Fluctuation-induced forces: from van-der-Waals to quantum friction

Outline:

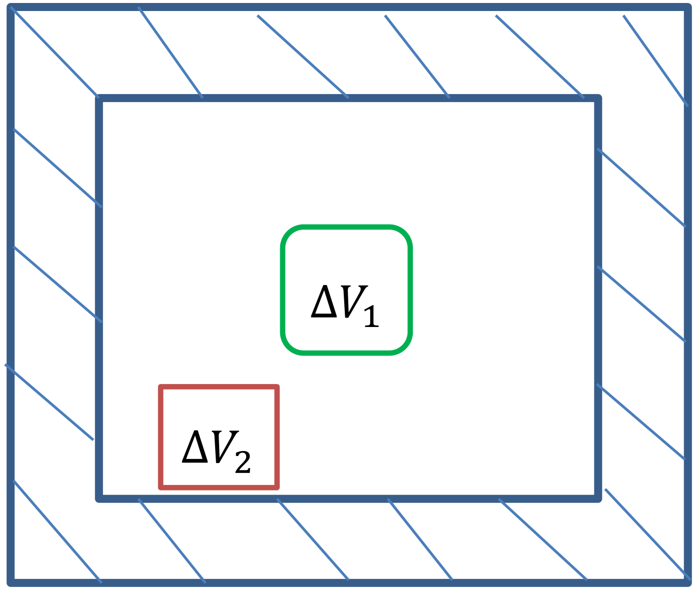
1) Fluctuating EM fields near the surface of a material
2) Casimir-Lifshitz forces and related phenomena
3) Fluctuation-induced forces out of equilibrium

I. Brevik, B.S., M. Sliveirinha, IJMP **A37**, 2241012 (2022) (Special Issue)

Acknowledgments: J. Avron, J. Feinberg, O. Kenneth, U.Sivan

Planck's formula

$u_0(\omega, T)\Delta\omega\Delta V$ - the energy in volume ΔV and frequency interval $\Delta\omega$ at temperature T



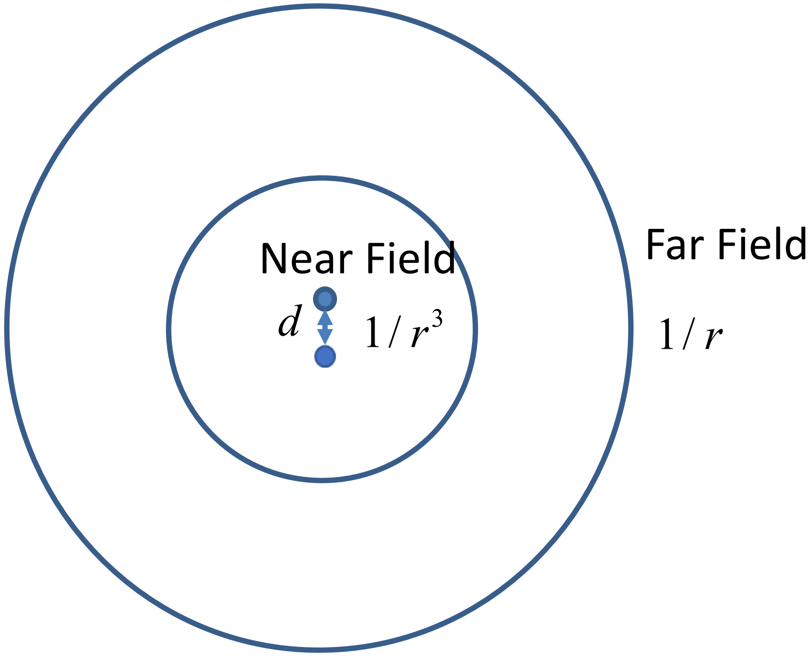
$$u_0(\omega, T) = \frac{\omega^2}{\pi^2 c^3} \frac{\hbar\omega}{\exp(\frac{\hbar\omega}{k_B T}) - 1}$$

Correct for ΔV_1 but not for ΔV_2

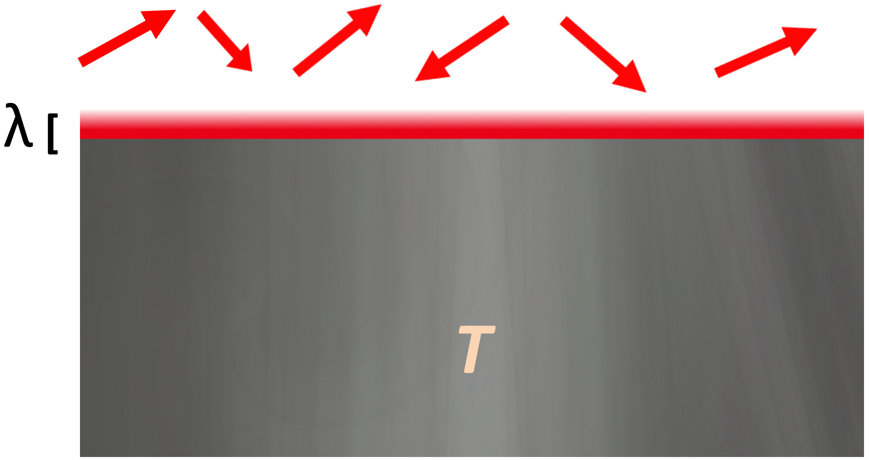
- Close to the wall means $d \ll \lambda$

