New precision experiments on the Casimir force sharpen problems in foundations of quantum statistical physics

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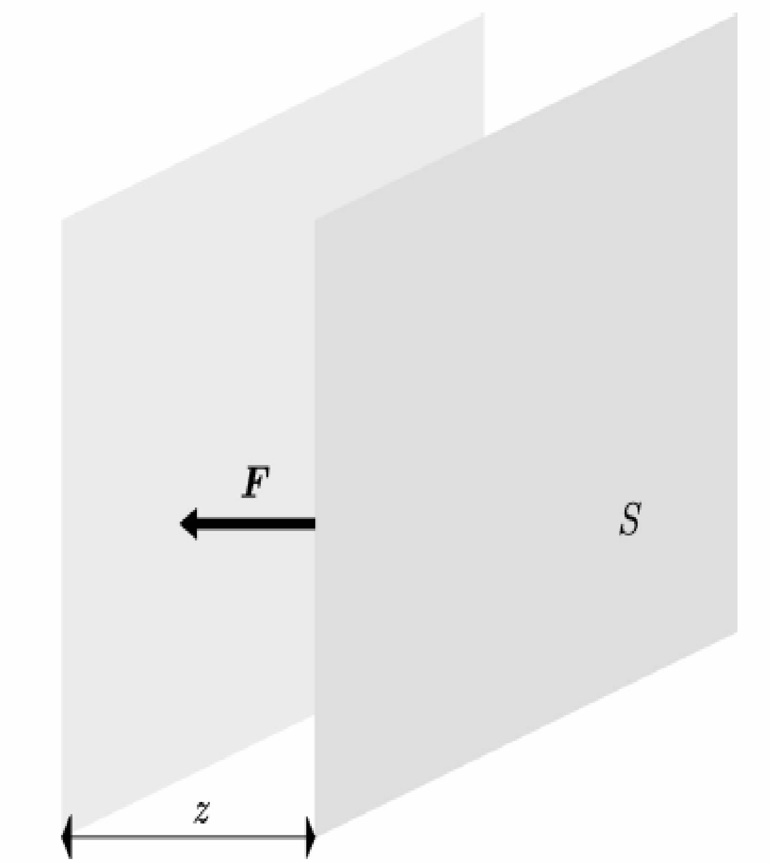
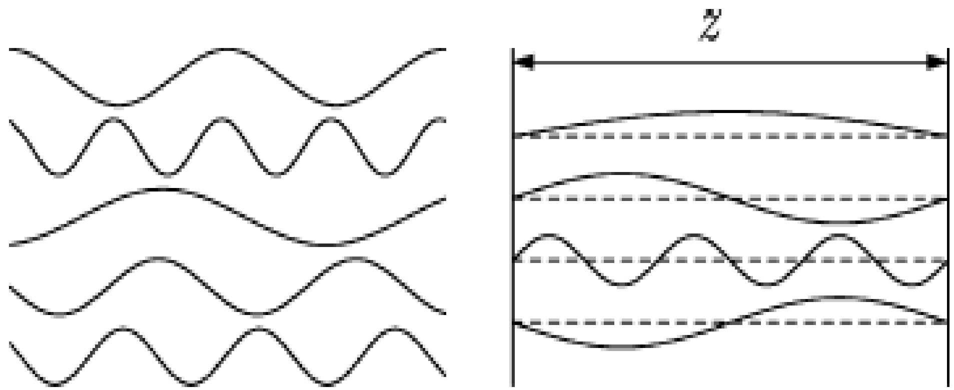
CONTENT

1. INTRODUCTION: DISPERSION FORCES AND THEIR ROLE IN NANOTECHNOLOGY





Dispersion forces arise due to the change of the spectrum of zero-point and thermal fluctuations of the electromagnetic field by material boundaries.

The van der Waals force (London, 1930)
The Casimir force (Casimir, 1948)

2. THE LIFSHITZ THEORY OF DISPERSION FORCES

Maxwell equations

$$\nabla \cdot \boldsymbol{D}(t,\boldsymbol{r}) = 0, \qquad \nabla \times \boldsymbol{E}(t,\boldsymbol{r}) + \frac{1}{c}\frac{\partial \boldsymbol{B}(t,\boldsymbol{r})}{\partial t} = 0$$

$$\nabla \times \boldsymbol{B}(t,\boldsymbol{r}) - \frac{1}{c}\frac{\partial \boldsymbol{D}(t,\boldsymbol{r})}{\partial t} = 0, \qquad \nabla \cdot \boldsymbol{B}(t,\boldsymbol{r}) = 0$$

Continuity boundary conditions

$$E_{1t}(t,\boldsymbol{r}) = E_{2t}(t,\boldsymbol{r}), \qquad D_{1n}(t,\boldsymbol{r}) = D_{2n}(t,\boldsymbol{r}),$$

$$H_{1t}(t,\boldsymbol{r}) = H_{2t}(t,\boldsymbol{r}), \qquad B_{1n}(t,\boldsymbol{r}) = B_{2n}(t,\boldsymbol{r}),$$

The free energy of dispersion interaction is:

$$\mathcal{F}(a,T) = \frac{k_B T}{2\pi} \sum_{l=0}^{\infty}{}' \Phi_E(\xi_l), \qquad P(a,T) = -\frac{\partial \mathcal{F}(a,T)}{\partial a},$$

$$\xi_l = 2\pi \frac{k_B T l}{\hbar}$$ are the Matsubara frequencies.

$$\Phi_E(x) = \int_0^{\infty} k_\perp dk_\perp \sum_\alpha \ln\left[1 - r_\alpha^{(1)}(ix, k_\perp) r_\alpha^{(2)}(ix, k_\perp)\, e^{-2aq}\right]$$

$$q \equiv q(ix, k_\perp) = \sqrt{k_\perp^2 + x^2/c^2}$$

E. M. Lifshitz, Sov. Phys. JETP (1956)

Reflection coefficients for two independent polarizations:

$$r_{\mathrm{TM}}^{(n)}(ix, k_\perp) = \frac{\varepsilon^{(n)}(ix)q - k^{(n)}}{\varepsilon^{(n)}(ix)q + k^{(n)}}$$

$$r_{\mathrm{TE}}^{(n)}(ix, k_\perp) = \frac{\mu^{(n)}(ix)q - k^{(n)}}{\mu^{(n)}(ix)q + k^{(n)}}$$

$$k^{(n)} \equiv k^{(n)}(ix, k_\perp) = \sqrt{k_\perp^2 + \varepsilon^{(n)}(ix)\mu^{(n)}(ix)\frac{x^2}{c^2}}$$

Models of the frequency-dependent dielectric permittivity

$$\varepsilon_c(\omega) = 1 + \sum_{j=1}^{K} \frac{g_j}{{\omega_j}^2 - \omega^2 - i\gamma_j\omega}$$

Permittivity of dielectric plates as determined by core electrons

$$\varepsilon_d(\omega) = \varepsilon_c(\omega) + i\frac{4\pi\sigma_0(T)}{\omega}$$

Permittivity of dielectric plates with dc conductivity included

$$\varepsilon_D(\omega) = \varepsilon_c(\omega) - \frac{{\omega_p}^2}{\omega[\omega + i\gamma(T)]}$$

The Drude model permittivity for metallic plates

$$\varepsilon_p(\omega) = \varepsilon_c(\omega) - \frac{{\omega_p}^2}{\omega^2}$$

The plasma model permittivity for metallic plates

Proximity force approximation for a sphere above a plate:

$$F_{sp}(a,T) = 2\pi R\mathcal{F}(a,T) \quad (a \ll R)$$

Derjaguin, Kolloid. J. (1934).
Blocki, Randrup, Swiatecki, Tsang, Ann. Phys. (1977).
Bimonte, Emig, Kardar, Appl. Phys. Lett. (2012)
Teo, Phys. Rev. D (2013).

