

#### 4.b Quantitative measurements of the electrostatic interaction in the 0.2 to 0.5 micrometers range.

Static measurements of attractive forces in the sub-nanonewton range need very soft cantilever in order to reach the required sensitivity on the basis of induced displacement. Therefore the non parabolic behaviour described previously has to be taken into account in the measurement analysis as we will show in the following. Again this behaviour cannot be here ignored. It is usually of no interest in AFM measurements but might be important for MEMS and NEMS as they can present well defined geometries, gap comparable to the one here used and similar voltage range.

As the force is measured versus the distance, the determination of parameters, as done before, allows a quantitative comparison between theory and measurements without any fitting parameters. For this comparison, following measurements described before, we measure capacitive forces as the sphere/surface distance is varied.

In the figure 7 are shown three experimental curves for a gap separation between the two surfaces varying from 210 nm up to 480 nm. The applied voltages on the sphere are -0.3 V, -0.25 V and 0.3 V which means (considering the linear variation shown in figure 4) an absolute gap voltage between the sphere and the surface at the smallest distance of 0.44 V, 0.39V and 0.16 V. Each curve is a direct average of five measurements.

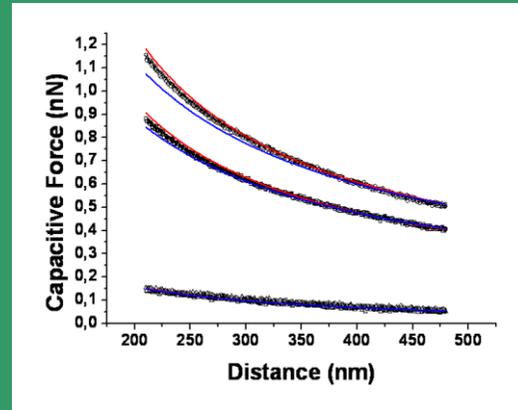


Figure 7 Capacitive force measurements (black dots) versus the distance for three different applied voltages (-0.3V, -0.25 V and 0.3 V). Experimental data are compared with theoretical prediction taking into account the deflection of the cantilever (eq 3.3, red line) and without taking into account the deflection of the cantilever (eq 3.2, blue line)

The investigated distance range is larger than the quarter of the wavelength of the laser diode use for the detection. Therefore a significant variation of the detected signal due to light interferences was observed. Moreover, for these distances and for an applied voltage on the sphere of 0.13 V (i.e. a gap voltage varying from 7 mV to 23 mV), Casimir interaction and the capacitive interaction are smaller than one piconewton and as we will see smaller than the force resolution, therefore a measurement in these conditions can be considered as a direct measurement of this interference signal which is a intrinsic contribution to the apparatus and cannot be suppressed. Its measurement is shown in figure 8. A subtraction of this curve to the capacitive curves allows us to safely subtract the interference contribution. In the remainder of the paper, we shall consider corrected results from this straight contribution.

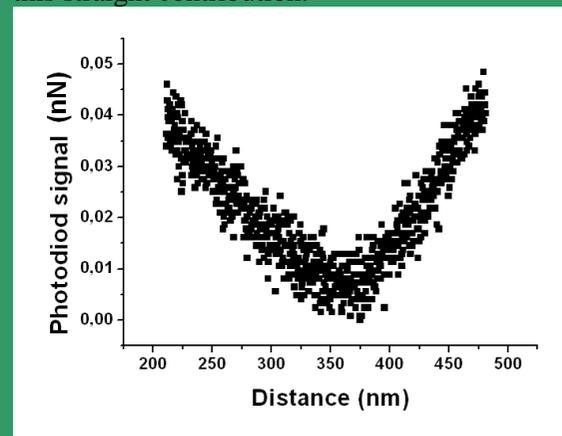


Figure 8 Laser interference measurement acquired far from the surface where interactions between the sphere and the plate are negligible.

The measured capacitive force is then varying from 400 to 900 pN.

All experimental curves are directly compared to results deduced from equations 3.3 (red curve) and 3.2 (blue curve) with no fitted parameters. Comparisons are apparent in figure 7. The consideration of the effect of the cantilever deflection in the calculation (equation 3.3) clearly improves the comparison with the experimental results if compared to the case where this deflection is not taken into account (equation 3.2). However, at short distances, a difference remains between measurements and both of the theoretical calculations. We can only attribute this difference to a drift of the distance between the sphere and the surface. According to this assumption, we observed that a constant shift of 5 nm onto the absolute distance without changing any other parameter significantly improves the whole agreement between measurement and theory. For the all the three curves, as shown on figure 9, this results in a clear and consistent improvement of the comparison. The force resolution, given by error bars shown in the graph, costs 10,4 pN and was determined according to the statistical analysis described hereafter. Moreover, for the sake of a better clarity, the number of points shown in the graph has been reduced by a factor of ten compared to the entire number of measured points.