Fluctuations in the near field

Near and Far Field of an oscillating point dipole:

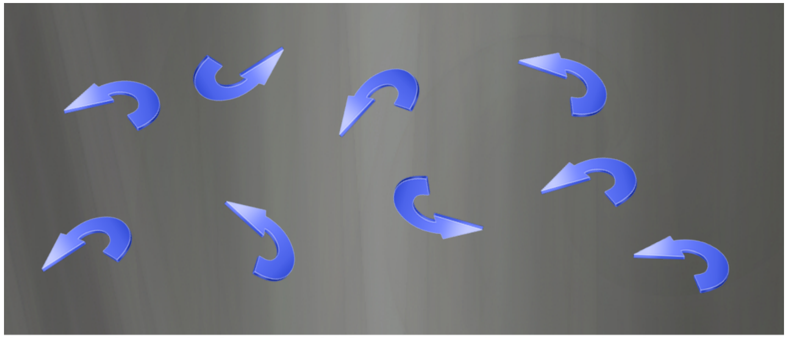


Near Field: for $r < \lambda$



Close to the surface of a body there is a fluctuating EM field of large intensity. This field is evanescent.

A microscopic picture of the thermal (and quantum) fluctuations of the EM field



$\varepsilon(\omega)$ - The dielectric function of the material

$\vec{J}(\vec{r},t)$ - Fluctuating currents (noise)

$<\vec{J}> = 0$

Fluctuation-dissipation Theorem (FDT)

$$\langle J_\alpha(\vec{r},\omega) J^*_\beta(\vec{r}\,',\omega')\rangle = \delta_{\alpha\beta}\frac{\hbar\,\omega^2}{8\pi^2}\mathrm{Im}[\varepsilon(\omega)]\coth\left[\frac{\hbar\omega}{2k_BT}\right]\delta(r-r')\delta(\omega-\omega')$$

* In the classical limit $(\hbar\omega \ll k_BT)$, $\coth\left[\frac{\hbar\omega}{2k_BT}\right] \to \frac{2k_BT}{\hbar\omega}$

* In the T $\to$ 0 limit, $\coth\left[\frac{\hbar\omega}{2k_BT}\right] = 1.$

Equations of stochastic electrodynamics

$$\mathrm{rot}\,\overrightarrow{E} = i\frac{\omega}{c}\overrightarrow{B}$$

$$\mathrm{rot}\,\overrightarrow{B} = -i\frac{\omega}{c}\varepsilon(\omega)\ \overrightarrow{E} + \frac{4\pi}{c}\ \overrightarrow{J}\,(\overrightarrow{r},\omega)$$

* These equations, supplemented with the FDT, contain the Planck law, the Casimir-Lifshitz forces and many other things, including Nyquist noise in electrical circuits.

Infinite Uniform Medium

Consider transparent medium, $\mathrm{Im}\,\varepsilon \to 0, \quad \sqrt{\mathrm{Re}\,\varepsilon(\omega)} \equiv n(\omega)$

$$u(\omega, T) = \hbar\omega \left[\frac{1}{2} + \frac{1}{\exp\left(\frac{\hbar\omega}{k_B T}\right) - 1} \right] \frac{\omega^2 n^2}{\pi^2 c^3} \frac{d(n\omega)}{d\omega}$$

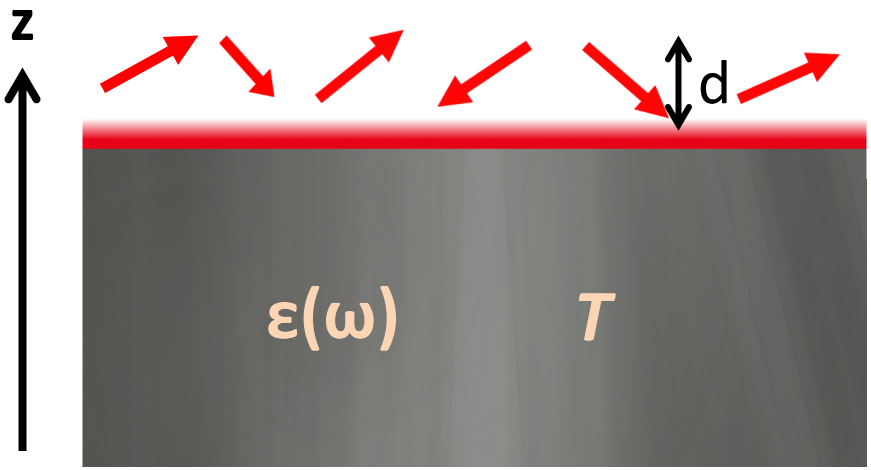
For $n \to 1$ Planck (plus the zero-point energy term)

Correlation function:

$$\langle \vec{E}(\vec{r}, \omega) \cdot \vec{E}^*(\vec{r}', \omega') \rangle = 4\pi \frac{\hbar\omega^2}{c^2 R} \sin\left(\frac{\omega n R}{c}\right) \coth\left(\frac{\hbar\omega}{2k_B T}\right) \delta(\omega - \omega')$$