$$P(a,T) = -\frac{1}{2\pi R}\frac{\partial F_{sp}(a,T)}{\partial a}$$

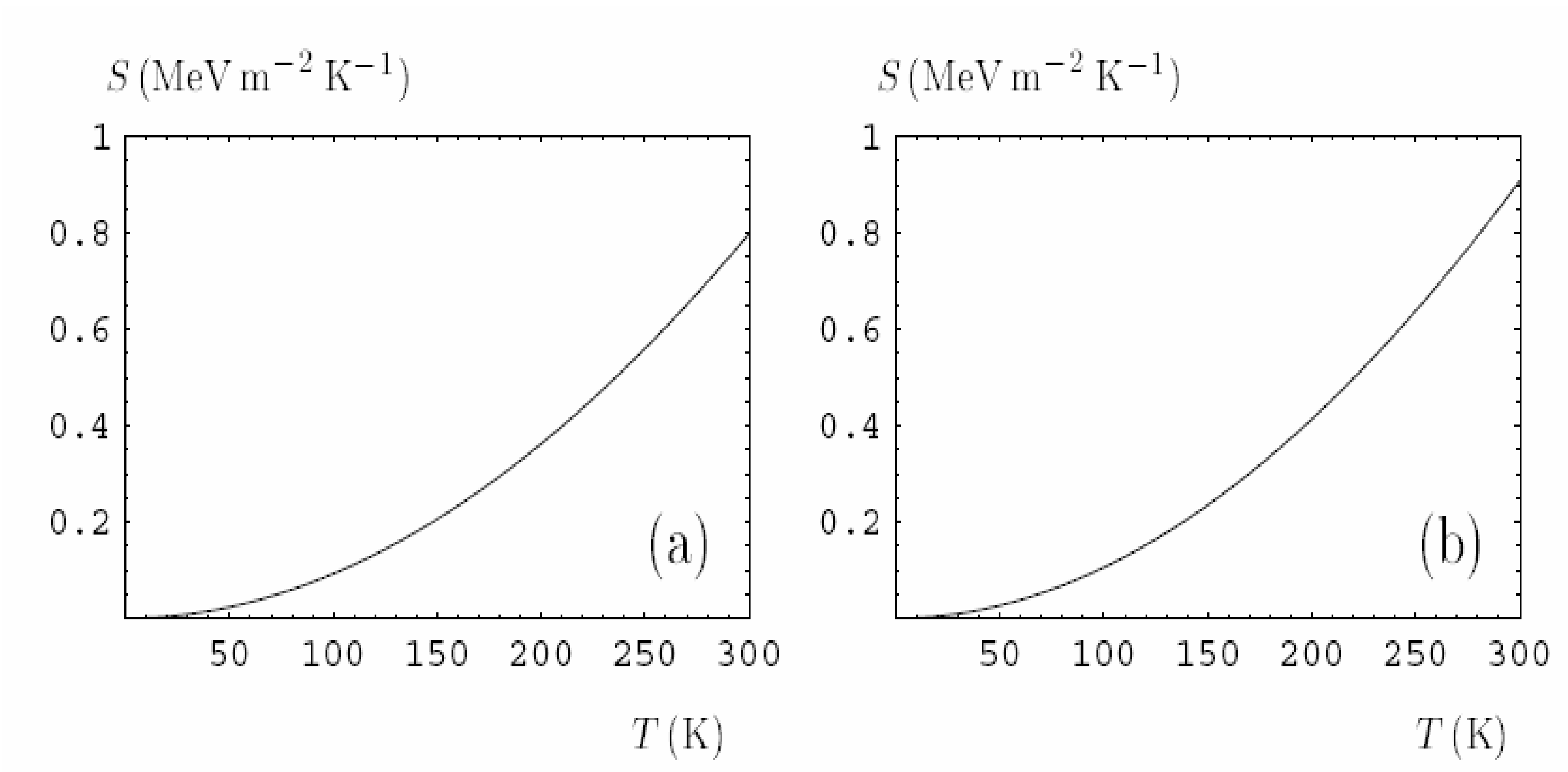
3. THE LIFSHITZ THEORY AND THE NERNST HEAT THEOREM

Entropy of dispersion interaction:

$$S(a,T) = -\frac{\partial \mathcal{F}(a,T)}{\partial T}$$

$$\lim_{T\to 0} S(a,T) = \mathrm{const}$$

According to the Nernst theorem, this constant MUST NOT DEPEND on the parameters of a system.



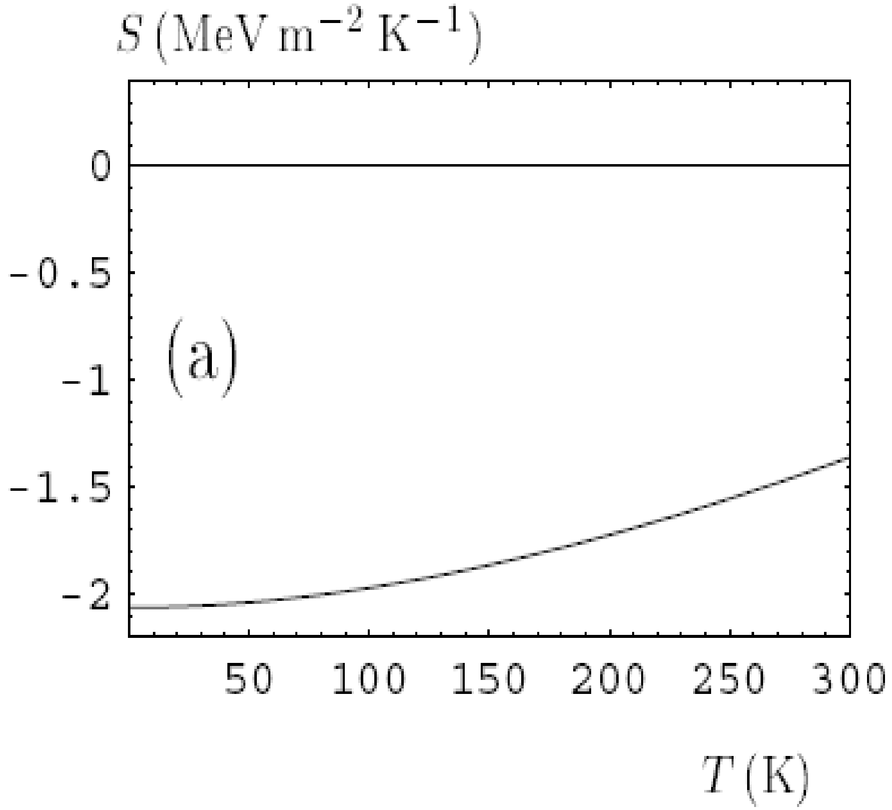
Ideal metals

Metals described by the plasma model

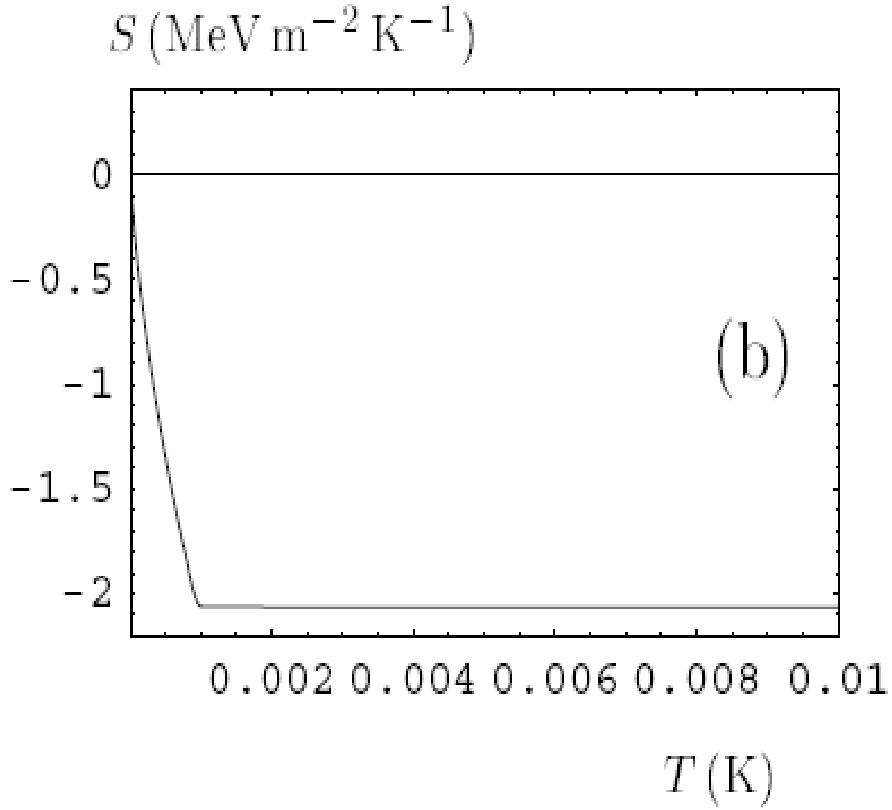
Mitter, Robaschik,
Eur. Phys. J. B (2000).

Bezerra, Klimchitskaya, Mostepanenko,
Phys. Rev. A (2002).

Metals described by the Drude model



Perfect crystal lattice



Lattice with impurities

Bezerra, Klimchitskaya, Mostepanenko, Romero, Phys. Rev. A (2004); Klimchitskaya, Mostepanenko, Phys. Rev. E (2008).

Hoye, Brevik, Ellingsen, Aarseth, Phys. Rev. E (2007, 2008).

For metallic plates described by the Drude model:

$$\lim_{T\to 0} S(a,T) = -\frac{k_B\zeta(3)}{16\pi a^2}\left(1 - 4\frac{\delta_0}{a} + 12\frac{\delta_0^2}{a^2} - \cdots\right) < 0$$

Bezerra, Klimchitskaya, Mostepanenko, Phys. Rev. A (2002);
Bezerra, Klimchitskaya, Mostepanenko, Romero, Phys. Rev. A (2004).

