Casimir effect and short-range gravity tests

Serge Reynaud & Astrid Lambrecht
Laboratoire Kastler Brossel
Paris, France

Thanks to M.-T. Jaekel (LPTENS Paris),
A. Canaguier-Durand, R. Guérout,
J. Lussange, G. Dufour (LKB),
P.A. Maia Neto (UF Rio de Janeiro),
G.-L. Ingold (U. Augsburg), D.A.R. Dalvit,
R. Behunin, F. Intravaia, Y. Zeng (Los Alamos),
C. Genet, T. Ebbesen, P. Samori (Strasbourg),
A. Liscio (Bologna), V.V. Nesvizhevski (ILL),
R. Decca, E. Fischbach (IUPUI Indianapolis) …
Search for scale dependent modifications of the gravity force law

- Exclusion plot for deviations with a generic Yukawa form

\[ V(r) = -\frac{GMm}{r} \left( 1 + \alpha e^{-\frac{r}{\lambda}} \right) \]

- Windows remain open for deviations at short ranges
  \[ \lambda < 1 \text{ mm} \]

- or long ranges
  \[ \lambda > 10^{16} \text{ m} \]

Excluded domain in the plane \((\lambda, \alpha)\)


Testing gravity law at short ranges

- Exclusion plot for an extra Yukawa potential
  \[ -\frac{G M m}{r} \left( 1 + \alpha e^{-\frac{r}{\lambda}} \right) \]

- From the mm down to the pm range
  - Torsion-balance measurements
  - Casimir experiments
  - Neutron physics
  - Exotic atoms


The Casimir force

Vacuum resists when being confined within walls: a universal effect depending only on $\hbar$, $c$, and geometry

$$F_{Cas} = -\frac{d\mathcal{E}_{Cas}}{dL}, \quad \mathcal{E}_{Cas} = -\frac{\hbar c \pi^2 A}{720L^3}$$

- Ideal formula written for
  - Parallel plane mirrors
  - Perfect reflection
  - Null temperature

- Attractive force = negative pressure

$$F_{Cas} = P_{Cas}A, \quad P_{Cas} = -\frac{\hbar c \pi^2}{240L^4}$$

$$|P_{Cas}| \sim 1\text{mPa}$$

at $L = 1\mu\text{m}$

The Casimir force between real mirrors

- Real mirrors not perfectly reflecting
  - Force depends on non universal properties of the material plates used in the experiment

- Experiments at room temperature
  - Effect of thermal field fluctuations to be added to that of vacuum fluctuations

- Effects of geometry and surface physics
  - Plane-sphere geometry used in recent precise experiments
  - Surfaces not ideal: roughness, contamination, electrostatic patches …

M. Jaekel, S. Reynaud, J. Physique I-1 (1991) 1395
A. Lambrecht, S. Reynaud EPJD 8 (2000) 309

Models for metallic mirrors

- Simple models for the (reduced) dielectric function for metals
  - bound electrons (inter-band transitions)
  - conduction electrons
    - determined by (reduced) conductivity $\sigma$
  - model for conductivity
    - plasma frequency $\omega_p$
    - Drude relaxation parameter $\gamma$

- Drude parameters related to the density of conduction electrons and to the static conductivity
  - finite conductivity $\sigma_0 \Leftrightarrow$ non null $\gamma$

$$\varepsilon[\omega] = \bar{\varepsilon}[\omega] + \frac{\sigma[\omega]}{-i\omega}$$

$$\sigma[\omega] = \frac{\omega_p^2}{\gamma - i\omega}$$

$$\omega_p^2 = \frac{nq^2}{\varepsilon_0 m^*}$$

$$\sigma_0 = \frac{\omega_p^2}{\gamma}$$

Pressure between metallic mirrors at $T \neq 0$

- Pressure divide by ideal Casimir formula

\[ \eta_P = \frac{P}{P_{\text{Cas}}} \]

\[ P_{\text{Cas}} = -\frac{\hbar c \pi^2}{240L^4} \]

- Effect of small losses tends to a factor 2 at large distance (high $T$)


Casimir experiments

- Dynamic measurements of the resonance frequency of a microresonator
- Shift of the resonance gives the gradient of Casimir force between a plane and a sphere

In the Proximity Force Approximation ($R \gg L$), the signal is proportional to the pressure $P(L)$ between two planes at distance $L$

Sphere Radius: $R = 150 \, \mu m$
Distances: $L = 0.16 - 0.75 \, \mu m$

Casimir experiments and theory ...