Vacuum limit: $n \to 1, \quad T \to 0$

Thermal EM fields close to a surface



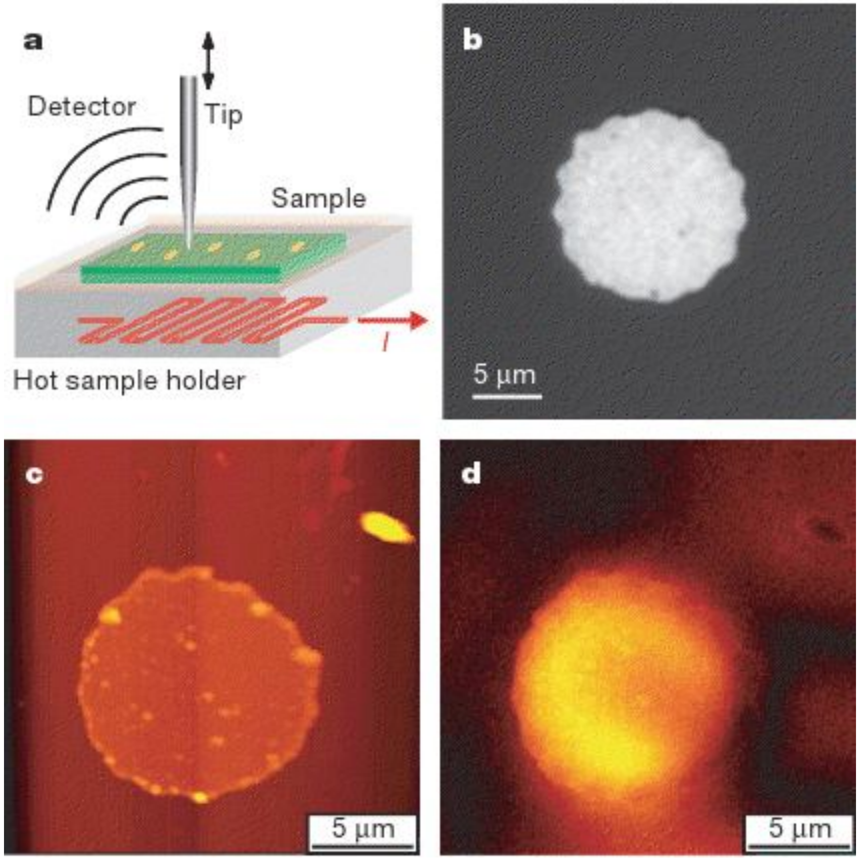
d is the distance from the surface of the sample.

For $d \ll \lambda$,

$$u(\omega, T, d) = \frac{\pi}{4} u_0(\omega, T) \left(\frac{c}{\omega d}\right)^3 \frac{\mathrm{Im}\,[\varepsilon(\omega)]}{|\varepsilon(\omega)+1|^2}$$

For $d \gg \lambda$ – Planck, $u_0(\omega, T)$

Passive near-field imaging

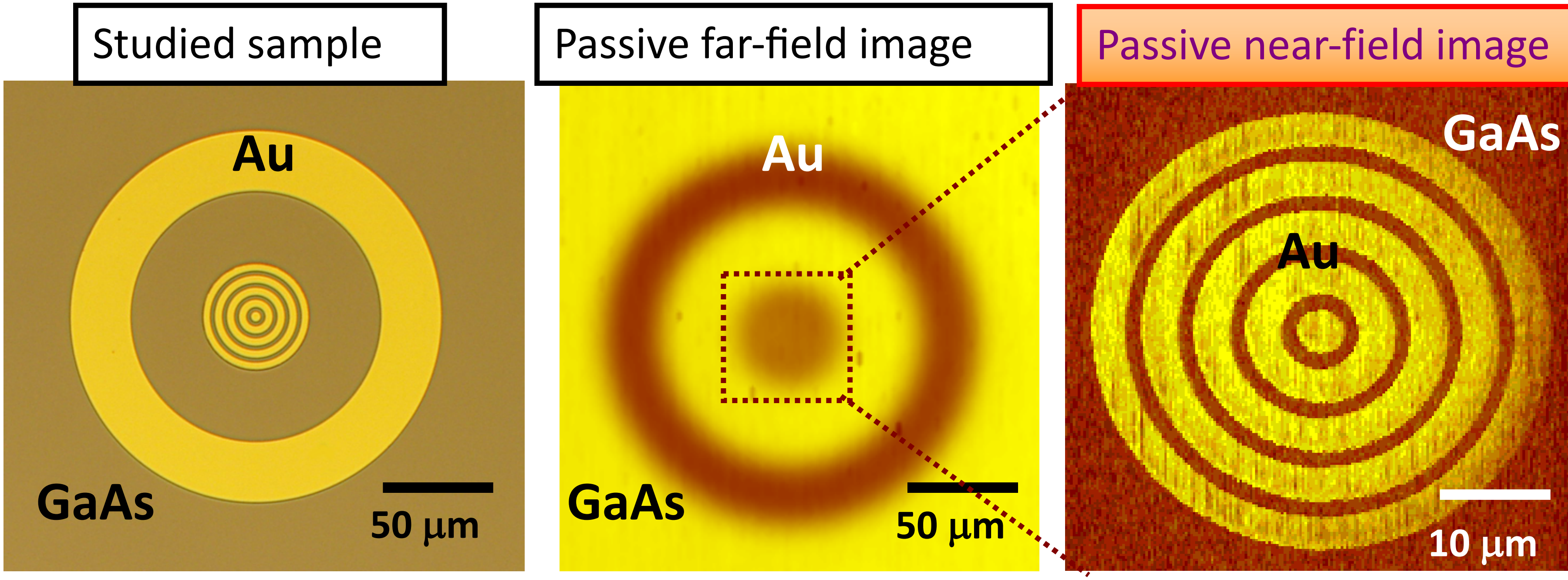


Experimental sketch (a) and images (b, c, d) of gold disks evaporated on a SiC substrate. (b), Image taken with a camera through a NA =0.9 microscope objective with visible illumination. (c), AFM topography of the gold structure on SiC, and (d) Image recorded at T =170 ^{o}C, showing the infrared near-field thermal emission scattered by the tip.

