Casimir effect in Napoli

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Summary

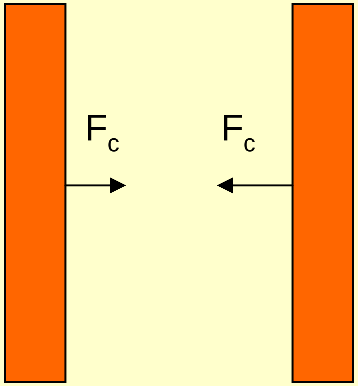
1) The Aladin2 experiment.
2) The Casimir effect and the equivalence principle, or the "weight of the vacuum"
3) Thermal corrections to the Casimir pressure and radiative heat transfer: a proposal for a new experiment.

The Casimir effect

The Casimir effect is a manifestation of retarded Van der Waals forces between neutral macroscopic bodies, that arise from zero-point quantum   fluctuations of the e.m. field.

It is one of the rare quantum phenomena that can be seen on a macroscopic scale.

For two perfectly conducting parallel plates, at T=0, Casimir (1948) obtained an attractive force between the plates, of magnitude:



$$F_C = \frac{\pi^2 \hbar c}{240 L^4} A$$

A = area of the plates

L= distance between the plates

The proportionality of F_c to ħ reveals the quantum origin of the effect

For A= 1 cm^2 and L=1 μm $\quad$ F_c=1.3 10^{-7} N

By modern experimental techniques, this force has now been measured with a precision of a few percent (the most accurate measurements are for the shpere-plate geometry)

The Aladin2 experiment

SCIENTIFIC MOTIVATIONS

- First direct measurement of the variation of Casimir energy in a rigid cavity.
- First demonstration of a phase transition influenced by vacuum fluctuations

Aladin has been selected by INFN as a highligth experiment in 2006

PARTICIPATING INSTITUTIONS

- INFN - Naples (Italy)

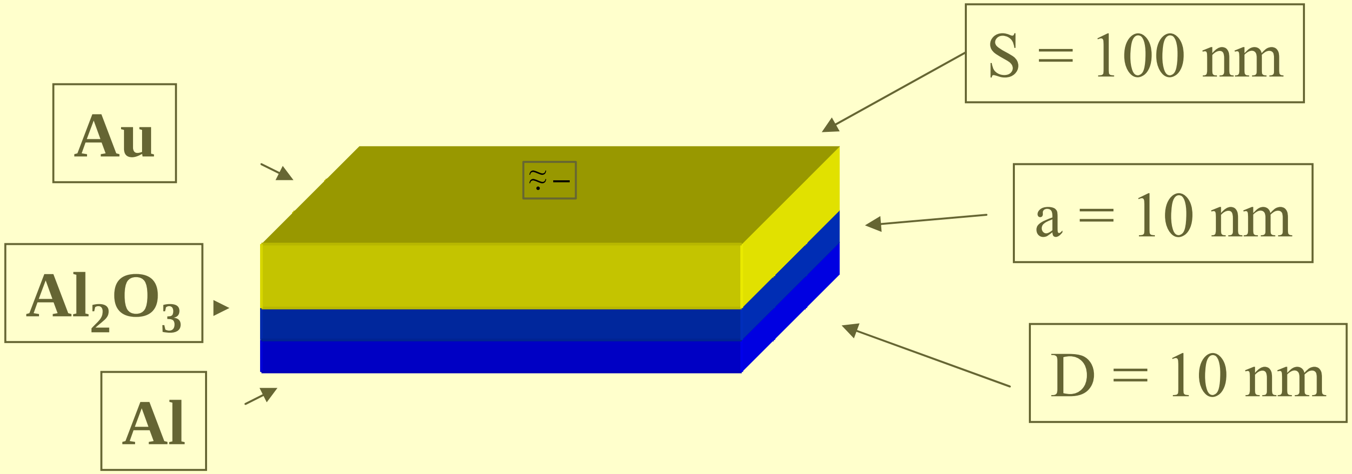
- IPHT (Institute for Physical High Technology) - Jena (Germany): U.Hubner , E. Il'Ichev

- Federico II University – Naples (Italy): E. Calloni (principal investigator), G. Bimonte, G. Esposito, L. Milano L. Rosa, R. Vaglio

- Seconda Università di Napoli -Aversa (Italy): F. Tafuri, D. Born

We have realized two-layer systems, consisting of identical thin superconducting Al film, covered with an equal thickness of oxide. A cavity is obtained by covering some of the samples with a thick cap of a non-superconducting metal (Au).

A three layer cavity



1) The Casimir pressure on the outer layers and the Casimir energy stored in the cavity depend on the reflective power of the layers, as the latter determine the spectrum of e.m. modes that can exist in the cavity.

2) The optical properties, in the microwave region, of a metal film change drastically when it becomes superconducting.

Therefore:

The Casimir pressure and energy change when the state of the film passes from normal to superconducting

The change in the Casimir pressure determined by the superconducting transition in the Al film is extremely small (of fractional order 10^{-8} or so) and practically unmeasurable even at the closest separations.

