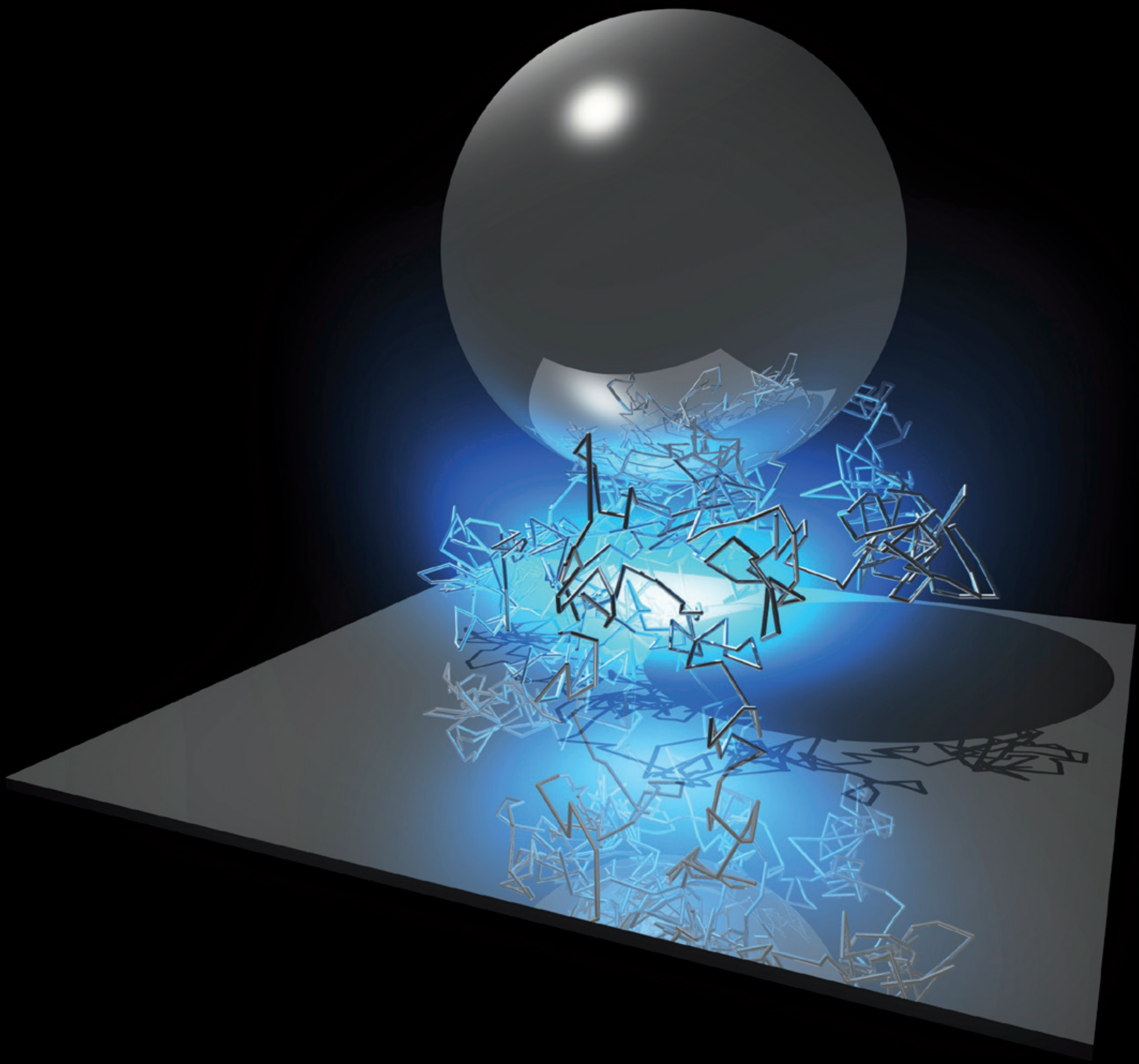
EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE

RESEARCH NETWORKING PROGRAMME

NEW TRENDS AND APPLICATIONS OF THE CASIMIR EFFECT (CASIMIR)

Standing Committee for Physical and Engineering Sciences (PESC)



