agence d'évaluation de la recherche et de l'enseignement supérieur

Vague A : Campagne d'évaluation 2014 - 2015

Unité de recherche

Dossier d'évaluation

Nom de l'unité : Laboratoire de Physique et Modélisation des Milieux Condensés
Acronyme : LPMMC
Nom du directeur pour le contrat en cours : Frank Hekking
Nom du directeur pour le contrat à venir : Anna Minguzzi

Type de demande :

Renouvellement à l'identique ×	Restructuration	Création ex nihilo

Choix de l'évaluation interdisciplinaire de l'unité de recherche :

Oui	Non ×

I. DOSSIER D'ÉVALUATION

1. Présentation de l'unité

1.1 Introduction

The *Laboratoire de Physique et Modélisation des Milieux Condensés* (LPMMC) is the only theoretical physics laboratory in Grenoble, located on the CNRS campus on the *polygone scientifique*. LPMMC's scientific activity focuses on the theory of condensed matter, combining expertise in the fields of statistical physics, quantum mechanics and electromagnetism. Part of this activity is at the interface with mathematical physics, with the geosciences and with computational physics. Members of LPMMC maintain strong collaborations with experimental and theoretical groups in Grenoble, France and worldwide.

LPMMC was founded in 1990 by R. Maynard and A. Pasturel, with the aim to develop a novel type of research activity in theoretical physics, close to experiment and using the – at the time – new generation of powerful computers. Located in the then recently built *Maison des Magistères* together with the Grenoble Physics Doctoral School, LPMMC (still under the name *Laboratoire de Physique Numérique*, LPN) was the first *pied-à-terre* of Joseph Fourier University on the CNRS campus.

Powerful computer facilities developed fast and soon became ubiquitous. As a result, LPN decided to become more theory-oriented and to broaden its scientific interests. The name changed to the current one and in 1998, LPMMC obtained the so-called *UMR*-status of a Mixed Research Unit (*Unité Mixte de Recherche*), with support from Joseph Fourier University (UJF) and CNRS. Since 1998, the laboratory has attracted many young international researchers. Today, the members of LPMMC originate from ten different countries.

The current research activities developed at LPMMC deal with a variety of phenomena of modern condensed matter physics: Anderson localization, superfluidity and superconductivity, out-of-equilibrium phase transitions, Bose-Einstein condensation, the physics of lasers, thermo-electric quantum transport, topological order and the quantum Hall effect. These phenomena occur in a variety of physical systems. Examples are ultracold quantum gases, graphene, semiconductor micro-cavities, superconductors and superconducting hybrid systems. Despite the large variety of phenomena and physical systems, our research is based on the use of a common set of theoretical and numerical tools enabling us to deal with four fundamental aspects of interest: waves and coherence, disorder and randomness, correlations and interactions, transport and nonequilibrium phenomena. Our research aims at the development of fundamental understanding of classical and quantum phenomena in condensed matter physics and also of applications in such fields as seismology, new sources of light, interferometry, high-precision measurements and quantum information.

LPMMC plays a central role in several important local, national and international projects. On a local level, we mention our strong implication in the *Centre de Physique Théorique de Grenoble – Alpes* (CPTGA), founded by members of LPMMC and the administrative part of which is governed at LPMMC. We also mention our strong implication in the RTRA *Fondation Nanosciences*, the Laboratory of Excellence LABEX-LANEF and in PHYNUM – CIMENT, a local computational platform used by a large community of scientists – not only physicists. On a national level, LPMMC is active in the research networks (GDR) *MésoImage, Physique Quantique Mésoscopique, Atomes Froids* and *Dynamique Quantique* as well as in the in the service network (GDS) *EcoInfo*, founded by and currently directed by members of LPMMC. Finally, as to international research projects, members of LPMMC are involved in collaborations with Canada, Finland, Germany, Italy, Japan, the Netherlands, Singapore, Spain, the United States and Urugay. We finally mention the strong implication of members of LPMMC in the *Société Française de Physique* (SFP) at both the local and the national level.

1.2 Scientific strategy: face challenges in modern condensed matter physics

LPMMC's scientific strategy is to pursue a research activity in theoretical condensed matter physics at the highest international level. As will be illustrated in this section with citations from the publication list Annexe 6.1, LPMMC members address most of the challenges in modern condensed matter physics, as identified in the recent review *Grand challenges in condensed matter physics: From knowledge to innovation*, by Evgeny Tsymbal and Peter Dowben (Frontiers in Physics 02/2014; DOI: 10.3389/fphy.2013.00032).

Condensed matter physics explores the fundamental properties of matter, as well as of their origin resulting from the interactions of a large number of degrees of freedom. Condensed matter physics is a vast field, constantly changing with new discoveries. Nevertheless, the basic challenges remain the same: to predict and observe new phenomena, properties and functionalities of matter, materials and devices. For more than half a century now, since the discovery of the transistor, condensed matter physics has revolutionized modern society. It continues to do so, by maintaining the interplay between fundamental sciences on the one hand and innovation and applications on the other. It is this very interplay that provides breadth to condensed matter physics.

In condensed mater systems, striking phenomena emerge *from interactions between the constituent particles* and the interplay between coupled degrees of freedom. The quantum-mechanical nature of these interactions makes condensed matter phenomena non-trivial and often counterintuitive. Extraordinary examples of such behavior are superconductivity and superfluidity [204], where quantum mechanics manifests itself on a macroscopic scale. These phenomena can be used to envisage devices useful in high-precision measurements or applications in quantum information processing [169].

The *emergence of non-trivial collective phenomena* in condensed matter physics is often driven by the interplay between well-known constituents; yet the collective behavior may be strikingly different and often unexpected, leading to new quantum states of matter. For example, the Tonks-Girardeau gas is a peculiar strongly interacting one-dimensional bosonic liquid which, due to strong interactions, shows Fermi-liquid type behavior [236].

Disorder and randomness are a central topics in many areas of physics, including condensed-matter physics, optics [209], acoustics, seismology [154], and the physics of ultracold atoms. Breakthrough experimental progress realized in all of these domains in recent years has paved the way to new theoretical challenges [32]. In particular, the interplay of disorder and interactions is one of the most challenging issues that one has to face in these systems [44].

Critical phenomena and phase transitions are an important ingredient of modern condensed matter physics. Continuous phase transitions are described by the Ginzburg-Landau theory, which exploits the so-called mean field approximation. However, a number of phase transitions, such as metal-insulator transitions, or transitions occurring under non-equilibrium conditions, do not follow the Ginzburg-Landau approach and their analysis requires different theoretical schemes [41].

Significant efforts in condensed matter physics are related to the exploration of *properties of materials and devices at the nanometer scale*. Properties at such distances may well deviate significantly from the bulk properties, leading to new phenomena and functionalities. As dimensions are reduced, quantum and fluctuation effects become more and more pronounced. Rolf Landauer's quote *Noise is the signal* indicates that the fundamental properties of these systems and possible new functionalities can often only be grasped with the help of physical theories beyond those only predicting average behavior. Current interest focusses on the properties of nanoscale thermal machines [247], with possible applications in nanorefrigeration [39].

An important class of nanoscale objects is based on an *intrinsically two-dimensional material* such as the well-studied two-dimensional electron gas in certain semiconductor heterostructures and the more recently discovered graphene. Under magnetic fields, these systems are host to a wealth of interesting phenomena, among others related to quantum Hall physics [118, 271], with applications in quantum metrology. More generally, there are a number of systems where key properties such as electric conductivity, spin-orbit coupling, and spin current are *protected by topology*. Among them are the topological insulators—electronic materials that have a bulk band gap like ordinary insulators, but exhibit conducting states on their edge or surface. The surface states of topological insulators are special due to being symmetry-protected by time reversal symmetry [160].

Research at LPMMC addresses all of the above challenges. LPMMC's relatively small size makes it possible to act as a single research team. Therefore, throughout this document, LPMMC's research activity (past and future) will be presented according to the following structure, based on research topics:

COMPLEX SYSTEMS
- Waves and photons in complex media
- Nonequilibrium phenomena

CORRELATED SYSTEMS
- Ultracold quantum gases
- Many-body theory
- Entanglement and quantum correlations

MESOSCOPIC SYSTEMS
- Electronic transport in nanosystems
- Quantum systems under strong magnetic fields

Research at LPMMC is carried out by its permanent staff in close collaboration with experimental and theoretical groups world-wide, mostly in the framework of funded research networks and collaboration schemes. An essential part of our activity is carried out together with PhD-students and postdocs, either at LPMMC or elsewhere. We thus continuously assure on-the-job training and transfer of scientific skills. All the obtained scientific results are published in the relevant peer-reviewed international journals and presented during international conferences and workshops. Detailed accounts of parts of LPMMC's activity appear in the PhD theses supervised by LPMMC members and in the habilitation theses written by LPMMC members. LPMMC members also regularly act as lecturers in training events such as international schools, thereby contributing to the pedagogical dissemination of recent scientific results. Several LPMMC members have teaching commitments at Joseph Fourier University at the Bachelor, Master and Doctoral level. Last but not least, LPMMC members regularly act as organizers of conferences, workshops and schools. All these activities are carried out in close collaboration with LPMMC's computer and administrative staff. The table below summarizes the efforts the laboratory's main activities.

Unité/Équipe	Recherche académique	Interactions avec l'environnement	Appui à la recherche	Formation par la recherche	Total
Ensemble	60	10	10	20	100 %

1.3 Organization of LPMMC

1.3.1 Direction & administration

During the current *quinquennal*, LPMMC was directed by B. van Tiggelen from January 2009 until October 2012 when he was appointed *directeur adjoint scientifique* at the *Institut de Physique* of CNRS. Because LPMMC acts as a single scientific team (*équipe*), its director is also scientific team leader. Until October 2012, financial and administrative matters were under the responsibility of LPMMC's *secrétaire générale* F. Berthoud, in close collaboration with the laboratory's secretaries C. Rabatel and L. Magnino.
As of October 2012, LPMMC is directed by F. Hekking. The organizational structure changed in that the position of *secrétaire générale* was abandoned, the director taking care directly of financial and administrative matters. This implies that more responsibility and autonomy is requested on the level of the secretaries.
Characteristic for the current *quinquennal* is a continuous sharpening of the rules concerning financial management, in particular at CNRS. LPMMC was audited in 2013, giving rise to a number of recommendations and new procedures that need to be implemented in the near future. Another recent change concerns the departure of L. Magnino early 2014 and the subsequent arrival of H. Tellas.
Given LPMMC's relatively small size, as far as the involvement of its members is concerned in the laboratory's management, many lab-related issues are discussed and decisions taken during regular, short informal meetings between the director and the staff. On average once a year, important issues such as budget, recruitment, scientific policy, are discussed and, if necessary, voted during a formal *Assemblée Générale.* The *Assemblée Générale* is also the occasion to discuss the evolutions of the laboratory's computational infrastructure, taken care of by F. Berthoud and J.-D. Dubois (see also 1.3.2. below) or certain administrative and secretarial matters, under the responsibility of C. Rabatel and H. Tellas. Finally, various members of the laboratory are responsible for specific aspects related to the LPMMC (see Annexe 4) or its environment (see Annexe

6.2.6); they also have the opportunity to present important issues during the *Assemblée Générale.*
In addition, a general two-day meeting is organized once a year *hors murs.* This is first of all the occasion for new members of the laboratory (permanent staff, visitors, postdocs, PhD-students and research students) to present their projects. Second, it is the occasion for more in-depth discussions on issues concerning LPMMC, but also on issues related to the (local) politics and strategies proposed by our main funding partners CNRS and UJF. Last but not least, this two-day meeting is to occasion for LPMMC members to meet and socialize in an informal setting during meals, breaks and outdoors activities. In this context we should also mention here LPMMC's annual fondue during the holiday season and the annual barbecue just before the summer break.

1.3.2 Computational infrastructure

1.3.2.1 Information System

The system architecture of the LPMMC has followed the general evolution of hardware, systems, and software. A standardized version of Ubuntu linux system adapted to the needs of members of the laboratory has been installed and is maintained on all workstations (desktop and laptop). Necessary tools for good management have been implemented, such as managing the database of hardware, management of equipment loans, a helpdesk system, the implementation of collaborative tools management, backups, etc. The LPMMC maintains its own website, collaborative website and dynamics websites related to its scientific activities (GDR, GDS, conferences, etc.) and *apmst* (association for parity in the scientific and technical occupations).

1.3.2.2 Use of tools to support scientific research

Concerning the access to scientific software licenses, we participate in the joint operation of the *Polygone Scientifique CNRS*, which offers to its whole community (approximately 600 scientists / ITA), floating licenses for the software that is most frequently used (for LPMMC mostly Matlab and Mathematica).
The high performance computing can be fulfilled by means of :

• A small cluster dedicated to pre-treatments, small simulations and post-treatments operations : 40 core, 128 GB of memory for sequential calculations.
• The access to the platforms of the meso-center CIMENT (ciment.grenoble.cnrs.fr. The biggest high performance equipment "Froggy" is a BullX DLC supercomputer (Bull Newsca) composed of nodes having 2 Intel SandyBridge processors and connected to a FDR Infiniband non-blocking low latency network. It has a Lustre filesystem for the scratch, a fatnode and a 3D visualization node. It offers more than 3000 core).
• The access to the grid CIGRI (about 6000 nodes over Grenoble) adapted for multi-parametric codes.
• Access to platforms GENCI (IDRIS, CINES, CLRB) for extensive calculations.

1.3.2.3 Availability and system security

The physical servers are been gradually replaced by virtual servers installed on only two computers. The energy consumption has been divided by 5 in this way. Maintenance and security have been enhanced by the possibility of switching from one machine to another in case of hardware problems.

1.3.3 Personnel

Since 2009, four permanent staff members left LPMMC: L. Magnino (secretary UJF, now in the private sector), A. Pasturel (DR, now at SIMAP - Grenoble), M. Peretto (secretary UJF, retired), and F. Pistolesi (DR, now at LOMA - Talence). New members are C. Rabatel (secretary CNRS, former secretary at LPSC - Grenoble), N. Rougerie (CR CNRS, former postdoc at Cergy Pontoise), D. Spehner (MC UJF, formerly full time at *Institut Fourier (IF)*, now with a 40% affiliation at LPMMC), H. Tellas (secretary UJF, formerly at UJF's Physics Department) and R. Whitney (CR CNRS, former ILL postdoc). LPMMC hosted several visitors: A. Joye and D. Spehner (both at the *Institut Fourier* in Grenoble) during a CNRS-delegation and H. Baranger (Duke University, USA) and D. Ceperley (University of Illinois, USA), both chairs of excellence at the *Fondation Nanosciences.* Furthermore, LPMMC hosted 29 bachelor and master students, 17 PhD-students and 9 postdoctoral fellows. Details can be found in Annexe 6.2.5.

Seven members of LPMMC were promoted: F. Berthoud (IR1 -> IR CE), F. Hekking (PR1 -> PR CE), M. Holzmann, A. Minguzzi, and S. Skipetrov (CR1 ->DR2), B. van Tiggelen and T. Ziman (DR2 -> DR1).

Several members of LPMMC received important distinctions, see Annexe 6.2.7 for details. Here we only mention F. Berthoud's nomination as *chevalier de la légion d'honneur* in 2013.

1.3.4 Scientific events

LPMMC currently does not organize a regular laboratory seminar with invited external speakers. The existing weekly Friday Theory Seminar (organized with support from LABEX-LANEF and CPTGA) and the Tuesday Nanoelectronics Seminar (organized with support from *Fondation Nanosciences*) suffice as main regular reference seminars. Members of LPMMC participate in the organizing committees of both of these seminars.

New members of LPMMC and PhD-students and Postdocs have the opportunity to present their work during the yearly *Journées Hors Murs,* or during informal LPMMC meetings.

In order to respond adequately to the latest scientific developments, LPMMC regularly hosts or co-organizes local workshops covering timely topics. Examples are the 2010 Workshop *Correlations, fluctuations and disorder*, organized with funding from the PEPS-PTI programme and the GDR MesoImage, the 2012 workshop *Many-body quantum mechanics and cold atoms*, funded by the PEPS-PTI programme and the 2013 *Séminaire Dautreppe* on *Phases topologiques et transitions de phases non-conventionelles*, co-organized with the Grenoble branch of the *Société Française de Physique.* A complete list of the over forty conferences and schools organized by members of LPMMC in Grenoble, France or abroad is presented in Annexe 6.2.3.

1.4 Important facts & developments

Being a laboratory for theoretical physics, LPMMC's main realizations during the past *quinquennal* are scientific publications in the relevant international peer-reviewed journals. Details of LPMMC's scientific achievements can be found in Section 2 below. Here we report two important and successful specific developments that have had significant impact on LPMMC during the current *quinquennal.*

1.4.1 Interface with mathematical physics

LPMMC has a long-standing tradition of collaboration with the mathematical physics group at *Institut Fourier (IF).* Already in the past, before the current *quinquennal*, members of both laboratories have organized joint scientific events (often in the framework of CPTGA) and benefited from fruitful exchange visits during CNRS-delegations. The scientific drive for this collaboration is two-fold. On the one hand, during the past decade or so, mathematical physicists have become increasingly interested in applying the rigorous ideas, techniques and insights of mathematical physics in the context of new physical models. On the other hand, recent developments in condensed matter physics have given rise to the appearance of novel physical model systems, of direct experimental relevance, and amenable to the rigorous methods of mathematical physics. Examples are the quantum Hall effect, the theory of quantum information, and various models of strongly correlated systems, most notably in connection with recent developments in the context of ultra-cold quantum gases.

During the current *quinquennal,* the impetus acquired due to these events has culminated in the actual creation of an interface between physics and mathematics at LPMMC. On the one hand, on a national level CNRS has recognized the importance of the development of this interface, and appointed Nicolas Rougerie, a mathematician, on a CR2-position with LPMMC, a theoretical physics laboratory, as the official affiliation. On the other hand, on a local level, Joseph Fourier University appointed Dominique Spehner, mathematician at *Institut Fourier*, partially at LPMMC. These appointments made it possible to strengthen the interface between mathematics and theoretical physics. Together with colleagues at IF and LPMMC, Nicolas and Dominique subsequently acquired funding for various projects: in about two years time, two PEPS-PTI projects and an ANR projected were selected for funding. As a result, LPMMC recently hosted several international visitors as well as an important international workshop. All this bodes well for the future of this interface during the *quinquennal* 2016-2020.

1.4.2 ECO-Info: towards green ICTs

As has been exposed in Section 1.1. above, LPMMC has been a strongly computational-oriented research laboratory since its creation. As such, LPMMC has played an important, founding role on the level of the creation during the 1990-ties and subsequent development of various Grenoble-based computational platforms, most notably CIMENT, see also Section 1.3.2. At the time, the scientific part of this activity was led by A. Pasturel. The technical part was taken care of by F. Berthoud, more recently joined by J.-D. Dubois. As a result of the strong technical involvement of LPMMC staff, important technical know-how has been acquired over the years, ranging from hard-ware related issues to soft-ware ones, including important insight in the actual professional activity and attitude of the computer engineer. This know-how has been

successfully exported and disseminated, both on a local and on a national level by F. Berthoud, through training and network activities aiming at both computer engineers and actual users of computational infrastructure.
An important spin-off of these activities has been the creation in 2012 of the *Groupement De Service* (GDS) Eco-Info at the initiative of F. Berthoud. Eco-Info is a national network focusing on the environmental and social impact of modern Information and Communication Technologies (ICTs), and encompasses both hard-ware and soft-ware aspects. This impact concerns in particular the use and management of resources and pollution as well as the impact of ITCs on human life and on biodiversity. The network's activities are concerned with databases and server systems, desk- and laptops, printers and other electronic equipment frequently used in a scientific context. Use, re-use and recycling possibilities are studied and evaluated. The network follows the relevant literature published on the general topic of green ITC and provides critical summaries to those concerned. On demand, GDS EcoInfo also organizes information and training sessions, provides advice and consulting when setting-up new ICT structures and platforms, and assesses and evaluates existing ICT infrastructure.
The success of EcoInfo can be measured from its history: what started as a small work group in 2006 has now grown out to a full-fledged professional network, regularly receiving requests for help and expertise not only from those active in academic research, but also by non-academic entities from the private sector, from France and abroad.

2. Réalisations

The presentation in this section is according to scientific topic, following the order indicated in Section 1.2., and concludes with a brief description of visibility and impact. It consists of 4 parts, organized as follows:

A. COMPLEX SYSTEMS
- Waves and photons in complex media
- Nonequilibrium phenomena

B. CORRELATED SYSTEMS
- Ultracold quantum gases
- Many-body theory
- Entanglement and quantum correlations

C. MESOSCOPIC SYSTEMS
- Electronic transport in nanosystems
- Quantum systems under strong magnetic fields

D. VISIBILITY AND IMPACT
- Academic visibility and impact
- Outreach: non-academic visibility and impact

A. COMPLEX SYSTEMS

2.1 Waves and photons in complex media

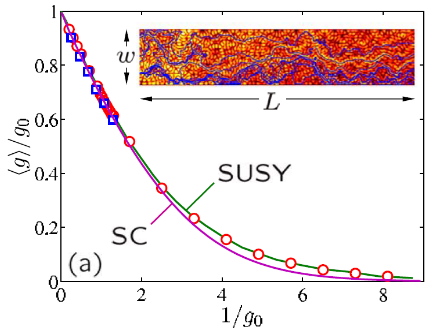
Contributors: D. Basko, F. Hekking, V. Rossetto, S. Skipetrov, B. van Tiggelen
Postdocs: J. Babington, M. Donaire, M. Piraud
PhD-students: A. Goetschy, S. Kawka

Propagation and scattering of waves in complex media has been one of the main research topics of LPMMC since the creation of the latter. Its main focus is on generic wave phenomena that take place in media where certain symmetries are broken due to, e.g., disorder, strong external fields, or asymmetries of constituent elements. We are interested in both fundamental phenomena such as Anderson localization or quantum vacuum fluctuations, and applications: imaging, random laser, the role of photons in nanorefrigeration. Our approach to all these problems benefits from an interdisciplinary viewpoint that consists in drawing analogies and exchanging ideas between optics and acoustics, solid state physics and seismology, atomic physics and elasticity.