*From de Wilde et al, Nature, 444, 740 (2006)

Passive near-field imaging

Wavelength: 14.5 μm

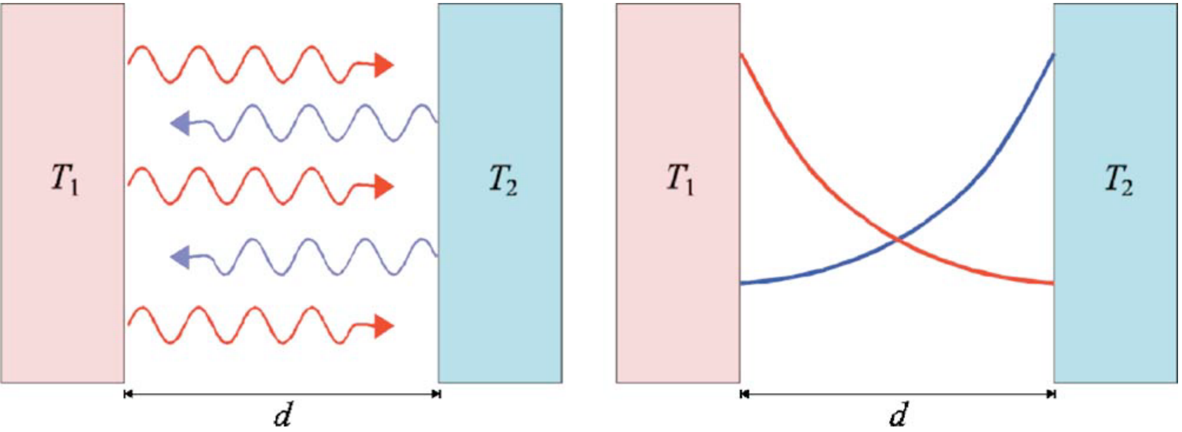


Spatial resolution:15 μm

Univ. Tokyo – Komiyama group
arXiv: 1601.00368

Some phenomena related to the evanescent thermal fields

1. Near field heat transfer



From Volokitin and Persson, Rev. Mod. Phys., (2007)

There are two modes for exchange of heat between two surfaces separated by vacuum: conventional radiative heat transfer via propagating electromagnetic waves and photon tunneling via evanescent waves.

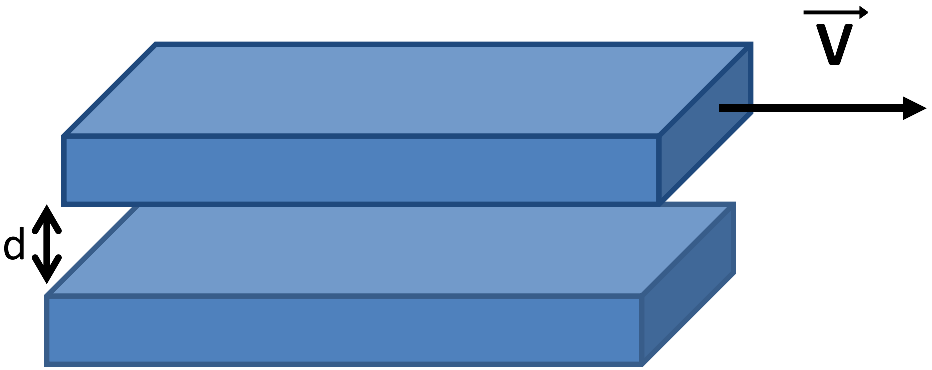
*Crossover between the two regimes occurs for:

$$d \simeq \frac{c\hbar}{k_B T}$$

(~ 10μ at T = 300° k)

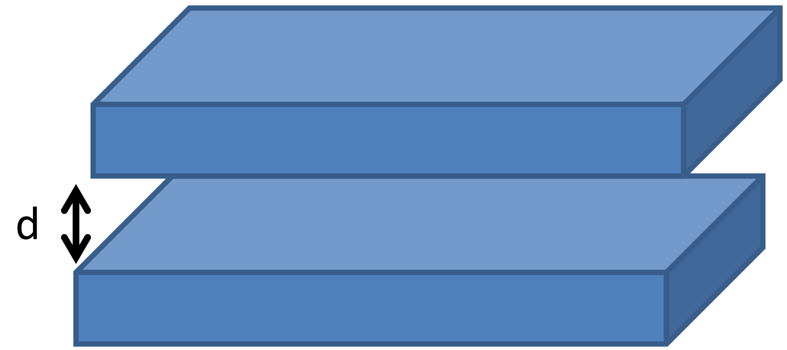
Some phenomena related to the evanescent thermal fields

2. Non–contact friction



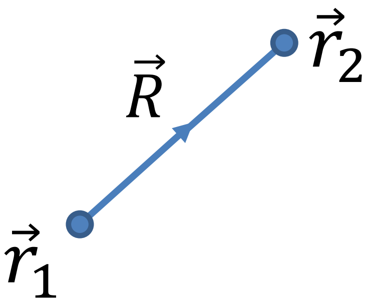
Two bodies separated by a gap, d, experience friction when one slides.