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Cover picture:
Density plot of the Casimir interaction energy density (blue) between a sphere and a plate for a Dirichlet scalar, computed with worldline numerics. One of the worldlines used in the computation is also shown. For details see Gies and Klingmüller (2006) Casimir Effect for Curved Geometries: Proximity-Force-Approximation Validity Limits. *Phys. Rev. Lett.* **96**, 220401.
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Introduction

The fundamental nature of the void, or empty space, has intrigued philosophers since ancient times. Democritus, who developed the original atomic theory around 440 BC, invoked the existence of a void between atoms so they could move. Later, Newton struggled with the concept but in the end simply resorted to defining it as an empty container acting as an absolute reference to matter. The startling realisation that has emerged since the birth of modern physics is that the void, i.e., the complete absence of any detectable particles or energy, is far from empty.

Theoretically this conclusion originated around 1900 from the work of Max Planck and the early pioneers of quantum theory. A consequence of the quantum behaviour of electromagnetic fields is that each field mode contains an intrinsic ‘zero-point’ energy when it is not vibrating. Thus a field containing no photons (in other words, empty space) has a huge intrinsic energy density. The zero-point energy, which manifests itself as quantum fluctuations of the field, is not just an arbitrary constant but has real observable consequences. In 1948 Hendrik Casimir showed that placing two perfect reflectors in empty space limits the number of field modes and thus locally depresses the zero-point energy leading to an attractive force between the plates. This simple prediction was hard to test with the technology of the time. The force drops rapidly with distance and above about 1 µm becomes very hard to measure, while at sub-micron separations it is technically difficult to make measurements between sufficiently flat parallel surfaces. An early attempt in 1958 by Marcus Sparnaay using a spring balance confirmed the existence of the Casimir force but with insufficient accuracy to compare its magnitude with calculations. Nevertheless, this ‘force from nothing’, which is one of the few known examples of a macroscopic quantum effect, was established as an experimental reality.

In modern times, sophisticated equipment has made it easier to study the Casimir effect. A sensitive torsion balance enabled the first modern measurement of the force between a metal sphere and a metal plate in 1997, producing an agreement with theory to a precision of about 10%. The sphere-plate geometry yields a smaller Casimir force at a given separation but it can still be rigorously calculated and it avoids the experimental problem of maintaining perfect parallelism between plates down to tiny separations. The field was given a significant boost by the invention of the atomic force microscope (AFM) and micro electro-mechanical (MEMS) oscillators carved out of silicon using technology developed in the semiconductor industry. Most of today’s experiments are performed using one of these instruments and, by virtue of the continuous effort by numerous groups in Europe and the US, there now exist measurements of the force between a range of materials including metals, semiconductors, quasicrystals and insulators at separations varying from more than 1µm to 10 nm and in different geometries including the configuration initially proposed by Casimir of two plates (see figure 1).

The field has attracted significant attention and has focused, on the one hand, on observations of the Casimir force in complex geometries and novel materials such as phase-change and metamaterials with a view to applications, especially in nano-machines. On the other hand there is a focus on fundamentals such as what the force can tell us about the quantum vacuum, for example, any possible relationship between zero-point energy and cosmological observations such as dark energy. In addition sufficiently accurate measurements could reveal a departure from Newtonian gravity at sub-micron separations, providing data for a quantum theory of gravity.

The importance of the field in both fundamental physics and blue-sky technology has been recognised in Europe and has attracted funding from the European Commission (e.g., the NANOCASE project) and this programme.

The running period of the ESF CASIMIR Research Networking Programme is for five years from April 2008 to April 2013.

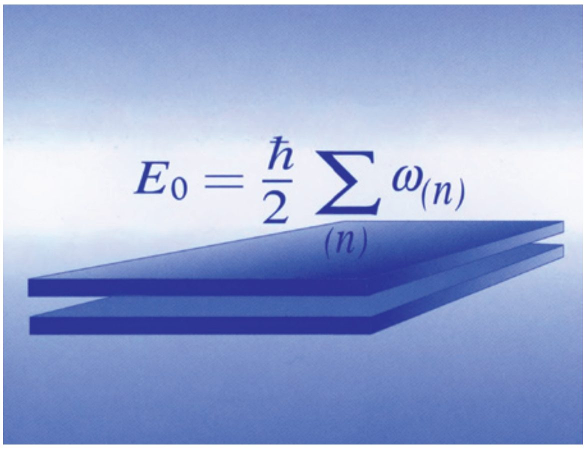

Figure 1. Geometry of two parallel plates in quantum vacuum, initially considered by Hendrik Casimir