2.1.1 Anderson localization of classical waves

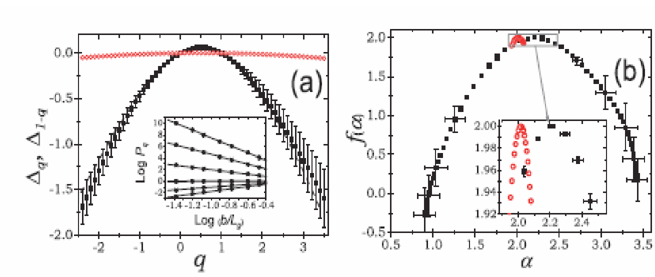
Collaborations: A. Aubry (Paris), A. Lagendijk (Twente, Netherlands), J. Page (Manitoba, Canada), A. Yamilov (Missouri, USA)

Anderson localization – the halt of transport due to destructive interferences of scattered waves – takes place for waves in disordered media. We studied this phenomenon theoretically for waves in quasi-one-dimensional (disordered waveguides) and three-dimensional (3D) geometries. For disordered waveguides, we established the limits of validity of the self-consistent theory of localization and demonstrated that the crossover from diffuse scattering diffusion coefficient (a collaboration with A. Yamilov, see figure). These results were confirmed experimentally in recent experiments in the group of Hui Cao (Yale, USA). We have also developed an approach that allows describing fluctuations of waves transmitted through a waveguide in the localized regime and made quantitative predictions of experimental conditions under which Anderson localization of terahertz waves may be observed.



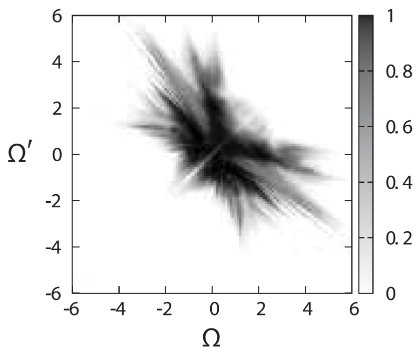
Average conductance <g> of a disordered waveguide as a function of the inverse of the nominal conductance $g_0 = \xi/L$ (with ξ the localization length). Symbols show our numerical results and the lines – predictions of the supersymmetric σ-model (SUSY) and the self-consistent theory (SC). The inset shows the typical wave trajectories (blue) superimposed on the intensity distribution (red-yellow) in the waveguide. From PRB **82**, 024205 (2010).

In 3D, we studied the spatio-temporal evolution of intensity profiles of waves transmitted through a disordered medium and the signatures of Anderson localization in these profiles. Our predictions were successfully used by the group of Georg Maret (Konstanz, Germany) to observe Anderson localization of light in 3D. A work in collaboration with J. Page and A. Aubry was devoted to a better understanding of fluctuations of wave intensities and of the time-dependent reflection in the localized regime. Collaboration with the teams of J. Page and A. Lagendijk has enabled a very complete observation of multifractality of elastic waves near the mobility edge (see figure).



Anomalous spectral components (left) and fractal singularity spectrum (FSP) for localized elastic waves at 2.4 MHz (black) and diffuse waves at 2.0 MHz (red). The inset (left) shows how different moments of the wave function decay algebraically with different slopes. The inverted parabola on the left is the theoretical prediction in a first-order dimensional expansion around $d = 2$. In the diffuse regime the FSP is concentrated near the physical dimension $d = 2$.

A contemporary issue in Anderson localization is its interplay with nonlinearity. The main question is whether the localization is destroyed by nonlinear effects or not. Even if the normal modes of the linearized system are localized by disorder, the system can still exhibit complex non-trivial behavior because the dynamics of different normal modes becomes coupled by the nonlinearity. The nonlinear coupling may produce chaotic motion of a few localized normal modes. This may happen even when the nonlinearity is weak provided that the local disorder configuration is favorable enough (i.e. allows for resonances between normal modes). We have shown that in a classical disordered nonlinear chain the probability of finding such configurations tends to unity in the thermodynamic limit. Then Anderson localization is destroyed by the chaos that allows for energy exchange between localized normal modes and thus allows the propagation of a perturbation through the system. We have studied the appearance of chaos in disordered nonlinear chains with localized normal modes by a combination of analytical and numerical methods. The analysis of local few-mode configurations (see figure) allowed determining macroscopic properties of a long chain such as, for example, its macroscopic transport coefficients.

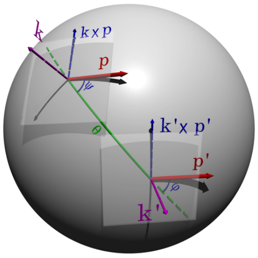


A greyscale plot of the probability of chaos for three coupled normal modes as a function of two relative frequency mismatches, determined numerically. From such three-mode configuration, one can determine the probability of chaos on a long disordered chain in the limit of weak nonlinearity. From PRE **86**, 036202 (2012).

2.1.2 Multiple scattering of vector waves

Collaborations: N. Le Bihan (Grenoble), S. Catheline (Lyon), I. Sokolov (St. Petersburg, Russia)

Even if many of wave phenomena in disordered media are common for all waves, the vector nature of light, elastic or any other waves may sometimes be important. In particular, it turns out that the multiply scattered wave keeps memory about its initial polarization longer than it does about its direction. The "survival time" of polarization is governed by the scattering anisotropy of the medium while the disorder controls the parallel transport of polarization. Using harmonic analysis on the rotation group, we discovered a general expression for the geometric phase statistics (a classical Berry's phase, see figure). This work generalizes previous results obtained for diffuse waves to any random scattering situation and any anisotropy for a fixed, random, or infinite number of scattering events. Following our theoretical prediction, the geometric phase of elastic waves in a solid rod has been observed for the first time in a work that we co-authored with Stefan Catheline.



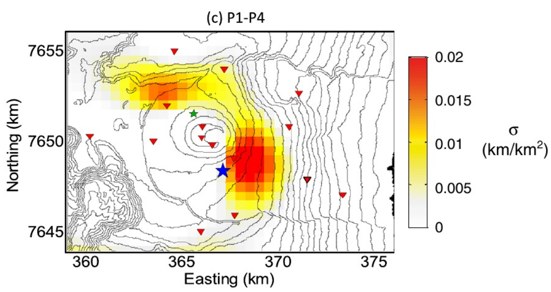
Parallel transport of polarization **p**. This figure illustrates the relation between Berry's phase and Euler angles.

Finally, we show in a recent theoretical work that the vector nature of light plays a crucial role for the Anderson localization phenomenon. Taking it into account prohibits Anderson localization in a random collection of point scatterers (atoms). This is in contrast with elastic waves which are also vector waves but which do show Anderson localization. These results call for a better understanding of the role that polarization plays in experiments in which Anderson localization of light and elastic waves was observed.

2.1.3 Imaging in disordered media

Collaborations: E. Larose (Grenoble), L. Margerin (Toulouse), F. Scheffold (Fribourg, Switzerland).

We studied a number of different approaches to imaging with multiply scattered light and elastic waves. The concept of differential imaging has been developed. It consists, in media where direct imaging is not possible, in imaging the changes between two acquisitions, using correlation techniques. This approach called LOCADIFF was successfully tested with elastic waves in concrete in 2010 and larger-scale experiments have been started in 2013. In combination with the ambient noise imaging, the same technique was used to detect pre-eruptive changes in volcanoes (see figure). The principle of differential imaging is based on a resolution kernel and an inversion technique. Several inversion techniques have been used in different contexts. It appears that the most accurate one is also the most sensitive to the fluctuations of disorder. The kernel used in LOCADIFF is a local time kernel. Using a diffusion propagation model, the local time kernel and its fluctuations have been computed exactly. This result is useful to control the fluctuations of disorder and hence the accuracy of the imaging method. Numerical estimates of a radiative-transfer kernel have also been used in situations where the sources of waves or the imaged region are close to the acquisition points.



Scattering cross-section changes obtained from experimental data on the volcano La Fournaise in La Réunion island by correlation of seismic ambient noise recorded before two eruptions (P1) and between them (P4). The first eruption was located at the large blue star on the map. One observes the co-location of strong structural changes. The second eruption was located at the small green star on the map. Even though it had not yet occurred, structural changes are observed at this position, that were induced by the first eruption. From J. Geophys. Res. **118**, 1–10 (2013).

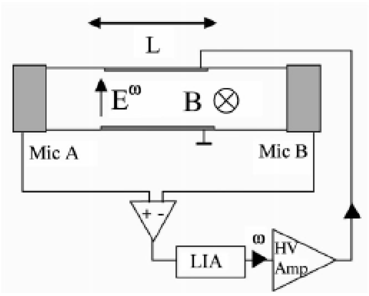
In the field of optical imaging, we studied the effects of noise due to the incomplete averaging arising from the limited acquisition time or averaging over a finite number of spatial positions. These effects are important in modern optical methods to probe soft materials (suspensions, emulsions, foams, etc.) and biological tissues. The scattered intensity is imaged on a camera and the pixels of the camera are grouped in "megapixels", *N* pixels in each. Statistical estimators are then obtained by averaging over the pixels belonging to the same megapixel. However, because *N* is typically not very large, these estimators are themselves fluctuating quantities. We analyzed this residual noise that limits the efficiency of modern optical correlation and imaging technique. The results are of interest for applications in biomedical imaging and soft matter physics.

2.1.4. Electromagnetic wave momentum

Collaborations: Geert Rikken (Grenoble & Toulouse)

Remarkably, the electromagnetic quantum vacuum contains an infinite amount of energy. Since this vacuum does not have any preferred direction, its translational momentum must vanish rigorously. The principal challenge of this project was to investigate whether this is still true in the presence of matter exposed to an electric and/or magnetic field.

To formulate a theory for the momentum of the vacuum, we have considered a microscopic model of an atom subject to magnetic and electric fields and coupled to the quantum vacuum. Diverging contributions have been identified and eliminated by the mass regularization, used first by Hans Bethe to calculate the Lamb shift. Mass renormalization remains fascinating since all divergences disappear. A second theory is developed for a chiral molecule exposed to a magnetic field only. The classical Abraham force here vanishes, but the quantum vacuum gives a finite contribution of the type $\alpha g(0)\mathbf{B}$ (α is the fine structure constant and g quantifies the static optical activity).

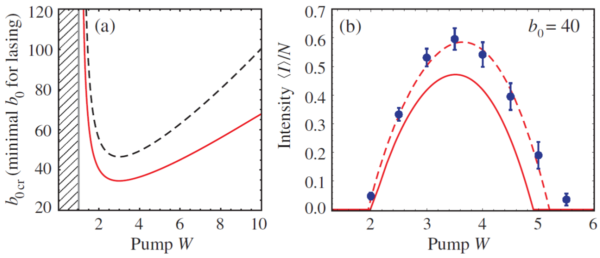


On the experimental side (LNCMI), we have developed several highly sensitive setups to observe the very small forces exerted by time varying fields on dielectrics by phase sensitive detection with cantilevers. In particular, we have observed the Abraham force $\alpha(0)\mathbf{E}\times\mathbf{B}$ on atoms and molecules, which also revealed the absence of a predicted (large) quantum-electrodynamical correction to this force. We have verified the full time dependence of the Abraham force, and the longitudinal forces associated with time varying electric fields on normal dielectrics, and with time varying magnetic fields on chiral dielectrics.

2.1.5 Random laser

Collaboration: V. Eremeev & M. Orszag (Santiago, Chile)

A random laser is a laser in which the feedback mechanism is provided by the multiple scattering from disorder instead of reflections on cavity mirrors. We studied random lasing in an ensemble of cold (i.e. immobile) atoms at random positions. A theoretical approach was developed that allows establishing a link between the threshold of the laser and the eigenvalues of a certain random matrix that we call the random Green's matrix describing the propagation of light between the scatterers. The predictions of this approach were compared to a simpler diffusion theory and the latter was shown to be inaccurate (see figure). We have also developed a theoretical framework for the calculation of eigenvalue densities of arbitrary Euclidean random matrices, Hermitian or not, of which the random Green's matrix is just an example. A quantum theory of a laser in which only two modes are excited was proposed.

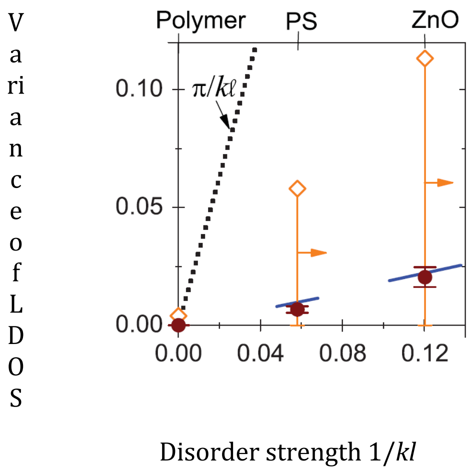


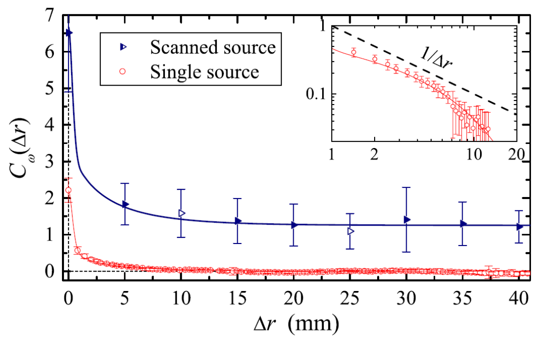
The minimal optical thickness of the cloud of atoms required for random lasing at a given power *W* of the pump. The prediction of the diffusion theory (dashed line) is compared to the result of our more precise random-matrix approach (solid line). (b) Average random laser intensity <*I*> per atom as a function of pump power *W* for a cloud of atoms with optical thickness b_0 = 40. Numerical results (blue circles) are compared with theoretical predictions (lines). From EPL **96**, 34005 (2011).

2.1.6. Local density of states and infinite-range correlations of waves in disordered media

Collaborations: J. Page (Winnipeg, Canada), A. Mosk & W. Vos (Twente, Netherlands)

We have studied the spatial fluctuations of the local photonic density of states (LDOS) in strongly disordered assemblies of dielectric particles. LDOS ρ(**r**) defines the decay rate of a quantum emitter (a molecule) embedded in a disordered sample at a given position **r** and thus systematic measurements of decay rates of fluorescent molecules at different positions inside the sample allow statistical characterization of ρ. We have been able to obtain probability distributions of ρ and the dependence of its variance $<\rho^2> - <\rho>^2$ on the strength of disorder (see figure). A theoretical description of this quantity has been obtained as well; it required taking into account the precise microscopic structure of the medium (size, shape and refractive index of scattering particles) and demonstrated that the fluctuations of LDOS are indeed nonuniversal as we predicted previously.





Variance of LDOS fluctuations in random photonic media with different strengths of disorder compared to a naïve theoretical prediction assuming point scatterers (dotted line) and the full calculation taking the scatterer size and shape into account (blue solid lines). From PRL **105**, 013904 (2010).

Intensity correlation function of sound waves transmitted through a disordered slab as a function of spatial separation Δ*r* between the measurement points. Symbols show experimental data, lines are theoretical fits. The inset shows the same data in log-log scale. From PRL **112**, 073902 (2014).

A complementary study using ultrasound instead of light was performed by us very recently in collaboration with J. Page. Fluctuations of the intensity of ultrasound transmitted through a disordered medium show infinite-range spatial correlations (see figure) that, in the limit of large separation between measurement points, were predicted to become equal to the variance of LDOS fluctuations at the point where the source of waves is located. These correlations were observed experimentally and described theoretically providing a clear evidence of validity of our previous theoretical work and giving access to LDOS fluctuations that were shown to have relative variance of order 1 in the vicinity of Anderson localization transition that was observed in the same samples previously.

2.1.7. Photon flow in nanorefrigeration

Collaborations: H. Courtois & B. Pannetier (Institut Néel), J. Pekola (Aalto University, Helsinki, Finland), L. Pascal, (PhD student, Institut Néel), M. Camarasa (PhD student, Institut Néel).

In the context of nanorefrigeration (see section *Electronic Transport in Nanostructures*), there is an important question of heat transfer due to photons. This is one of the two types of particle that always carry heat from hot to cold thereby impeding refrigeration (the other particles being phonons). As such it is crucial to understand, and if possible control the heat flow carried by photons.

In this context we consider heat transfer by photons between two metals coupled by a circuit containing linear reactive impedances. Using a simple circuit approach we calculated the spectral power transmitted from one metal to the other and found that it is determined by a photon transmission coefficient which depends on the impedances of the metals and of the coupling circuit. We studied the total photonic power flow for different coupling impedances both in the linear regime where the temperature difference between the metals is small and in the nonlinear regime of large temperature differences.

Photons also play an important role for a voltage-biased normal metal-insulator-superconductor (NIS) tunnel junction, connected to a high-temperature external electromagnetic environment. This model system features the commonly observed subgap leakage current in NIS junctions through photon-assisted tunneling which is detrimental for applications. We investigated the link with the phenomenological Dynes parameter and discussed our results in view of the performance of NIS junctions in applications.

Finally, the statistics of the photon exchange between a driven quantum system and a heat bath is an important issue. We applied the quantum jump approach to address this problem and demonstrated how this question can be analyzed by counting photons absorbed and emitted by the environment in repeated experiments. We found that the common nonequilibrium fluctuation relations are satisfied identically. The usual fluctuation-dissipation theorem for linear response applies for weak dissipation and/or weak drive.

2.2 Nonequilibrium systems

Contributors: L. Canet, A. Minguzzi, D. Spehner, R. Whitney
Postdocs: S. Datta, T. Kloss

2.2.1. Critical phenomena in nonequilibrium systems

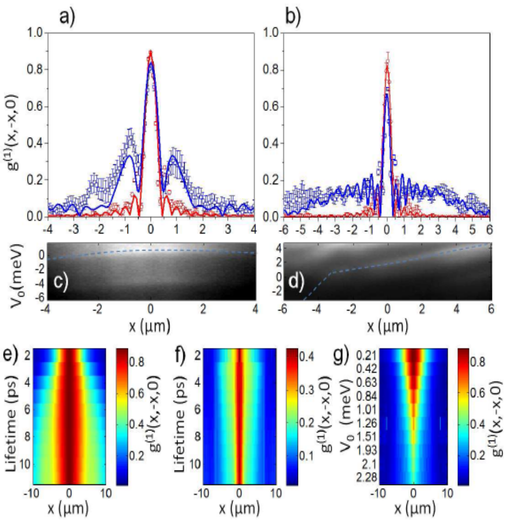
Collaborations : H. Chaté (Saclay), B. Delamotte (Paris), N. Wschebor (Montevideo, Uruguay)

This research work is anchored in the general framework of nonequilibrium statistical physics. It aims at investigating critical phenomena in classical nonequilibrium systems, which are characterized by scale invariance and universal behaviors. It mainly addresses problems of interface growth and the associated kinetic roughening transition, the universal behavior of which is captured by a celebrated stochastic (Langevin type) equation, originally formulated by Kardar, Parisi and Zhang. The KPZ equation has since become a fundamental model for nonequilibrium generic scale invariance and nonequilibrium phase transitions, as it turned out to describe a large class of critical phenomena, such as Burger's turbulence, paper combustion, nucleation of turbulent states in liquid crystals, bacterial colony growth, directed polymers in random media …

An important part of our work was to generalize a powerful analytical method, the nonperturbative renormalization group (NPRG) to classical nonequilibrium systems. It consisted in deriving the general framework to properly apply the NPRG methods to study nonequilibrium steady states, dealing in particular with the presence of response fields, with causality issues and with supersymmetric properties. This approach has enabled us to access, for the first time in a controlled and systematic way, the rough phase of the KPZ problem in any dimensions. In particular, we calculated the universal scaling functions associated to the correlation and response functions of a one-dimensional interface, for which exact results were obtained recently by Praehofer and H. Spohn. The comparison revealed an impressive quantitative agreement, up to the finest details of the tails of these scaling functions (without any fitting parameter). Furthermore, we provided analytical predictions for these universal scaling functions in dimensions 2 and 3, and associated universal amplitude ratios. These predictions were then confirmed very accurately by large scale numerical simulations due to Halpin-Healy. We also studied, using the same approach, the influence on the KPZ growth of long-range correlations in the microscopic noise (instead of a purely local noise as in the original KPZ formulation), which is of experimental relevance. We established in particular the full phase diagram of the system in the presence of long-range noise, and were able to describe the new emerging fixed point governing a long-range dominated phase, with the exact associated critical exponents, and the phase boundaries.

2.2.2 Quasi-one dimensional polaritons: quantum gases out-of-equilibrium

Collaboration: M. Richard (Néel Institute)



(a) and (b) First order correlation function measured by Michelson interferometry in a quasi-1D Polariton gas (symbols) and theoretical modeling (lines) including losses and disorder effects. (c) and (d) experimental results for the potential felt by the polaritons (e)-(g) simulations for the first-correlation at varying disorder strength and lifetime. Depending on the experimental conditions, the decay of correlations is determined either by losses or by disorder effects. From PRB **88**, 121407 (2013).

Polaritons are composite bosons obtained by hybridation of cavity photons and excitons in a semiconductor. Due to the losses of the cavity, the system is continuously replenished by a pump. Therefore, it is an example of driven-dissipative quantum fluid. In an experiment led by Maxime Richard and co-workers (Neel Institute, Grenoble), a quasi-1D polariton condensate has been observed and the first-order correlation function has been measured. In particular, a decay of correlations has been observed. Using a mean-field description of the condensate under non-resonant pump and losses, we have understood that the origin of this decay is due to the combined effect of disorder in the cavity and polariton losses, and have found a good agreement with the experiment.

2.2.3. Nonequilibrium dissipative systems

Collaborations: D. Bicout (VetAgro Sup Lyon and ILL), M. Clusel (Montpellier)", W. De Roeck (Heidelberg), A. Petukhov (ILL)

We have worked on the dynamics of spins coupled to various dissipative environments. These works are motivated by experimental observations (or in one case a numercial observation) in very different systems. However they are connected by the theoretical techniques used.

An example is the study of the depolarization of the magnetization of cells of spin-polarized He3 gas (used by A. Petukhov and many others to polarize neutrons at the I.L.L.). Many experimental features of this depolarization are poorly understood. We

have been studying the limits on the usual model of the process, and investigated alternative models.
We also asked how a phonon bath could enhance the coherent oscillations of a molecular magnet swept through a Landau-Zener transition - observed in numerical simulations of {V15} and {Cu3} molecular magnets. We showed that such an enhancement can occur via the interplay of Landau-Zener with the Lamb shift (renormalization) induced by the phonon bath. In a variety of physically relevant systems, this enhancement dominates over the suppression induced by the well-known decoherence effect of the phonon bath.
In a joint work with W. De Roeck (Center for Theoretical Physics, Heidelberg), we have studied a model for quantum Brownian motion consisting of a particle with an internal degree of freedom (spin) moving on an infinite lattice and coupled to a bosonic bath. We have proven rigorously that in some scaling limit the dynamics of the particle follows a translation-invariant markovian Lindblad master equation.