For dielectric plates with account of dc conductivity:

$$\lim_{T\to 0} S(a,T) = \frac{k_B}{16\pi a^2}\mathrm{Li}_3(r_0^2) > 0, \quad r_0 \equiv \frac{\varepsilon(0)-1}{\varepsilon(0)+1}$$

Geyer, Klimchitskaya, Mostepanenko, Phys. Rev. D (2005).
See review in: Klimchitskaya, Mohideen, Mostepanenko, Rev. Mod. Phys. (2009).

4. WHAT EXPERIMENTS SAY

4.1 Measurements with Au-Au test bodies

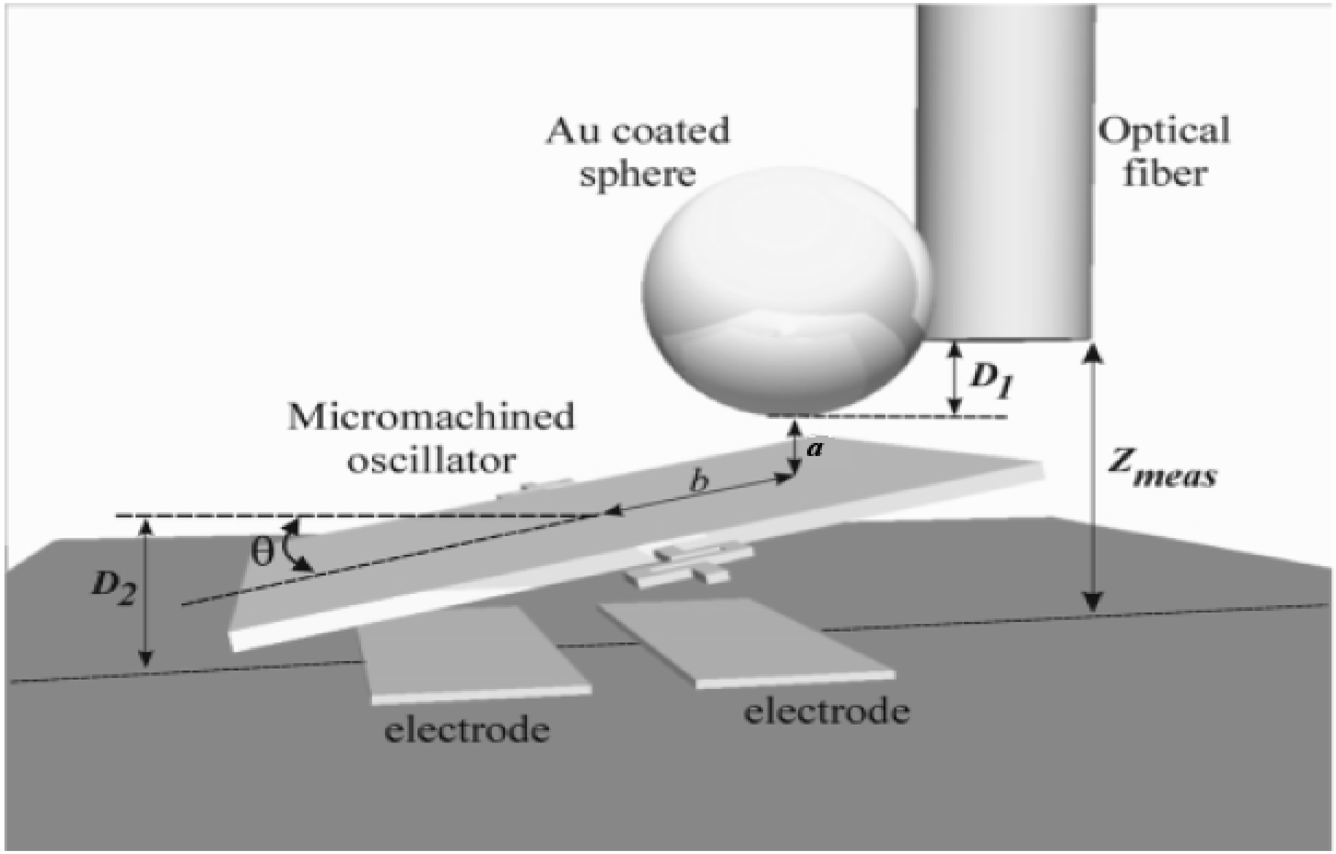
The gradient of the Casimir force between a sphere and a plate is measured using:

a) micromachined oscillator

Decca, Lopez, Fischbach, Klimchitskaya, Krause, Mostepanenko, PRD (2003); Ann. Phys. (2005); PRD (2007); EPJC (2007); Decca, Lopez, Osquiguil, IJMPA (2010).

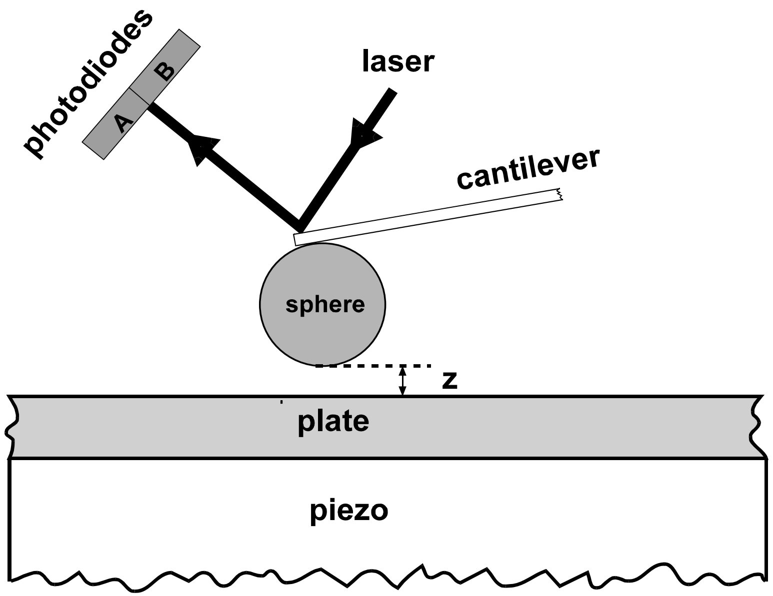
b) atomic force microscope

Chang, Banishev, Castillo-Garza, Klimchitskaya, Mostepanenko, Mohideen, PRB (2012).



