REPORT ON ESF SCIENCE MEETING

ENGINEERING THE CASIMIR FORCE - THEORETICAL AND EXPERIMENTAL PERSPECTIVE

ORGANISERS: Ricardo Brito (Universidad Complutense Madrid) and David Dean (Université Bordeaux 1)

1. Summary

The meeting was held 8th -11th November at the Hotel Spa Villalba in the village of Vilaflor in Tenerife. Participants arrived on the evening of the 8th November and left on the morning of the 11th November. The whole of Friday was used for seminars as was the following Saturday, with the exception of the afternoon which was left free for discussions. The aim of the conference was to look at new directions for Casimir research notably how the Casimir effect can be engineered. It had a rather unusual composition for a conference on the Casimir effect as it mixed scientists looking at the traditional QED Casimir effect long with scientists looking at thermal Casimir effects in systems such as membranes and binary liquid mixtures. In both cases there were experimental and theoretical talks. Despite the fact that the list of people who attended was not exactly that given in our proposal (a few speakers were unable to attend due to other professional or personal engagements), the overall scientific composition of the conference was respected. The conference being a small one, most of the participants were fairly senior but a number of junior scientists (1 PhD student, 2 Postdocs and 2 recently recruited academics) were also present.

The meeting had quite an eclectic flavor as fluctuation induced interactions were discussed in a wide variety of contexts, traditional Lifshitz theory in non-planar geometries (theory and experiments), Casimir forces between systems held at different temperatures and heat transfer, using the critical Casimir force to control colloidal phase diagrams, Casimir effects in granular materials and the fluid mechanics of binary liquid mixtures, the link between the Casimir effect and quantum phase transitions, fluctuation effects in nano-bubbles and numerical methods to treat Casimir interactions

An important point of the meeting was the presentation of Vitaly Svetovoy, who after his talk presented the activities of the ESF Casimir network running from 2008-13 and discussed the perspectives for renewing the activity of this network (possibly via an EU funded COST program). The organizers of this meeting (R. Brito and D.S. Dean) have been invited by George Palasantzas (coordinator) of the ESF Casimir network to send a list of problems and potential research directions in the Casimir effect for eventual use in a new network funding proposal.

2. Scientfic Content

2.1. **Morning 1.** The conference started with two theoretical talks, the first (Soto) on the computation of Casimir interactions via the method of stochastic quantization and the second on mathematical appearance of Casimir like interactions when calculating the work done in quantum quenches by mapping the d dimensional quantum problem onto a $d+1$ dimensional classical problem in the thin film geometry (hence the link with Casimir interactions). There then followed a talk (Grosfils) on the stability of nano-bubbles and then a talk on fluctuation induced interactions in granular media and binary liquid fluids (Kellay). It was shown how two large intruders in a horizontal glass tube half filled with sand experience an effective interaction when the tube is rotated. Low rotation speeds leads to an attractive interaction and the formation of aggregates but when the rotational speeds increased the interaction becomes repulsive and the aggregates break up. Then the possible role of the Casimir effect in the break up of liquid columns (formed by lasers due to the low surface tensions between the two fluids close to the critical temperature) of one phase in the other phase of a binary liquid mixture close to the demixing transition was described. The Casimir interaction may play a role in the latter stages of the breakup of these tubes.

2.2. **Afternoon 1.** The first talk (Maggs) discussed how the sorts of partition functions arising in the thermal Casimir effect could be computed numerically. The method is based on a system of charges and electric field variables on the links of lattice. It presents a major advance in the simulation of electrostatic and dielectric systems as it avoids the computationally costly solution of Poisson's equation and numerical problems associated with long range Coulomb and dipolar interactions.

The following talk (Dietrich) was a wide ranging review of the critical Casimir effect. The development of the theory and first experiments on films were described before the more recent theoretical and experimental results of the Stuttgart group were expounded, notably recent results on tailoring the surface properties of interfaces in the Casimir effect where several different boundary conditions can be applied by chemically patterning surfaces.