B. CORRELATED SYSTEMS

2.3 Ultracold quantum gases

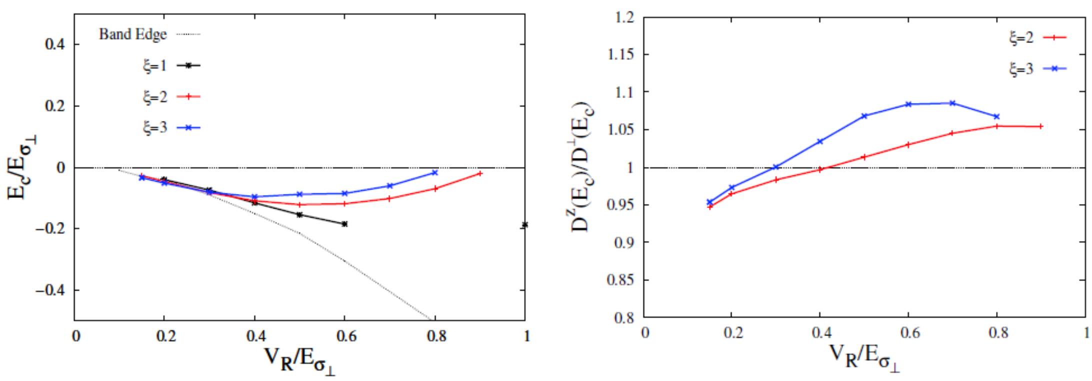
Contributors: F. Hekking, M. Holzmann, A. Minguzzi, N. Rougerie, P. Schuck, D. Spehner, B. van Tiggelen.
Postdocs: S. Datta, V. Golovach, M. Piraud
PhD-students: F. Cartarius, M. Cominotti, C. Schenke, A. Yedjour

2.3.1. Anderson localization in atomic gases

Collaboration: Laurent Sanchez-Palencia (LCF Palaiseau).

Recent experiments with cold atoms have investigated the expansion of a Bose-Einstein condensate in a disordered optical speckle potential. When the laser speckle is red-tuned with respect to the optical transition the electrostatic interaction with the atom is repulsive.

When the disorder is strong, Anderson localization can occur. Localization of cold atoms has several challenges: it has long correlations - an ideal speckle has spatial correlations proportional to $\mathrm{sinc}^2(x)$ - , it is non-Gaussian (since the complex optical field is Gaussian, not the intensity), and is often very anisotropic. The thesis work of Afifa Yedjour already established a theory for expanding (nearly) localized, noninteracting atoms. This theory showed the need to include the full spectral function A(E,p) of the atoms. As a postdoc project, we have extended this theory to an anisotropic Gaussian speckle, and developed a FORTRAN code that now runs on the IDRISS machine in Orsay.



Major results. Left: The mobility edge occurs "below sea level" (the average speckle potential). As the anisotropy increases this critical energy slowly increases, and for not too small disorder amplitudes, moves above sea level. Right: Localization significantly suppresses the anisotropy of the diffusion tensor. At the mobility edge diffusion vanishes in all directions but the ratio $D_{zz}/D_{||}$ goes to a number close but not equal to one (thus almost isotropic). So far we have no heuristic explanation for this unexpected result.

2.3.2. Low-dimensional quantum gases

Collaborations : R. Citro (Samerno), E. Orignac (Lyon), L. Glazman (Yale, and Nanoscience foundation excellence chair), C. Miniatura (CQT Singapore and INLN Nice), B. Fang (Master student at CQT Singapore (2009-2010)), M. Gattobigio and P. Vignolo (INLN Nice), M. Rizzi (Johannes Gutenberg University Mainz), D. Rossini (Scuola

Normale Superiore Pisa)

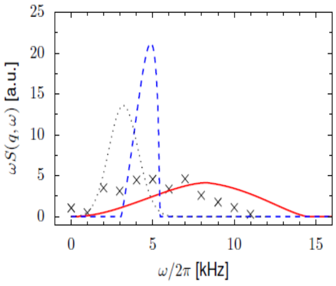
In one dimension the effects of interactions and quantum fluctuations are very important. This requires to use models beyond mean field. We have studied the strongly interacting regime for one-dimensional bosons by combining two methods : an exact solution in the limit of infinitely strong interactions and a low-energy quantum hydrodynamics approach (Luttinger liquid theory for bosons). Our results contribute to the understanding of strongly correlated gases, inhomogeneous gases both at equilibrium and out-of-equilibrium.

2.3.2.1 Exact solutions

The Tonks-Girardeau gas is a gas of impenetrable bosons corresponding to the limit of infinitely strong repulsive interactions. Girardeau first proposed an exact solution for the many-body wavefunction by mapping onto a gas of noninteracting fermions, times a mapping function which restore the proper bosonic symmetry under particle exchange and introduces correlations. This exact solution is very powerful as it allows to describe not only the ground state, but also the equilibrium state at finite temperature, as well as the out-of-equilibrium dynamics. We have extended the Girardeau solution to describe a multi-component gas. This has allowed us to identify the properties of the ground state, which at difference of the single-component case is highly degenerate. Secondly, we have studied the first-order coherence properties of a Tonks-Girardeau gas at finite temperature. We have demonstrated that the momentum distribution tails display universal properties at finite temperature and have a weight which decreases with temperature.

2.3.2.2 Dynamical properties of an interacting Bose gas

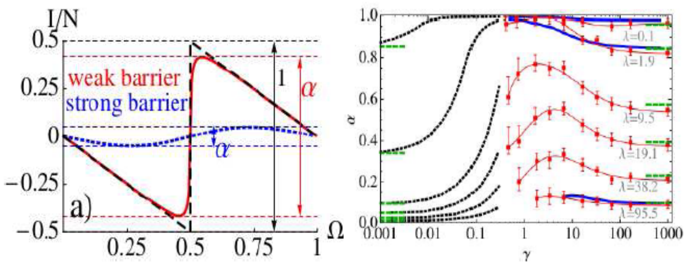
We have studied the dynamic structure factor of an interacting 1D Bose gas in the presence of an external harmonic confinement. We have shown that the dynamic structure factor is very different from the one of a homogeneous gas, and depends strongly on the interaction regime. If an additional lattice potential is considered, at strong interactions the inhomogeneous system alternates shells of superfluid and Mott insulator. We have shown that the superfluid shells give an important contribution to the dynamic structure factor, and have compared our predictions with an experiment at LENS (Florence, Italy), obtaining information on the interaction and temperature regime in the experiment.



Dynamic structure factor for an interacting 1D Bose gas on a lattice (solid line : theoretical predictions at zero (blue dashes) and finite temperature (red solid line) as compared to the experimental results of the Florence group (crosses) without adjustable parameters. From PRA **80**, 043611(2009)

2.3.2.3 Bosons on a tight ring trap

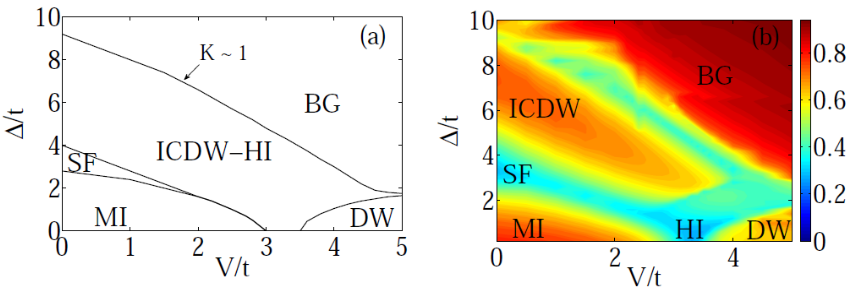
A rotating barrier on a ring gives rise to an artificial gauge field (effective magnetic field) for neutral atoms. In 1D quantum gases, interactions can be tuned from weak to very strongly repulsive. For all these regimes we have studied the response of the gas to the rotating barrier and the possibility to transfer angular momentum to the system. If rotation is set in adiabatically, persistent currents are generated. We have found that the persistent currents amplitude display a non-monotonous behaviour with interaction strength. This is due to the competition of classical screening at weak interactions and quantum fluctuations at large interactions. If the barrier is suddenly set into motion, oscillations between different current states are induced. In the limit of infinitely strong interactions we have found an exact solution for the quantum dynamics of the system. At specific times, we have found a novel macroscopic superposition, corresponding to the superposition of two effective Fermi spheres. This is the equivalent at strong interactions of the 'NOON' state (superposition of the type |N,0>+|0,N>, where |k1,k2> are two current states) predicted at weak interactions.



Definition of persistent current amplitude (left) and its behaviour as a function of the interaction strength (right) for various values of the barrier strength. From PRL **113**, 025301 (2014).

2.3.2.4 Quantum simulators: polar bosons in quasiperiodic lattices

The understanding of the interplay between disorder and interactions is an open question in condensed matter physics. We have considered a specific model of polar bosons with nearest-neighbour interactions, as described by the extended Bose-Hubbard model. Pseudo-disorder effects are realized by adding a secondary lattice with incommensurate periodicity with respect to the primary lattice – a configuration which is experimentally realizable using the 'optical lattice' technique. For sufficiently large secondary lattice the noninteracting system is known to undergo localization. We have studied the effect of such pseudo-disorder on the phases of the extended Bose-Hubbard model (density wave phase, incommensurate density wave, Mott insulator, Haldane insulator). We have obtained the phase diagram both from the analysis of correlation functions and using the entanglement spectrum, thereby demonstrating also the utility of this latter method for disordered systems.



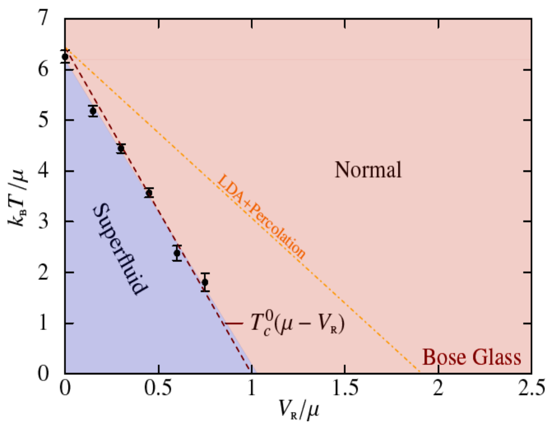
Phase diagram for the Extended Bose-Hubbard model in the presence of a quasiperiodic potential of strength Delta, at increasing nearest-neighbour interactions V. Left: result from the analysis of correlation functions, Right : result from the study of the entanglement spectrum. From PRB **87**, 190101 (2013) and NJP **15**, 045023 (2013)

2.3.3 Correlations and disorder in two dimensional Bose gases

Collaborators : A. Aspect, T. Bourdel, G. Carleo, L. Sanchez-Palencia (LCF, Paileseau), Z. Hadzibabic (Cambridge), W. Krauth (LPS-ENS), M. Chevallier (LPS-ENS, PhD 2008-2011)

We have studied the Kosterlitz-Thouless transition in quasi-two dimensional trapped Bose gases and quantified correlation effects in the fluctuation region using Monte Carlo calculations with experimentally relevant parameters. We have shown that for sufficiently large number of bosons the system is well described by an effective, strictly two-dimensional classical field theory describing Kosterlitz-Thouless physics around the transition temperature, whereas a cross-over to Bose-Einstein condensation takes places for small system sizes. Our simulations provided a directed comparision between quantum-many-body theory and experiments in the correlation region without any adjustable parameter.

We further explored the effects of a correlated disorder on the coherence properties close to the phase transition. We have shown that the superfluid transition is strongly protected against disorder and remains of the Kosterlitz-Thouless type up to signicant strong disorder strength. In the strong disorder regime, the calculated conductance exhibits a thermally activated behavior and points towards the existence of a Bose bad-metal phase as a precursor of the zero temperature Bose glass phase. Critical correlation effects on the Bose-Einstein transition in three dimensions have been measured in the group of Z. Hadzibabic.



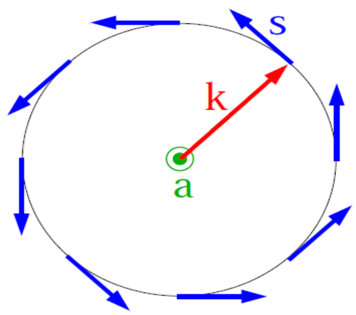
Phase diagram of two-dimensional interacting bosons at fixed chemical potential and interaction strength ~g = 0:1. The dark dashed line is the critical temperature of the clean system with a renormalized chemical potential; the lighter dashed line is the prediction of a combination of LDA and percolation theory. For strong disorder, the normal system goes to the Bose-glass phase in the zero-T limit. From Phys. Rev. Lett. **111**, 050406 (2013).

2.3.4 Superfluid fermions and Bose-Fermi mixtures

Collaborations : X. Vinas, T. Sogo, M. Urban, T. Miyakawa

We have been interested in what happens to superfluid Fermi-liquid in a narrow container which opens up to a wide one at a certain energy when the filling is such that the chemical potential passes from below to above the break point (overflow). A little to our surprise the gap at the Fermi energy is dramatically reduced once the chemical potential passes the threshold that is the superfluid pours into the large container. In principle the effect is relatively easy to understand, however, the abruptness of the effect is surprising starting already before the chemical potential reaches the threshold. We propose to verify this effect experimentally with cold atoms. The effect might be interesting to increase the gap in loading a superfluid from a wide into a narrow container.

Since a certain time, we are interested in boson-fermion (BF) correlations in a BF mixture. The interesting point is that with an infinitessimal attraction, one still creates a stable BF bound state in the mixture. The effect is due to the presence of a sharp Fermi-surface (at T=0) and is analogous to the formation of a Cooper pair in a purely (2-component) fermionic system. However, here the 'Cooper' pair is a correlated fermion and interesting questions arise, e.g., how a free BF gas goes over into gas of bound BF pairs under the influence of an attractive force. We treat this in T -matrix approximation.
In a recent paper, we considered a technical aspect. Under the influence of interaction the fermionic occupation numbers get 'rounded'. The occupation numbers should satisfy the Luttinger theorem implying that kF stays unchanged when the correlations are switched on. We satisfy this theorem with our T matrix approach. We have applied this approach also to a strongly spin polarised Fermi systems and showed that the Luttinger theorem is also fullfilled there. This is not at all the case in the literature and has recently lead to publications where the authors find a chemical potential of the minority fermions larger than the one of the majority fermions, being, of course, a non-sense.
We have considered unpolarised cold atoms with dipolar interaction. We applied RPA theory to this system and found that in a certain range of model parameters, the system spontaneously creates an order parameter of the spin-orbit type, see figure. This is a



new predicted phase of the system. It has not been detected so far.

Graphical representation of the spin-orbit order parameter in a gas of cold atoms with dipolar interaction. From PRA **85**(2012)031601(R).

2.3.5 Mathematical approaches to quantum gases

Collaborations: M. Correggi (Roma),M. Lewin and Phanh Thanh Nam (Université de Cergy-Pontoise)

2.3.5.1 Superfluidity and superconductivity

The nucleation of vortices in rotating Bose-Einstein condensates is a spectacular demonstration of the superfluidity of these objects. We have worked on the mathematical description of this phenomenon. Together with Michele Correggi (Università Roma Tre) we investigated vortex patterns in a rotating BEC when the rotation frequency is above but close to the critical frequency for nucleation, in the framework of Gross-Pitaevskii theory. It turns out that an approximation to the mean vortex density can be rigorously derived by adapting and improving known mathematical methods. Perhaps surprisingly, the vortex density turns out not to be

homogeneous close to the critical the rotation frequency, but progressively homogeneizes when the rotation frequency is increased.
It turned out that the techniques previously employed (together with Michele Correggi, Florian Pinsker and Jakob Yngvason) to study the ``giant vortex phase transition'' in rotating Bose-Einstein condensates could shed some new light on the surface superconductivity phenomenon occuring in type II superconductors. More precisely, significant refinements of the method allowed us to derive a simplified expression for the energy of a superconductor in an applied magnetic field varying between the second and third critical fields, and to prove a strong form of uniformity of the surface superconducting layer appearing in this regime. This solved two longstanding open problems in the mathematical analysis of Ginzburg-Landau theory.

2.3.5.2 Derivation of effective models for many-body bosonic systems

The derivation of effective theories starting from first-principle Hamiltonians is a major challenge in theoretical and mathematical physics. In the case of quantum gases, it is desirable to develop efficient methods to explore the link between the many-body Schrödinger equation and mean-field theories of Gross-Pitaevskii type that assume Bose-Einstein condensation.
At LPMMC we have developed such a method, based on the so-called quantum de Finetti theorem. Roughly speaking, it asserts that the k-body density matrix of a N-body bosonic states approaches a convex combination of Hartree (factorized, BEC) states when N gets large compared to k. The classical de Finetti theorem is a well-known tool in the mathematical analysis of classical many-body systems. However using the quantum version for rigorous derivation of mean-field theories for bosonic systems has been largely overlooked. The renewed interest in the mathematical physics of large bosonic systems following the discovery of Bose-Einstein condensation made a more thorough understanding of this issue highly desirable.
In work with Mathieu Lewin and Phanh Thanh Nam, we gave a new proof of the quantum de Finetti theorem and of a useful variant thereof. Applications to the derivation of mean-field theories for many-body bosonic systems are described at length, with an emphasis on the generality and clarity of such an approach.
Following this paper we realized that the quantum information community had been working on quantifying error terms in the de Finetti theorem. We provided a new proof of a formula due to Chiribella, which implies a quantitative version as a corollary.

2.4 Many-Body Theory

Contributors: M. Holzmann, N. Rougerie, P. Schuck

Fundamental questions in many-body theory are adressed in the LPMMC ranging from rigorous descriptions of correlated classical Coulomb systems over formal developments of self-consistent RPA theory to Hartree-Fock and quantum Monte Carlo calculations of ground and spectral quantities of simple metals.

2.4.1 Classical Coulomb systems beyond mean-field theory

Collaboration: Sylvia Serfaty (Université Paris 6 and Courant Institute, New York)

Together with Sylvia Serfaty we studied the equilibrium statistical mechanics of a many-body classical Coulomb system in an external electrostatic potential, in space dimension

D=2 and larger. In addition to its intrinsic interest, in 2D such a system also describes some ensembles of random matrices, vortices in clasical and quantum fluids and the matter density of the Laughlin state. Our new results include a precise description of the ground and thermal states beyond mean-field theory. The main mathematical tool, following earlier works of Sandier and Serfaty in 2D, is the use a so-called ``renormalized energy functional''. Our results are the first of their kind in space dimension larger than 3, and we provide a simplified approach of the 2D case. A natural conjecture about the crystallization transition is also formulated in view of our rigorous estimates.

2.4.2 Self-Consistent RPA theory

Collaborations: M. Jemai, D.S. Delion

We have made progress in formal developments of the Many-Body problem. For instance, we have succeded to build an extended version of RPA which is based on the ground state of 'Coupled Cluster Theory' (remember that standard RPA is built on a HF state). Since this ground state depends itself on the RPA correlations, a self-consistent theory for two body correlation functions emerges. Applications of this 'Self-Consistent RPA (SCRPA)' to model cases like the Hubbard model give very encouraging results.

2.4.3 Quantum Monte Carlo calculations of spectral quantities of simple metals

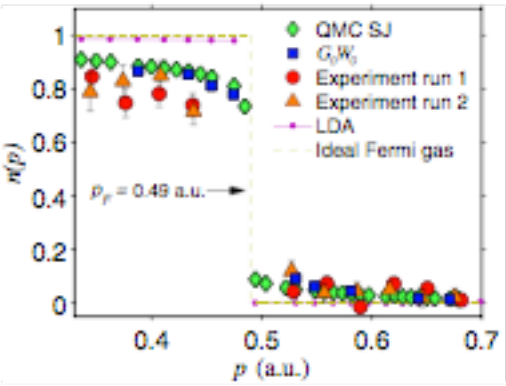
Collaborations: D. Ceperley (UIUC and Nanoscience Foundation chair of excellence), B. Bernu (LPTMC, Paris), S. Huotari (ESRF), V. Olevano (Néel)

An overwhelming part of Quantum Monte Carlo calculations aims at the calculation of the electronic ground state energy in the (pseudo-) potential of ions which determines the crystallographic structure of the solid. Only very few attempts have been made to calculate spectral properties using Quantum Monte Carlo methods to establish the validity of methods from many-body perturbation theory, such as RPA, GW, or Bethe-Salpeter calculations, which are numerically less expensive and can be compared with experiments.

We have studied the ground state momentum distribution and the effective mass characterizing the single particle excitations of the two dimensional electron gas at metallic densities. Our work clearly established that Quantum Monte Carlo calculations of the Fermi liquid parameters suffer from huge size effects and a correct extrapolation to the thermodynamic limit reduces the discrepancy to GW/RPA values in the high density regime. At low densities, our calculations further show that vertex corrections and/or self-consistency issues must be included in the GW approach.

We have further calculated the momentum distribution of jellium in three dimensions. Our calculations established that non-selfconsistent GW without vertex corrections are quite accurately in a rather large region of metallic densities.

The closest realization of the three dimensional electron gas in nature is provided by the valence electrons in solid sodium. The group of S. Huotari measured the Compton profile of sodium at the ESR synchrotron in Grenoble which has allowed us a rather direct comparison of the momentum distribution of its valence electrons with Quantum Monte Carlo calculations and GW calculations on sodium and on the electron gas. The agreement between experiment, Quantum Monte Carlo, and GW on the momentum



distribution and the renormalization factor Z was satisfactory, however, small differences in the Compton profile remain which need further investigation.

The momentum distribution of the valence electrons of Na determined by experiment, QMC SJ, G0W0, and DFT calculations. The ideal-Fermi gas step function is also shown (from PRL **105**, 086403 (2010)).