Schematic setup with a micromachined oscillator

Schematic setup with an atomic force microscope



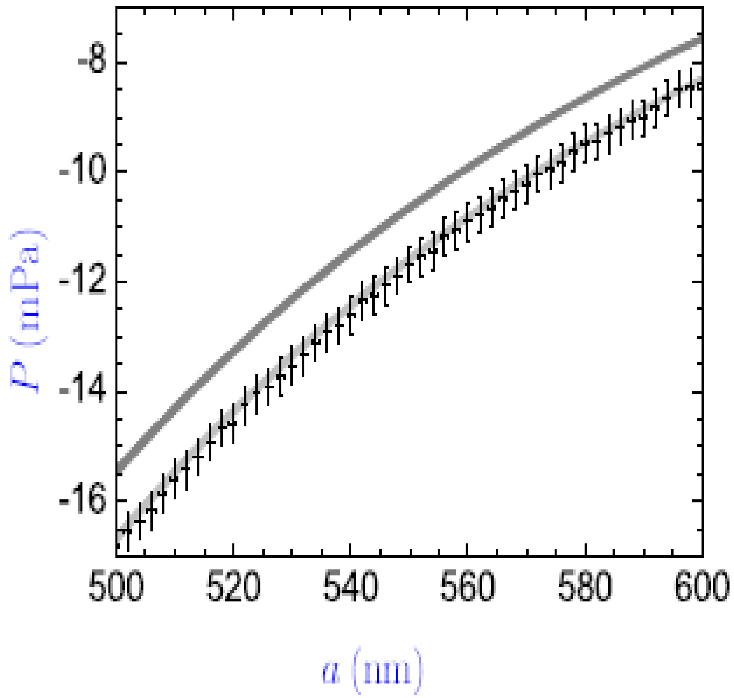
Force sensitivity 10^{-17} N possible

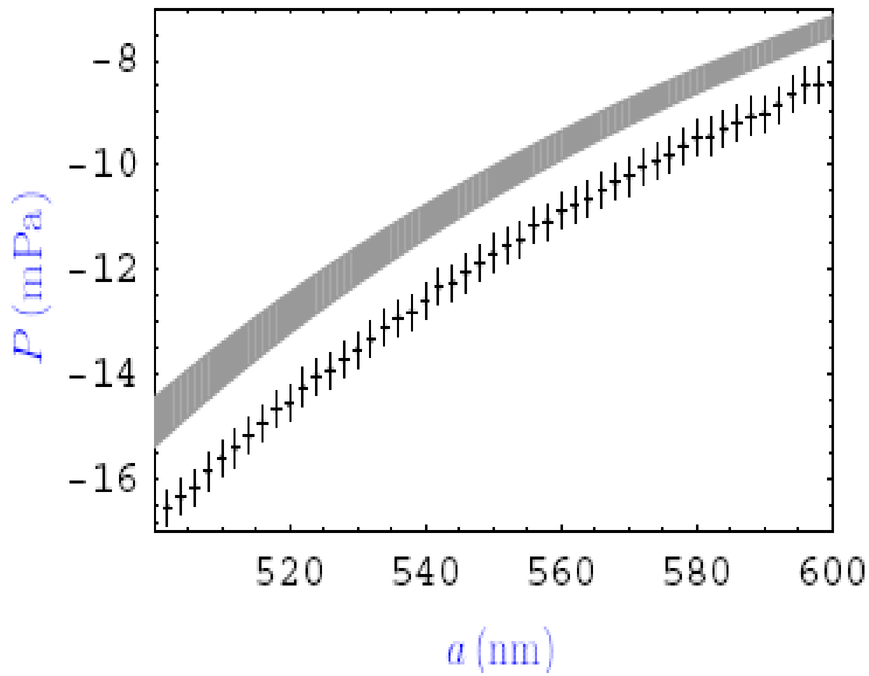
We achieve 10^{-13}N

Room temperature

$10^{-7} - 10^{-8}$ Torr vacuum

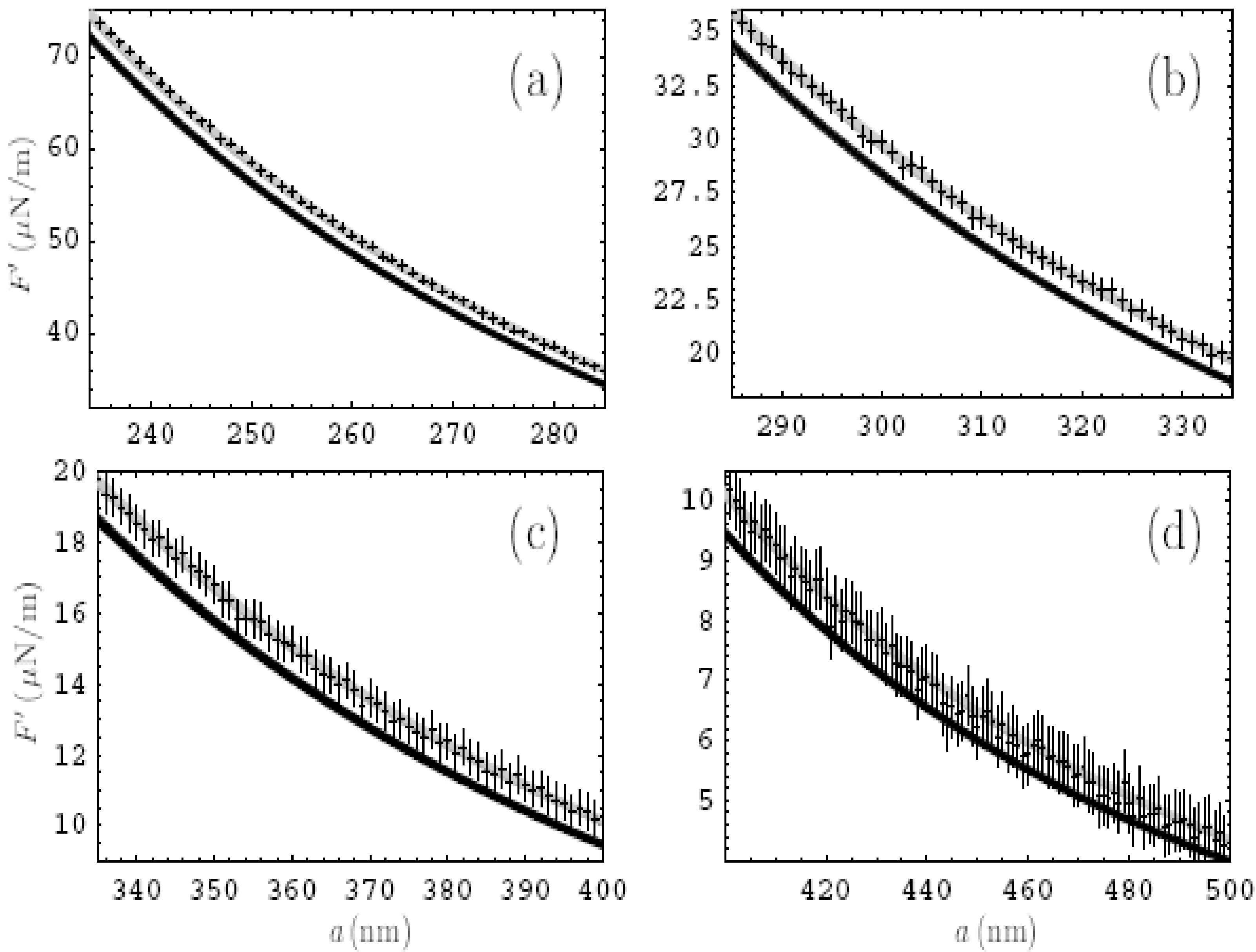
Comparison between experiment and theory





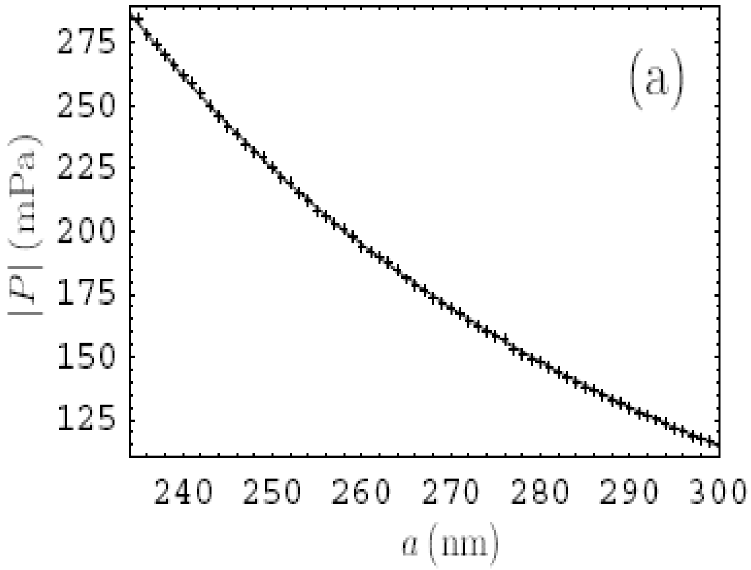
The relative experimental error (at a 95% confidence level) varies from 0.19% at 162 nm to 0.9% at 400 nm and 9% at 746 nm.

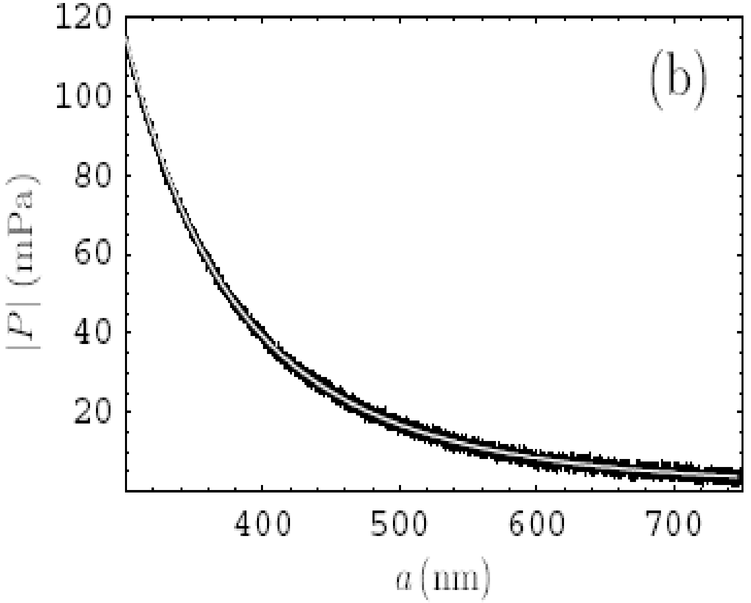
The Drude model is excluded by the data at a 95% confidence level.



(a)
(b)
(c)
(d)
F' (μN/m)
F' (μN/m)
a (nm)
a (nm)

Comparison between two experiments





Measurement data obtained using an AFM are shown as crosses with total experimental errors determined at a 67% confidence level.
Black (a) and white (b) lines show measurement results obtained using a micromachined oscillator.