Fluctuations about mean field electrostatics for systems such as electrolytes lead to Casimir-like, usually screened, fluctuation induced interactions. In the third afternoon talk (Holdsworth) it was shown how spin ice systems exhibit effective magnetic monopoles and behave as a magnetic Coulomb gas. The possibility of Casimir like interactions in these systems and exotic non-equilibrium properties in the presence of applied fields were discussed.

2.3. **Evening 1.** Monopolar fluctuation interactions of the Kirkwood-Schumaker type were discussed (Podgornik). These forces are of longer range than dipolar induced van der Waals forces. A full understanding of these forces depends requires the understanding of surface charge regulation in the presence of dielectric discontinuities. It was shown how they can be formulated within a field theoretic formalism.

One of the major problems in computing Casimir interactions is dealing with the effect of complex boundaries. A method was introduced (Fournier) based on discretizing the boundaries in the problem imposing the boundary condition at a set of points. It was shown how universal results for Casimir forces can be recovered within this formalism. Finally the possibility of tuning the Casimir effect using topological insulators was discussed (Rodriguez). One of the out standing problems in the QED Casimir effect is how to obtain repulsive forces between media across the vacuum, the approach proposed may help in realizing this goal.

2.4. **Morning 2.** There were three talks on the critical Casimir effect in colloidal systems (Schall, Bonn and Veen) by scientists at the University of Amsterdam. The solvent in these systems is a critical binary mixture which induced long range interactions between charge stabilized colloids close to the critical temperature. Both equilibrium and non-equilibrium aspects can be studied and molecular liquid and solid phases have been found. The results can be rather well described by effective pair potentials. Significant differences are found between systems with and without gravity in terms of fractal structures that can be grown and the kinetics of growth.

The optical properties of gold films and there use in Casimir force prediction were discussed (Svetovoy). The effects of roughness were treated theoretically, two contributions are found, the first from typical fluctuation effects that can be treated perturbatively within Lifshitz theory and the second from extreme statistics of local maxima treated in the pairwise approximation. The activities of the ESF Casimir network were described at the end of this talk.

2.5. **Evening 2.** The scattering formalism was used to compute Casimir interactions between nano-structured surfaces in equilibrium and for surfaces held at different temperatures (Guérout). The role of the geometry of the surface was investigated.

Measurements of the Casimir force in a sphere-plane geometry using a cryogenic force microscope were described (Laurent). It was shown how the electrostatic environment of the interacting surfaces plays an important role in weak force measurements and can overcome the Casimir force at large distance. It seems that dielectric surfaces as far as 5cm from the measurement apparatus can affect the force measurements !

3. Assessment of the results

Here we concentrate on the new perspectives aspect of the conference. These notes are based on discussions during and after the seminars and general discussions over dinner and in the evening.

3.1. **Engineering.** As the conference was based on engineering or tailoring the Casimir effect it should be noted that the critical Casimir effect is today being tailored or engineered in the field of colloidal science. When used as a solvent, as binary liquid mixture mediates a tunable, particularly in temperature, critical or near critical Casimir interaction between colloid particles. Along with this interaction there are also electrostatic interactions, which themselves can be tuned relatively easily by adjusting salt concentration. It was shown that very rich phase diagrams can be obtained in such systems. This experimental activity seems to have a large advance on theory, as understanding the statistical mechanics of such systems will probably require the understanding of n-body fluctuation effects in a many particle system. A number of participants also pointed out that our current understanding of the coupling between electrostatics and the critical Casimir effect (the behavior of salt in the solvent) requires a better understanding. Additional control is available for colloidal systems near interfaces which can be chemically treated and where the effective sign of the interaction can even be controlled. Another interesting point in the critical Casimir effect, raised in the experiments of the Bonn/Schall group in Amsterdam, is to how the universal component generated by order parameter fluctuations is related to, or perhaps can be decoupled from, local wetting preferences for surfaces to one or other of the phases. Finally in colloidal experiments one tries to eliminate dispersion interactions by optical index matching, to what extent does doing this really eliminate these interactions at the level of non-visible frequencies ?