The reason is easy to understand: the main contribution to the Casimir energy arises from modes of energy $\hbar c/L \approx 10$ eV (for L=20 nm), while the transition to superconductivity affects the reflective power only in the microwave region, at the scale $k\,T_c \leq 10^{-4}$ eV (for $T_c \approx 1$ K).

A feasible alternative approach involves directly the variation ΔF_c of Casimir free energy across the transition:

$$\Delta F_c = F_c^{(n)} - F_c^{(s)} \neq 0$$

Indeed ΔF_c is expected to be positive, because, in the superconducting state, the film should be closer to behave as an ideal mirror than in the normal state, and so F_c (s) should be more negative than F_c (n) .

Is there a way to measure ΔF_c?

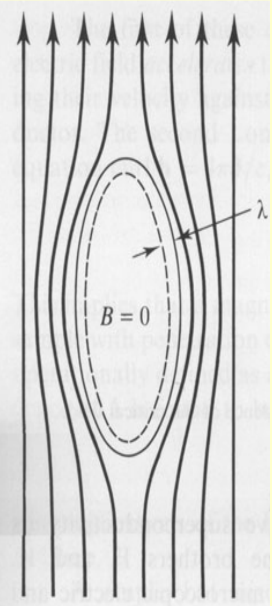
ΔF_c can be measured by means of a comparative measurement of the (parallel) critical magnetic field $H_{c\parallel}$ required to destroy the superconductivity of the three layer cavity, as compared to the critical field of the two-layer system (not forming a cavity).

Because of the Casimir energy ΔF_c, the three-layer critical field is larger.

Since the effect depends on an energy scale (the film condensation energy E_{cond}) which is orders of magnitude smaller than typical Casimir energies F_c, even tiny variations ΔF_c of Casimir free energy give rise to measurable shifts δH_c

Magnetic properties of superconductors

- Meissner effect: they show perfect diamagnetism.
- Superconductivity is destroyed by a critical magnetic field



The critical field depends on the shape of the sample and on the direction of the field. For a thick flat slab in a paralle field, it is called thermodynamical field and is denoted as H_c.

The value of H_c is obtained by equating the magnetic energy (per unit volume) required to expel the magnetic field with the condensation energy (density) of the superconductor.

$$\frac{H_c^2(T)}{8\pi} = e_{cond}(T)$$

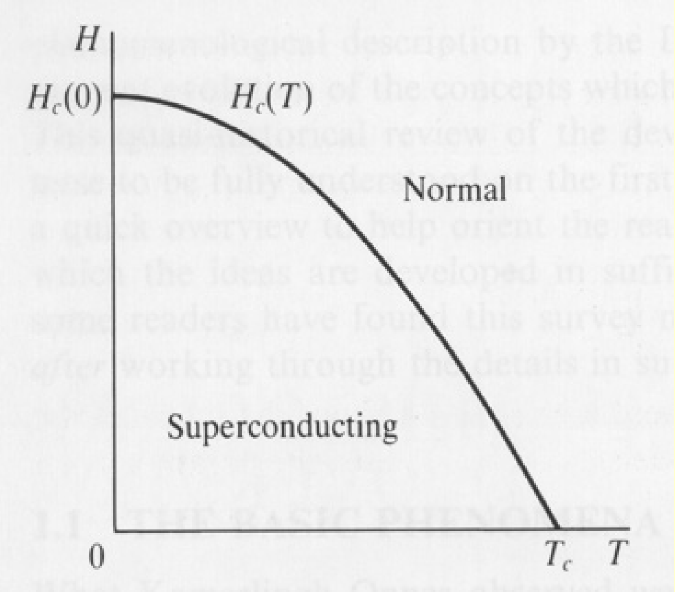
(thick flat slab in parallel field)

$$e_{cond}(T) = f_n(T) - f_s(T)$$

$f_{n/S}(T)$: density of free energy at zero field in the n/s state

$H_c(T)$ follows an approximate Parabolic law

$$H_c(T) = H_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$



Superconducting film as a plate of a Casimir cavity

When the superconducting film is a plate of the cavity, the condensation energy E_{cond} of the film is augmented by the difference ΔF_c among the Casimir free energies

$$\frac{1}{8\pi}\left(\frac{H_{c\parallel}^{(cav)}(T)}{\rho}\right)^2 V = E_{\mathrm{cond}} + \Delta F_c$$

ΔF_c causes a shift of critical field δH_c:

$$\frac{\delta H_c}{H_c} \approx \frac{1}{2}\frac{\Delta F_c}{E_{\mathrm{cond}}}$$

For an area A=1 cm^2 and L=10 nm

$$F_c \approx E_c = -\frac{\pi^2}{720}\frac{\hbar c A}{L^3} = -0.43 \ \ erg$$

For an Al film with A=1cm^2, a thickness D=10 nm , and for T/Tc=0.995:

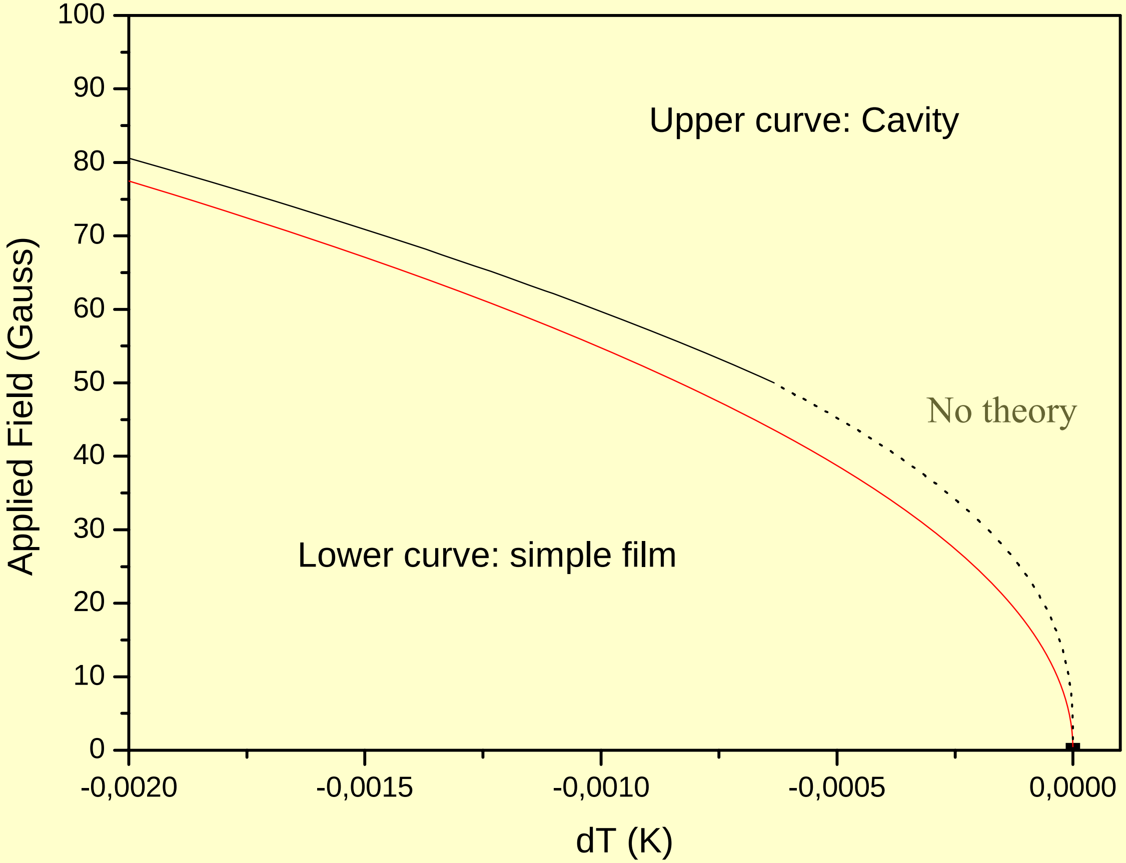
$$E_{\mathrm{cond}} = 4.4\times 10^{-8}\, erg$$

F_c is 10 million times larger than E_{cond}!

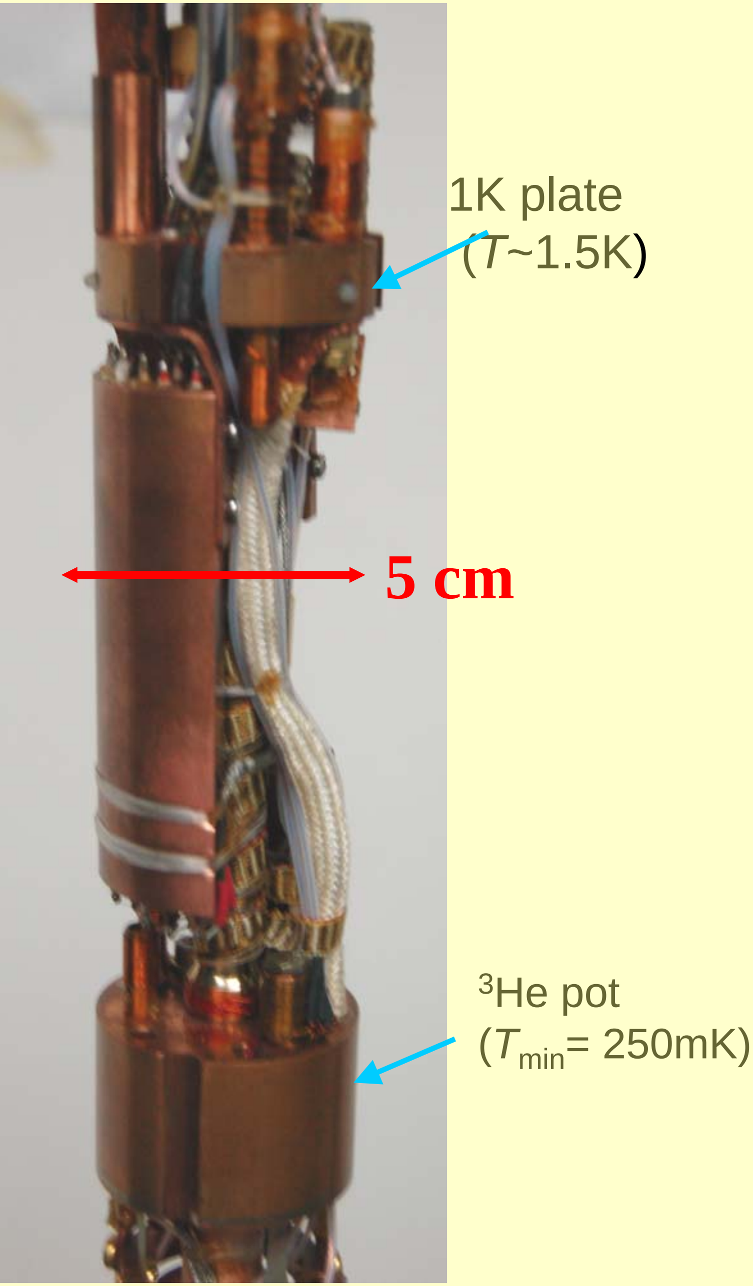
So even a tiny fractional change of Fc can be large compared with Econd, and cause a measurable shift of critical field.