4.2 Optical modulation of the Casimir force

1. Need to increase carrier density from 10^{14} (impure dielectric) to 10^{19} /cc (metal):

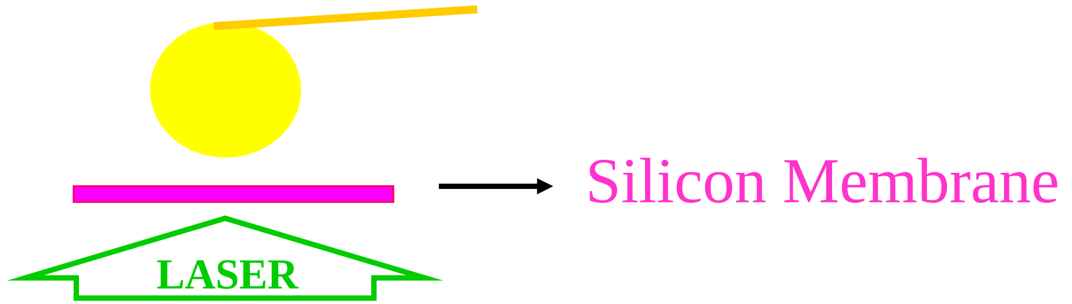
   long lifetimes + thin membranes

2. Flat bands at surface and no surface charge traps:

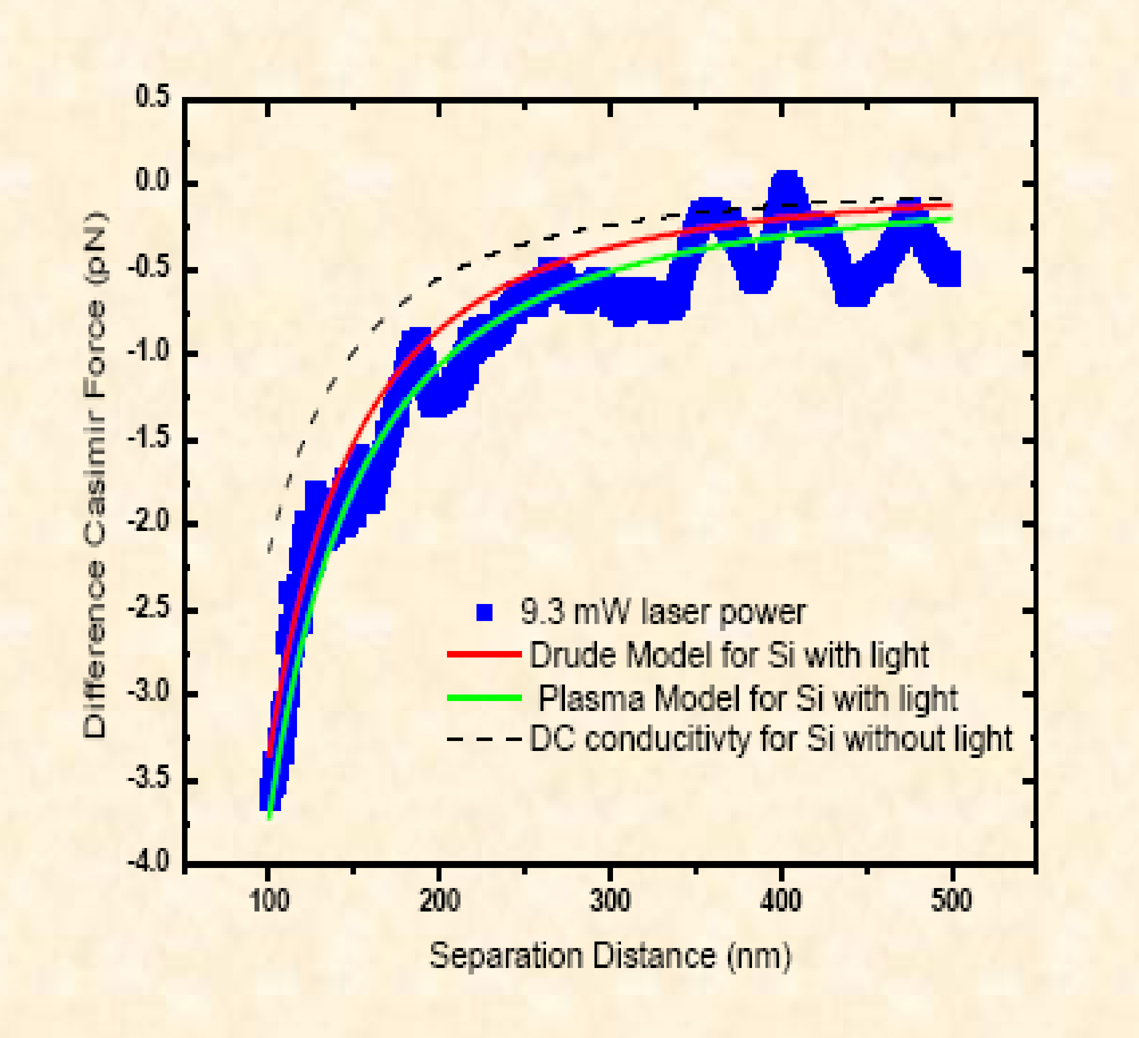
   control electrostatic forces

3. Allow excitation from bottom to reduce photon pressure systematics

4. Need 2-3 micron thick samples to reduce transmitted photon force (optical absorption depth of Silicon= 1 micron)



Comparison of experiment with theory using different models of permittivity

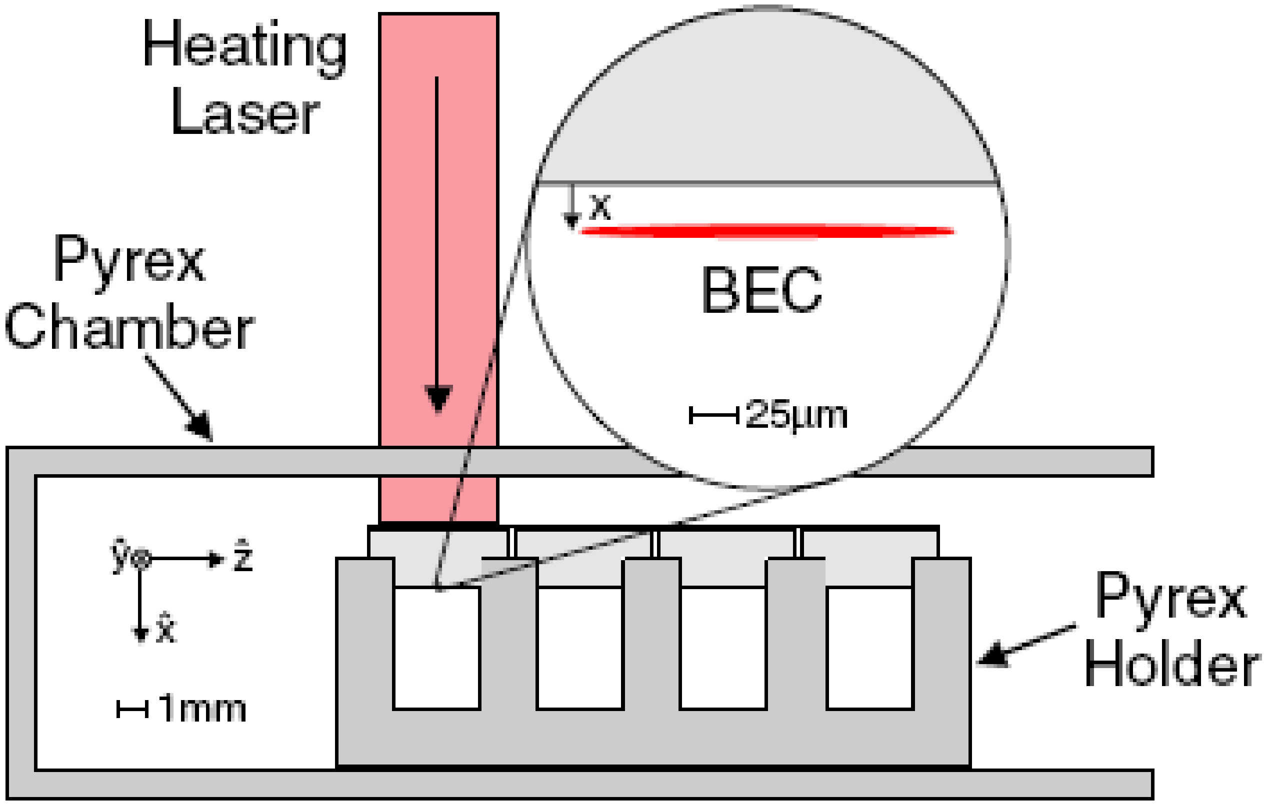


Within error bars one cannot discriminate between Drude and plasma model for high-conductivity silicon

Inclusion of DC conductivity for high-resistivity Si (in dark phase) does not agree with experimental results