At the level of engineering the quantum Casimir effect, some pessimism was expressed (by the experts in the quantum field) as to the possibility of achieving repulsive Casimir forces across the vacuum, this problem is of course tremendously important in NEMS (indeed our funding for this meeting was from the ESF program *Exploring the physics of small devices*). Pablo Rodriguez's talk showed that there may be some hope of changing the interaction sign between topological insulators by tuning the topological magnetoelectro coupling. In addition perhaps some progress could be made in this direction by exploiting non-equilibrium effects. In the talk of Hamid Kellay, it was clearly shown that the interaction between large intruders in granular materials could change sign (as a function of the driving of the granular system).

3.2. **Disorder.** Measurements of the quantum Casimir effect are plagued by additional, seemingly still poorly understood, parasitic forces of electrostatic origin. The talk by Justine Laurent on her experiment clearly demonstrated this effect. As well as interactions due to patch effects and charge disorder on the actual sphere plate system, effects due to dielectric materials surrounding the sphere plate system seem surprisingly large. As experimental precision increases, deviations from the idealized Lifshitz theory theory due to disorder will be increasingly amenable to experiments. The effect of surface roughness was extensively discussed. At the first level of approximation the distribution of material becomes random within the context of the Lifshitz theory. However surface roughness should also change electrical properties, could this produce an effectively random potential for conduction electrons near the surface and could this potential produce novel electrical response properties, for example could Anderson localization play a role ? Clearly localization effects are not present in the Drude model. Recently Rudi Podgornik and collaborators have shown that net neutral objects baring random charges can exhibit long range forces (due to an image charge effect) that can even dominate the usual Casimir interaction. It was also pointed out by Podgornik that systems such as proteins have complex charge distributions. In solution charged groups are formed by disassociation in the solvent to give net charges, however these net charges will exhibit fluctuations leading to a mono-polar Casimir effect first identified by Kirkwood and Schumaker. Because the fluctuations are mono-polar the resulting fluctuating induced interaction is of longer range than the traditional dipolar one. To really attack complex systems such as proteins and viruses it seems that the numerical methods being developed by Tony Maggs will be very useful to study both the mean-field and one-loop corrections in such systems.

3.3. **Dynamics.** The dynamics of the Casimir effect received some attention. In the critical Casimir effect the dynamics can be rather slow at a microscopic level, this means that such in such systems one may be able to see dynamical effects. In this area dynamical calculations are limited to the simplest system and dynamical models (free Gaussian field theories and simple stochastic dynamics of the model A type with no hydrodynamic coupling). There is even some ambiguity as to how forces should be defined out of equilibrium. In the talk of Hamid Kellay it was shown that the critical Casimir effect probably plays a role in the dynamics of the pinching (how the Rayleigh Plateau instability takes place) of a neck in a column of a colloidal rich phase in the dilute colloid phase near a critical demixing transtion. Theoretically the problem is very challenging as one must understand how critical Casimir fluctuations are coupled to hydrodynamics. The problems of computing the fluctuations and probability distributions of Casimir forces were also discussed. For these problems there are questions about which representations for the force are appropriate and also as to the precise sense of the fluctuations of forces in quantum mechanics where one is more used to talking about potentials. The talk of Gambassi on the distribution of work done in quantum systems is clearly relevant to this problem. A number of approaches find force fluctuations in zero temperature quantum systems, in statistical physics this usually implies a drag force. This then raises the question of how a diffusion generated by Casimir force fluctuations respects the Lorentz invariance of the quantum vacuum.

The Casimir à la Lifshitz effect has been studied in the presence of temperature differences. In soft matter and liquid systems non-equilibrium conditions can be imposed by mechanical driving or chemical reactions. Do systems of active matter exhibit fluctuation induced interactions ? The effects of temperature gradients in critical binary systems are presumably very hard to study due to hydrodynamic effects such as convection.

ENGINEERING THE CASIMIR FORCE

Hotel Villalba
Vilaflor, Tenerife
November 9–11, 2012

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Stochastic quantization and Casimir forces

Rodrigo Soto
The Rudolf Peierls Centre for Theoretical Physics, Univ. of Oxford, UK.