3. Casimir-Lifshitz forces



A force between two bodies in equilibrium separated by a gap.

Fluctuation Induced Forces: Van der Waals



$\vec{P}_{sp}(\vec{r}_1, t)$-spontaneously fluctuating dipole of atom 1.

$\vec{E}(\vec{r}_2, t)$-field created by this dipole at point 2. $(E \sim 1/R^3)$

$\vec{P}_{ind}(\vec{r}_2, \omega) = \alpha_2(\omega)\vec{E}(\vec{r}_2, \omega)$ - the dipole induced in atom 2.

The interaction energy $U(R)$ between $\vec{P}_{sp}$ and $\vec{P}_{ind}$ is proportional to $1/R^6$.

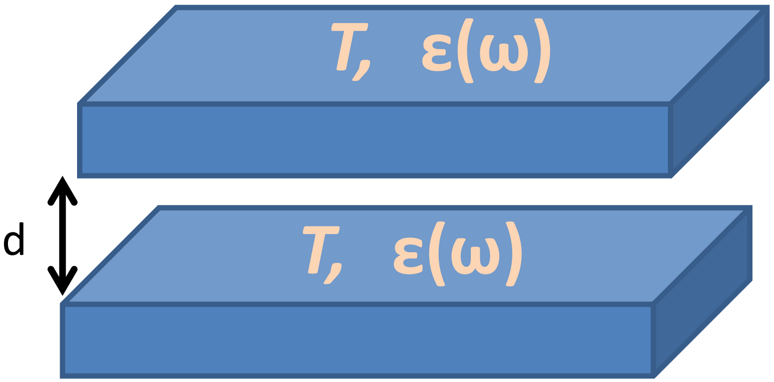
We need the Fluctuation Dissipation Theorem:

$$\left\langle P_{sp,x}^2 \right\rangle_\omega = \hbar\alpha''(\omega)\coth\frac{\hbar\omega}{2k_BT} \qquad F \sim \frac{\hbar\omega_0\alpha^2(0)}{R^7}$$

* True for atoms, molecules or nanoparticles.

* No retardation - otherwise Casimir-Polder.

Lifshitz theory



F - force per unit area

A simple limit: $\frac{c}{\omega_0} << d << \frac{\hbar c}{\mathrm{T}}$

$$\mathrm{F} = -\frac{\pi^2}{240}\frac{\hbar \mathrm{c}}{\mathrm{d}^4}\frac{\varepsilon_0 - 1}{\varepsilon_0 + 1}\mathrm{f}(\varepsilon_0)$$

$\varepsilon_0 \equiv \varepsilon(0)$

For $\varepsilon_0 \to \infty,\ f = 1$

$$F = -\frac{\pi^2}{240}\frac{\hbar c}{d^4}$$

(Casimir, 1948)

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Precision Measurement of the Casimir Force from 0.1 to 0.9 μm

U. Mohideen* and Anushree Roy

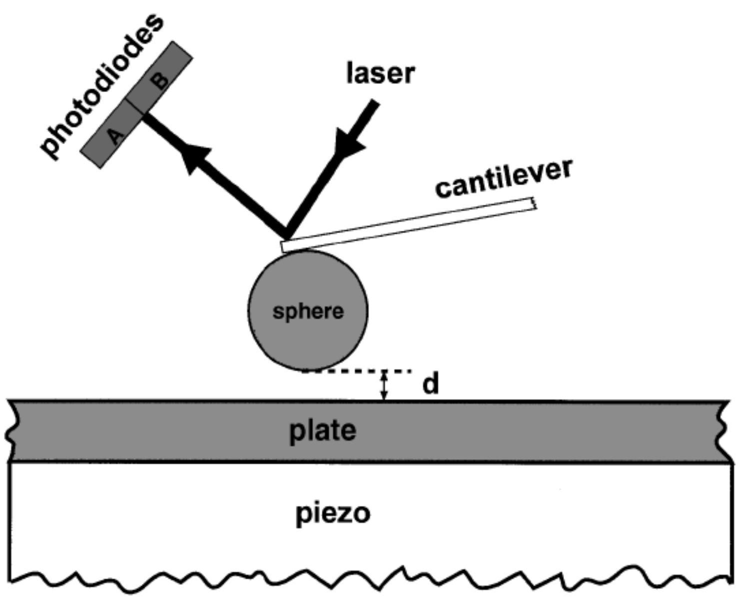


FIG. 1. Schematic diagram of the experimental setup. Application of voltage to the piezo results in the movement of the plate towards the sphere. The experiments were done at a pressure of 50 mTorr and at room temperature.

