The Casimir Effect: A Force from Nothing

Hendrik Casimir

\[ F(d) = -\frac{\pi^2 \hbar c}{240d^4} A \]

attraction due to confinement of quantum mechanical vacuum fluctuations

Experimental Observations

- **Mechanical Balance**
  *Sparnaay, Physica 24, 751 (1958)*

- **AFM**
  *Mohideen and Roy, PRL 81, 4549-4552 (1998)*

- **Actuation of MEMS**
  *Chan, Aksyuk, Kleiman, Bishop, Capasso, Science 291, 1941 (2001)*
Failure Mechanisms in MEMS

Casimir forces $\implies$ STICCTION

repulsive Casimir forces:

$\mu > \varepsilon$

meta-materials

Kenneth et al. PRL 89, 33001 (2002)

The Critical Casimir Effect

„Phenomena at the walls in a critical binary mixture“

Confinement of order parameter fluctuations close to critical points

\[ F(z) = A \frac{k_B T_c}{z^3} \mathcal{G}(z/\xi) \]

\[ \xi = \xi_0 \left| \frac{T}{T_c} - 1 \right|^{-\nu} \]
Binary Critical Mixtures

water - lutidine

$m = C - C_c$

$T_C \approx 33^\circ C$

$T < 33^\circ C$ critical opalescence

$T \approx 33^\circ C$

1-Phase Region

2-Phase Region

$C_L = 0.29$

$C_L = 0.1$

$\text{H}_3\text{C}$

$\text{CH}_3$

$\text{N}$

$\text{CH}_3\text{H}_3\text{C}$
Silica Spheres in Binary Mixtures

- binary mixture of water – 2,6 lutidine
- lower consolute point
- silica spheres (2R = 0.16μm)

Beyesens, Estève, PRL 54, 2123 (1985)

Prewetting ? Capillary condensation ?
How to Measure Tiny Forces

How to resolve pico … femto Newton

- **Surface Force Apparatus (SFA)**

- **Atomic Force Microscopy (AFM)**

Resolution limited by spring constant \( D \geq 0.01 \text{N/m} \)

→ ‘freely’ suspended colloidal probe particle

- **Total Internal Reflection Microscopy (TIRM)**
Experimental Setup

\[ \Delta T = \pm 0.005°C \]
**Sensitivity of TIRM**

![Graph with data points and legend](image)

| $\rho$ (g/cm³) | H₂O  | 1.0  |
|               | PS   | 1.05 |
|               | D₂O  | 1.1  |

resolution < 10 fN!

_Helden, Roth, Koenderink, Leiderer, Bechinger, PRL 90, 48301 (2003)_)
Scaling Function & Boundary Cond.

Sphere-Plate:

\[ \frac{\Phi}{k_B T} = \frac{R}{z} \mathcal{G} \left( \frac{z}{\xi} \right) \quad z \leq R \]

\[ Vasilyev, Gambassi, Maciolek, Dietrich \ \text{arXiv:0708.2902v1 (2007)} \]

attractive and repulsive critical Casimir forces
Critical Casimir Forces: ++

++: particle & wall: preferential adsorption of lutidine

PS 3.7μm (x-linked, weakly charged)
HMDS treated silica wall (hydrophobic)

similar results for 0.25 < c_L < 0.32
Critical Casimir Forces: --

--: particle & wall: preferential adsorption of water

- sulfate-terminated PS 2.4μm (10.1μC/cm²)
- hydrophilic silica wall

σ [μC/cm²] | phase
---|---
5.70 | W
3.85 | W
0.38 | L

Critical Casimir Forces: --

- - - particle & wall: preferential adsorption of water

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sulfate-terminated PS 2.4μm (10.1μC/cm²)
hydrophilic silica wall


A. Gambassi, S. Dietrich
MPI Stuttgart, Germany

\[ \xi(T) = \xi_0 \left( \frac{T}{T_c} - 1 \right)^{-0.63} \]
Correlation Length

\[ \xi(T) = \xi_0 \left| \frac{T}{T_c} - 1 \right|^{-0.63} \]

\[ \xi_0 \approx 0.2 \pm 0.02 \text{nm} \]
Critical Casimir Forces: +- asymetric boundary conditions
repulsive critical Casimir force

\[ \Phi [k_B T] \]

\[ z [\mu m] \]

\[ T_c - T [K] \]

- 0.90
- 0.43
- 0.34
- 0.32
- 0.30
- 0.28
- 0.25
Critical Casimir Forces: +- asymmetric boundary conditions repulsive critical Casimir force

\[ \Phi [k_B T] \]

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\]

\[ z [\mu m] \]
Correlation Length

\[ \xi(T) = \xi_0 \left| \frac{T}{T_c} - 1 \right|^{-0.63} \]

\[ \xi_{\text{fit}} \] vs. \[ T_c - T \text{ (experimental)} \text{ [mK]} \]
Off-Critical Composition: ++

- $T_1 = 31.88°C$
- $T_7 = 32.01°C$
- $T_8 = 32.02°C$
- $T_{10} = 32.06°C$
- $T_{11} = 32.08°C$
- $T_{12} = 32.12°C$

- $\phi$ [k_B T]

- Reduction of surface energy by BRIDGE FORMATION

- No bridge formation for $c_L > c_C$ ✔
Summary & Outlook

• Direct observation of critical Casimir forces in binary liquids
  → attractive and repulsive interactions on the order of many kT

  → tunable interaction potential: no salt, no depletion agent, reversible!

• novel phases (photonic crystals)
• colloidal self-assembly on chemically patterned surfaces
• anti-stiction coatings for MEMS