It is shown how the stochastic quantization method developed by Parisi and Wu can be used to obtain Casimir forces. Both quantum and thermal fluctuations are taken into account by a Langevin equation for the field. The method allows the Casimir force to be obtained directly, derived from the stress tensor instead of the free energy. It only requires the spectral decomposition of the Laplacian operator in the given geometry. The regularization of the divergent stress tensor is described, being able to implement it numerically. As an application we compute the Casimir force on the plates of a finite piston of arbitrary cross-section and the case of a piston with triangular cross section is analyzed in detail. Asymptotic expressions valid at low and high temperatures, as well as short and long distances are obtained. The formalism provides also an expression for the fluctuations of the force and it is shown that, in the piston case, the variance of the force is twice the force squared.

Work, large deviations, critical Casimir effect, and universality in quantum quenches

Andrea Gambassi
SISSA, Trieste

Recent experimental progresses in the physics of ultracold atomic gases have revived interest in the behavior of thermally isolated quantum statistical systems, especially after sudden changes (quenches) of their control parameters. Considering the quench as a thermodynamic transformation, it is natural to study the work done on the system, which is characterized by a certain probability distribution. By focussing on large deviations, i.e., rare fluctuations of the intensive work, we establish a connection with the physics of a classical system confined in a film geometry. If the quench of the quantum system occurs close to a (quantum) critical point, the large deviations of the work acquire universal features dictated by the critical Casimir effect in the corresponding classical system. In addition, for large values of the work and in systems of bosons, the statistics of the work may display a transition which is analogous to the equilibrium Bose-Einstein condensation.

The Stability of Surface Nanobubbles

Patrick Grosfils

Université Libre de Bruxelles, Belgium

Surface nanobubbles are tiny gas-filled cavities that form in water-gas mixtures in contact with hydrophobic surfaces. For a long time the existence of surface nanobubbles was questioned because it seems to contradict theoretical arguments suggesting that such a gas state did not exist. Their existence, however, was confirmed through atomic force microscope images, experiments using infrared spectroscopy have elucidated their gaseous state, and recently nanobubbles have been observed by optical interference-enhanced reflection microscopy. Despite these observations, the mechanism for the formation and stability of surface nanobubbles remains unknown. A recent study suggests that the stability of nanobubbles may be attributable to a dynamic equilibrium between a Knudsen gas, filling the bubble, and the surrounding liquid. We will shown how the problem of surface nanobubbles can be investigated using a coarse-grained nonequilibrium model of water-gas mixtures.

Fluctuation effects in two different systems: granular segregation and droplet pinch off

Hamid Kellay

Laboratoire d'Ondes et Matière d'Aquitaine, Université de Bordeaux, Bordeaux, France

During this talk I will discuss two experimental situations where fluctuation mediated interactions seem to play an important role. In the first situation, where large particles are embedded in a sea of smaller ones, the velocity fluctuations of the small beads seem to be responsible for attractive interactions between the larger ones. These interactions lead to size segregation of the assembly of grais. In a second situation, where a thin neck of fluid is monitored during its thinning process leading to neck break up or pinch off, the interfacial fluctuations of the neck give rise to a crossover from the classical visco capillary pinch off to a recently predicted fluctuation dominated break up. The fluctuation pressure within the neck is shown to be responsible for this crossover.

Constrained partition functions and Casimir interactions

Anthony Maggs
ESPCI, Paris, France

Our interest in this problem arose when studying dynamical systems with local update rules, which converge to a Gibbs distribution characterising electrostatic interactions. We showed that these local dynamic systems sample a partition function constrained by Gauss' law. Application of the method to dielectric media then leads to a new formulation of Casimir/Lifshitz/van der Waals interactions. We discuss the application to dielectric media, and look forwards to applications in Poisson-Boltzmann theory.

Critical Casimir Forces

Sigfried Dietrich
Max Planck Institute for Metals Research, Stuttgart, Germany, and Institute for Theoretical and Applied Physics, University of Stuttgart, Germany

Long-ranged correlations in a fluid near its critical point lead to clearly identifiable effective forces acting on confining walls. The corresponding universal scaling functions are discussed for different boundary conditions and geometries. The theoretical predictions are compared with high precision experimental data for He^4 and He^3/He^4 wetting films near the superfluid phase transition as well as with synchrotron scattering data from classical binary liquid mixtures. Direct measurements and applications for collidal suspensions are discussed.