2.4.4 Spin and charge density wave ground states of the electron gas

Collaborations: L. Baguet (PhD, LPTMC, Paris), B. Bernu (LPTMC, Paris), F. Delyon (CPHT, Palaiseau)

Up to now, Slater determinants based on Hartree-Fock (or related density functional based methods) have been used as starting point for more elaborate methods treating correlations, e.g. inside the trial wave function of QMC calculations or reference state for many-body perturbation theory (GW) and coupled cluster methos. However, from old works of Overhauser in 1962, it is generally believed that the ground state of the high density electron gas has not the structure of the simple ideal gas like Fermi liquid, but consists of spin or density waves, at least within the Hartree-Fock approximation. It is astonishing that during the fifty years following the work of Overhauser, no numerical confirmation of the scenario is found in the literature.

We have studied the phase diagram of the two and three dimensional electron gas within the Hartree-Fock approximation. Using an efficient algorithm which does not impose the symmetry of the solution, we have established that the high density ground state of the polarized electron gas within Hartree-Fock consists of a charge density state forming a triangular lattice with about 11% more sites than electrons. Lowering the density, the electrons undergo a metal to insulator transition from this conducting charge density wave state to the insulating Wigner crystal. Including the possibility of these exotic phases, we established the full Hartree-Fock phase diagram of jellium in two and three dimensions.

Finally, we have studied the influence of a finite extension of the two dimensional electron gas within Hartree-Fock, introducing the quasi-two-dimensional electron gas model where the three-dimensional electrons are confined by a strictly two-dimensional homogeneous positive charge density at z=0. Similar to the electron gas model in strictly two dimensions, the phase diagram of the quasi-two-dimensional electron gas at zero temperature is completely described by a single parameter, r_s. However, the phase diagram is richer than in two dimensions due to possible transitions from single- to multimode occupation in z.

2.5. Entanglement and quantum correlations

Contributors : Frank Hekking, A. Minguzzi, S. Skipetrov, D. Spehner,
Postdoc : H. Jirari
PhD students : M. Candé, N. Didier, J. Ferrini

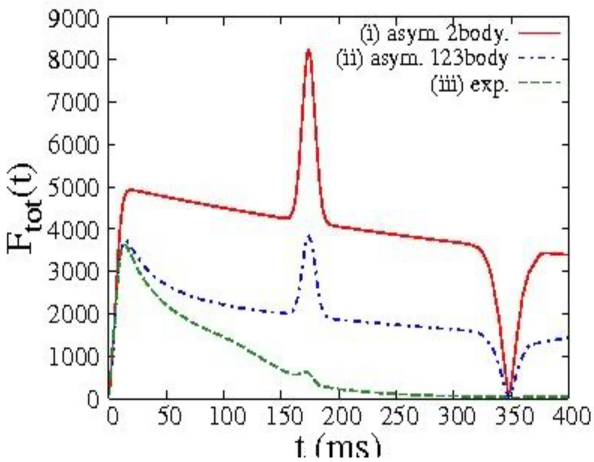
Collaborators: O. Buisson, W. Guichard (Institut Néel), Y. M. Blanter (TUDelft, Netherlands), L. Faoro (LPTHE Jussieu), K. Pawlowski (postdoc, LKB Paris), M. Orszag (PUC Santiago, Chili)

Entanglement is a unique feature of quantum mechanics. It is at the origin of the observed violation of the Bell inequalities, but also of the higher efficiencies of quantum algorithms and communication protocols over their classical analogs, and of the improved precision of quantum interferometers. However, entanglement is fragile and is strongly affected by experimental noises, interactions with a disordered medium, or particle losses. A main issue is to look for systems which behave coherently and present strong correlations so as to produce entanglement and keep it for a relatively long time. The LPMMC possesses a strong expertise on condensed matter systems at very low temperature, like Bose-Einstein condensates, superconducting nanostructures, or artificial atoms coupled to quantum resonators, which are promising examples of such coherent correlated systems. Based on this expertise, we have studied theoretically the dynamics of specific systems closely related to current experiments, focusing in particular on the evolution of the amount of entanglement. Another field of interest at the LPMMC since many years is the propagation of light in complex media. The role of photon entanglement in multiple scattering of light in a disordered medium has been investigated. The more general issue of quantifying quantum correlations in mixed states in arbitrary finite systems has been also addressed.

2.5.1 Quantum correlations and dynamics in BEC

2.5.1.1 Decoherence in Bose Josephson junctions

Bose Josephson junctions are formed by clouds of ultracold atoms in Bose-Einstein condensates (BEC) in two different modes (e.g. two internal energy levels). Because of interactions between atoms, the dynamical evolution generates quantum correlated states after a sudden quench to zero of the inter-mode tunnel energy. This yields to the formation of squeezed states, and, at later times, macroscopic superpositions of phase states. These non-classical states are of current interest due to recent applications in high precision interferometry. For instance, squeezed states have been demonstrated experimentally in Bose Josephson junctions to improve the interferometer sensitivity below the shot noise limit. The work done at the LPMMC has mainly focused on macroscopic superposition states. We have proposed a full-counting statistics protocol to reconstruct these states and to evidence their coherences. We also studied the robustness of the superpositions against decoherence. The two mechanisms of decoherence which are most relevant in experiments are magnetic fluctuations and atom losses. Magnetic fluctuations can be described as a phase noise and treated exactly, going beyond the usual Markov approximation. This exact analytical treatment shows that the induced decoherence is not so detrimental for the superpositions of phase states as it does not increase with the number of atoms. The situation is different for particle losses. In a joint work with K. Pawlowki, a post-doctorant at the LKB in Paris, we have analyzed in detail the effect of atom losses in Bose-Josephson junctions. The main result of this anaysis is that the macroscopic superpositions can be partially protected from decoherence for strongly asymmetric losses in the two modes, by using Feshbach resonances to tune the interaction energies (see figure).



Amount of quantum correlations useful for interferometry in a Bose-Josephson junction as a function of time t. The peak near t=170ms corresponds to the macroscopic superposition of two phase states. Quantum correlations are much better preserved if atoms are lost in one mode only (two upper curves) than if they are lost in the two modes (lower curve, with parameters extracted from the experiment in Heidelberg). From Phys. Rev. A **88**, 013606 (2013).

2.5.1.2 Entanglement in binary mixtures of ultracold atoms in a ring-shaped potential

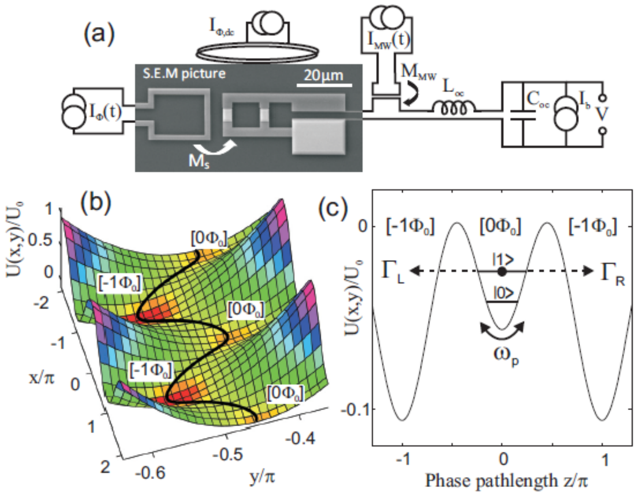
In a collaboration with physicists from Santiago de Chile, we investigated a model with two interacting atomic species in a BEC on a ring lattice in the presence of a synthetic magnetic field. There have been recently proposals for realizing similar systems experimentally. For certain values of the interactions and magnetic field, it has been pointed out that there exists a robust eigenstate of the Bose Hubbard Hamiltonian with maximal entanglement between the two species. A protocol to reach this state from the ground state by varying the field and an indirect way to detect it by measuring the currents of particles in the ring has been also proposed.

2.5.2 Quantum correlations and dynamics in superconducting nanocircuits

Using a dc SQUID at near-zero current bias and flux bias near half a flux quantum, we analyzed theoretically in collaboration with experimentalists from the Institut Néel a novel potential for a fictitious phase-particle that constitutes an anharmonic oscillator formed by a potential well between two potential barriers. Escape out of the central well can occur via tunneling through either of the two barriers. A good agreement with a generalized double-path macroscopic quantum tunneling theory was found. The existence of an "optimal line" in current and flux bias along which the oscillator, which can be operated as a phase qubit, is insensitive to decoherence induced by low-frequency current fluctuations, was demonstrated.

We also considered a current-biased dc SQUID in the presence of an applied time-dependent bias current or magnetic flux. The phase dynamics of such a Josephson device

is equivalent to that of a driven multilevel quantum system. The problem of finding the required time-dependent control field that will steer the system from a given initial state to a desired final state at a specified final time was formulated in the framework of optimal-control theory. It was shown that the optimal field inducing a coherent population transfer between quantum states is represented by a carrier signal having a constant frequency but which is time-varied both in amplitude and phase.
An important issue is to test cross correlations between charge and critical-current noise in the small superconducting contacts of an asymmetric Cooper-pair transistor coupled to a phase. A protocol for doing that has been worked out in collaboration with L. Faoro in Paris. The superconducting circuit behaves as a tunable four-level quantum system that can be prepared in two different configurations where cross-correlation terms are, respectively, absent or present and therefore, in principle, detectable.



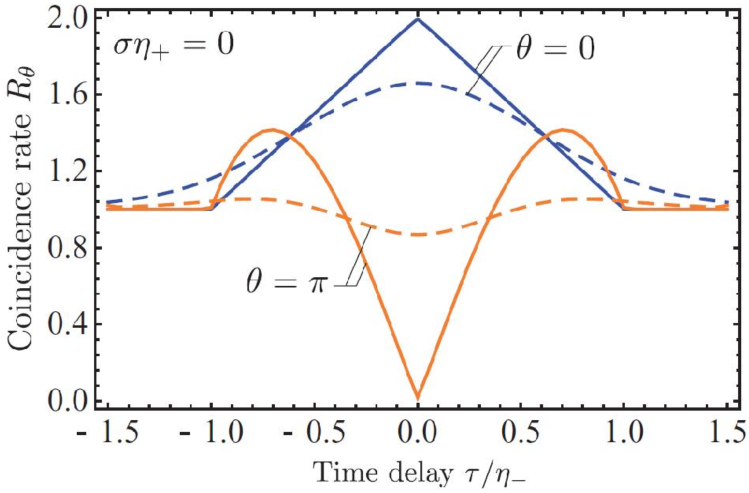
(a) Experimental set-up of a SQUID acting as an anharmonic oscillator. (b) Minimal energy path for quantum tunnelling. (c) Potential along the minimum energy path, parameterized by the path length, used for the calculation of the escape rates. From PRL **102**, 097004 (2009).

2.5.3 Dynamics of a three-level atom coupled to a quantum-mechanical resonator

Motivated by experiments, we analyzed in a collaboration with Y.M. Blanter in Delft the quantum dynamics of a three-level atom coupled to a quantum-mechanical resonator in the presence of a driving on the cavity, within the framework of the Lindblad master equation. They studied the dynamics of the atomic level populations and the photon number in the cavity as well as of the output spectrum. The results of the quantum approach agree with the experimental findings.

2.5.4 Quantum correlations of photons in multiple scattering

When two photons in an entangled state are incident on a disordered medium, unusual phenomena can be observed in the scattered light. In particular, depending on the symmetry of the entangled state, the two photons may have a tendency to be scattered in the same outgoing mode or, on the contrary, to be most likely found in different modes (see figure). This behavior resembles the one known for bosons and fermions because the latter cannot find themselves in the same mode (= the same quantum state) due to the Pauli principle. Therefore, manipulating the entanglement of the input state allows simulating behavior of particles with bosonic or fermionic quantum statistics despite the fact that the particles used in the experiment (photons) remain bosons. On the other hand, the control over the quantum state of the incident light allows a certain degree of control over the scattered light because the two incident photons can be directed into the same outgoing mode or, on the contrary, can be forced to be scattered in different modes.



Photocount coincidence rate for two photodetectors behind a random medium for bosonic ($\theta = 0$) and fermionic ($\theta = \pi$) symmetries of the incident two-photon entangled state, as a function of the time delay τ between the two photons. PRA **87**, 013846 (2013).

2.5.5 Quantum correlations and distinguishability of quantum states

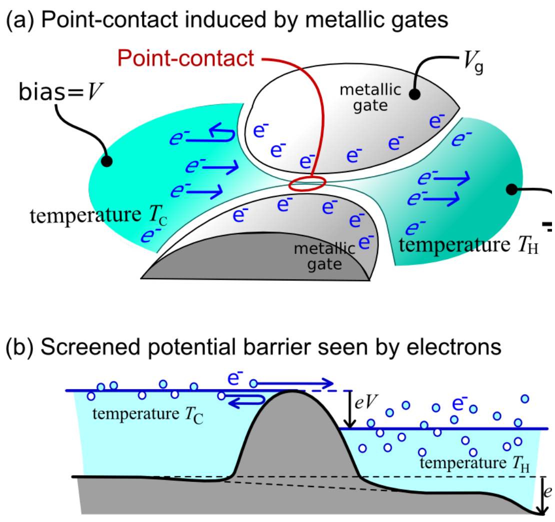
A central question in quantum information theory is to characterize quantum correlations in general composite quantum systems. Such correlations may exist even in a non-entangled mixed state if it has a non-zero quantum discord. With M. Orszag from Santiago de Chile we studied a new measure of quantum correlations defined as the Bures distance of a given state to its closest classical state. This distance is a geometric analog of the quantum discord. Remarkably, the problems of evaluating this geometric discord and of finding the closest classical state reduce to a quantum state discrimination task, thereby demonstrating an explicit link between the degree of quantumness of a state and the distinguishability of certain quantum states. By applying this result, the geometric discord can be calculated explicitly when one of the subsystem of the bipartite system is a qubit.

C. MESOSCOPIC SYSTEMS

2.6 Electronic transport in nanostructures

Contributors: D. Basko, F. Hekking, S. Skipetrov, R. Whitney
Postdoc: G. Rastelli, A. Vasenko
PhD-student: A. DiMarco, Li-Jing Jin

We all have experience of the physics of electron flow – in the form electrical currents. Every time we turn on a light or run a computer program, the desired effect is the result of a flow of electrons, which experts called "electronic transport". In most existing technological applications, this flow is well modelled by classical laws. However, as we reduce the size of circuit elements, the quantum nature of electrons becomes increasingly important. Consequences of this quantum nature of electron flow (interference effects, Coulomb blockade, etc) are visible at room temperature when the circuit elements are reduced to a nanometre or so. At temperatures below a Kelvin, quantum effects become crucial and more varied (including superconductivity, long-lived quantum superpositions and entanglement) and lead to numerous electronic transport phenomena in circuit elements smaller than a few microns across. The fundamental issue is to understand the flow of quantum particles in disordered or confined systems. This has far reaching consequences; from the development of non-equilibrium quantum dynamics and thermodynamics, to proposals for future electronic technology.

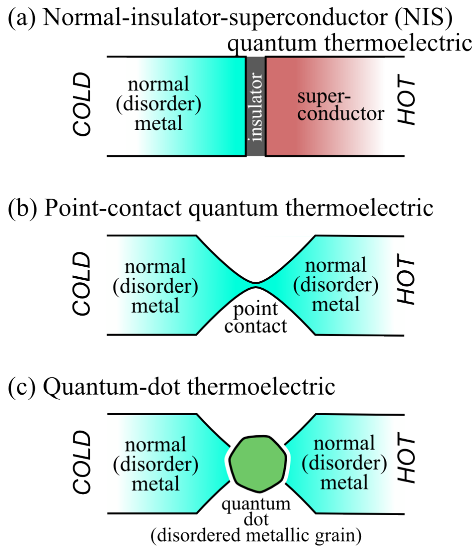


Quantum effects ensure the quantization of electronic flow through a point-contact. In the upper sketch, we show a point-contact. In the lower sketch, we show the potential barrier this induces, impeding the flow of electrons from right to left. The barrier's height depends on the transverse quantization of the electrons (adapted from PRB **88**, 064302 (2013)).

2.6.1 Thermoelectricity, nano-refrigeration and quantum thermodynamics.

Collaborations: M. Büttiker (Geneva, Switzerland), H. Courtois(Institut Néel), P. Jacquod (Arizona, USA), B. Pannetier (Institut Néel), J. Pekola (Aalto University, Helsinki, Finland), F. Giazotto (Scuola Normale Pisa, Italy), M. Camarasa (PhD-student Institut Néel), S. Rajauria (PhD-student Institut Néel), L. Pascal, (PhD-student Institut Néel).

Mobile electrons carry heat very efficiently, which is why metals typically conduct heat better than electrical insulators. What is more, the flow of electrons can be controlled using voltage biases, thereby controlling heat carry by electrons. This leads to thermoelectric effects, in which an electrical current can induce a heat current and vice-versa. Our projects have been to understand such phenomena in nanostructures where quantum mechanics has a significant effect on the electron flow. These works vary from understanding the basics thermodynamics of these phenomena, to considering applications in nano-refrigeration.



Sketch of three different quantum thermoelectrics considered in our research projects.

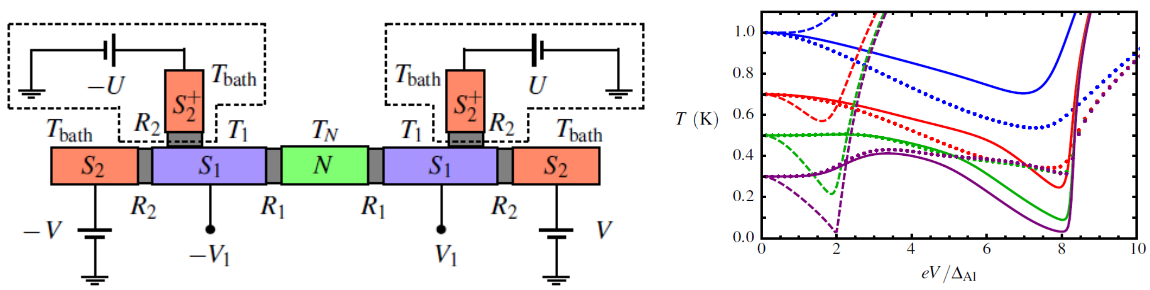
We investigated heat and charge transport in NN′ IS tunnel junctions in the diffusive limit. Here, N and S are massive normal and superconducting electrodes (reservoirs), N′ is a normal metal strip, and I is an insulator. The flow of electric current in such structures at subgap bias is accompanied by heat transfer from the normal metal into the superconductor, which enables refrigeration of electrons in the normal metal. We showed that the two-particle current due to Andreev reflection generates Joule heating, which is deposited in the N electrode and dominates over the single-particle cooling at low enough temperatures. This results in the existence of a limiting temperature for refrigeration.

In the context of refrigeration, it is important to describe quasiparticle electric and heat currents in NIS tunnel junctions in the dirty limit. We considered the effect of inelastic relaxation in the S lead. We find that in the absence of strong relaxation the electric current and the cooling power for voltages smaller than the superconducting gap are suppressed. We ascribe this suppression to the effect of backtunneling of nonequilibrium quasiparticles into the normal metal.

Interestingly, voltage fluctuations generated in a hot resistor can also cause extraction of heat from a colder normal metal electrode of a hybrid tunnel junction between a normal metal and a superconductor. We analyzed this heat rectifying system that bears resemblance to a Maxwell's demon. Explicit analytic calculations show that the entropy of the total system is always increasing. We analyzed also the cooling effect from nonequilibrium fluctuations instead of thermal noise, focusing on the shot noise generated in another tunnel junction. We conclude by discussing limitations for an experimental observation of the effect.

We proposed the design and operation of an electronic cooler based on a combination of superconducting tunnel junctions. The cascade extraction of hot-quasiparticles, which

stems from the energy gaps of two different superconductors, allows for a normal metal to be cooled down to about 100 mK starting from a bath temperature of 0.5 K. We discussed the practical implementation, potential performance and limitations of such a device. In the context of other proposals for electron refrigerators, we consider point-contacts (see figure).
We have shown how important nonlinear effects are in good refrigerators. A typical point-contact has a highly nonlinear cooling curve which often exhibits a fold-catastrophe which aid aids the refrigeration.
We have worked on thermodynamic relations in quantum systems, such as Onsager relations, and the second law of thermodynamics. More recently, we considered the fundamental upper bound on a heat-engine and refrigerator efficiencies at *given* power output and *given* system size. Carnot efficiency is only achievable at zero power, which is of little practical interest. Our work on a broad class of quantum thermoelectric systems shows that there is a different fundamental bound at given power; it equals Carnot's at zero power, but reduces with increasing power output. This bound is a quantum quantity, which cannot be calculated from classical thermodynamics. Despite this, it can play a significant role at the macroscopic scale. For example it tells us that under typical conditions a thermoelectric heat-engine of cross-section of $0.5 cm^2$ producing 100W of power, cannot have an efficiency of more than 90% of Carnot's. This raises the prospective that quantum thermodynamics will lead to a new understanding of everyday macroscopic thermodynamic processes, as well as microscopic ones.



Left panel: cascade cooler geometry. Right panel: calculated temperature as a function of the bias voltage applied across the cascade structure. Solid lines correspond to the temperature of the normal part of the cascade structure, dashed lines to the temperature of the normal part in an ordinary SINIS cooler; dotted lines are the temperature reached by the superconducting electrode S1. [from Appl. Phys. Lett. **104**, 192601 (2014)]

We have studied thermoelectric transport of a Coulomb-blockaded quantum dot (small metallic grain) in the regime of elastic cotunneling. When the Coulomb energy cost of adding one electron to the dot exceeds the temperature or the applied bias, the transport is strongly suppressed unless the electrostatic potential of the dot is tuned to special values by an external gate. We consider the thermoelectric effect in the regime where transport is suppressed and dominated by so-called elastic cotunneling. Then electrons traverse the dot via a coherent quantum superposition of virtual dot states. The thermopower can be a more sensitive probe of this physics than a conventional conductance measurement, and we show how the thermopower depends sensitively on randomness induced by disorder in the dot or the dot shape.