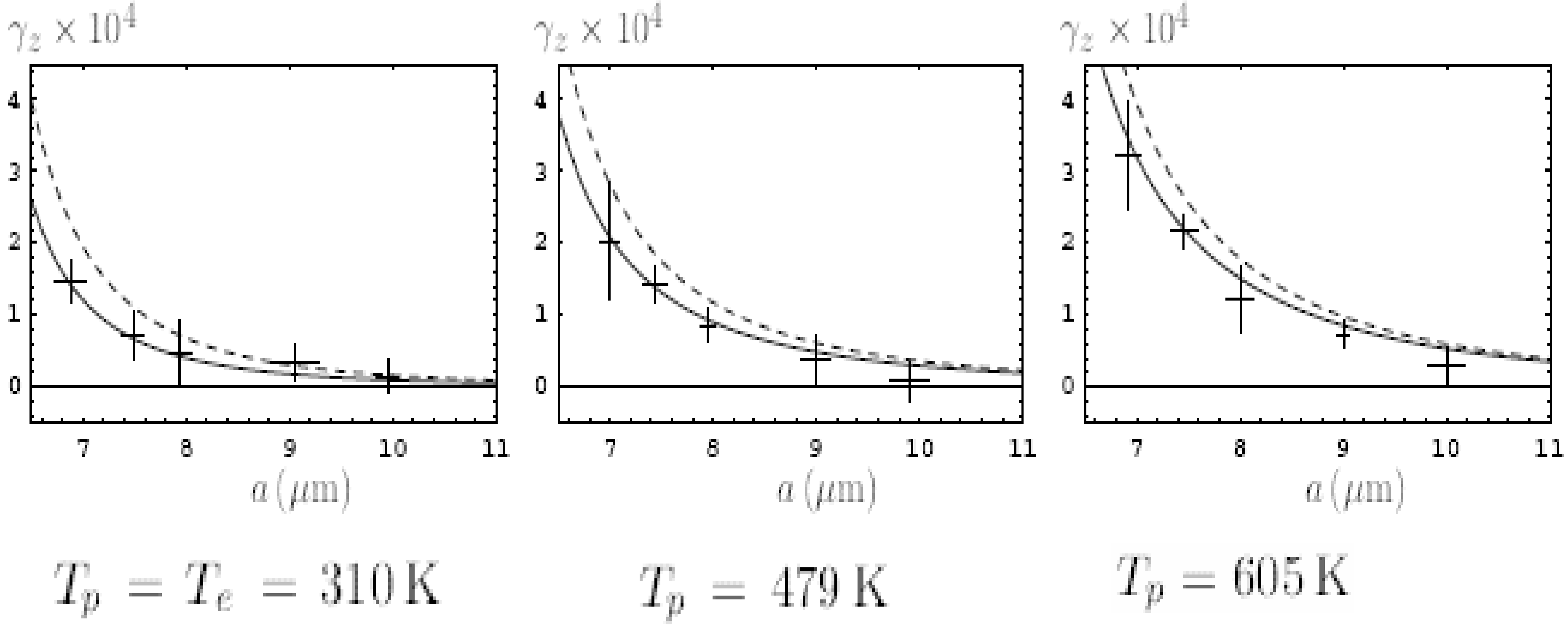
Chen, Klimchitskaya, Mostepanenko, Mohideen, Optics Express (2007); Phys. Rev. B (2007).

4.3 Measurements of thermal Casimir-Polder force



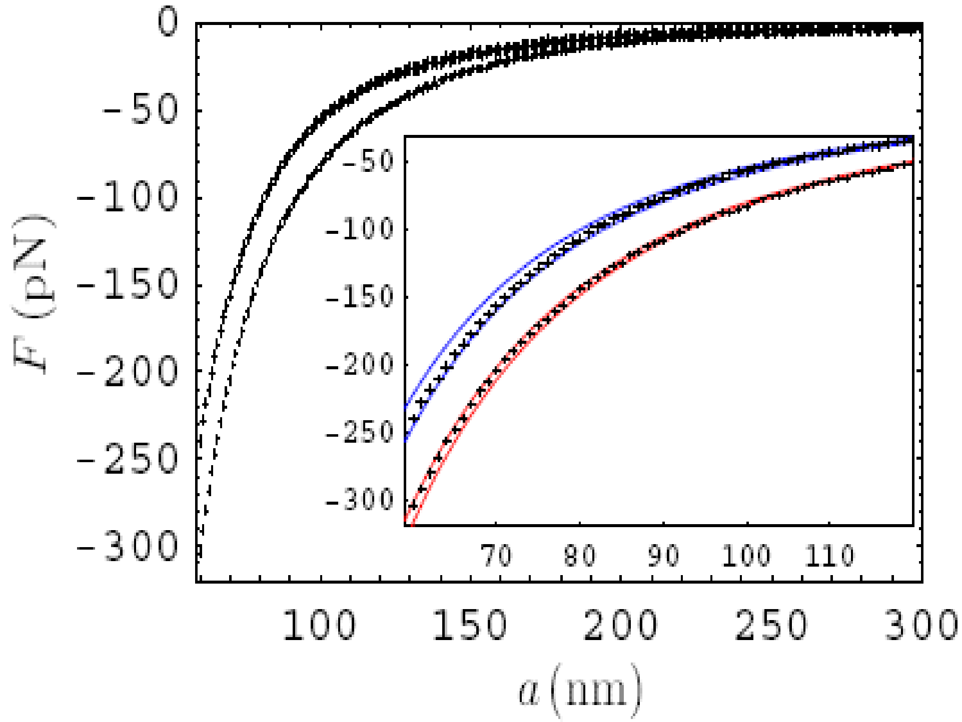
Obrecht, Wild, Antezza, Pitaevskii, Stringari, Cornell, Phys.Rev.Lett. (2007).

Experiment is performed through measuring center-of-mass oscillations of Bose-Einstein condensate of Rb atoms below a SiO2 plate



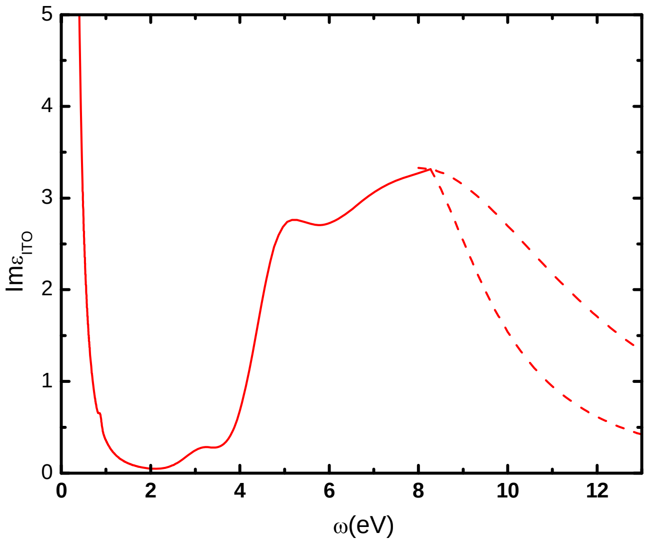
Obrecht, Wild, Antezza, Pitaevskii, Stringari, Cornell, Phys. Rev. Lett. (2007); Klimchitskaya, Mostepanenko, J. Phys. A (2008).

4.4 Dispersion forces acting on ITO test bodies

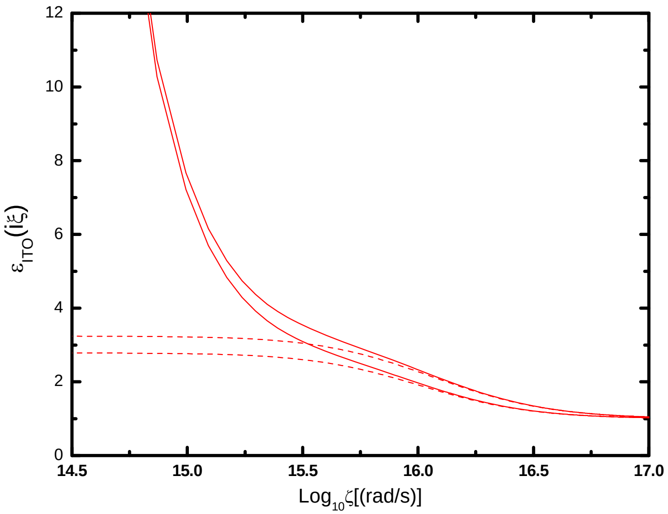


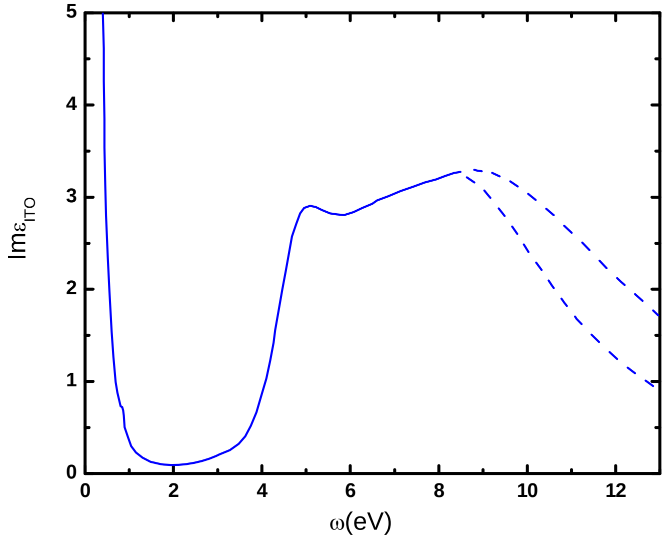
Chang, Banishev, Klimchitskaya, Mostepanenko, Mohideen, Phys. Rev. Lett. (2011); Phys. Rev. B (2012).