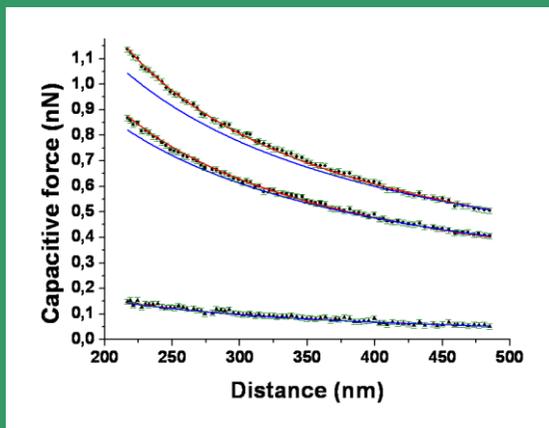


Figure 9 Capacitive force measurements (black dots) versus the distance for three different applied voltages (-0.3V, -0.25 V and 0.3 V). Compare to curves shown in fig8, we have here applied a constant shift of 5nm onto the absolute

distance. Experimental data are compared with theoretical prediction taking into account the deflection of the cantilever (eq 3.3, red line) and without taking into account the deflection of the cantilever (eq 3.2, blue line). Except for this 5 nm shift due to thermal drift, there are no fitting parameters.

Figure 9 asks for several comments:

- For long range interaction measurements using a microsphere, the contribution of the cantilever deflection must be taken into account.
- For this measurement the linear variation of the difference of the surface potential  $\Delta V$  was also taken into account although its origin has not been clearly identified.
- Not surprisingly, the comparison between the theoretical prediction and the experimental datas measured at room temperature with no feedback control must consider some thermal drift. These z curves have been actually acquired after a delay of almost fifteen minutes after the V-curves used to determine the absolute distance. A variation of five nanometers corresponds roughly to a thermal drift speed of 3 Å/min which is a value compatible with that of the classical and often observed thermal drift at room temperature. For this measurement we acquired one curve for each voltage applied on the microsphere and repeated this sequence five times. The time acquisition during a sequence (i.e. acquisition of the three curves for different applied voltage) was kept very short (less than one minute). Therefore, we can consider the same distance and so apply the same distance shift for the three curves.

In order to establish the largest distance used for measurement, we have used the thermal noise as a noise floor. This is not exactly correct. Others noises should be taken onto account. We want to address this point is this final paragraph.

The sensitivity of the measurement is given by the level of the different sources of noise integrated over the whole bandwidth of the measurement. In order to estimate the sensitivity of our measurements, we present here a statistical analysis based on a frequency count of the deviation of the measured data compare to

the theoretical prediction. In figure 10 is plotted the distribution of the deviation between the experimental data and theory given by equation 3.3.

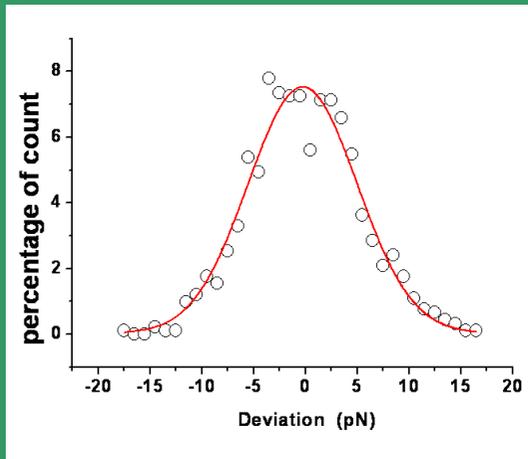


Figure 10 Deviation between experimental data and theoretical prediction.

The experimental data are an average of 5 measurements obtained for an applied voltage of  $-0,3V$ . This leads to a force resolution given by the width of the Gaussian of  $10.5$  pN. Similar studies for the other applied voltages reach to the same force resolution. Moreover, we could verify that the average of 5 curves has improved the force resolution by a factor  $\sqrt{5}$ . At last, considering the bandwidth of the measurement given in particular by the acquisition time of each curve, and the thermal noise as the only source of noise, the force resolution would be almost  $2.5$  pN. This comparison shows that noise from environment and broadband detection noise from instrument cannot be neglected. In static measurement of lever deflection integrated over a very large band of frequencies, these non thermal noise even dominate the error. Finally, the comparison between this value and measured values of the deviation to the parabola (figure 6) justifies once again the importance to consider quantitatively the deflection. The signal variation due to laser interference is also in this case 5 times bigger than the force resolution. Detailed static measurements of Casimir force in this set up are then clearly impossible.

## 5. Conclusion

In this paper, we have presented capacitive force measurements between a microsphere and a plane surface using an atomic force microscopy in static mode. We performed an accurate comparison between experimental data and theoretical analysis. In this comparison, taking benefits of the well known geometry, all parameters have been determined experimentally and separately. The deflection effect has been precisely investigated and quantified. In the analysis, considering the distance separation between the basis of the cantilever and the surface instead of the distance between the sphere and the surface, we have demonstrated that it introduces a non parabolic  $V^4$  behaviour in the capacitive force. For such measurements, we propose a new non destructive method to determine spring constant of cantilever using the deviation to classical parabolic behaviour introduced by the deflection.

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