2.6.2 Searching for thermal signatures of persistent currents in normal-metal rings

Collaboration : O. Bourgeois (Institut Néel)

According to basic quantum mechanics, a metal ring threaded by a magnetic field should carry a weak non-dissipative, "persistent" current. However experiments have shown that this effect is anything but simple in realistic systems which contain disorder and magnetic impurities and electron-electron interactions. In such realistic systems, there is not as yet a full consensus as to the persistent current's magnitude or even direction. Previous experiments relied on the measurements of the magnetic moment associated with the persistent current and therefore could not make a distinction between non-dissipative persistent currents and those possibly induced by fluctuating electromagnetic fields that can exist in the ring's environment. We developed an alternative approach based on the measurement of a thermodynamic property – the heat capacity C – of the ring in a varying magnetic field B. According to the theory, C is a periodic function of B with the amplitude of oscillations C_2 depending on temperature T. The figure presents the measured C_2 compared with two different theoretical predictions assuming either repulsive (AE) or attractive (BEI) interactions between electrons. Surprisingly enough, both theoretical predictions yield very similar results that, however, differ from measured signals by 2 orders of magnitude. At the moment, the quality of our experimental data does not allow us to conclude if this discrepancy can invalidate the theories and further, more sensitive experiments are clearly necessary.

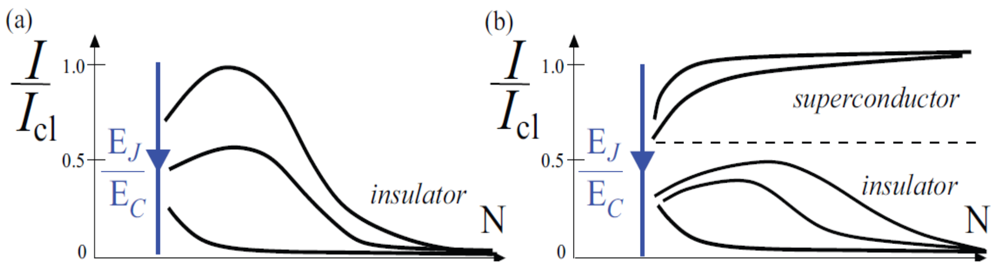
2.6.3 Superconducting tunnel junctions

Collaborations: W. Guichard (Institut Néel), I. Pop (PhD-student Institut Néel), J. Pekola (Aalto University, Helsinki, Finland)

The superconductivity order parameters is a *complex* number consisting of an amplitude and a phase. The phase can fluctuate a little in bulk superconductors, but these fluctuations average out, and have no effect on the transport. However, in chains of small Josephson junctions, the phase can change rapidly by 2π in a small regions which is then called a *phase-slip.* The transport properties of the Josephson junction chain are highly dependent on the dynamics of these phase-slips.

We investigated the physics of coherent quantum phase slips in two distinct circuits containing small Josephson junctions: (i) a single junction embedded in an inductive environment and (ii) a long chain of junctions. We formulated the conditions under which the resulting quasicharge dynamics is exactly dual to the usual phase dynamics associated with Josephson tunneling. In both cases we elucidated the role of the inductance, essential to obtain exact duality. Since both systems are governed by a model exactly dual to the standard resistively and capacitively shunted junction model, we expect the appearance of current-Shapiro steps. We numerically calculated the corresponding current-voltage characteristics in a wide range of parameters. Our results are of interest in view of a metrological current standard.

We then studied details of *quantum phase-slip* processes in a superconducting ring containing *N* Josephson junctions. In such a system, a quantum phase-slip consists of a quantum tunneling event connecting two distinct classical states of the phases with different persistent currents. When the Josephson coupling energy E_J of the junctions is larger than the charging energy $E_C=e^2/2C$, where C is the junction capacitance, the quantum amplitude for the quantum phase-slip process is exponentially small in the ratio E_J/E_C. We studied the dependence of the phase-slip amplitude on the ring size *N*, taking into account the effect of a finite capacitance C_0 to ground, which leads to the appearance of low-frequency dispersive modes. Josephson and charging effects compete



Left panel : schematic behaviour of the maximum supercurrent in a Josephson junction ring, sustaining quantum phase-slips. The nonmonotonic depencdence on the ring size N is a resumt of the competition between quantum tunnelling and charging effects. Right panel: effect of the superconductor-insulator, driven by the parameter E_J/E_C on the maximum supercurrent. [from PRB **87**, 174513 (2013)]

and lead to a nonmonotonic dependence of the ring's critical current on *N*.
In other work, we studied the effect of disorder on the electromagnetic normal modes of a Josephson junction chain. As is typical for one-dimensional disordered systems, all the modes are localized by an arbitrarily weak disorder, and we have calculated their frequency-dependent localization length. We have estimated the fluctuations of the chain impedance due to disorder.

2.7. Quantum Systems in strong magnetic fields

Contributors: D. Basko, T. Champel, N. Rougerie
PhD-students: Daniel Hernangomez-Perez

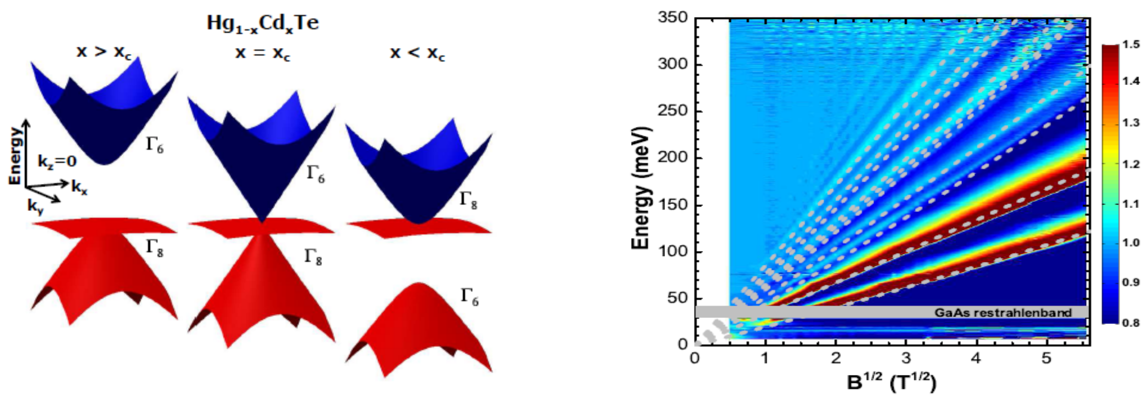
A magnetic field has a profound effect on electron dynamics. Quasi-classically, the Lorentz force acting on the electronic charge bends the trajectories, which affects transport properties of metals and semi-conductors. One example is the appearance of an electric field perpendicular to the direction of the current flow, known as classical Hall effect. Quantum-mechanically, the electronic kinetic energy in the direction transverse to the magnetic field becomes quantized into discrete levels, as shown in the early days of quantum mechanics by Landau.
The Landau quantization has especially dramatic consequences for systems in reduced dimensionality such as two-dimensional electron gases in semiconducting heterostructures, graphene, layered organic compounds, etc… The most famous and spectacular manifestation is the quantum Hall effect, that is the quantization of the Hall (transverse) conductance in integers or special rational fractions of the conductance quantum e^2/h (here e is the electron charge and h is Planck’s constant). This

quantization is accompanied by a vanishing of the (bulk) longitudinal conductance, indicating dissipationless transport. In spite of intense research during the last 30 years, many theoretical issues in the quantum Hall effect still remain unsolved. Also, recent technological developments offer new experimental techniques to probe the quantum Hall physics, or even reveal new physics. Thus, new theoretical questions are arising and the research field continues to be very active today.
One of the topics studied at LPMMC is the effect of the magnetic field on the optical properties of graphene and related materials, by including effects of various interactions (electron-electron or electron-phonon). The LPMMC has also developed theoretical methods to capture the effect at high magnetic fields of a smooth disordered potential on the electronic states, a crucial ingredient to understand the quantum Hall effect. Another line of research is the strong correlations between the electrons, which give rise to a rich physics with a wealth of exotic properties that are a challenge for theoreticians. Most of these theoretical activities at LPMMC have benefited from close collaborations with experimental teams located in Grenoble or Europe.

2.7.1 Magneto-optical spectroscopy of novel materials

Collaborations: C. Faugeras, M. Orlita & M. Potemski (LNCMI, Grenoble)

Application of a strong magnetic field to a material quantizes the spectrum of electronic motion in the directions transverse to the field into a series of discrete Landau levels. The transitions between Landau levels can be probed by optical techniques. The energies of the levels depend on the electronic dispersion in the material and on the magnetic field strength. Typically, for fields of 10-30 Tesla, the energies of the transitions are in the near-infrared spectral region, and can be probed by infrared absorption and Raman scattering spectroscopy. Measuring the magnetic field dependence of the transition energies, one can deduce information on the electronic band structure, for which some theoretical input is needed. The work on this topic is done in close collaboration with the semiconductor optics experimental group at the Grenoble National High Magnetic Field Laboratory (LNCMI), the LPMMC providing theoretical support for the experiments. Using these techniques, we have characterized electronic properties of various novel materials, such as graphene and its modifications, as well as topological insulators.
As an example, we can mention a recent observation of massless Kane fermions in a three-dimensional material. Until very recently, the conical (massless) electronic dispersion had been observed only in low-dimensional structures (carbon nanotubes, graphene, surface states of topological insulators). Our work has demonstrated such behavior for electrons in a crystal of zinc-blende structure, a HgCdTe alloy, at the point of topological phase transition from a semiconductor to a semimetal. In this system, the electronic band structure can be tuned by varying the cadmium concentration (see figure). For a particular concentration, the gap between the conduction and the valence band shrinks to zero. Such material was grown at the Institute of Semiconductor Physics in Novosibirsk for the first time, its magneto-optical properties were measured at the LNCMI in Grenoble (see figure 1), and the theory was provided by the LPMMC. Our work has clearly demonstrated that the electron dispersion was indeed massless, and that the gap can indeed be very precisely controlled in the fabrication process.



Left panel: The electronic dispersion of HgCdTe at k_z = 0 for three different cadmium concentrations. At the point of the topological transition, the conduction band and the light-hole valence band have a 3D conical dispersion, which is crossed at the vertex by an almost flat heavy-hole band. Right panel: False-colour map of the magnetic-field-dependent absorption spectrum measured in HgCdTe at the critical cadmium concentration. From Nature Physics **10**, 233 (2014).

2.7.2 Microscopic aspects of the quantum Hall effect

Collaborations: S. Florens (Néel, Grenoble), M. Morgenstern (Aachen, Germany), K. Hashimoto (Sendai, Japan), M. Raikh (univ. of Utah, USA)

While originally exclusively limited to semiconducting heterostructures, the quantum Hall effect has been observed within the last decade in a large spectrum of new two-dimensional electronic systems: graphene, oxide heterostructures, and topological insulators. The advent of surface two-dimensional electron gases has opened the way to direct high resolution measurements of the electronic probability density under high magnetic fields. Scanning tunneling microscopy (STM) experiments in the quantum Hall regime have yet been performed at the surfaces of doped semiconductors, topological conductors, and graphene. Because the Landau levels are highly degenerate, the associated electronic wave functions are strongly disturbed by any perturbation such as disorder, so that one has to deal in spectroscopic measurements with the inherent complexity of disorder. More fundamentally, a smooth disorder is crucial for the understanding of the quantum Hall effect by giving rise to the localization of most of the electronic states, as directly revealed for the first time in 2008 with STM measurements by the group of Markus Morgenstern in Aachen.
During the past years, we have developed at LPMMC (also in collaboration with S. Florens at Néel Institute) an original quantum-mechanical approach to study quantitatively the microscopic interplay between the cyclotron motion and a smooth (confining and disordered) potential, since the standard diagrammatic techniques turn out to be ill-adapted to describe the nonperturbative process of lifting the huge Landau level degeneracy. This theory based on a specific use of vortex states (representing the fast cyclotron motion characterized by topological quantum numbers) and formulated in the framework of semi-coherent Green's functions has provided a better understanding

of the properties of quantum Hall systems at the microscopic scale. The methods have been extended to graphene in 2010. They now provide a controlled analytical access to several observable quantities, such as the local density of states and its correlations (theoretical collaboration with M. Raikh, at university of Utah). For example, a detailed confrontation of the theory with recent STM experiments performed by the group of Markus Morgenstern in InSb surface gases within high Landau levels has been very successful in 2012, with the revelation of the robust nodal structure associated with the quantization of the cyclotron orbits, see figure 2.

The local electron density of states in the reciprocal space presents a number of minima depending on the Landau level index, as a result of the quantization of the cyclotron orbits. The positions in momentum of these minima seen in the experimental data (red circles) perfectly correspond to the theoretically expected positions, without use of any free parameter. From Phys. Rev. Letters **109**, 116805 (2012).

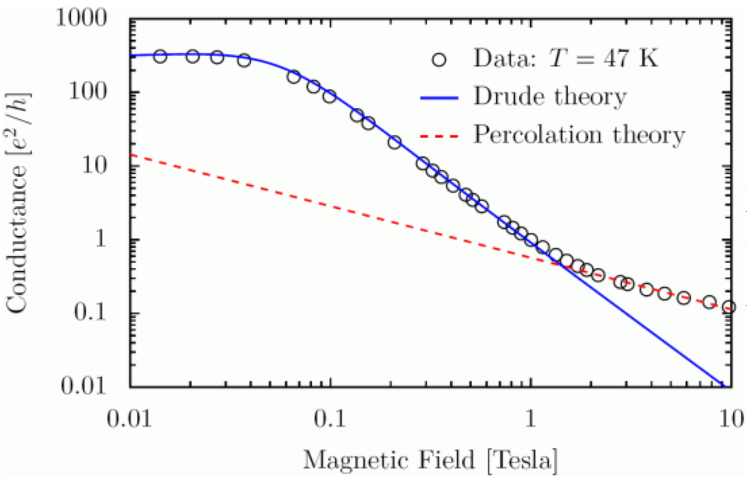
More recently, Daniel Hernangomez-Perez has extended during his PhD (years 2011-2014) the formalism to include the effect of a Rashba spin-orbit coupling, which can be very important in some semiconducting heterostructures due to the transverse confinement. This extension was also motivated by other STM experiments of Morgenstern *et al.*, reporting a spatial dispersion of the energy spin-splitting induced by both the Zeeman and Rashba spin-orbit, which was, unexpectedly, directly correlated with local electrostatic disordered potential landscape. Daniel's work has shown that this puzzling effect results from the interplay of a smooth potential and the peculiar spinorial structure of the electronic wave functions imposed by the spin-orbit interaction.

2.7.3. High magnetic-field electronic transport

Collaborations: Martina Flöser (PhD Néel Institute), Serge Florens (Néel), Benjamin Piot (LNCMI, Grenoble)

Quantum Hall systems offer a surprising dichotomy between very universal macroscopic properties, such as the near perfect quantization of the Hall conductance, and sample-dependent physics dominated by local imperfections, as observed in STM experiments in different systems. Macroscopic transport coefficients at high magnetic fields are clearly dominated by long-range spatial inhomogeneities, with an electronic current density essentially spreading along extended complex structures via a percolation mechanism. From a theoretical perspective, a consistent transport theory of the quantum Hall effect requires bringing together the geometric concept of percolation (and fractality) with dissipative processes such as quantum tunneling through the

saddle points of the disordered potential landscape, or interactions with phonons. Such a transport problem constitutes as a whole an important theoretical challenge, which is still topical.
During the PhD of Martina Flöser (years 2009-2012, shared between LPMMC and Néel Institute), we have investigated in detail how some degree of universality can be recovered in transport properties within this passage from the microscopic (local) to the macroscopic (global) scales. We have focused our work on the simpler (albeit still nontrivial) high-temperature regime of the quantum Hall effect, for which a semiclassical transport theory can be formulated by neglecting coherence effects. We thus have to deal with a purely classical problem (Landau level quantization is, however, still taken into account), i.e. a percolation problem within an advection-diffusion regime, which is nonperturbative in nature. However, we have shown that conductances can be computed analytically in this regime by an interpolation of the perturbative series expansion within a general diagrammatic formalism specifically developed for this classical problem. As a result, we have found that the Hall conductance is independent of the spatial inhomogeneities, while the longitudinal conductance receives nontrivial corrections that encode the interplay of dissipation and percolation, with a characteristic exponent close to the 10/13 value conjectured 20 years ago by Simon and Halperin.
Our theoretical predictions for the temperature and magnetic field scalings of the longitudinal conductance at high temperatures (typically, between 1 and 50 K) have motivated in 2013 experimental tests in different GaAs samples (collaboration with B. Piot at LNCMI, Grenoble). While the magnetic field dependence of the classical Hall law presents no anomaly at high temperatures, a clear breakdown of the Drude-Lorentz law (assuming chaotic electronic motion) for the longitudinal conductance has been found (see figure), which turns out to be correlated with the onset of the quantum Hall effect at low temperatures (characterized by the vanishing of the longitudinal conductance). This breakdown in the classical realm signals the onset at high magnetic fields of a different transport regime, where percolation effects play a prominent role. The extracted exponents in this regime are in good agreement with the theoretically expected values for classical percolation, and turn out to be only consistent with dissipation processes brought by the phonons.



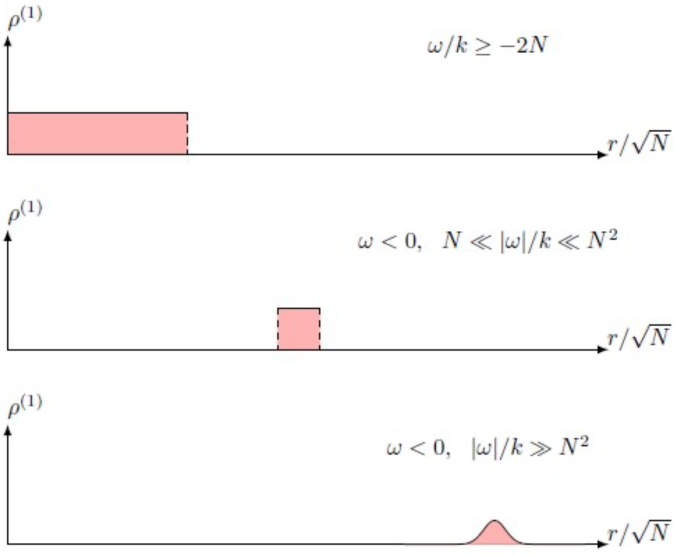
Longitudinal conductance as a function of magnetic field at high temperature (T=47 K). A clear breakdown of the Drude-Lorentz law (blue curve) is observed at fields above 1 Tesla, signaling the onset of a percolative transport regime. The scaling in magnetic field above 1 Tesla is characterized by an exponent close to the expected value 10/13 ≈ 0.77. From New Journal of Physics **15**, 083037 (2013).

Finally, the semiclassical transport approach has been extended in the very recent years to other two-dimensional electron gases, e.g. graphene within the ANR Metrograph. The signatures of the Rashba spin-orbit interaction on the macroscopic properties have also been studied within Daniel Hernangomez-Perez PhD's work, by providing analytical insight into the structure of the spin-polarized edge states and the characteristic features of the spin transport in the quantum Hall regime.

2.7.4. Fractional quantum Hall states

Collaborations: Sylvia Serfaty (univ. Paris 6, France), Yakob Yngvason (Vienna, Austria)

Whereas the integer quantum Hall effect may be understood using only single particle physics, the fractional quantum Hall effect has its microscopic origin in strong correlations between the many electrons of the sample. The new collective phases, such as the Laughlin states, that are at the basis of this physics display a wealth of exotic properties that are a challenge for theoreticians. More recently, it has been conjectured that they could be created in cold rotating gases, exploiting the analogy between the Lorentz and the Coriolis force. This experimental possibility has motivated recent theoretical studies of quantum Hall phases in rotating boson clouds at the LPMMC.
The case for the Laughlin state appearing as a ground state of rapidly rotating Bose gases is based on it being an exact eigenstate of the Hamiltonian for rotating bosons in a harmonic trap. However, it has been recognized that experimental limitations make the relevant regime unreachable with current techniques, due to the centrifugal force competing with the harmonic trapping potential. Recent proposals then involve using a steeper trapping potential, e.g. quadratic plus quartic, for better confinement. The Laughlin state is then no longer an exact eigenstate and a more detailed theoretical investigation is called for in order to single out the parameter regime in which it could be stabilized.
We have developed a rigorous mathematical approach to compute the one-particle density of Laughlin's and related wave functions, based on a mapping to a classical Coulomb system known as the "plasma analogy" and a controled mean-field approximation for the latter system. This permits to precisely estimate the parameter regime where the Laughlin state or a variant of it could be stabilized. In fact, due to the interplay between trapping and centrifugal force it turns out that in some regime a different state, where a giant vortex located at the center of the trap is added to Laughlin's state, becomes more favorable (see figure). This research project is currently being pursued with an investigation of the incompressibility properties of the Laughlin state, in the form of a strong rigidity of its response to an imposed external potential.



Sketch of the matter density of rotating Bose gas in the fractional quantum Hall regime, depending on particle number N, effective harmonic confinement (trapping - centrifugal force) ω and anharmonic component of the trap k. The three plots correspond to different transitions in the nature of the state as the experimental parameters are varied.

D. VISIBILITY AND IMPACT

2.8. Academic visibility and impact

During the period 2009-2014, members of LPMMC published over 270 articles in the relevant international refereed journals (Annexe 6.1), and were invited to numerous international conferences (Annexe 6.2.1) and schools (Annexe 6.2.2). Members of LPMMC regularly participate in organization of conferences and schools (Annexe 6.2.3).

During the period 2009-2014, Nicolas Rougerie and Robert Whitney were hired on CR positions with CNRS. Dominique Spehner, *maître de conférences* at *Institut Fourier* obtained a 40% affiliation at LPMMC from Joseph Fourier University. Seven important promotions were awarded to members of LPMMC : one IE CE, three DR2, two DR1 and one PR CE.

About 30 bachelor and master students performed an internship at LPMMC (Annexe 6.2.5). As to training of early stage researchers, LPMMC supervised 17 PhD-students and 9 postdoctoral fellows. It is important to stress the strongly international character of LPMMC: at any given moment members of LPMCM represented at least 10 different nationalities during the period 2009-2014.