Spin ice - a surprising Lattice Coulomb gas

Peter Holdsworth

ENS, Lyon, France.

Models for the frustrated magnetic material *spin ice* show the remarkable property of fractionalization of magnetic moments into effective free magnetic charge : magnetic monopoles [1]. The low energy theory is therefore that of a magnetic Coulomb gas in the grand canonical ensemble. In this talk I will review this unusual physics and give recent experimental and theoretical developments. I will present numerical results for the conductivity for such a lattice gas, showing strong non-Ohmic behaviour in the so called Wien effect [2].

[1] Castelnovo, C., Moessner, R. and Sondhi S. *Magnetic monopoles in spin ice* , Nature 451, 42

[2] L. Onsager, J. Chem. Phys. 2, 599, (1934).

Kirkwood-Schumaker forces and monopolar thermal Casimir interactions

Rudolf Podgornik

Josef Stefan Institute, University of Ljubljana, Slovenia

I intend to reassess the nature of the KS interaction originally invoked in the context of protein physics that recently gained renewed interest. The KS theory has two facets: the dielectric decrement of proteins and the KS interaction proper, which is if the monopolar fluctuation type. I will focus on the latter and show how it can be formulated and further developed within a field-theoretic scenery.

Universality in the point discretization method for calculating Casimir interactions with classical Gaussian fields

Jean-Baptiste Fournier
Laboratoire Matière et Systèmes Complexes (MSC), Universit Paris VII, France

We study how universality arises when computing Casimir interactions between arbitrary bodies by discretizing their boundaries into pointlike constraints viewed as pointlike inclusions. Introducing ad-hoc cutoff and regularization for the field's correlation function, we find that universality arises when (i) the separation delta between the point-like inclusions is less than the cutoff Λ^{-1}, and (ii) the bodies are much larger than the cutoff. A sharp transition from discrete to continuous boundaries occurs at $\delta = \pi/\Lambda$ in the thermodynamic limit for rods at large separation. We illustrate our findings in two-dimensions with rodlike bodies and more complex bodies shaped as moons.

Casimir effect between Topological Insulators: a proposal for quantum levitation

Pablo Rodriguez
Universidad Carlos III de Madrid, Spain

In this talk I will study the Casimir interaction between Topological Insulators (TIs). I will start with a brief description of the TIs, to explain what a TI is, and why they are interesting from a Casimir effect point of view. In particular, a thee dimensional Topological Insulator is characterized by its topological magnetoelectric coupling $\theta \neq 0$. We will discuss the electromagnetic response of the TIs, how a magnetoelectric coupling between TE and TM modes appears in this material and its consequences. We will show how, by tuning the parameter θ of the TI, we will be able to change the behavior of the Casimir energy between TIs. From attraction to repulsion for all distances, and even the appearance of an equilibrium distance in the system. Then TIs can be potentially used to obtain "quantum levitation" and to avoid the stiction phenomena in NEMS.

Critical Casimir Interactions: New temperature control of colloidal assembly

Peter Schall

Institute of Physics, University of Amsterdam, The Netherlands

Because of their exquisite temperature dependence, critical Casimir interactions provide new opportunities for the assembly of colloidal and nanoparticle structures. In this talk, I will present an overview of our recent equilibrium and non-equilibrium assembly by critical Casimir forces. Using new index-matched colloidal systems, we image the assembly in three dimensions and at the particle scale with confocal microscopy. In equilibrium, we find analogues of molecular liquid and solid phases the formation of which is well described by effective pair potentials. We elucidate the nucleation and growth of the colloidal liquid phase in three dimensions, and measure its surface tension directly. The advantage of the temperature control, however, is that it allows active quenches to non-equilibrium structures. We use precisely controlled temperature quench to obtain new insight into non-equilibrium colloidal aggregation. Such reversible temperature control opens new routes for the growth and annealing of designed colloidal structures.