Aims and Objectives

The topics covered by the CASIMIR Programme are studied by experimentalists and theorists, with a significant number of groups having overlapping research projects. The programme provides a forum for a quick and efficient exchange of techniques and ideas as well as for close collaboration between experiment and theory. The Casimir effect has seen a very rapid development in recent years, due to its importance for fundamental physical questions and at the same time for technological applications. It has relevant overlaps with other important areas of physics, such as condensed matter, nanophysics, cosmology and gravitation and statistical physics.

In particular, the CASIMIR Programme aims to:

- Integrate and disseminate the work carried out by the Casimir physics communities in different countries in Europe by the exchange of junior researchers and students between research groups via short visit or exchange grants;
- Facilitate the smooth exchange of new ideas;
- Provide interdisciplinary training and foster collaboration by creating links with leading groups in different areas of adjacent communities;
- Provide transmission of new concepts and techniques from research frontiers to the basic training level by organising topical workshops and schools.

All these are necessary to maintain theoretical and experimental activity at a competitive level. The expected benefits from the CASIMIR Programme are a consolidation and increase of the European Casimir physics community and an enhanced visibility and attractiveness of European Casimir physics for scientists and students all over the world. The CASIMIR Programme involves teams and individual researchers from 10 European countries. All teams are well-established and led by renowned researchers with a high international profile.

Topic Areas

The main topic areas of groups working within the CASIMIR Programme are described below. A number of novel experiments concerning the static or dynamic Casimir effect have been developed in the last few years in Europe. Experimental techniques are based on recent technological developments in nanotechnology including atomic force microscopy and MEMS devices. On the theoretical side, Casimir effect calculations use numerous different methods ranging from quantum field theoretical approaches and renormalisation methods to quantum statistical methods and scattering approaches to the worldline formalism.

Casimir effect: measurement and theory

The magnitude of the Casimir force between perfect reflectors in vacuum is given by the famous formula derived by Casimir in 1948 but in real materials the force is modified by the dielectric function of the interacting surfaces and the optical properties of the intervening medium (Fig. 2). So far, mainly homogeneous dielectric materials have been studied, such as metals, silicon and silicon oxide separated by vacuum or air. In this situation the Casimir force is always attractive and the lower the reflectivity of the material the smaller the force. A promising avenue to control the Casimir force is to use novel materials, such as carbon nanotubes, nanoparticles, metamaterials, quasicrystals, birefringent materials, superconductors, photonic crystals and switchable materials. These show unique and controllable optical properties and they could be used to control the Casimir force in a predictable manner, leading also to lateral forces or vacuum torques.

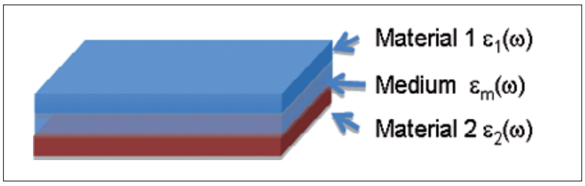

Figure 2. The magnitude of the Casimir force depends on the optical properties of the two interacting materials and those of the intervening medium.

An interesting example is to attempt to reverse the sign of the force. One proposed method is to use cavities in which one side is a metamaterial, i.e., a film with a nanoscale patterning whose morphology can be used to control the dielectric function of the surface (Fig. 3). A commonly used type of metamaterial is composed of nanoscale split ring resonators (SRRs) patterned into a gold film. The size of the resonators determines the frequency of the optical resonance, which in turn determines the length-scale at which a Casimir repulsion is expected to occur.