Dielectric permittivity of ITO as a function of frequency

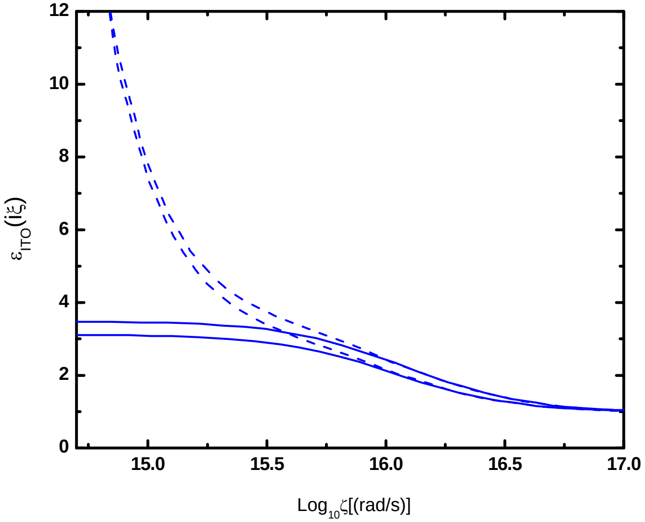


No UV

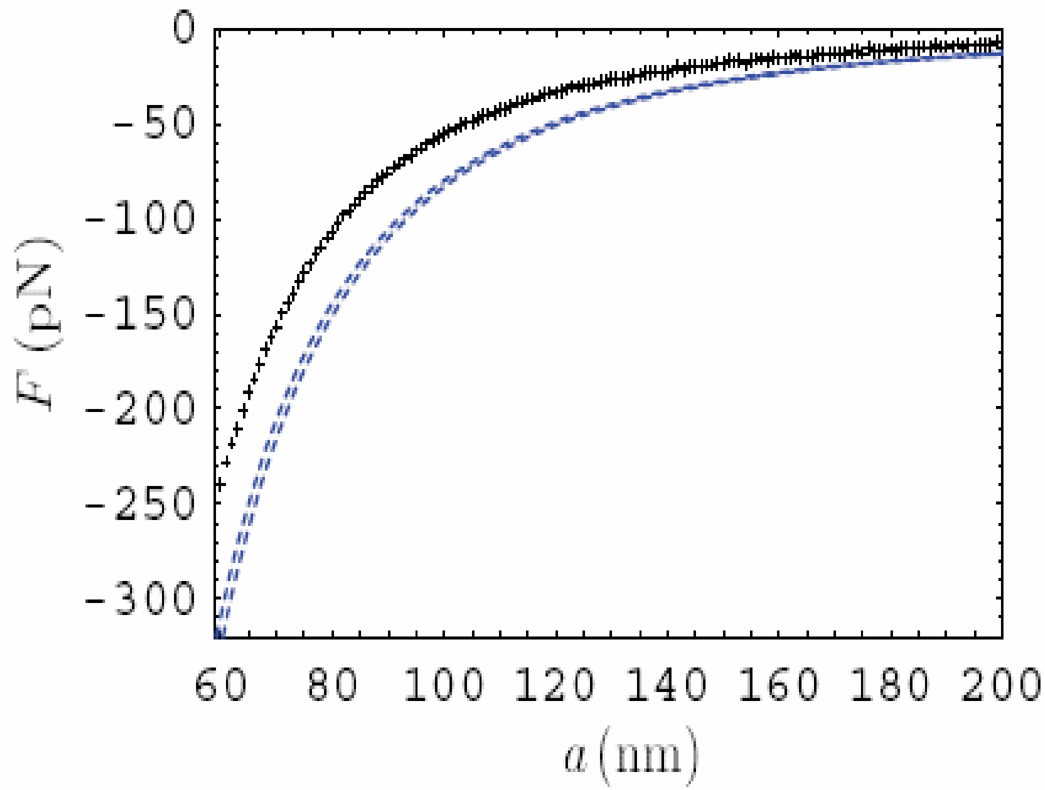




After UV



Almost no difference in dielectric permittivities before and after UV treatment.



0
-50
-100
-150
-200
-250
-300
F (pN)
60
80
100
120
140
160
180
200
a (nm)

4.5 Measurements with ferromegnetic test bodies

The gradient of the Casimir force between a sphere and a plate covered by Au-Ni and Ni-Ni layers, respectively, was measured using an atomic force microscope.

Banishev, Chang, Klimchitskaya, Mostepanenko, Mohideen, Phys. Rev. B (2012);
Banishev, Klimchitskaya, Mostepanenko, Mohideen, Phys. Rev. Lett. (2013), Phys. Rev. B (2013).

Ferromagnets: $\mu(0) \gg 1$ at $T < T_C$

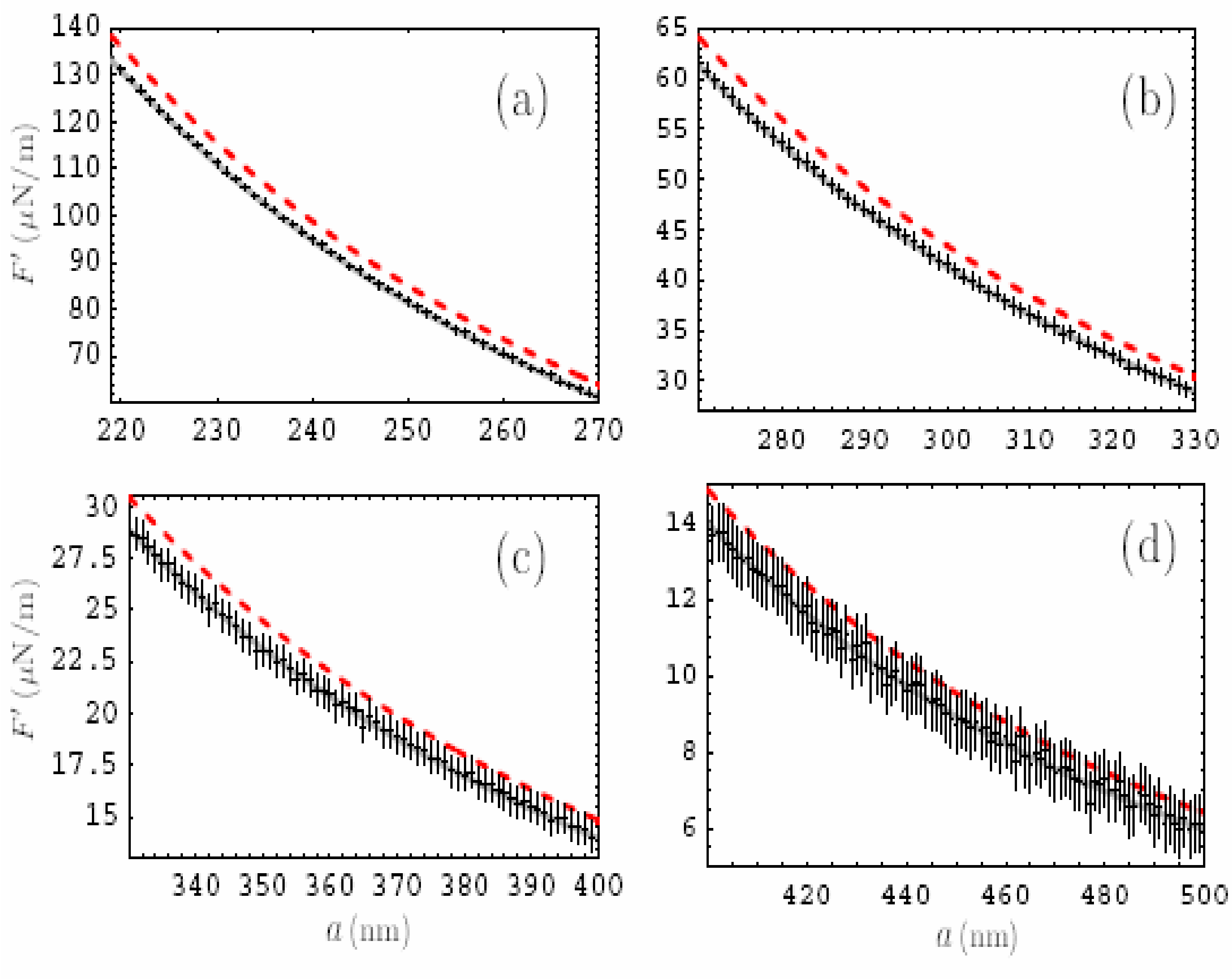
$$\mu(\mathrm{i}\xi) \approx 1 \text{ at } \xi \text{ above } \begin{cases} 10^4\,\mathrm{Hz} & \textbf{ferromagnetic metals} \\ 10^9\,\mathrm{Hz} & \textbf{ferromagnetic dielectrics} \end{cases}$$

The first Matsubara frequency at room temperature is $\xi_1 \sim 10^{14}\,\mathrm{Hz}$