Purdue (and Riverside) measurements favor the lossless plasma model and thus deviate from theory with dissipation accounted for.

Theory with the Drude model

Experiment

Theory with the plasma model

 Courtesy R.S. Decca et al (IUPUI)

\[ T = 300 \text{K} \]

\[ L \text{ (nm)} \]

FIG. 1. Experimental data for the Casimir pressure as a function of separation \( z \). Absolute errors are shown by black crosses in different separation regions (a–f). The light- and dark-gray bands represent the theoretical predictions of the impedance and Drude model approaches, respectively. The vertical width of the bands is equal to the theoretical error, and all crosses are shown in true scale.

Casimir experiments and theory …

Experimental data kindly provided by R. Decca (IUPUI)
Theoretical pressure calculated by R. Behunin, D. Dalvit, F. Intravaia (LANL)

Deviation looking like a superposition of power laws

 différente modèle utilisé ici

d’IUPUI

D → L

\( P_{\text{exp}} - P_{\text{th}} \)

\( \sim 8\% \) of \( P_{\text{exp}} \)

Drude model used here
(difference smaller for the lossless plasma model)
Casimir experiments ...

- Lamoreaux group @ Yale
  - torsion-pendulum experiment
  - larger radius: \( R = 156 \text{ mm} \)
  - larger distances: \( L = 0.7 - 7 \mu m \)


- Thermal contribution seen at large distances (where it is large)
- Results favor the Drude model after subtraction of a large contribution of the electrostatic patch effect

- Results of different experiments point to different models
- Some experiments disagree with the best theoretical model

Surfaces of metallic plates are not equipotentials
- Real surfaces are made of crystallites
- Crystallites correspond to ≠ crystallographic orientations and ≠ work functions

For ultraclean surfaces →
(ultra-high vacuum, ultra-low temperature)
- Patch pattern is related to topography
- AFM, KPFM, EBSD maps are directly related

Contaminated surfaces correspond to a different story

Patch effect has been known for decades to be a limitation for high precision measurements
- C. W. F. Everitt et al., PRL 106 221101 (2011)
Modeling the patches …

- A “quasi-local” representation of patches
- Similar models used to study the effect of patches in ion traps

This produces a smooth spectrum (no cutoff)
**Modeling the patches …**

**Quasi-local model (**)**

\[ V_{\text{rms}} = 80.8 \text{mV} , \ell_{\text{max}} = 300 \text{nm} \]

(**) same parameters as in R. Decca et al (2005)

**Best fit parameters**

\[ V_{\text{rms}} = 12.9 \text{mV} , \ell_{\text{max}} = 1074 \text{nm} \]

**Sharp cutoff model (*)**

\[ V_{\text{rms}} = 80.8 \text{mV} , k_{\text{min}} = 20.9 \mu\text{m}^{-1} \]

(*) same model and parameters as in R. Decca et al (2005)

Provisional conclusions

- Casimir effect is verified but there is still room for improvement
- Puzzle: some experiments deviate from theory!

Maybe due to the contribution of electrostatic patches?
- Differences between IUPUI data and Drude model predictions have been fitted by the quasi-local model for electrostatic patches
  - This is only a fit which has been done within PFA
  - Best fit parameters are not compatible with patches identified as crystallites
  - They are compatible with a contamination of the metallic surfaces (contaminants enlarge the patch sizes and spread out the patch voltages)

Next steps
- Measure real patch voltages with Kelvin Probe Force Microscopy
  - Ongoing with ISIS Strasbourg and ISOF Bologna
- Deduce the force in the plane-sphere geometry
  - Ongoing with LANL Los Alamos
- Compare with knowledge from other studies

R.O. Behunin et al, PRA 86 (2012) 052509