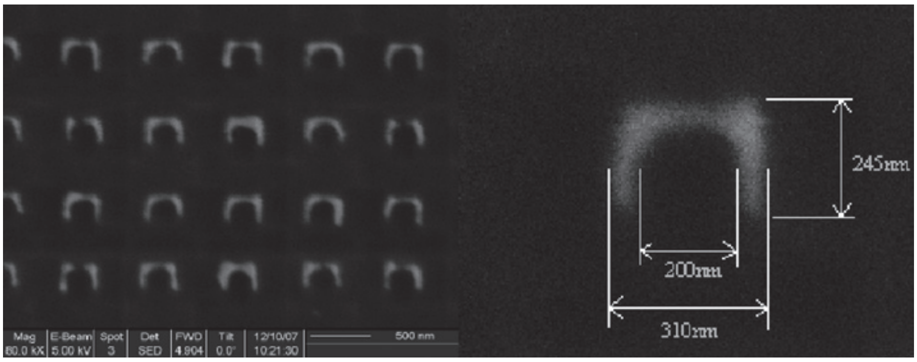

Figure 3. A metamaterial composed of gold nanoscale split-ring resonators pattered into a surface using focused ion beam milling

Another possibility to reverse the sign of the Casimir force is to use a medium between the reflectors with a dielectric function lying between those of the two reflectors. This has been experimentally verified recently in Harvard. In order to meet this condition the medium must be a liquid and members of the CASIMIR Programme are actively researching new methods to measure Casimir forces in liquids using inverse colloid probe atomic force microscopy.

The magnitude of the Casimir force depends not only on the material of the reflectors but also their microscopic roughness, which produces a strong deviation from the normal scaling of the force with separation. Roughness is important for dispersive forces and might also influence functional properties of MEMS and NEMS devices. More generally, the geometry of Casimir experiments plays an important role. Experiments are mostly performed between a plane and a sphere and calculations for geometries other than infinite parallel plates involve the so-called Proximity Force Approximation (PFA), which amounts to averaging over the force calculated between infinitesimal parallel plates following the required surface. This treatment of geometry cannot reproduce the rich interconnection expected to take place between the Casimir effect and topology. Precise information can only be obtained by pushing the theory beyond the PFA.

The study of Casimir force in complex geometries and novel topologies, such as patterned or corrugated surfaces, nanospheres or small spheroid shaped bodies, has become a highly active research area. A specific nontrivial geometry that is of particular interest for applications is that of surfaces with periodic corrugations. As lateral translation symmetry is broken, the Casimir force contains a lateral component, which is smaller than the normal one but has been suggested as a method to achieve contactless force transmission in a micromachine (Fig. 4). Alternatively a vacuum torque arises when breaking the rotational symmetry, i.e., when the corrugations are not aligned.

The influence of temperature on the Casimir effect has given rise to intense discussions over the last decade, in particular because the force exhibits an unexpectedly strong correlation with the detailed description of optical properties of the metallic surfaces used in the experiments. Understanding these discrepancies is a topic of great interest with acute research activity on the theoretical as well experimental side.

While plates and spheres probe global properties of the quantum vacuum interaction, atoms and molecules constitute local field probes and may provide access to different information. The interaction between atoms and surfaces is normally called the Casimir-Polder interaction and is actively studied by members of the network, including its impact in far-reaching topics such as interference between macro-molecules and quantum decoherence. The standard theory for the Casimir-Polder interaction assumes thermal equilibrium, yet in some experimentally and technologically important situations this is not achieved. In a recent experiment in Boulder, a Bose-Einstein condensate was trapped in a magnetic field close to a surface and the Casimir Polder force

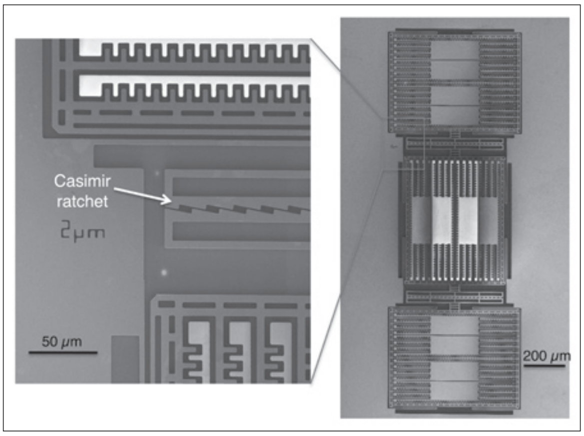

Figure 4. A MEMS machine constructed to study the lateral Casimir force between corrugated surfaces.

between the condensate and a heated surface was measured. The theory to describe such experiments is based on a non-equilibrium approach, allowing for new phenomena such as heat transfer and ensuing repulsive forces.