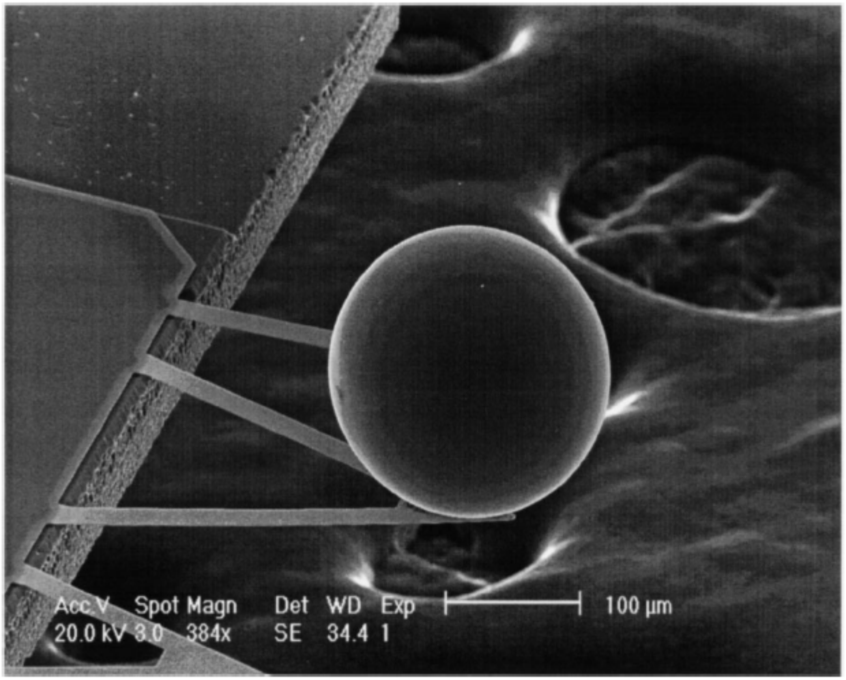
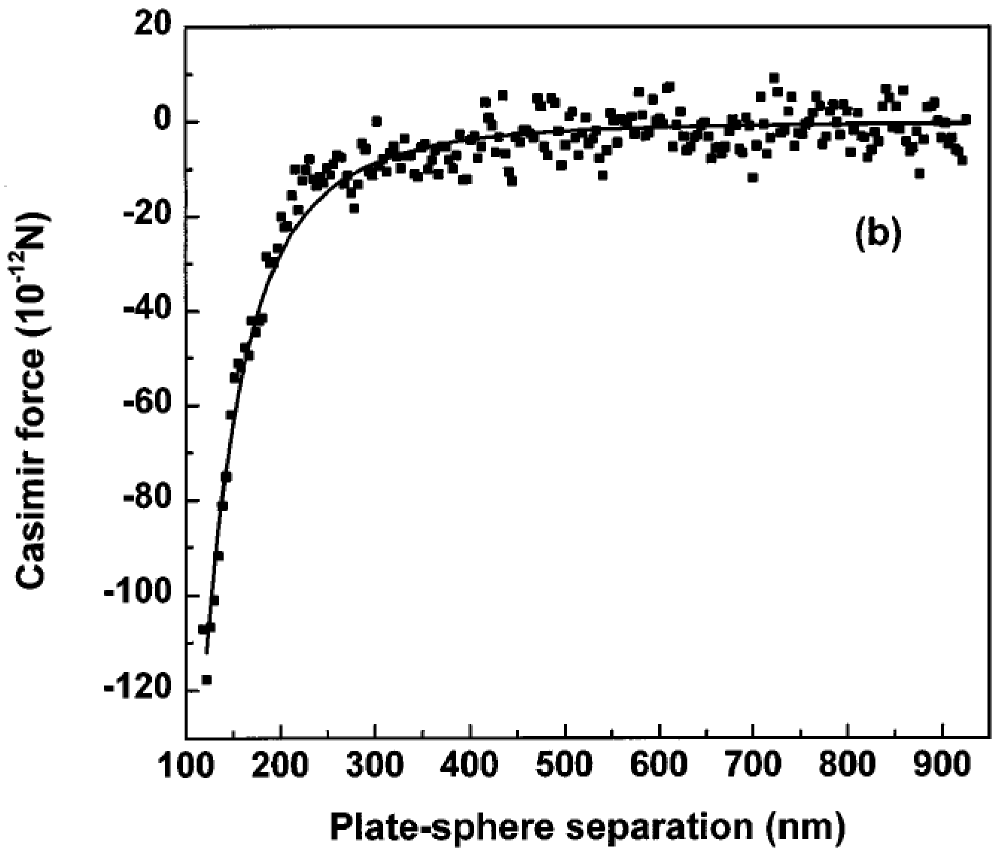
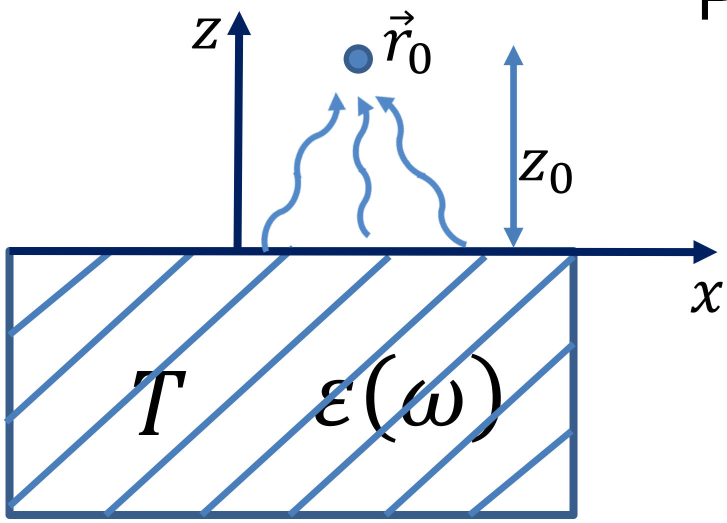


FIG. 2. Scanning electron microscope image of the metallized sphere mounted on a AFM cantilever.