Indeed, as can be seen from the detailed description of the scientific activities presented above, as well as from the publication list (Annexe 6.1), research at LPMMC is strongly collaborative, with research partners world-wide. LPMMC is an active member of the relevant national research networks GDR, one of them being directed and managed at LPMMC (GDR MésoImage). As can be seen from Annexe 7, members of LPMMC have been involved in over 40 funded research projects, more or less equally divided over international, national and local funding sources. These projects include several European consortiums, involving top teams from around Europe working on issues that are relevant at LPMMC, as well as smaller national consortiums favoring close collaboration between specialists on more specific topics. On a local level, LPMMC is involved in collaborative projects favoring inter-disciplinarity, in particular at the interface with mathematics and with the geosciences, as well as in projects which are centered around the venue of outstanding international visiting scientists, funded by the *Fondation Nanosciences*. For the period 2009-2014, these include prof. L. Glazman (Yale, USA), prof. H. Baranger (Duke, USA), prof. Yu. Nazarov (Delft, Netherlands) and prof. D. Ceperley (Urbana, USA). Many collaborative projects at LPMMC also involve experimental groups; members of LPMMC have a long-standing tradition to collaborate closely with experimentalists. Current examples are the participation of members of LPMMC in two prestigious experimental ERC projects at Néel Institute: one by W. Guichard on Josephson junction arrays and one by M. Richard on polaritons. In view of all the above collaborations, LPMMC frequently hosts short and long-term visitors.

Members of LPMMC serve as scientific experts on many occasions. All regularly act as referees for international journals; four LPMMC members have been awarded distinctions as outstanding referee (Annexe 6.2.7). Members of LPMMC regularly participate in hiring committees for CNRS and universities nation-wide (Annexe 6.2.6).

We finally list specific individual distinctions in Annexe 6.2.7.

2.9. Outreach, non-academic visibility and impact

Being a theory laboratory, active in fundamental research, LPMMC's contributions to outreach and non-academic visibility are naturally limited. A list of activities and contributions presented outside Academia is presented in Annexe 6.3, whereas Annexe 7.2 lists contracts with non-academic partners and patents.

As can be seen from these Annexes, members of LPMMC contribute to outsource activities on an individual basis. We mention here Nicolas Rougerie's contribution to the educational comic book *L'équation du millénaire*, outlining to the general public some of the major steps in the development of fluid mechanics in the 18th and 19th century, in particular the invention of the Navier-Stokes equation. We also mention the patent obtained by V. Rossetto and co-workers *Ultrasound control of concrete Detection and Location of the appearance of defects in multi-composite materials with mesoscopic ultrasound.*

Several items pertain to the activity developed by F. Berthoud and J-.D. Dubois in the framework of the service network (GDS) Eco-Info, see also section 1.4.2. Various invited talks have been delivered on topics related to the green ICT activities developed by this nation-wide operating professional network. Eco-Info also performs assessments for private sector partners, these activities give rise to various contracts.

Finally, LPMCM is a partner in the European Initial Training Network (ITN) *Quantum Nano-Electronics Training* (Q-NET), funded as a Marie Curie action in 2010. Q-NET is a European network of experts providing state-of-the-art training for young researchers in the general field of experimental, applied and theoretical Quantum Nano-Electronics. Q-NET's partners include two non-academic partners: the private companies AIVON (Helsinki, Finland) and ATTO-CUBE (Munich, Germany). All Q-NET PhD-students perform secondments in these non-academic partners.

3. Implication de l'unité ou de l'équipe dans la formation par la recherche

LPMMC is very strongly implied in various research-related training activities. First of all, as can be seen in Annexe 6.2.5, about 30 bachelor and master students, 17 PhD-students and 9 postdoctoral fellows have been supervised since 2009 by LPMMC members. Ten theses, (co)supervised by LPMMC members have been defended since 2009. PhD-students at LPMMC are registered at *Université de Grenoble - Alpes* and enroll in the doctoral program of the Grenoble Physics Doctoral School *Ecole Doctorale de Physique* (ED 47).

LPMMC teaching staff L. Canet, F. Hekking and D. Spehner as well as CNRS staff V. Rossetto fulfill regular teaching commitments in the Physics and Mathematics Departments of Joseph Fourier University. L. Canet and F. Hekking teach various courses in the Grenoble Physics Research Master programs, both at the M1 level (L. Canet & V. Rossetto: Statistical Physics, F. Hekking: Classical Field Theory) and the M2 level in the *filière Physique de la Matière et du Rayonnement* PMCR (L. Canet: Advanced Statistical Physics, F. Hekking: Advanced Quantum Mechanics, Theory of Quantum Transport).

CNRS staff D. Basko and M. Holzmann regularly teach advanced doctoral courses in the framework of the Grenoble Physics Doctoral School. A. Minguzzi has lectured in the Les Houches Predoctoral Training Session *Frontiers of Condensed Matter,* organized by the Grenoble Doctoral School. More generally, various members of LPMMC have given pedagogical lectures and/or co-organized schools see Annexe 6.2.2 and 6.2.3 for a detailed list.

LPMCM is a partner in the European Initial Training Network (ITN) *Quantum Nano-Electronics Training* (Q-NET), funded as a Marie Curie action in 2010. Q-NET is a European network of experts providing state-of-the-art training for young researchers in the general field of experimental, applied and theoretical Quantum Nano-Electronics. Q-NET addresses spintronics, molecular electronics, single-electronics, quantum dots and nanowires, nano-cooling. Q-NET's partners include two non-academic partners: the private companies AIVON (Helsinki, Finland) and ATTO-CUBE (Munich, Germany). All Q-NET PhD-students perform secondments in these non-academic partners.

F. Hekking directed the Grenoble Physics Doctoral School (*Ecole Doctorale de Physique* ED 47) from January 2007 until October 2012. With over 350 enrolled PhD-students this is one France's largest Physics Doctoral Schools. In Grenoble, the director of the Doctoral School also acts as president of the Physics Habilitation Committee.

An important regular event, organized for the first time in 2010 in Les Houches at the initiative of the Grenoble Physics Doctoral School, is the International Doctoral Training Session *Frontiers of Condensed Matter.* The session is organized in collaboration with two European research schools: the *Ecole Doctorale de Physique et d'Astrophysique* PHAST (Lyon, France) and the *Casimir Research School* (Delft-Leiden, the Netherlands). The organizing research schools share certain common features: they are embedded in similar – albeit complementary – scientific environments and all of them operate on a regional level (Delft-Leiden for Casimir and Grenoble - Lyon - Annecy for PHAST and *Ecole Doctorale de Physique de Grenoble*). The main idea behind the organization of a joint doctoral training session is to combine training efforts on a European level and create a partnership in order to provide high-quality doctoral training. Given the success of the 2010 event, sessions were organized in Les Houches 2011 and 2013, with additional European partners (Munich, Karlsruhe and San Sebastian). The 2014 event will take place in San Sebastian.

4. Stratégie et perspectives scientifiques pour le futur contrat

The presentation in this section is according to scientific topic, following the order indicated in Section 1.2., and concludes with a brief outline of LPMMC's main future strategy. It consists of 4 parts, organized as follows:

A. COMPLEX SYSTEMS
- Waves and photons in complex media
- Nonequilibrium phenomena

B. CORRELATED SYSTEMS
- Ultracold quantum gases
- Many-body theory
- Entanglement and quantum correlations

C. MESOSCOPIC SYSTEMS
- Electronic transport in nanosystems
- Quantum systems under strong magnetic fields

D. FUTURE STRATEGY
- Service informatique
- LPMMC towards horizon 2020: a SWOT-based analysis

A. COMPLEX SYSTEMS

4.1 Waves and photons in complex media

Contributors: D. Basko, F. Hekking, V. Rossetto, S.E. Skipetrov, B.A. van Tiggelen

Our research project in the field of wave physics aims at the solution of a number of open problems that either exist in the field for some time already (the impact of nonlinearity on Anderson localization, going beyond the diffusion approximation in imaging) or has been realized only recently (the role of polarization in Anderson localization, near-field effects in photon transport, single-atom photon Hall effect, and the mechanical momentum of a chiral molecule subject to magnetic field). Its different subtasks are either directly motivated by recent experiments with light, elastic and matter waves, or propose new experiments to be performed in the near future. An important part of the project is to be carried out in close collaboration with experimentalists.

4.1.1 Anderson localization in linear and nonlinear wave systems

Although the Anderson localization phenomenon has been extensively studied for already several decades, a number of issues relevant to recent experiments remain poorly understood. First, the vector character of waves (light or elastic waves) is not fully taken into account in theoretical models. This problem has gained particular importance after the recent publication of experiments on Anderson localization of light and elastic waves in 3D disordered media. Theoretical interpretation of these results cannot be achieved using approaches developed for electronic disordered systems because of the vector character of waves used in the experiments. Moreover, our recent theoretical study shows that the vector character of a wave may be detrimental for the very existence of Anderson localization in 3D (see figure). Thus the main purpose of the present project is to study the role of polarization in the experiments on Anderson localization. This will be achieved by, on the one hand, generalizing the self-consistent theory of localization to the vector case using a model with a tensor diffusion coefficient renormalized by interferences, and, on the other hand, by conducting extensive numerical and analytic studies of localization effects in the random Green's matrix model that we have recently developed. This project will benefit from collaborations with the teams of Robin Kaiser (Nice) and John Page (Winnipeg, Canada) who conduct experiments with light and elastic waves, respectively, and is expected to provide explanations to a series of puzzling experimental results: unexpectedly high values of transport velocity and an extremely slow decay of return probability at the mobility edge for elastic waves; observation of localization of light in TiO_2 powders but not in nominally stronger disordered porous semiconductors or semiconductor powders, etc. The results of this study will be strongly relevant to recent and ongoing experiments of other groups working on Anderson localization of light in fully disordered (the group of Georg Maret, Konstanz) and ordered (the group of Aristide Dogariu, Orlando) ensembles of small dielectric particles. Proper understanding of these experiments is one of our main objectives.

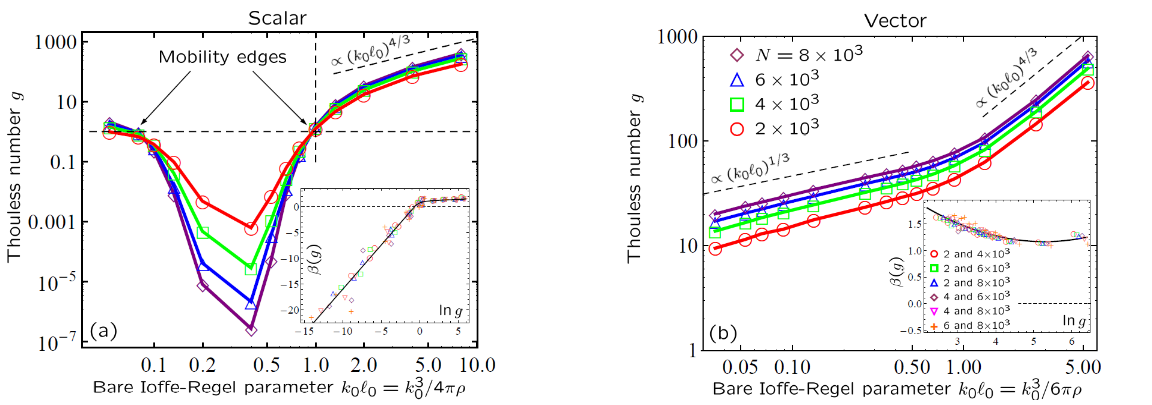


Illustration of the qualitatively different behaviors of scalar (a) and vector (b) waves in a 3D random ensemble of point scatterers. Scalar waves exhibit Anderson transition manifested by the dimensionless conductance $g < 1$ (Thouless criterion) for $k_0 l_0 < 1$ (Ioffe-Regel criterion), see (a). In addition, the scaling function $\beta(g) = d\ln g/d\ln(k_0 R)$ changes sign at $g \approx 1$ (inset). In contrast, vector waves do not exhibit any of these signatures of Anderson localization (b). From PRL **112**, 023905 (2014).

Another issue of contemporary importance is the fate of Anderson localization in the presence of nonlinearity. This problem is particularly relevant for experiments with atomic Bose-Einstein condensates in disordered potentials that can be approximately described by a nonlinear Schrödinger (Gross-Pitaevskii) equation although it also arises for light in nonlinear disordered media. One of the fundamental questions in this context concerns the evolution of an initially localized wave packet at very long times. In a linear system with Anderson localization, the wave packet remains exponentially localized at all times, due to the superposition principle. In the presence of nonlinearity, the wave packet width was found to increase as a subdiffusive power of time in several works reporting direct numerical simulations of the classical equations of motion. At the same time, rigorous mathematical arguments, as well as our previous results, indicate that at long times the spreading, if any, should be slower than any power of time. These arguments can be reconciled with the above-mentioned results of direct numerical simulations, if one assumes that the numerically observed power-law spreading is still an intermediate asymptotics, which should break down at very long times, inaccessible in the direct numerics. Some indications for slowing down of the power-law subdiffusion have been observed in the scaling analysis of numerical results. To make progress in this direction, it is important to elucidate the main mechanisms responsible for the observed power-law subdiffusion and to predict when these mechanisms cease to work. At present, both qualitative understanding and a quantitative theory of the observed power-law regime are lacking. One of our future goals is to resolve this problem which is puzzling the community already for several years.

4.1.2 Causal Green's function with applications to imaging

In a complex medium, the time a wave lasts in a domain and the energy on its boundary are distributed in ways that depends on the domain and its inner transport properties. Pulsed sources provide more information concerning the medium than permanent sources, because time resolved signals depend on the statistics of path lengths and time integrated signals do not. Such statistics have been extensively studied for Brownian motion, corresponding to a diffusion process, using specific methods based on space and time transformations and Green's functions. Yet, for short times, the diffusion approximation displays pathology because it is not causal. Causality must be restored by introducing a finite wave velocity and the above mentioned techniques have to be developed in order to take a finite velocity into account. The corresponding master equation transforms into a first-order equation in space and time, closely related for scalar waves to Boltzmann and Bethe-Salpeter equations. For long times, the diffusion approximation is recovered while the difference is significant for short times. Angular resolution can be obtained using the structure of the Bethe-Salpeter equation and is important for applications. The solutions to these problems strongly depend on the dimension of space. This is a consequence of the non-trivial behavior of free-space Green's functions as a function of the space dimension, a well-known fact for the wave equation, for instance. Depending on the dimension's parity, the solution to a problem will have an analytic expression or not. As an example, in two dimensions the exit time distribution has no analytic expression but the radiative transfer is expressed with elementary functions, this is the opposite in three dimensions. A strategy consists in solving a problem in "neighboring" dimensions and performing a numerical interpolation or solving it in all even or odd dimensions and continuing the solution analytically.

These methods and results will be applied in various domains of physics. In geophysics, complex media at small scale are met in volcanoes. Volcanology studies natural risks of eruption and therefore implies society issues in which more than a single observable is needed. Local time kernels have been already successfully used to detect pre-eruptive signals. The new observables will be able to give complementary and independent information. In optics, most of the techniques of imaging in disorder are based on the suppression of the time variable, either by using permanent sources or by the use of time-reversal setups. Using the space-time distributions, a time-resolved inversion kernel can be designed. The amount of input data is therefore very large, a necessary condition for the treatment of errors.

The approach described above has strong advantages for designing time-resolved resolutions kernels. It suffers nonetheless from some limitations: it is directed towards system of uncorrelated disorder of isotropic point scatterers. A physical description of more realistic systems should include finite size scatterers and take into account correlations between scatterers. Standard techniques of multiple scattering will be used with the causal Green's functions instead of the usual diffusion Green's functions. A correct treatment of the finite size of the scatterers results in an excluded volume, a singularity of the same mathematical nature as causality, which should therefore be treated rigorously to preserve the accuracy of the causal Green's functions. Considering disorder correlations implies solving Dyson equation and performing diagrammatic expansions including Hikami-like terms. Anisotropic scatterers have to be described by a phase function, modifying the dressed Green's functions. The stochastic process becomes a compound Poisson process, which can be studied using tools we have recently developed to determine the Berry phase statistics in disordered media.

4.1.3 Light scattering by atoms in magnetic field

Single atoms or ensembles of many atoms at low temperatures represent a fantastic model system to study fundamental physics because, on the one hand, the interaction of an atom with electromagnetic field can be described theoretically with high degree of accuracy and, on the other hand, the modern technology provides means to probe atomic systems with high precision. In this framework, we plan to study the scattering of light by atoms in strong magnetic fields. For a single, isolated atom an interesting phenomenon – the photon Hall effect – has been predicted recently. The theory has been developed for the hydrogen atom and it has to be adapted to atomic species more suitable for experimental realizations, such as, e.g., strontium. This project will be performed in tight collaboration with David Wilkowski at NTU Singapore where an international laboratory co-funded by CNRS has been recently established (UMI Merlion) and where facilities exist for the experimental observation of the predicted phenomenon.

An interesting question to ask about the impact of magnetic field on light scattering by clouds of many identical atoms concerns Anderson localization. More precisely, given the absence of Anderson localization in an ensemble of atoms that we have recently discovered, can application of a strong magnetic field change the situation? We will study this question theoretically in collaboration with Igor Sokolov (St. Petersburg, Russia). The idea is that the magnetic field lifts the degeneracy of atomic sublevels due to the Zeeman effect and makes the atom closer to a two-level system. On the other hand, magnetic field affects the near-field coupling between neighboring atoms and can therefore reduce its detrimental impact on Anderson localization.

4.1.4 Mechanical momentum of quantum vacuum

Our previous theoretical work resulted in an interesting and surprising prediction of a non-zero mechanical momentum of a chiral molecule subject to magnetic field. This momentum is related to the breakdown of translational symmetry of space induced by the field. We will now aim at the experimental observation of this phenomenon. The experiment will be performed at LNCMI (Toulouse and Grenoble) by the team of Geert Rikken. We expect to measure velocities of molecules as small as 0.03 nm/s. This is small but measurable with modern equipment. The existing theory will have to be adapted to the experimental situation.

4.1.5 Near-field effects in photon transport

Two bodies placed far apart can exchange energy by photons that can be viewed as propagating monochromatic waves. However, when the two bodies are closer than a wavelength apart another transport channel opens up that do not rely on wave propagation in free space between the bodies. This channel is due to the so-called near field effects. The latter are of primary importance in modern nanoscale systems and devices and we plan to study their impact in the following contexts.

First, near-field effects can play an important role in heat transfer between elements of nanoscale electrical circuits. According to the theory of black-body radiation, a net heat flow exists between two bodies kept at a temperature difference ΔT. This flow behaves as $T^3\Delta T$, where T is the average temperature of the bodies. This mechanism is also at work in nanoscale electrical circuits: two resistive elements kept at different temperatures exchange heat with a heat flow behaving as $T\Delta T$. This channel might well dominate the phonon channel for heat transfer. These results are based on a treatment of far-field photons: propagating solutions of Maxwell's equations. Since the pioneering work of Polder and Van Hove in the early seventies the relevance of near-field photons has been well-known: decaying solutions of Maxwell's equations close to the radiating body's surface. If two bodies are placed at a distance within the decay length, an additional channel for heat transfers might open up that should be taken into account. We intend to generalize earlier work on photon heat transfer in nanocircuits and include the near-field channel. This might be relevant for applications, such as the heat transfer between the different parts of a microcooler.

Another problem in which near-field effects may play an important role is the Anderson localization of light. In a random collection of strongly scattering impurities ("scatterers") the propagating-photon transport channel can be blocked by interference effects – the phenomenon known as Anderson localization. However, when the neighboring scatterers are closer than a wavelength apart, they can exchange energy (and hence sustain energy flow) by near-field effects without emitting "real" photons (in atomic physics, one speaks of "virtual" photons even though the term might not be appropriate). This new non-radiative transport channel is expected to open at high scatterer density, precisely when Anderson localization should take place, and it can counteract the latter. In this context, our aim will be to better understand the role of near-field effects and to find the ways to limit their impact by either adjusting the scatterer shape and mutual configuration or applying a magnetic field.

4.2 Nonequilibrium systems

Contributors: L. Canet, A. Minguzzi, D. Spehner, R. Whitney

Very few of the things we see around us are in equilibrium. The sun and stars, life on earth, and most man-made machines are all far from equilibrium. Despite this, understanding the behaviour of out-of-equilibrium systems is an extremely challenging problem that crops up in almost all areas of physics. Here we discuss three classes of out-of-equilibrium problems that we plan to address: out-of-equilibrium phase-transitions in classical and quantum systems, driven dissipative systems and the dynamics of spin glasses. Connections between these projects will be made at the level of techniques and concepts used to treat them.

4.2.1 Non-Perturbative renormalization group: Interface growth and turbulence

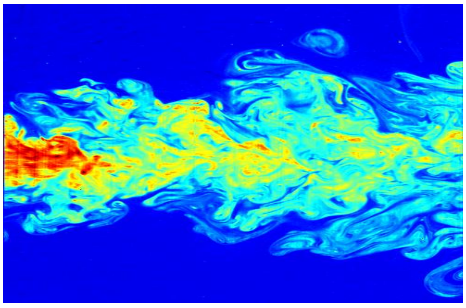


Figure: Flow visualization of a turbulent jet, made by laser-induced fluorescence (reproduced from wikipedia article “turbulence”).

In the domain of classical nonequilibrium systems, we plan to tackle two main problems, related to interface growth and turbulence respectively. The line of research dedicated to interface growth is a continuation of on-going works. We plan to exploit the theoretical framework we have developed, based on nonperturbative renormalisation group methods, to investigate related open issues. An important one is to determine the upper critical dimension, if any, of the KPZ equation, which still constitutes a long-standing and unsolved question. Another issue concerns the influence of spatial anisotropy on the KPZ growth. The aim is to determine how anisotropy may alter the phase diagram and to theoretically describe the new emerging phases. The study of anisotropy turns out to be of particular relevance in the physics of driven Bose-Einstein condensate, such as polaritons, as the universal behavior of the system in a specific critical regime has been shown to be described by a strongly anisotropic KPZ model.

The other part of the research we plan to undertake is the study of the regime of *fully developed turbulence* of the Navier-Stokes (NS) equation. Turbulence is a ubiquitous phenomenon in any real flow in Nature. The dynamics of fluids is described at the microscopic level by the NS equation. As this equation is dissipative, energy has to be permanently injected in the system to maintain a turbulent flow. This can be modeled by adding a stochastic stirring force to the NS equation. In presence of such a stochastic forcing, the NS equation stands as a Langevin equation, and the associated field theory may be derived using standard techniques. The non-perturbative renormalization group approach, that we have developed to study classical nonequilibrium systems, hence appears as a promising candidate to investigate the universal properties of the turbulent flow. One of the main open theoretical challenges is to characterize the phenomenon of intermittency, which generically encompasses violations to the famous Kolmogorov 41 theory. To achieve this, our aim is to compute the structure functions (equal-time correlation functions of the longitudinal velocity increments) in order to determine the associated critical exponents, and deviations from their Kolmogorov values.