The Casimir effect in binary liquid mixtures

Daniel Bonn

Institute of Physics, University of Amsterdam, The Netherlands

Colloidal aggregation in microgravity by critical Casimir forces

Sandra Veen

Van der Waals-Zeeman Institute, University of Amsterdam, The Netherlands

By using the critical Casimir force, we study the attractive strength dependent aggregation of Teflon colloids with and without gravity by means of Near Field scattering. The critical Casimir effect induces interactions between colloids due to the confinement of bulk fluctuations near the critical point of liquids. The strength and range of the interaction depends on the length scale of these fluctuations which increase as one approaches the critical point. The interaction potential can thus be tuned with temperature. Significant differences were seen between microgravity and ground experiments, both in the structure of the formed fractal aggregates as well as in the kinetics of growth. In microgravity purely diffusive aggregation is observed. By using the continuously variable particle interaction potential we can for the first time experimentally relate the strength of attraction between the particles and the structure of the aggregates.

Casimir force between real materials

Vitaly B. Svetovoy
University of Twente, The Netherlands

Optical properties of gold films prepared in different conditions are discussed. The optical response measured ellipsometrically demonstrates considerable sample effect. It is important for comparison between the theory and experiment with a precision of 10% or better.
Possibility to tailor the force by changing the material optical properties is briefly reviewed with a special attention to the phase change materials. The observed variation of the force for AIST films in the crystalline or amorphous states is discussed with a careful comparison of optical properties in these states.
Roughness of interacting bodies is typically taken into account as a perturbation effect. However, strong deviation from the perturbation theory prediction was found experimentally. Statistical analysis of rough gold films revealed rare high peaks responsible for the distance upon contact. A model separating high and normal asperities is proposed and agreement with the experiment is demonstrated.
Tailoring of the Casimir force and the radiative heat transfer between dielectric bodies covered with graphene are discussed. The thermal component of the force is the most sensitive to the Fermi level in graphene and presence of the band gap. It is demonstrated that graphene can dramatically influence the radiative heat exchange turning a poor heat emitter/absorber into a good one and vise versa.

Heat transfer and non-equilibrium Casimir force with structured surfaces

Romain Guérout
Laboratoire Kastler Brossel, Université Paris VI, Paris, France.

In my talk, I'll review recent calculations for Casimir interactions between nanostructured surfaces both at thermodynamic equilibrium and out of equilibrium in the framework of the scattering theory. I'll emphasise on the interplay between the thermal Casimir force and the geometry of the surfaces.

Casimir force in Au-Au and Au-Si cavities at low temperature

Justine Laurent
ENS, Lyon, France

In this talk, I will report on measurements of the Casimir force in a sphere-plane geometry using a cryogenic force microscope to move the force probe in situ over different materials. I will show how the electrostatic environment of the interacting surfaces plays an important role in weak force measurements and can overcome the Casimir force at large distance. After minimizing these parasitic forces, the Casimir force measurements will be presented between a gold-coated sphere and either a gold-coated or a heavily doped silicon surface in the 100—400 nm distance range. By comparing the experimental data with theoretical predictions, I will discuss the consequence of a systematic error in the scanner calibration on the agreement between experiment and theory. At the end, we will see that the relative force over the two surfaces compares favorably with theory at short distance, showing that this Casimir force experiment is sensitive to the dielectric properties of the interacting surfaces.

Venue:

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Engineering the Casimir Forces

Friday Nov. 9th		Saturday Nov. 10th	
08:55	Welcome		
09:00	R. Soto	09:00	P. Schall
09:45	A. Gambassi	09:45	D. Bonn
10:30	*Coffee*	10:30	*Coffee*
11:00	P. Grosfils	11:00	S. Veen
11:45	H. Kellay	11:45	V. Svetovoy Description of EU Network
12:30	*Lunch*	12:45	*Lunch*
14:15	A. Maggs	Afternoon free for discussions	
15:00	S. Dietrich		
15:45	P. Holdsworth		
16:30	*Coffee*		
17:00	R. Podgornik	17:30	*Coffee*
17:45	J.-B. Fournier	18:00	R. Guerout
18:30	P. Rodriguez-Lopez	18:45	J. Laurent
20:00	*Dinner*	20:00	*Dinner*