20
0
-20
-40
-60
-80
-100
-120
Casimir force (10-12N)
(b)
100
200
300
400
500
600
700
800
900
Plate-sphere separation (nm)

Atom – surface interaction



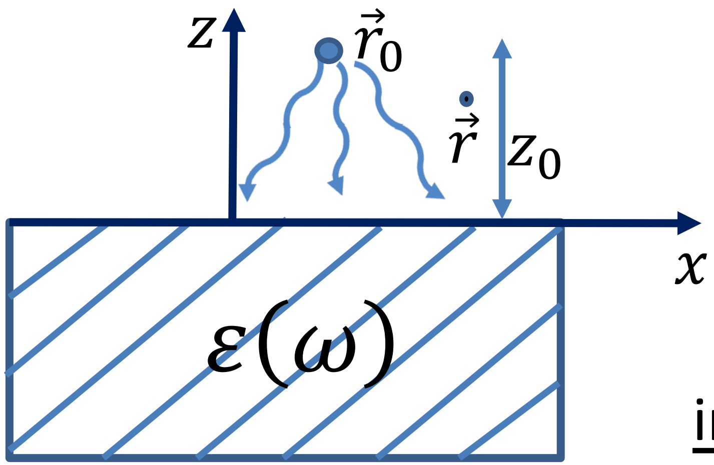
Particle at distance z_0 from the surface.

$E(\vec{r}_0, \omega)$- fluctuating EM field at $\vec{r}_0$

$$\langle E^2(\vec{r}_0)\rangle_\omega = \frac{\hbar}{z_0^3} \frac{\varepsilon''}{|\varepsilon(\omega)+1|^2} \coth\frac{\hbar\omega}{2k_B T}$$

$$U_1(z_0) = -\frac{1}{2}\int_0^\infty \frac{d\omega}{2\pi}\alpha(\omega)\langle E^2(\vec{r}_0)\rangle_\omega$$

Atom – surface interaction



Second contribution to $U(z_0)$ comes from the spontaneous fluctuations of the dipole moment of the atom.

Total force for a metallic surface, in the low temperature limit

Drude model: $\varepsilon(\omega) = 1 - \frac{\omega_p^2}{(\omega+\imath\nu)\omega}$, $\omega_p^2 = \frac{4\pi e^2 n_0}{m}$,

Atom – surface interaction

$$F_z(z_0) = -\frac{3\hbar}{8z_0^4}\alpha(0)\omega_0\frac{\omega_{sp}}{\omega_{sp}+\omega_0},$$

$\omega_{sp} = \frac{\omega_p}{\sqrt{2}}$ - Surface plasmon frequency

ω_0 - Resonant frequency of the particle.

$\alpha(0)$ - Particle susceptibility

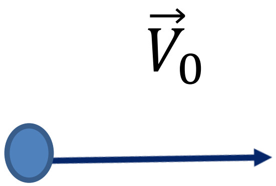
For an atom, at $z_0 \sim 10\text{nm}$, $F \sim 10^{-5}$ pN

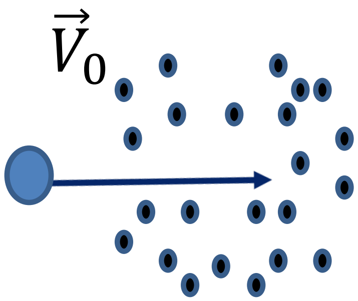
For a nanoparticle ($R \sim 10\text{nm}$), $F \sim 10$ pN

* Calculation can be extended to the case $T_{particle} \neq T_{surface}$

Non-Contact Friction

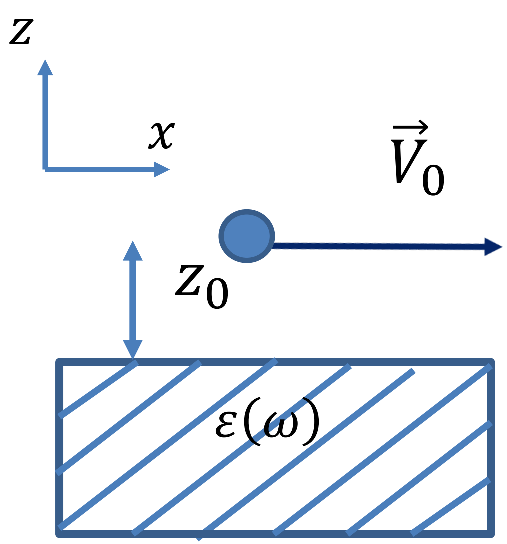
1) particle in vacuum, no friction





2) particle moving through the black body radiation experiences friction

Non-Contact Friction



Particle moving above a surface:
Non-contact friction.