$\delta T \approx 0.06 \div 0.1$ mK

$\delta H \approx 5$ Gauss



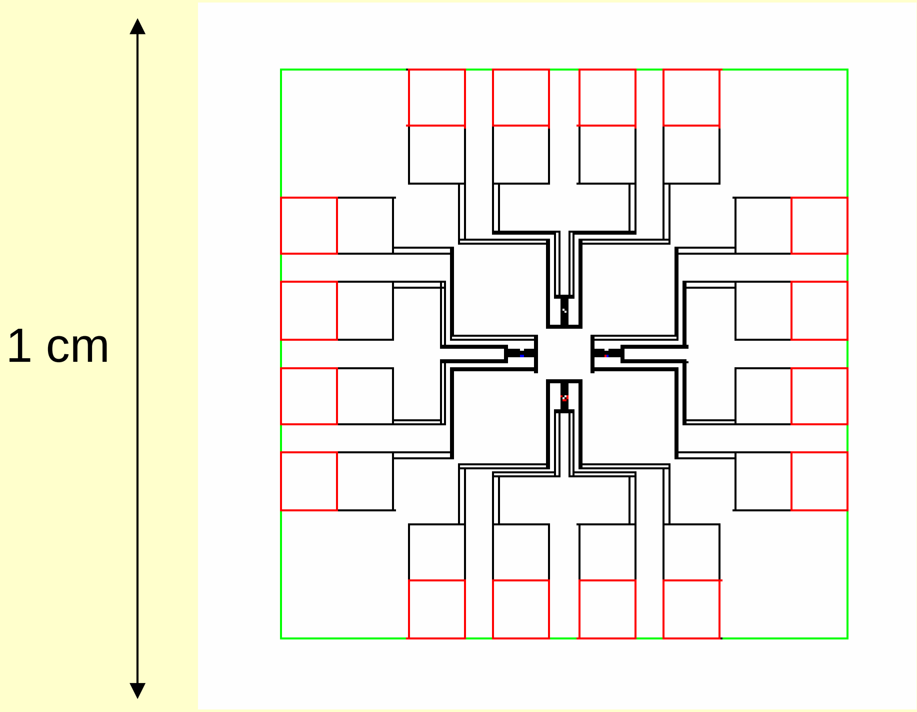
Expected signal



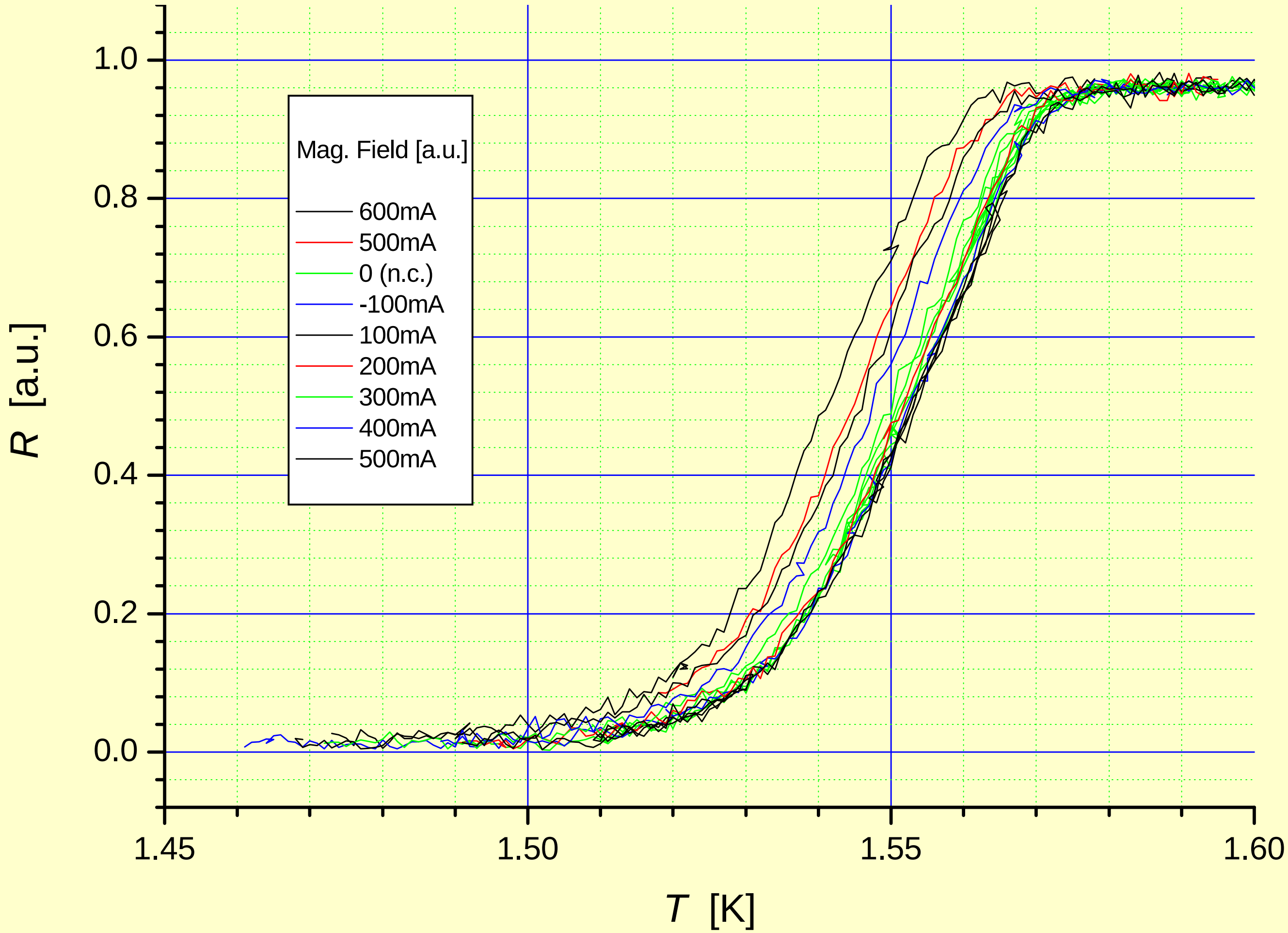
Two and three-layers are deposited close to each other, by a single deposition on the same chip. This procedure ensures:

1) that the two and three layer systems have identical features.

2) that the applied magnetic field is the same for both.



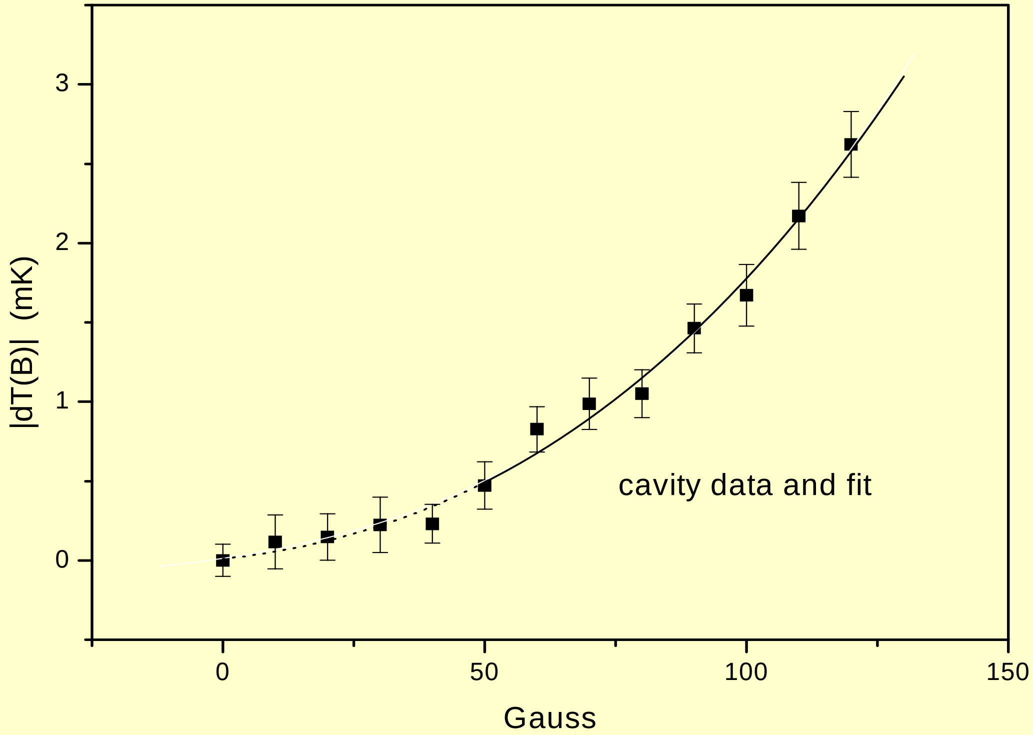
Layout of a sample



The transition width is about 50 mK.