4.2.2 Driven-dissipative quantum gases: polaritons with disorder and strong correlations

This topic has strong connections with the topics “Quantum gases of cold atoms” and “Waves and photons in complex media”.

Exciton polaritons are obtained by hybridation of excitons in a semiconductor and cavity photons. This composite bosonic particles can undergo Bose-Einstein condensation even at room temperature, thanks to their light effective mass. The evolutions of semiconductor microcavity fabrication techniques allow for obtaining a quasi-one-dimensional geometry, as well as e.g. a necklace lattice geometry. Polaritons constitute

an ideal system to explore quantum-mechanics and macroscopic quantum coherence effects on much less severe constraints than ultracold atomic gases. They also differ from atomic gases in the fact that their lifetime is extremely short, requiring the presence of a pump to compensate the losses. This creates a driven-dissipative steady-state different from the equilibrium one, whose properties have to be addressed with out-of-equilibrium techniques. For example, the nature of the phase transition could be accessed by non-perturbative renormalization group methods described in the section above.
One of the main goals of this project is to characterize the polariton state and obtain the experimentally relevant observables under driven-dissipative conditions. While at weak interactions a well-established theoretical model is based on a mean-field approach (Gross-Pitaevskii equation, generalized to include pump and losses), very little is known beyond. Our goal is to obtain a theoretical description for the 1D geometry (uniform or lattice case) beyond mean field, using as a starting point the LPMMC expertise on quantum field theory models and exact solutions developed in the context of equilibrium gases.
A second topic which will be explored is the effect of disorder in polariton gases. The competition of Anderson localization, effect of interactions and losses will lead to explore the generalization of the already rich equilibrium phase diagram for bosons. This project will be led in close collaboration with the experimental team of Maxime Richard at Neel Institute.

4.2.3 Dissipative quantum mechanics in spin-systems

Strong connections with "Electronic transport in nanostructures".

New experiments by L. Saminadayar and L. Levy (Inst Neel) are using mesoscopic transport measurements as a novel probe of a class of spin-glasses (randomly placed magnetic impurities interacting via RKKY interactions). They have achieved unprecedented sensitivity to the dynamics of small clusters of spins within the glass. However their experiments are in a low temperature regime where quantum effects are likely to be very important. This raises two related types of theoretical problems to address. The first is the fundamental issue of understanding the dynamics of small clusters of spins in a spin-glass, in particular this type of quantum spin-glasses with Heisenberg interactions (which are much less studied than classical Ising spin-glasses). The second is to develop a method of extracting the maximum amount of quantitative information about the spin-glass from the transport measurements made by Saminadayar and Levy.

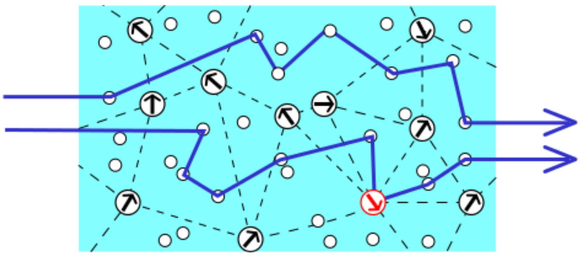


Figure: Sketch of a disordered spin-glass probed by measuring the universal conductance fluctuations in the electron flow from left to right.

In this project, we are forming a collaboration capable of working on both aspects of this problem. We will work with the experimentalists to develop their experimental set-up and interpret their experimental results. In parallel, we will look at the dynamics of spin-clusters in the glass (building on connections between the works of Whitney and

Cugliandolo on spins coupled to environments). The small size of the experimental spin-glass (as few as a few thousand spins) allows us to ask; how small can a spin-glass be? What is the minimum number of spins in a randomly interacting network necessary to see glassy dynamics on experimentally observable time scale (from micro-seconds to many hours). For a smaller number of spins in the network, what would be the nature of the spin dynamics?

B. CORRELATED SYSTEMS

4.3 Ultracold quantum gases

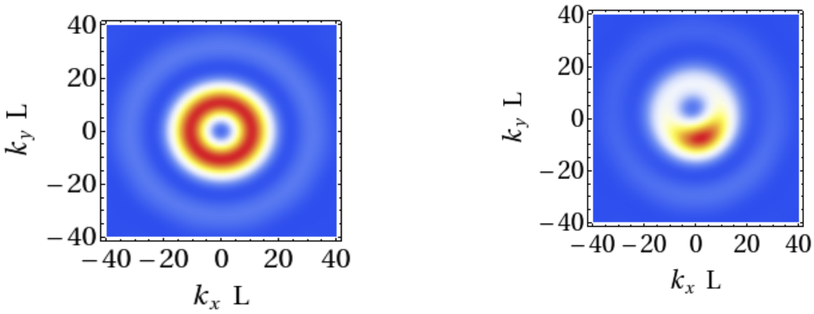
Contributors: F. Hekking, M. Holzmann, A. Minguzzi, N. Rougerie, P. Schuck, D. Spehner, B. van Tiggelen.

We will focus on the study of quantum gases at the interface with condensed matter. With respect to their condensed matter counterparts, ultracold atoms offer access to novel observables and an unprecedented tunability of parameters, allowing to explore the effect of interactions, geometry, topology, and of a manufactured disorder with tunable strength. Open fundamental questions in this context are the understanding of novel phases and correlation effects at equilibrium both at zero and finite temperature, as well as the out-of-equilibrium properties of interacting quantum fluids. This calls for the development of complementary numerical and analytical approaches, the latter being possible in specific regimes (e.g. at low energy, at weak or at very strong interactions, ...). The progress in the understanding of these model systems is expected to yield useful input in the design and understanding of condensed matter devices, and for the applications to metrology, quantum state manipulation and quantum information..

4.3.1 Mesoscopic physics with ultracold atoms on a ring

Recent experimental advances allow the realization of geometries typical of mesoscopic physics, such as ring trapping potentials. The ring geometry allows to explore the response of the system to an artificial gauge field. This can be realized for neutral atoms eg with a rotating barrier, (as well as with laser-induced tunneling, or lattice shaking techniques). As a consequence of the presence of the gauge field, several physical properties are periodic in the Coriolis flux, allowing eg to design a rotation sensor based on atom interferometry. The main goal of the present studies will be the study of the dynamical response of an interacting Bose gas to a rotating barrier, in close connection with the experimental activities led in Villetanneuse (Paris 13) and in Singapure (Center for Quantum Technologies). We will employ various theoretical approaches depending on the interaction regime: a Gross-Pitaevskii mean-field treatment at weak interactions and low temperatures, the Luttinger Liquid method at intermediate interactions and low energy, and the exact Girardeau solution at infinitely strong interactions. A good understanding on the mechanism of angular momentum transfer in the fluid is the pre-requisite to the realization of a macroscopic superposition state with atomic currents, the neutral analog of a flux qu-bit. The realization of such a state is a very challenging stepforward in the quantum gases community, which is currently pursued by several experimental groups.
After considering the bosonic case, also the case of interacting ultra-cold fermions on a ring will be addressed. This will allow to go beyond the usual paradigm of electrons in normal metallic ring by focusing on a regime where interactions overcome the effects of disorder on the ring. Finally, the effect of the range of interactions will be addressed. We will go beyond the description of short-range interactions, suitable to describe neutral alkali atoms, by studying the behavior of quantum dipoles, displaying anisotropic intermediate-range interactions. Dipolar quantum gases with large magnetic or electric moment are currently realized by trapping and cooling rare-earths atoms,

hetero-nuclear molecules or Rydberg atoms.



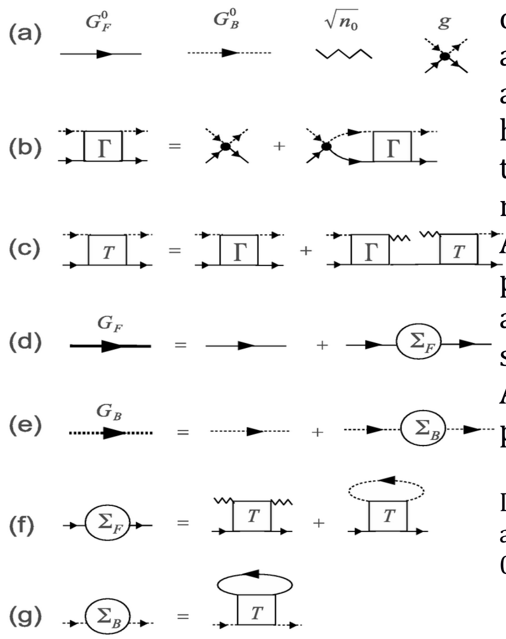
Time-of-flight expansion simulations for ultracold atoms on a ring stirred by a rotating barrier, then released from the trap. The left panel corresponds to a state with angular momentum l=1 and the right panel corresponds to a macroscopic superposition state between l=0 and l=1, analogous of a flux qu-bit. From D. Aghamalayan, M. Cominotti, et al., in preparation (june 2014).

4.3.2 Transport and thermoelectric effects with ultracold atoms

A two-terminal geometry, recently realized in an experiment at ETH in Zurich, will be used to explore thermal transport in bosonic nanowires. It will allow to obtain in particular the thermo-electric coefficients for the bosonic case, and explore the possibility of developing new coooling schemes for ultracold atoms. The effects of bosonic statistics and of interactions will be studied. This will contribute to the understanding of the out-of-equilibrium dynamics of interacting quantum gases.

4.3.3 Fermi gases and Bose-Fermi mixtures

We will focus boson-fermion (BF) correlations in BF mixtures. One of the main objectives will be to go beyond the simple T-matrix approximation and to include finite temperatures and the situation of many BF pairs. In this way we hope to be able to study the nature of the transition from an uncorrelated BF mixture to a new Fermi gas whose constituents are BF pairs.
A rather related problem is the one of strongly polarised two component Fermi gases. Also there arises the question of the transition to the paired state as a function of asymmetry and temperature. A comparison with existing experimental data is planned.



Diagrams used for the Bose-Fermi mixture in the T-matrix approximation. From T. Sogo, P. Schuck, M. Urban, PRA 88, 023613 (2013)

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4.3.4 Anderson localization of matter waves in anisotropic disorder

We will pursue the modeling of the Anderson localization of cold atoms. A tunable disorder is realized in these systems with a speckle potential. The main theoretical challenges in this context are the treatment of long-range correlations and the anisotropy which are both characteristics of the speckle potential. Due to the complexity of this type of disorder, the standard analytical approaches are not sufficient, and one has to resort to novel schemes, which require massive numerical calculations. The first codes are currently run at IDRIS. This project will be led in collaboration with LCF-Palaiseau.

4.3.5 Bosons with spin-orbit coupling

Introducing a Rashba-Dresselhaus spin-orbit coupling between bosons in two hyperfine (pseudospin) states modifies the single-particle spectrum which is in competition with the effects of interparticle interactions. Depending on the details of the interactions, striped ground states and more exotic states at finite temperature have been predicted. In particular, mean-field arguments lead to the occurrence of a first order transition between the condensed and normal phases for three-dimensional Bose gases with isotropic in-plane Rashba spin-orbit coupling. We want to explore quantitatively the phase diagram using classical field and quantum Monte Carlo calculations to establish the precise order of the phase transition, the asymptotic form of the transition temperature, and possible exotic phases at low temperature.

4.3.6 Mean-field limit for large bosonic systems

We recently introduced a new mathematical method to investigate the validity of mean-field theories for the description of the ground state of large bosonic systems. Based on a systematic refinement and use of the quantum de Finetti theorems, this approach has allowed us to unify and extend several existing results about the derivation of Hartree and Gross-Pitaevskii type functionals. The method is now widely used for the description of evolution problems and one may expect that it becomes an instrumental tool in the many-body theory of bosonic particles. We would now like to go beyond this unification and refinement steps by tackling new, more challenging problems. The new mathematical tools developed will allow us to address some important questions:

i) the derivation of mean-field functionals with highly singular interaction potentials. A central example is that of Bose gases with dipole-dipole interactions, which have become a hot topic in the quantum gas community. Several very interesting phenomena occur in these systems due to the long range and anisotropic nature of dipole-dipole interactions.

ii) the study of nonlinear Gibbs measures for interacting bosons at large temperature. The construction of Gibbs measures based on effective Hartree/Gross-Pitaevskii like functionals is an important tool in very different contexts. This is the central paradigm of so-called constructive quantum field theory, where these Gibbs measures constitute the classical field theory one should then quantize. These measures also appear in the mathematical theory of dispersive partial differential equations, but their relation to many-body physics is rather unclear. We hope to be able to shed light on this issue by showing that the thermal state of a large interacting bosonic system can, at least in some simple cases, be described using a non-linear Gibbs measure, that is a measure over Hartree (BEC) states.

4.3.7 Rigorous derivation of the Bose-Hubbard model and the Superfluid-Mott Insulator transition

In a related direction, we will work on situations implying effects beyond mean-field. We would like in particular to investigate the quantum phase transition from delocalized (BEC, superfluid ...) to localized (Mott insulator) states in deep multiple well potentials, such as those generated using optical lattices in quantum gases experiments. For low filling (low ratio number of particles / number of sites) this transition can be efficiently modeled using Bose-Hubbard Hamiltonians. Mathematically speaking, the derivation of these models from the many-body Schroedinger equation is still unclear, and the precise calibration of the effective parameters could benefit from a detailed analysis. For large filling, e.g. in a simple double well potential realizing a Bose-Josephson junction, the situation is more complicated and a new approach could shed some light on the quantum fluctuations present in these systems.

4.4 Many-Body Theory

Contributors: M. Holzmann, N. Rougerie, P. Schuck

We plan to extend our formal developments and apply them to various open many-body problems, such as the existence of the liquid-crystal transition of the classical Coulomb plasma or the computation of the ground state of the 2D Hubbard model within self-consistent RPA theory. Beyond ground state properties, our projects also aims to obtain quantitative information for spectral functions. Quantitative calculation of spectral and transport quantities based on the microscopic Hamiltonian is one of the most challenging issue in quantum many-body theory. We plan to develop quantum Monte Carlo methods to compute excitation spectra and dynamical linear response in electronic systems.

4.4.1 Crystallization in classical Coulomb systems

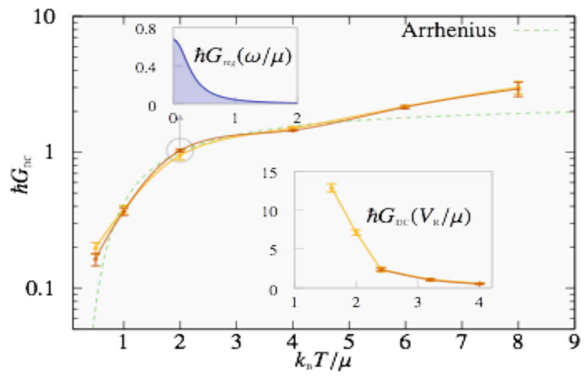
The natural way forward in the studies of classical Coulomb Hamiltonians is to investigate the liquid to crystal transition for the thermal state of such systems. Mathematically speaking, the existence and nature of the phase transition is a famous open question. Previous work with Sylvia Serfaty lead to a natural conjecture about the order of magnitude of the critical temperature at which the transition should happen. The next step would be to obtain more conclusive evidence, which would require to include an entropy term in the effective ``renormalized energy'' functionals we have been studying. Better characterizations of the liquid phase would also help in giving a cleaner mathematical formulation to the problem.

4.4.2 Microscopic calculations of spectral properties of quantum many-body systems

Quantum Monte Carlo (QMC) methods are currently considered to furnish the most precise results for ground state properties of electronic matter, and we plan to generalize our actual work on the QMC determination of Fermi liquid parameters to obtain the full information on spectral quantities. Central part are calculations on the homogeneous electron gas in two and three dimensions (jellium) and liquid 3 He, which should allow us to establish the methodology and to provide reference values for perturbative methods based on RPA or GW approximations or on approximate solutions of the Bethe-Salpeter equation. The project aims to reach a quantitative description of spectral properties starting from jellium, the most simple and fundamental model of condensed matter theory, over simple metals and band insulators, which will allow us first comparisons with experiments, towards more complicated materials, where current methods fail.

4.4.3 Transport quantities for correlated Fermions and Bosons

Dynamical linear response is contained in the imaginary time correlations of path integral Monte Carlo calculations. Our quantum Monte Carlo calculations of disordered Bosons have shown that it is possible to access transport properties in continuous path-integral calculations of bosonic systems. We plan to extend our approach to fermions in order to obtain the conductivity in electronic and coupled electron-ion calulations.



Finite-temperature, zero-frequency longitudianl conductance of a disordered Bose gas as a function of temperature and as a function of disorder intensity (lower inset). In the upper inset the full frequency dependence is shown (from PRL **111**, 050406 (2013)).

4.4.4 Self-Consistent RPA

A further more general research line will be the continuation of considering the ground state of Coupled Cluster Theory in the extension of the RPA approach into the so-called Self-Consistent RPA. Applications to the 2D Hubbard model and to condensation of quartets are planned.

4.5. Entanglement and quantum correlations

Contributors : A. Minguzzi, S. Skipetrov, D. Spehner

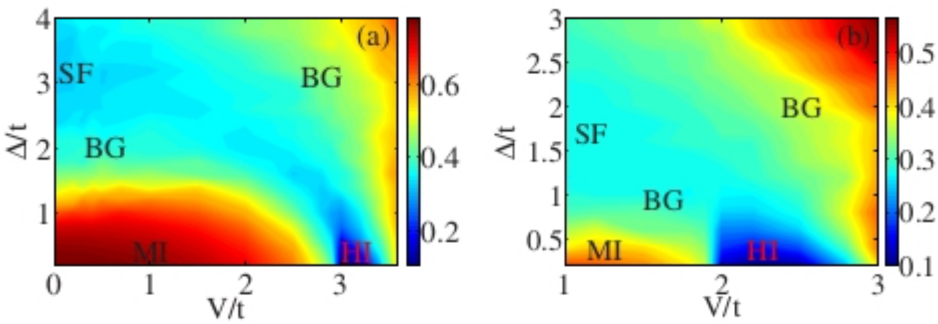
One of the open questions in condensed matter physics is whether entanglement could bring a new understanding of well-known physical phenomena such as the Anderson localization or quantum phase transitions. Another interesting problem is to design protocols for generating entangled states that could improve the efficiency in information processing tasks and imaging, or the phase precision in interferometry, with applications to quantum metrology. We aim to study these problems by focusing on particular physical systems such as ultra-cold atoms and light scattering in random media, and by developing new general mathematical tools to study and characterize quantum correlations in those and in other systems.

4.5.1 Quantum correlations in atomic rings: towards the realization of macroscopic superpositions of atomic current states.

The possibility of realizing non-classical states in a ring geometry (see Sec.2.3.2.3) is a fascinating challenge for the forthcoming years. It would open the way to several applications, ranging from beyond shot-noise atom interferometry on a ring, to metrological applications. From the theoretical point of view, this calls for the study of the protocols to realize such states, and their characterization in terms of entanglement useful for atom-interferometry applications. We will employ various estimators (fidelity, quantum Fisher information,...) to identify the characteristics of the various non-classical states, and to follow their time evolution. Also, we will consider possible effects of decoherence, such as particle losses, effect of temperature and magnetic fluctuations along the ring, and study the possible ways of reducing them. More generally, this study will address the question on how to exploit interactions and correlation effects as a resource for quantum computation.

4.5.2 Quantum correlations in the ground state near a phase transition.

In the last years it has been pointed out that one may see the signature of a quantum phase transition by looking at the entanglement properties of the ground state. In particular, right at the transition one sometimes observes a degeneracy of the highest eigenvalue in the so-called Schmidt spectrum of the ground state, and it has been shown in some spin models that the gap between the first and second eigenvalues exhibits a scaling behavior near the transition with the critical exponents of the universality class of the model. We plan plan to investigate this problem in the light of previous results obtained at the LPMMC on the geometrical description of quantum correlations (see section 2.5.5). These results show that the aforementioned degeneracy is related to a symmetric situation in which there are infinitely many closest classical states to the ground state. A particular phase transition of interest is the Mott insulator-superfluid transition in Bose-Einstein condensates.



Entanglement spectrum in a Bose-Hubbard model for dipolar bosons in a 1-D optical lattice in the presence of an Anderson-type disorder (random on-site energies uniformly distributed in the interval [-Delta,Delta]), as a function of Delta/t and of the nearest-neighbour interaction V divided by the tunnel energy t, for one-site interaction U=5t (a) and U=3t (b). One can clearly identify from the values of this spectrum the different phases, namely the Mott-insulator (MI), Superfluid (SF), Bose-glass (BG), and Haldane-insulator (HI) phases, which are determined from the study of correlation functions. From New J. Phys. **15**, 045023 (2013).

4.5.3 Entangled photons in random media

Light scattering in random media have been studied for a long time but the quantum aspects of this problem have started to be explored only recently. Our interest in this context will be in the transport of quantum entanglement through random media and the possible use of entanglement for (secure) communication in random environments.

The basic problem that we are interested in is the following: given an entangled state incident on a random medium (e.g., an ensemble of randomly distributed dielectric particles) what will be the entanglement of the transmitted light? The auxiliary questions to ask are the following: How can we characterize the entanglement of a multi-photon, multi-mode quantum state? How can the entanglement of the randomized state resulting from the transmission of the initial entangled state through a random medium be made useful? And do entangled states have any advantage with respect to disentangled or classical states for communication, imaging, or any other application known in optics of random media?
Another interesting problem in the same context concerns the link between Anderson localization and entanglement. In particular, Anderson localization (which is a classical wave phenomenon) changes the statistics of transport coefficients of a random medium. It is not clear, however, whether this change will be directly seen in the entanglement properties of scattered light and which kind of signature will it have on the quantitative measures of entanglement. In particular, it would be interesting to find out if entanglement-related quantities may serve as hallmarks of Anderson localization.

4.5.4 Relations between the quantum correlation measures.

Many open questions remain to be investigated concerning distance measures of quantum correlations. In particular, one should study the role of the distance and the possible links between the measures based on the minimal distance between a state and the corresponding classical state obtained after a local measurement on the system. The connection of the geometric quantum discord with a recently proposed symmetrized version of the quantum Renyi entropies is also an interesting issue. We plan to work on these problems, as well as on the relation of the measures of quantum correlations with the quantum Fisher information quantifying the correlations usefull for high-precision quantum interferometry.

