New Trends and Applications of the Casimir Effect: Final Report

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CASIMIR was a five year RNP, funded by ESF starting from April 2008. The main aim was to explore the (very) many facets of the Casimir effect, namely the forces resulting from fluctuations around the background (non-empty vacuum) of classical and quantum fields in the presence of geometric confinement. Originally derived within the framework of quantum fluctuations of electromagnetic fields, it has later been realized that the notion of Casimir forces and interactions goes way beyond the original context, as it derives from selective confinement of long-range fluctuations of any field, regardless of its quantum or classical nature. The actual strength of the Casimir forces depends on the details of the geometry of the confining bodies, as well as on their physico-chemical composition. However, regardless of these details, the Casimir forces increase sharply as the distance between the bodies is reduced typically below hundreds of nanometers. Such conditions are becoming more and more frequent in micro and nanotechnolgy, whence the major upsurge of interest towards casimir-like effects across a wide body of disciplines, from electromagnetics, to micro and nanodevice design, all the way up to cosmology.

The present RNP, comprising 58 research groups from 11 countries has poised to reflect this broadband richness, on both theoretical and experimental sides. Moreover, the PI's, some of whom I happen to know in person, are extremely serious and highly esteemed professionals in the field. Thus, I am not surprised that they have delivered in full complinace with their promises. In fact, at project completion, I can literally borrow the words of the mid-term rapporteur, on a verbatim basis, namely:

"... objectives have been met in full with no change in programme direction and with significant scientific progress having been made in all seven areas studied."

These words are fully supported by factual evidence. More in detail:

1. *Material properties, liquids, surfaces*

   These have been investigated in depth for various materials, liquids, surfaces and metamaterials, with special focus on the conditions under which the Casimir force would reverse its sign, from attractive to repulsive. This is of utmost importance for many practical applications as it can lead to major savings in nanofriction.

2. *Casimir-Polder interaction (atoms and molecules)* This pertains to the interaction betwen atoms and surfaces, which is of particular interest, as it can probe local interface phenomena, like interference between macromolecules and quantum decoherence. The RNP has been active in exploring this phenomena under -nonequilbrium- conditions of great relevance to current experiments and not covered by the original casimir-Polder theory.

3. *Thermal Casimir effect* Casimir forces arising in connection with thermal fluctuations in nano-confined environments are of great relevance to many applications in soft-matter (colloids) and micro-nanotechnology. The effect of temperature on the strengths makes the object of a very intense debate. The RNP has contributed proposals for new high-precision measurements, as well as a variety of new theoretical and numerical techniques to investigate such phenomena.

4. *Dynamic Casimir effect* This is a recent offspring of Casimir research dealing with the dissipative effects arising from dynamic geometries (moving boundaries), typically photon emission from the vacuum. Implications are far reaching, from high-tech all the way to cosmological scales and general relativity. The RNP has identified a number of potential experimental setup's such as oscillating mirrors within optical cavities, which, under resonant conditions, would lead to an exponential growth of the otherwise immeasurable number of photons (similar to Hawking's effect)

5. *Complex geometries (MEMS)* This topic cuts at the heart of many high-tech applictions, typically in the MEMS area. A major effect, known as -stiction- is the coalescence of components under the effects of casimir-like force when the separation gap falls within submicrometric distances (at 100 nm the Casimir energy is of the order of 0.1 eV, hence larger than kT). The RNP has proposed and investigated the effects of surface nanocorrugations which would permit to achieve contactless force transmission in micromachines.

6. *Different geometries* This topics deals with the computation of casimir forces in general geometries beyond the simple plate-plate original derivation. These calculations are extremely laborious, and demand qualitatively new techniques beyond the so-called proximity-force-approximation (PFA) developed by Derjaguin back in the mid 30's. The RNP has been very active in proposing new analytical and numerical techniques, with specific focus on a number of fundamental effects resulting from the combination of finite temperature and non-ideal geometries. Among others, potental violations of the third law of thermodynamics and the occurrence of negative entropies.

7. *Quantum vacuum and cosmology* Casimir forces may have a strong bearing on current problems in cosmology, especially in connection with the famous problem of the cosmological constant, introduced by Einstein to recover his picture of a static universe in the face of dynamic solutions to his own equations. The cosmological constant has been intensely revived in modern times esp by observations of the ecceleartaed expansion of the universe, and it has been speculated that it may arise from the quantum fluctuations of the vacuum. Unfortunately, the energy associated with such fluctuations is formally infinite, which raises a major riddle in modern physics. Among others, The RNP has developed a variety of new regularization techniques to tame the infinities which plague the energy of the quantum fluctuations of the vacuum.

The RNP has served as dynamic forum for active exchange of ideas and techniques and to encourage close collaboration between experimenters and theoreticians. Short visits, exchange grants, interdisciplinary training and topical conferences, workshops and schools have been organized to a pace and extent largely consistent with the promised plan. A very substantial amount of high-quality scientific papers has been produced, including high-visibility dissemination ones targeted to a very broad audience. ESF support appears to have been acknowledged to a good extent (based on a random sample I took on my own; I had been asking for explicit data on this item, but i got none). At completion, the network has published **330** research papers of very high quality in journals of high impact factor and aspects of the research have been highlighted in Nature News and views and in New Scientist. The network has been involved in the organisation of **13** Conferences and Workshops including 3 with US collaboration, has funded **57** short visits and **14** exchange grants. The extent to which all the research groups have been involved in publications, workshops etc is difficult to judge from the report, but by and large it appears that a reasonable effort along these lines has been put in place. Evidence of industrial collaboration remains scanty after completion, but the opportunity for this in the future, particularly in the MEMS-NEMS area, is definitely there. The programme has succeeded in pulling together the European community, both theoretical and experimental, and enhanced collaboration with the USA, thus adding significant value to the (leading) European research. Many of the researchers are young and the opportunity to attend conferences and workshops and to take part in exchange visits etc has been of particular value to them. The programme has been well managed in terms of making scientific progress and pulling the community together. Overall, I believe the RNP was excellent value for money, and has contributed to enhance the prestige and competitiveness of European research in this area.