The applied fields are of the order of 100 Gauss

Sensitivity study: as we have seen, detection of the signal requires a sensitivity in the measurement of dT slightly less than 0.1 mK.



Our present sensitivity is about 0.2 mK (and better for small magnetic fields.)

The dotted part of the cavity curve refers to the region in which the Casimir energy variation in not simply a perturbation of the condensation energy. (It is in principle even more interesting because the superconductors cannot be regarded as a background)

References:

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The Casimir effect and the equivalence principle, or the "weight of the vacuum"

Einstein's equations $$R_{ab} - \frac{1}{2} g_{ab} R = \frac{8\pi G}{c^4} T_{ab} + \lambda g_{ab}$$

Present cosmological observations favour a non-zero value for the cosmological constant λ

$$\lambda \leq 10^{-57}\, cm^{-2}$$

The cosmological constant problem

Small values of λ are unnatural in Quantum Field Theory, because quantum vacuum fluctuations give rise to a large vacuum energy

For example, in the case of a scalar field, quantum fluctuations give

$$\langle\rho\rangle = \frac{1}{(2\pi)^3}\int_0^\Lambda 4\pi k^2 dk \frac{1}{2}\sqrt{\hbar^2 c^2 k^2 + m^2 c^4} = \frac{\hbar c}{16\pi^2}\Lambda^4$$

Since every form of energy is a source of gravitational field

$$T_{ab} = \langle\rho\rangle g_{ab}$$

$$\lambda_{eff} = \lambda + \frac{8\pi G}{c^4}\langle\rho\rangle = \lambda + \frac{1}{2\pi} l_P^2 \Lambda^4$$

$$l_p = \sqrt{\frac{G\hbar}{c^3}} \approx 10^{-33}\, cm \qquad \Lambda \approx l_p \Rightarrow l_P^2 \Lambda^4 = l_p^{-2} = 10^{66}\, cm^{-2}$$

120 orders of magnitude larger than the present observed value !

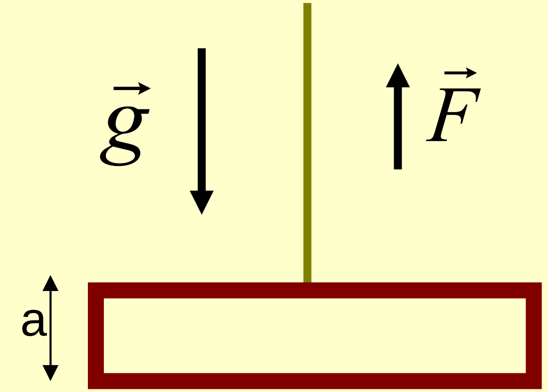
A Casimir cavity in a gravitational field

If vacuum energy satisfies the equivalence principle

$$\vec{F} = \frac{E_C}{c^2}\vec{g} = -\frac{\hbar\pi^2 A}{720\, c a^3}\vec{g}$$

Since $E_c<0$, the push is upwards!

By realizing a million layers with an area A of 1 m^2,
One would have a push of about 10^{-14} N.



Rigid suspended cavity

The gravitational field gives rise to a trace anomaly τ in the e.m. stress tensor, of mean integrated value:

$$\int \tau\, d^3\Sigma = \frac{\pi^2}{360}\frac{\hbar g}{c a^2} A$$

References:

E. Calloni, L. Di Fiore, G. Esposito, L.Milano and L. Rosa, Phys. Lett. A 297, 328 (2002)

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Thermal corrections to the Casimir pressure and radiative heat transfer

The present level of precision in the Casimir force measurements (some percent) calls for accurate theoretical estimates of the force, taking into account real experimental conditions:

1) Non-zero temperature
2) Surface roughness
3) Finite conductivity of the boundary metals.

Surprisingly, while separate consideration of temperature and finite surfaces conductivity poses no special difficulties, problems arise when the two are studied simoultaneously, as the results strongly depend on the chosen model for the metal

- If ohmic dissipation is neglected (plasma model), qualitative agreement with the ideal metal case is obtained (Genet et al. (2000), Bordag et al. (2000))
- If dissipation is considered (Drude model) the thermal correction is much different from ideal case, even for an arbitrarily small amount of dissipation! (Bostrom et al. (2000))