The Casimir Polder force is also important for guiding and trapping molecules in 'atom chips'. While an atom in its ground state is very close to thermal equilibrium in ambient temperature since its excitation energies are very large compared to thermal energies, this is not the case for molecules which can easily be excited by thermal photons. Ground state molecules are therefore typically strongly out of thermal equilibrium and a fully non-equilibrium theory is required to describe the resulting molecule-surface force.

Critical Casimir effect

There is a thermodynamic analogue to the quantum-electrodynamical (QED) Casimir force known as the Critical Casimir force. This acts between surfaces immersed in a binary liquid mixture close to its critical point and generated by the confinement of its concentration fluctuations by the introduction of surfaces. The Critical Casimir force may be attractive or repulsive depending on the surface properties and its study re-builds a bridge between quantum-electrodynamics and colloidal physics, a field in which Hendrik Casimir, who discovered the QED force, was himself active.

Dynamical Casimir effect

Any mirror placed in vacuum experiences fluctuations of the quantum vacuum radiation pressure. When moving with a non-uniform acceleration, these fluctuations give rise to a dissipative force, opposing the mirror's motion and, as a consequence, the mirror should emit photons into the vacuum because of energy conservation. Although predicted 30 years ago by Fulling and Davies, this so-called dynamical Casimir effect has not yet been observed experimentally, mainly because the predicted photon flux is very small, but experiments to detect it are currently being developed in Europe. Attempts made in the past to observe the dynamical Casimir effect include exploiting the resonant enhancement of radiation inside an oscillating cavity and amplifying the Casimir signal with a sample of super-radiant ultra-cold alkali metal atoms. Another possibility consists of simulating the physical displacement of a mirror by rapidly modulating its optical properties. The dynamical Casimir effect bears a direct relationship to the concept of time refraction.

New challenges in vacuum properties

The Casimir effect has a strong bearing on current problems in cosmology. Quantum theory states all modes of the electromagnetic field have a zero-point energy of half a quantum which, if summed up to a reasonable cut-off frequency, corresponds to a huge energy density. This energy density should contribute to gravity as would any other source of energy provided that it fulfils the Equivalence Principle. However, its contribution is not observed. Einstein's General Relativity also predicts an intrinsic energy density of space (vastly smaller than the zero-point energy), referred to as the cosmological constant. The relationship between quantum vacuum fluctuations and the cosmological constant is an open and intriguing question.

Another frontier of modern physics is the study of gravitational forces at small length scales below 1 mm. Newton's inverse-square law of gravitation has been tested many times at astronomical distances by observing the motion of planets. A number of groups are now trying to verify the law at microscopic length scales with great precision. Such tests are important because many theoretical models that attempt to unify the four fundamental forces of nature predict the existence of previously undiscovered forces that would act at such scales, where the Casimir force becomes dominant. Any deviation between experiment and theory could hint at the existence of new forces. And even if there is agreement the measurements would then put new limits on existing theories.

Activities

The CASIMIR Programme supports scientists visiting laboratories as well as science meetings and schools. The activities can be found on the CASIMIR website **www.casimir-network.com** and include:

Workshops, schools and conferences

The CASIMIR Programme aims to fund at least one focused workshop and a few smaller topical meetings per year, international conferences in the 2nd and 4th years and two summer schools for young researchers and PhD students. So far, the Programme has financed a networking workshop in 2008 to bring together all participating groups at the beginning of the Programme. It also co-sponsored three international conferences in 2009, namely the 'Ninth Conference on Quantum Field Theory under the Influence of External Conditions (QFEXT09)', 'New Frontiers in Casimir Force Control' and the 'Workshop on Casimir Forces and their Measurements (Casimir09)' and will finance a summer school in Les Houches in 2010.

Applications for science meetings should be submitted online on the ESF CASIMIR website. They will be received on a continuous basis.

Short visits and exchange grants

CASIMIR supports collaborations among groups in the field by short visit grants for periods of up to 14 days and exchange grants covering stays between two weeks to six months. Applications can be submitted online on the ESF CASIMIR website, and they will be received on a running basis.

Up to now, CASIMIR has supported about 25 long and short term visits.

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