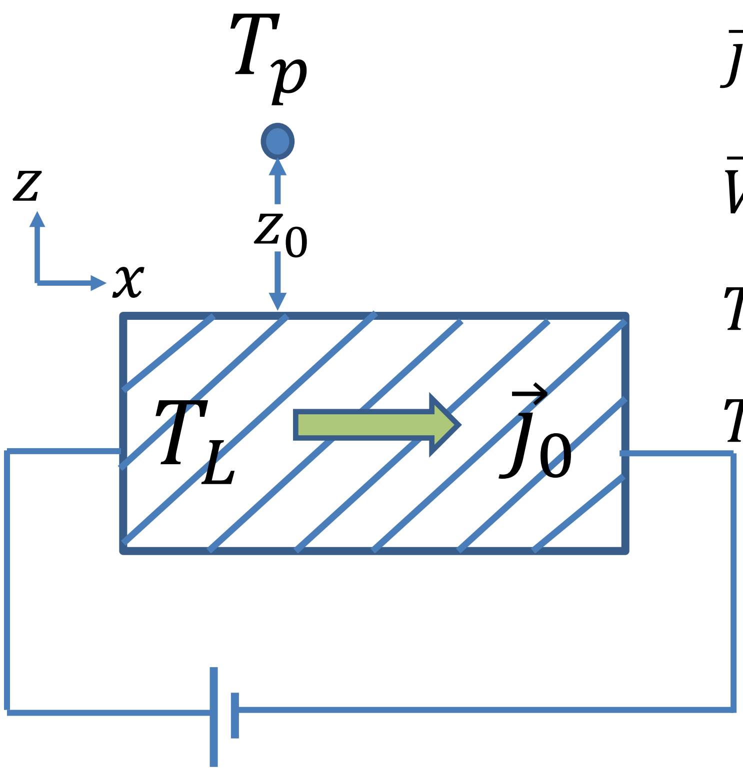
($\mathrm{T} \to 0$ - quantum friction)

A lateral force F_x appears: $\mathrm{T} \to 0$,

$$F_x \sim V_0^3 \quad \text{for} \quad V_0 \ll V_m = \omega_0 z_0 \sim 10^6 \ \text{cm/sec}$$

$$F_x \sim V_0^{-2} \quad \text{for} \quad V_0 \gg V_m$$

FIF in the presence of carrier drift



$\vec{j}_0 = en_0\vec{V}_0$ - the dc current density

$\vec{V}_0$- carrier drift velocity

T_L- temperature of the sample lattice

T_p- temperature of the particle

B.S., PRB **96** 075407 (2017).

Is there any drag on the particle?

Is the Casimir - Lifshitz force modified?

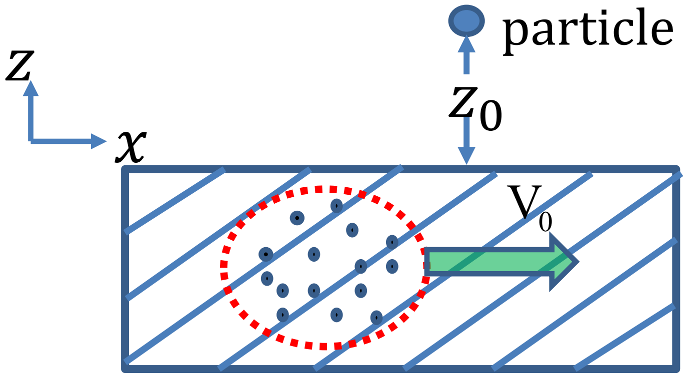
FIF in the presence of carrier drift

$$\vec{E} = \vec{E}_0 + \vec{E}(\vec{r}, t),$$

$$\varepsilon(\omega, \vec{k}) = \varepsilon_L(\omega) + \varepsilon_{el}(\omega, \vec{k})$$

$$\varepsilon_L(\omega) = \varepsilon_L'(\omega) + \iota\varepsilon_L''(\omega),$$

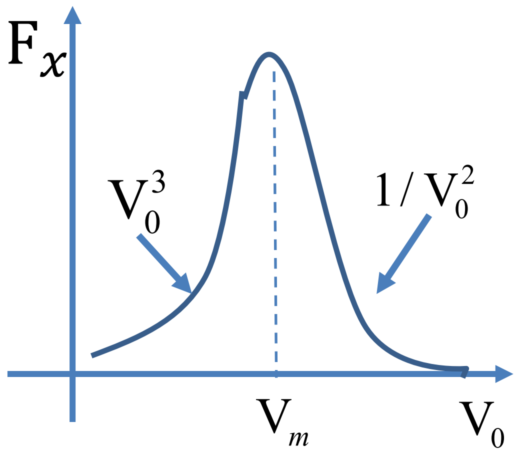
$$\varepsilon_{el}(\omega, \vec{k}) = -\frac{\omega_p^2}{(\omega - \vec{k}\cdot\vec{V}_0 + \iota\nu)(\omega - \vec{k}\cdot\vec{V}_0)}$$



electron plasma drifting on the background of the lattice

FIF in the presence of carrier drift

Model 1: spontaneous fluctuations originate in the electron plasma
$(\nu \neq 0, \varepsilon_L'' = 0)$ For $T \to 0$,



$F_x \propto V_0^3$ $(V_0 \ll V_m \sim 10^6$ cm/sec)

$F_x \propto V_0^{-2}$ $(V_0 \gg V_m)$

* F_x at maximum is comparable with Casimir-Lifshitz force

FIF in the presence of carrier drift

Model 2:

Spontaneous fluctuations originate in the lattice $(\varepsilon_L'' \neq 0, \nu = 0)$

Drag appears only if $T_p \neq T_L$

$$F_x \sim \frac{\alpha(0)\ \varepsilon_L''\ \omega_{sp}^2}{z_0^5\ \omega_0^3} V_0\ (T_L - T_p) \qquad (V_0 \ll V_m)$$

The drag force can have either sign.

- Possible experiments

Conclusion

- All bodies are "dressed" by fluctuating EM fields.
- These fields give rise to phenomena like Casimir-Lifshitz forces, non-contact friction, and more...