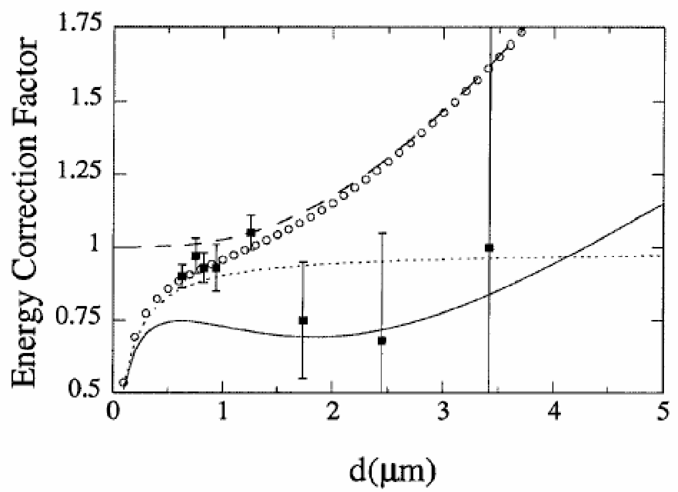


FIG. 1. The energy correction factor for Au at 0 K (dotted line), Au at 300 K (solid line), Au at 300 K with the static transverse electric part incorrectly treated as in the perfect conductor case (circles), and finally the energy between perfect conductors evaluated at 300 K (dashed line). We have, as a comparison, also plotted the experimental energy of Ref. [5] (squares).

The theoretical tool to study this problem is Rytov's-Lifshitz theory of electromagnetic fluctuations in dispersise and dissipative media. In this theory the physical origin of e.m. fluctuations resides in the microscopic fluctuating currents that exist inside any absorbing medium (fluctuation-dissipation theorem).

Basic assumptions are:

- The medium is in thermal equilibrium.
- Only large distances are involved (macroscopic Maxwell eqs.)
- The medium is treated as a **dielectric** with an $\varepsilon(\omega)$ (neglect of space-dispersion)
- Fluctuating currents at different points are uncorrelated.

$$\langle j_\alpha(\mathbf{r},\omega)\, j^*_\beta(\mathbf{r}',\omega')\rangle = \frac{1}{4\pi}\,\hbar\omega^2 \coth\left(\frac{\hbar\omega}{2kT}\right)\, \epsilon''(\mathbf{r},\omega)\,\delta(\omega-\omega')\,\delta^3(\mathbf{r}-\mathbf{r}')\,\delta_{\alpha\beta}$$

$$\langle j, j\rangle = \langle j^*, j^*\rangle = 0$$

Both quantum zero-point and thermal fluctuations are included

The radiated e.m. fields extend beyond the body boundaries, partly as propagating waves (PW), partly as evanescent near-fields (EW). Such fields give rise to interactions between closely spaced bodies.

The controversy on thermal corrections to the Casimir force in real metals

Recent studies (Torgerson et al. (2004), G.Bimonte (2006)) shows that disagreement between the various models stems from largely different predictions for the contribution of thermal evanescent modes with transverse polarization (TE EW) of low frequencies (from infrared to microwaves).

Therefore, an accurate estimate of the thermal correction to the Casimir force requires a good model for TE EW at low frequencies.

Casimir force measurements at separations of a few microns, where disagreement among rival theories is largest, are very difficult at the present time. Therefore, the question arises:

Can one get experimental information on TE EW modes, other than Casimir force measurements?

TE EW and heat transfer

Another physical phenomenon involving thermal electromagnetic fluctuations is radiative heat transfer between two metallic plates separated by an empty gap, kept at different temperatures

Polder and van Hove (1971) studied this problem long ago, usimg Rytov's theory and they showed that thermal EW give the dominant contribution, at submicron separations. The frequencies involved are same as in thermal corrections to the Casimit force.

Therefore, experiments on heat transfer provide independent information on thermal TE EW (G. Bimonte 2006), that can be used to complement Casimir force experiments.

We have compared the powers S of heat transfer impled by various models of dielectric functions and surface impedances, that are used to estimate the thermal Casimir force (G.B., G. Klimchitskaya and V.M. Mostepanenko (2006)).

The models that we considered are (for gold):

- The Drude model (Lifshitz theory): $$\varepsilon_D = 1 - \frac{\Omega^2}{\omega(\omega + i\gamma)}$$

- The surface impedance of the normal skin effect Z_N: $$Z_N = (1-i)\sqrt{\frac{\omega}{8\pi\sigma_0}}$$

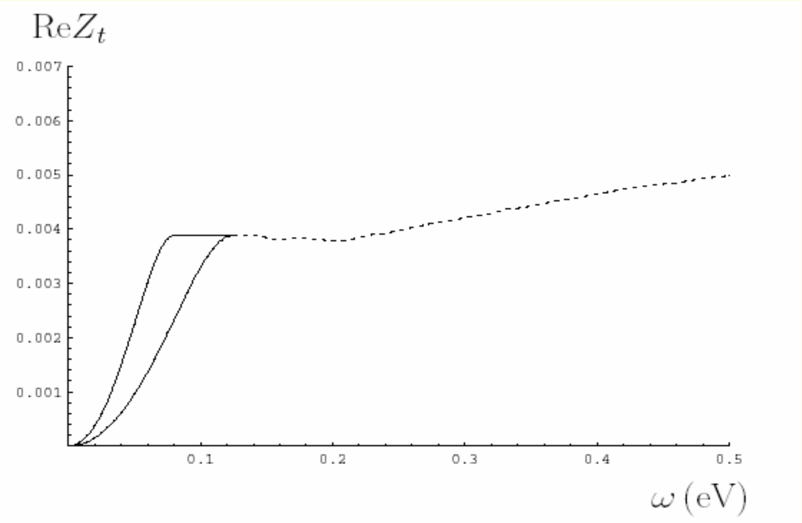
- The surface impedance of the Drude model Z_D: $$Z_D = \frac{1}{\sqrt{\varepsilon_D}}$$