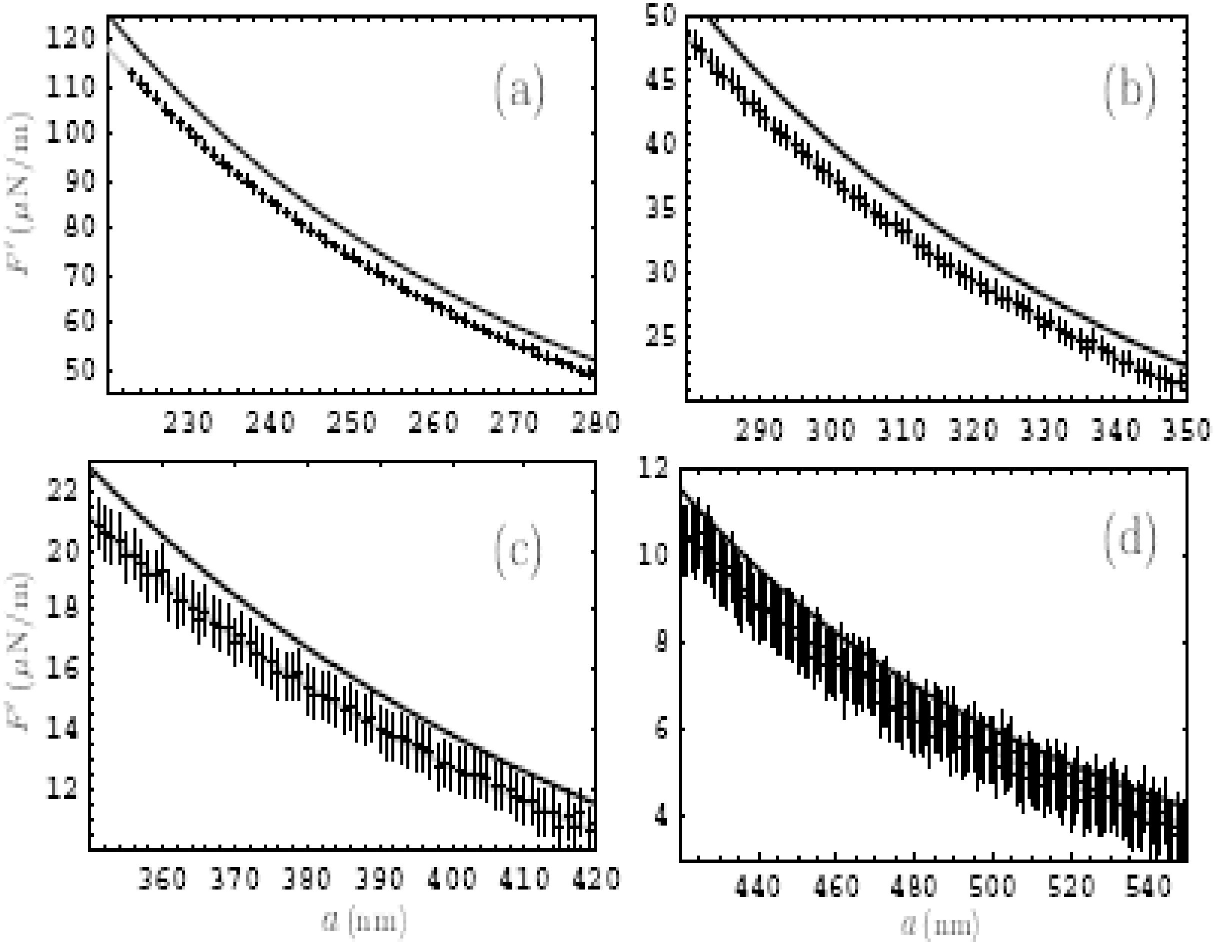
Ferromagnets may affect the Casimir force between macroscopic bodies ONLY through the contribution of the ZERO-FREQUENCY term of the Lifshitz formula.

Geyer, Klimchitskaya, Mostepanenko,
Phys. Rev. B (2010), Int. J. Mod. Phys. A (2010).

Comparison between experiment and theory for an Au sphere above a Ni plate



Comparison between experiment and theory for a Ni-coated sphere and a Ni plate

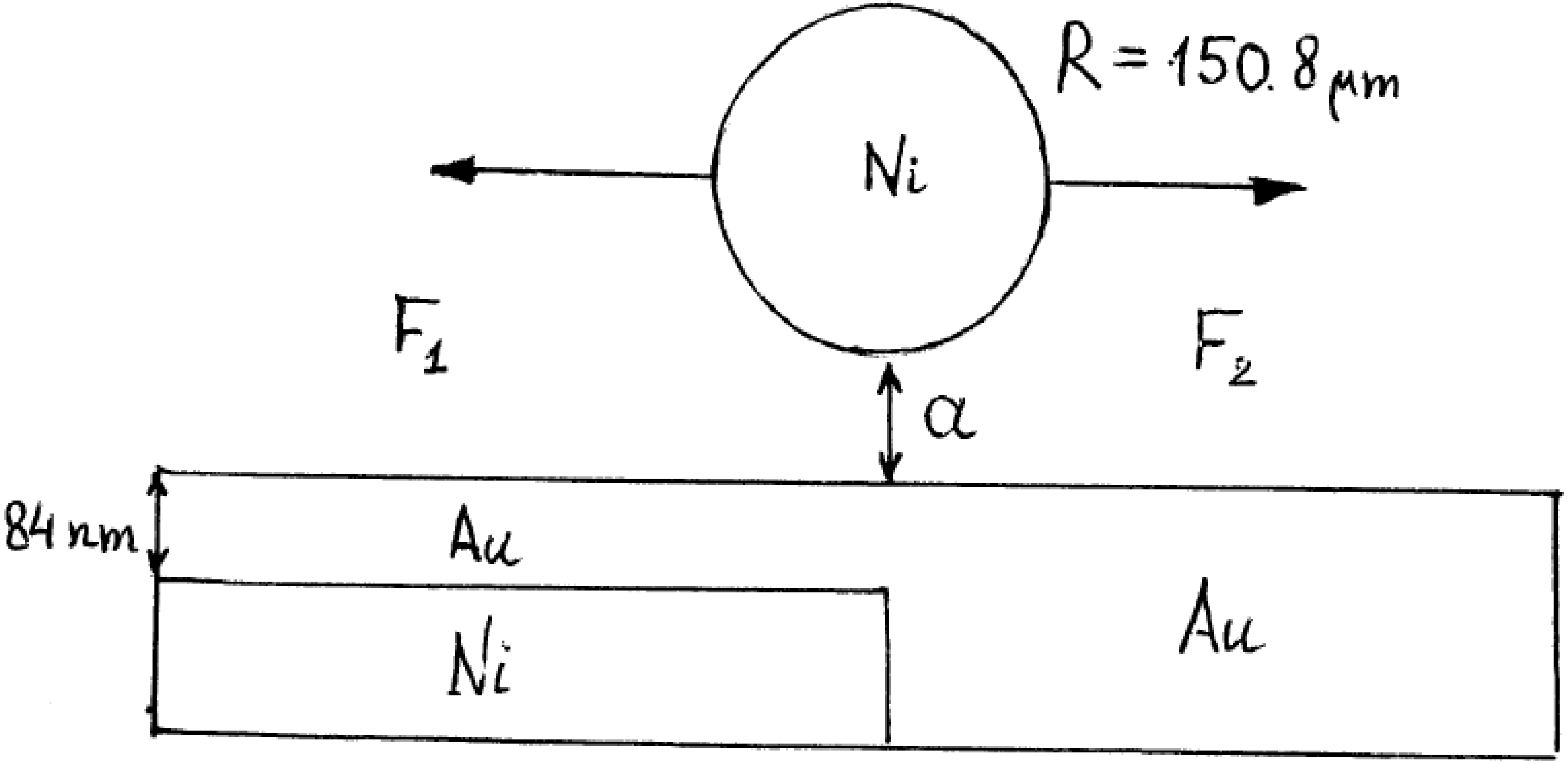


New experiment by Decca and Bimonte

The difference of the Casimir forces between a Ni-coated sphere and either a Au or a Ni strips covered by a Au over-layer was measured. The predicted magnitudes for this difference using the Drude and the plasma models are of orders of 1200 fN and 1fN, respectively.

THE DATA ARE FOUND TO BE IN AGREEMENT WITH THE PLASMA MODEL AND EXCLUDE THE DRUDE MODEL.

Bimonte, Phys. Rev. Lett. (2014); Decca, Talk at “Materials Relevance in Fluctuation-Induced Interactions”, Cancun, Mexico, August, 2014.



$$(F_2 - F_1)_P \approx 0.8 \times 10^{-15}\,N$$

$$(F_2 - F_1)_D \approx 10^{-12}\,N$$

5. CONCLUSIONS

1. **Dispersion forces caused by the electromagnetic fluctuations attracted much recent attention in both fundamental physics and nanotechnology.**

2. **There are contradictions between theoretical predictions of the Lifshitz theory and basic principles of thermodynamics and statistical physics.**

3. **The same predictions are also in contradiction with several experiments performed by three experimental groups with metallic, dielectric and semiconductor test bodies. During 2014 the results of these experiments acquired a status of the solid facts.**

4. **Thus, there is a demand for changes in fundamentals of physics related to the interaction of quantum fluctuations with matter, including the fluctuation-dissipation theorem.**