- A modified form of the surface impedance of infrared optics, including relaxation effects Z_t $$Z_t = -i\frac{\omega}{\sqrt{\omega_p^2 - \omega^2}} + Z_t'$$

$$Z_t' = \begin{cases} B \sin\left(\dfrac{\pi\omega^2}{2\beta^2}\right), & \omega \le \beta \\ B, & \beta \le \omega \le 0.125\ eV \\ Y(\omega), & \omega \ge 0.125\ eV \end{cases}$$

Y(ω) stands for tabulated data, available for ω >0.125 eV

We allowed 0.08 eV < β < 0.125 eV



Power S of heat transfer

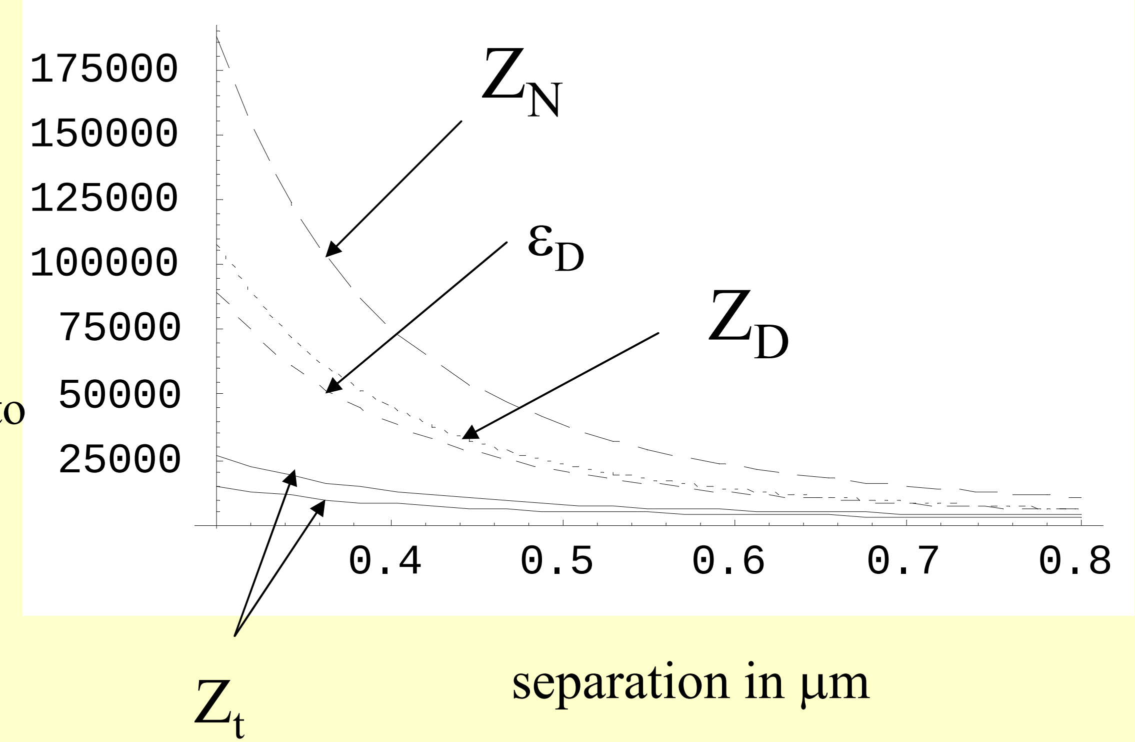
$$\varepsilon_D = 1 - \frac{\Omega^2}{\omega(\omega + i\gamma)}$$ (Lifshitz theory)

$$Z_D = \frac{1}{\sqrt{\varepsilon_D}}$$

$$Z_N = (1-i)\sqrt{\frac{\omega}{8\pi\sigma_0}}$$

Z_t optical data + extrapolation to low frequencies

S (in erg cm^{-2}sec^{-1}))



separation in μm

CONCLUSIONS

1) We have shown that heat transfer is a valuable tool to resolve the long-standing controversy on thermal correction to the Casimir effect between real metals.

2) New experiments on heat transfer are in order, using the same metals as in Casimir experiments

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G. Bimonte, Phys. Rev. E 73, 048101 (2006)

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G. Bimonte, G. Klimchitskaia and V. Mostepanenko, submitted.