C. MESOSCOPIC SYSTEMS

4.6 Electronic transport in nanostructures

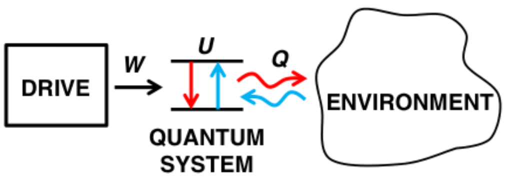
Contributors: D. Basko, F. Hekking, R. Whitney

Nanostructured electronic systems are ideal for exploring the interplay of quantum mechanics, interaction effects, thermodynamics and information. This is because we can now construct structure (quantum dots, wires, Josephson junction chains, etc) in which the effects of interest manifest themselves in the total electron flow through that structure (a quantity that is easily measured). Recent advances have been made in methods of nanoscale thermometry and refrigeration, especially within Inst Neel. However, the challenge of understanding such systems remain. In particular, the total electron flow in such systems is always coupled to other degrees of freedom, such as low lying phonons or photons modes or internal states of the electron gas. The coupling causes entanglement, which can be observed as dissipative or heating effects, entropy generation and loss of information.

Our future work will study the physics of a variety of such systems, and using it to advance our understanding of quantum thermodynamics, quantum information, and interacting quantum systems far from equilibrium. This knowledge is expected to help in the development of promising candidates for applications in quantum information, quantum metrology, thermoelectric refrigeration, and thermoelectric power production.

4.6.1 Heat flow and quantum thermodynamics

Strong links to "Out of equilibrium phenomena"



Heat flow in a simple driven quantum system. What are the thermodynamics of this system?

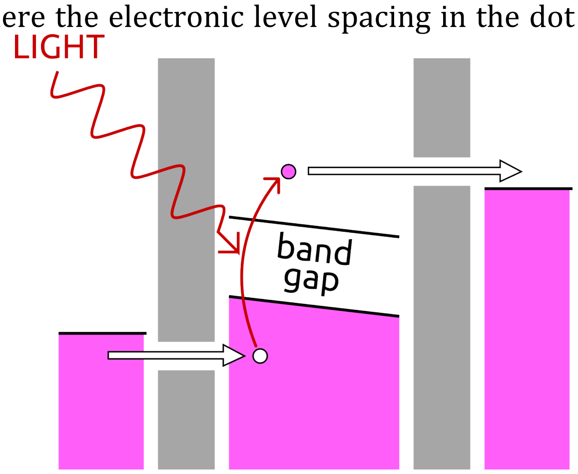
An outstanding challenge of quantum physics is to describing the thermodynamics of quantum systems coupled to reservoirs of heat or particles. Pioneering work by Feynman and Vernon and by Caldeira and Leggett, started to clarify the dynamics of a quantum system far from equilibrium with the heat bath to which it is coupled. Keldysh transport theory is dedicated to understanding quantum systems far from equilibrium with the particle reservoirs to which they are coupled. Despite this, relatively little is understood about the heat flow and thermodynamics in such systems. Quantum systems can manifest counterintuitive heat flows, with interesting fluctuation and entropy production relations. The statistics of the work and heat exchanged with the system's environment is only partially understood. For example, how does one define entropy? How much entropy is associated with entanglement? What is the form of the second law of thermodynamics for quantum systems? We will implement novel approaches to investigate the thermodynamics of strongly driven open quantum systems, relevant for applications where non-equilibrium fluctuations dominate the thermodynamic behaviour of actual devices.

We are planning to study the connection between the quantum transport approach to quantum thermodynamics (used by Whitney) and the "quantum jump" approach (used by Hekking). This requires extending the quantum jump approach to allow it to treat multiple fermionic or bosonic reservoirs out of equilibrium with each other. This will allow us to apply many results of the quantum jump method (such as fluctutation relations accounting for the violation of the second law of thermodynamics on short timescales) to quantum transport through nanostructures.
We are starting a project with Splettstoesser, Sanchez and Haupt (as part of the COST European network on "Quantum Thermodynamics"). The objective is to understand whether quantum systems can generate work non-locally, i.e. can a quantum system generate work in one region from a heat-current in another region, without an energy or particle flow between the two regions? The mechanism for such non-local power generation would be quantum entanglement, and we believe that it could occur in quantum dot thermoelectrics. We hope that the study of this effect will greatly clarify aspects of quantum thermodynamics, such as how one defines entropy in the presence of quantum entanglement.

4.6.2. Electronic and thermoelectric transport in out-of-equilibrium Coulomb-blockade

Strong links to "Out of equilibrium phenomena"

It is well known that transport through a quantum dot in the Coulomb blockade regime is sensitive to the electron distribution in the dot. This is especially important at strong voltage bias, when the distribution can significantly differ from the equilibrium one. The equilibrium regime has been thoroughly studied in the past, but the non-equilibrium physics is much less well understood. We will collaborate in their study of such systems. We will consider the physics of systems where the electronic level spacing in the dot is large enough for many-body localization to suppress electron-electron interactions. In this case, electron-electron interactions in the dot may be weak enough that the electrons do not completely relax to a quasi-equilibrium state with an effective temperature. Instead, they will be in a complicated non-equilibrium many-body state, described by complicated linear combinations of electron states. It is natural to expect that under a strong bias, this effect would result in the internal state of the dot somewhat intermediate between the non-interacting one and the fully equilibrated one. We plan to study how this affects the transport through the quantum dot.R. We will investigate thermoelectric refrigeration in micron-sized structures. Here the level-spacing is small (so the electron-electron interactions is not suppressed) and the electrons rapidly relax to a quasi-equilibrium state. However the Coulomb charging energy in such structures is of order a



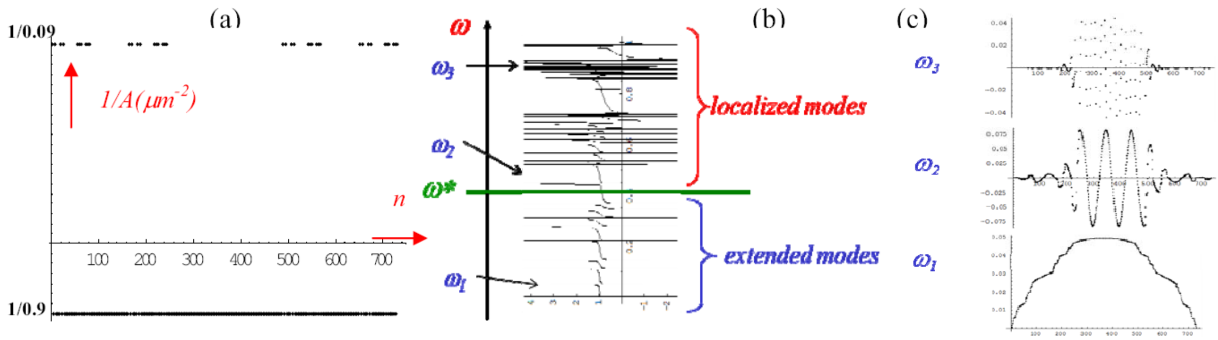
Proposed hot-electron photovoltaic, which attempts to increase photovoltaic efficiency by combining it with a thermoelectric effects.

Kelvin, so it is likely to have a huge effect on schemes to use thermoelectrics to refrigerate the electrons to sub-Kelvin temperatures. Crucially, as we showed recently, a good thermoelectric refrigerator must operate far from equilibrium (large biases are required to generate large temperature drops). Thus this study will concentrate on Coulomb blockade in this far-from-equilibrium regime.
We have started working with the experimental group of J.-F. Guillemoles (Ecole Polytechnique), and Marseille theorists F. Michelini and A. Crepieux, on a project with two related aspects; (1) a fully interacting theory of efficiency at finite power output, and (2) efficiency of so-called ``hot-electron photovoltaics''. Part one involves the theorists working together to extend R. Whitney's recent works to arbitrary interactions (rather than just mean-field interactions), by working with the Meir-Wingreen version of the Keldysh formalism for out-of-equilibrium systems. Part two involves collaboration between experimentalists and theorists to understand the efficiency of ``hot-electron photovoltaics'', these are experimental devices under development which are intended to combine photovoltaic and thermoelectric effects to achieve higher efficiencies. However there is currently no quantitative theory for such devices, making it difficult to know how they could be optimized.

4.6.3 Josephson junction-based meta-materials: engineering phonon-like modes.

Strong links to “Waves and photons in complex media”

For more than a decade now, one-dimensional chains of Josephson junctions have been used as controlled electromagnetic environments in experiments on superconducting nanocircuits. This includes their use as high-impedance environments, and more recently as superinductors. Very recently, such metamaterials have been used to observe the dynamical Casimir effect. Josephson chains behave as LC transmission lines, sustaining phonon-like propagating electromagnetic modes. Details of the chain's electromagnetic response depend on the properties of these modes. We propose to investigate the possibility to “engineer” these modes in order to realize dedicated electromagnetic environments with well-defined response at given frequencies. This can be achieved by modulating the parameters of the Josephson junctions forming the chain, see the fugure for an example of a fractal Josephson chain.



Fractally distributed Josephson chain with 729 junctions. The junction size takes two values (0.09 and 0.9 μm^2), according to a fractal pattern. (b) Mode frequencies. (c) Distribution of the phase along the chain for frequencies belonging to different parts of the spectrum. Localized modes vanish at the chain’s ends and effectively decouple, leading to reduced response at the corresponding frequencies.

4.6.4 Heat-flow due to near-field phonon and photons

Strong links to "Waves and photons in complex media"

Phonons and photons typically carry heat rather efficiently and thus have a profound effect on the thermoelectric properties of any quantum system. Such heat flows are sometimes known as Casimir effects, because they are the dissipative equivalent of Casimir forces. In the nanoscale systems proposed for sub-Kelvin refrigeration, their behaviour can be very different from in bulk materials, because their wavelength can be greater than the system size. As a result they are often quantized in a manner very similar to the electrons in quantum dots.
Thus we propose studying such problems, using similar techniques to those currently being applied to electrons; circuit theory, nonlinear scattering theory and nonlinear Green's function techniques. According to the theory of black-body radiation, a net heat flow exists between two bodies kept at a temperature difference ΔT. This flow behaves as $T^3\Delta T$, where T is the average temperature of the bodies. This mechanism is also at work in nanoscale electrical circuits: two resistive elements kept at different temperatures exchange heat with a heat flow behaving as $T\ \Delta T$. This channel might well dominate the phonon channel for heat transfer. These results are based on a treatment of far-field photons: propagating solutions of Maxwell's equations. Since the pioneering work of Polder and Van Hove in the early seventies the relevance of near-field photons has been well-known: decaying solutions of Maxwell's equations close to the radiating body's surface. If two bodies are placed at a distance within the decay length, an additional channel for heat transfers might open up that should be taken into account. We intend to generalize earlier work on photon heat transfer in nanocircuits and include the near-field channel. This might be relevant for applications, such as the heat transfer between the different parts of a microcooler.

4.7 Quantum systems under strong magnetic fields

Contributors: D. Basko, T. Champel, N. Rougerie

The theme of quantum systems under strong magnetic fields is at the heart of an ensemble of important theoretical and experimental challenges. Although the keen interest in these systems has started long time ago, their study remains a major research field which is still supported by the constant report of new phenomena and/or new systems. We therefore plan to continue our efforts in this very active theme, with a special focus on the following issues:

4.7.1 Spin-orbital effects

Two-dimensional electron gases based on semiconducting heterostructures offer the possibility to manipulate the electronic spin degree of freedom through the Rashba spin-orbit coupling which can be controlled by the application of the application of an electric field in the transverse direction of the gas. This property has generated a considerable research activity due to the possible applications in the field of spintronics. We shall address the spin transport properties specifically in the quantum Hall regime, which constitutes one of the preferred playgrounds for the fundamental study of the charge and spin couplings, since the effect of disorder can be well captured semiclassically. In particular, we plan to pay attention to the mechanisms governing the spin relaxation/dephasing at high magnetic fields.

4.7.2 Microwave-induced quantum oscillations

Our expertise in electronic (percolative) magnetotransport in a smooth disordered potential will be used to shed light on the nonequilibrium dynamical response of ultra-high mobility two-dimensional electron gases subject to microwave irradiation. We project to generalize our coherent states Green's function theory, well suited for dealing microscopically with smooth potentials, by taking into account the periodical time dependence imposed by the microwave field. Our aim is to highlight the relevant microscopic mechanism responsible for the microwave-induced resistance oscillations and the zero-resistance states, whose physical origin still remains unclear one decade after their discovery.

4.7.3 Magneto-optical spectroscopy of novel materials

We plan to study carrier dynamics and relaxation processes in a strong magnetic field. This work is motivated by a potential application – a tunable laser, based on transitions between Landau levels, which would operate in far-infrared or terahertz spectral range. Indeed, to achieve population inversion, (i) the relaxation of optically excited electrons and holes towards low Landau levels should be efficient, and (ii) the non-radiative relaxation of population between these low Landau levels should be inefficient. The contradictory nature of these requirements has made the construction of Landau-level lasers based on conventional semiconductors a challenging task. Graphene and topological insulators, due to their strongly non-parabolic electronic dispersion, which results in strongly uneven spacing of Landau levels, bring a new hope to overcome this contradiction. To check theoretically whether this hope can be realized, we will calculate the rates of various relaxation processes due to electron-phonon and electron-electron interactions. These rates will be plugged in the kinetic equation, from which the populations of Landau levels will be found. This theoretical work will be complemented by experiments at the LNCMI Grenoble.

4.7.4 Strong interaction effects

An ambitious objective is to build a microscopic non-perturbative theory which can enclose both the smooth disorder aspects and the strong interaction effects in the fractional quantum Hall regime. Up to now the studies on these interaction effects have been undertaken either in the framework of trial many-body wave functions with heavy numerical computations or in the framework of the Chern-Simons field theory which relies on the phenomenological introduction of the composite fermions concept. Disorder effects are completely disregarded in these approaches although they are crucial for the explanation of the formation of fractional plateaus of the Hall conductance. Our original approach is to highlight a specific basis of two-body (entangled) coherent states, which are characterized by topological properties that make them robust against any smooth (ony-body and two-body) perturbations, in a way similar to the original construction of the coherent states Green's function formalism introduced by our group in the past years for the microscopic description of the integer quantum Hall effect.

Another line of research is to put on a more rigorous basis the expected incompressibility properties of states built on the Laughlin wave function. Indeed, much of the success of Laughlin's approach is its robustness with respect to trapping and/or disorder potentials, crucial to experiments in 2D electron gases. However, this robustness is an experimental fact whose theoretical basis is still unclear. We would like to make progress in this direction, in particular by studying a novel class of variational problems introduced in a joint work with Jakob Yngvason. The main theoretical evidence for the occurrence of the Laughlin state is that it is the ground state of some model repulsive interaction operators. We propose to study the minimization of some simple energy functionals including the effect of trapping, disorder and/or residual interaction within the class of ground states to those model interaction operators. The goal is here to get some information about the possible deformations (or absence thereof) of the Laughlin wave function due to these effects, neglected in the usual theory of the fractional quantum Hall effect.

D. FUTURE STRATEGY

We start the presentation of LPMMC's future strategy by a brief outlook on the computational infrastructure. We conclude by a more general perspective, based on a recently performed SWOT analysis of LPMMC's strengths and weaknesses, opportunities and threats.

4.8 Service informatique

Contributors: F. Berthoud and J.-D. Dubois

En complément à sa mission de base de maintien et développement du système d'information du LPMMC, tout en poursuivant le développement d'actions/missions d'intérêt général et transverses à la demande de certaines directions du CNRS, le service informatique du LPMMC va focaliser ses activités autour de deux axes principaux :

1 – Au niveau local (Grenoble), le développement, l'appui et le support au calcul numérique pour les membres du laboratoire, dans le cadre de leurs projets scientifiques, mais aussi pour l'ensemble de la communauté des physiciens numériciens concernés par le mésocentre CIMENT. Ce soutien va de la formation à l'assistance au portage des codes en passant par l'aide à la parallélisation et à l'optimisation / débogage le cas échéant. Cet axe inclut l'ensemble des actions relatives à la co-gestion du mésocentre CIMENT, y compris la participation au comité de pilotage, comité technique, participation aux actions d'achats/renouvellement et support technique.

2 – Au niveau national, la direction et le développement du groupement de service EcoInfo (soutenu par l'INS2I depuis 2013). Les enjeux nationaux en termes de consommation énergétique de notre informatique, face notamment à l'explosion des besoins en puissance de calcul, placent le GDS EcoInfo au cœur de la stratégie nationale. Le GDS mène depuis plusieurs années des actions d'expertise, de formation, de conseil auprès de l'ensemble de la communauté recherche. Les résultats de ces actions peuvent aujourd'hui se mesurer, y compris au niveau des spécifications techniques des équipements achetés au sein du marché national. Ces actions doivent être intensifiées et portées par l'organisme au plus haut niveau. L'implication de notre service informatique dans ce projet devrait s'intensifier au cours des prochaines années, notamment au travers de la fonction de direction du GDS et du développement d'actions autour des questions énergétique et des déchets électroniques.

4.9 LPMMC towards horizon 2020: a SWOT-based analysis

The general philosophy behind LPMMC's research proposal as outlined above is straightforward: to continue those research activities where LPMMC has been most successful during the period 2009-2014, at the same time focusing on those challenges in condensed matter physics that currently are among the most outstanding. The general consensus at LPMMC is that the laboratory is scientifically doing well, and not currently facing major problems. There is therefore no need for radical changes on the management or scientific level in the near future.

Nevertheless, evaluation procedures such as the one carried out by AERES are a good occasion to perform a critical self-evaluation. During the *journées hors murs* earlier this year, all members of LPMMC have participated in a SWOT analysis of the laboratory, of its functioning in general as well as of its various activities. SWOT stands for the structure's internal Strengths & Weaknesses as well as its external Opportunities and Threats. The main results of this analysis are summarized in the SWOT table below.

SWOT	Positive	Negative
Internal	*Strengths:* • Scientific excellence • Broad spectrum of research topics • Excellent administration and computational infrastructure • Small size: good atmosphere, fast decisions, flexibility • Relatively young staff: many are active in research networks, various responsibilities and activities • International character	*Weaknesses:* • In order to keep good atmosphere: absence of scientific policy • Dispersion of topics • No internal laboratory seminar • Not enough suitable office space • Separation between scientific staff, technical staff and PhD-students and post-docs • Ratio UJF/CNRS staff too small
External	*Opportunities:* • Top-level international collaborations & visibility • Localisation on CNRS campus • LPMMC members active in various local committees, LPMMC's *rôle fédérateur* • Grenoble computational infrastructure • Presence of strong experimental groups • Current creation of M2R theory curriculum	*Threats:* • Difficulty in attracting excellent students/postdocs • Increasing funding & hiring uncertainties • Difficulty in finding appropriate office space • Small size: Necessity to merge • Small size: Lack of national visibility • Sharpening of administrative rules, loss of financial flexibility

Most items on the positive side (Strengths & Opportunities) speak for themselves. Today, LPMMC constitutes a relatively young, dynamic and international research team, active in local, national and international networks and successfully working on a broad range of relevant research topics in condensed matter physics. Its relatively small size enables an efficient and flexible management scheme without much formalities. As a result LPMMC easily responds to the (frequent) changes in the local scientific-political landscape. The active participation of LPMMC's members in local, national and international research structures and networks creates many opportunities for collaborations, organization of scientific events, and acquiring funding. An important point is the active participation of members of LPMMC in the current preparation of the new Physics Master Research Program that will lead to the creation of a Theory curriculum on the Master level.

On the other hand, several Weaknesses & Threats have been identified that LPMMC members feel might have a negative impact on future evolution. Since a relatively small number of staff works on a broad variety of topics, regular scientific communication is essential between staff members and between staff and PhD-students and postdocs. The lack of a regular laboratory seminar is an obstacle that will be removed.

Another obstacle to internal communication is the actual housing condition of LPMMC. The laboratory currently occupies five disconnected parts of *Maison des Magistères.* The configuration of these parts has led to a physical separation of permanent scientific staff, administrative staff, and PhD-students and postdocs. An internal re-distribution of office space can only solve this problem partially. A longer-term solution requires either thoroughly re-structuring *Maison des Magistères* or finding adequate space elsewhere. Whenever opportunities for correct office space appear, LPMMC participates in the discussions and presents a project. Unfortunately, so far none of the options became concrete. LPMMC currently waits for the results of negotiations between CNRS and UJF concerning the *Maison des Magistères.* UJF would like to withdraw the teaching activities from the building and then transfer the building to CNRS. This would offer LPMMC the possibility to increase its office space, provided the building undergoes some restructuring.

Although LPMMC has been relatively successful during the past years on the level of acquiring funding, the general feeling is that the situation is getting more difficult. The percentage of rejected research proposals is increasing, notably on the national level (ANR) and on the European level. Another negative feature is the strong tendency to favoring big, prestigious, high-risk individual research projects. This is definitely interesting in an experimental context; funding for theory however can be much smaller scale, and on the level of a small laboratory as LPMMC with strong internal collaboration should be collective, rather than individually oriented. Finally, a drawback of current funding programs is the strong emphasis on applied research. For a theory laboratory it is hard to argue *directly* in favor of its research activities from an application point of view. Yet, as argued in Section 1, what gives the breadth to condensed matter physics and is responsible for its success is the continuous interplay and exchange between theory, experiment and application.

As to hiring scientific staff, LPMMC has been quite successful at the level of CNRS over the years. We deeply regret that UJF has not been able to grant LPMMC a teaching position. The result is a strong disequilibrium between CNRS and UJF scientific staff. Currently, only three members of LPMMC are regularly teaching in UJF's Physics curriculum. This has a negative impact on the visibility of LPMMC with respect to prospective UJF Master and PhD-students, and adds to the difficulty the laboratory has to maintain a high-level population of PhD-students. More generally, LPMMC is worried about the limited possibilities for young, talented theoreticians to find a permanent job in academia, all the more so as there currently is a big number of highly talented potential candidates available.

Several of the abovementioned Threats & Weaknesses can be faced by using the various Opportunities available. Given LPMMC's international visibility and tradition of collaboration, funding can be assured by joining international research networks and through collaboration with experimental groups. International contacts also make it possible to attract outstanding candidates for permanent positions, as well as for postdoctoral positions and PhD-Fellowships. The newly proposed Grenoble theory curriculum is another opportunity to increase the visibility of the Grenoble theory efforts and attract students.

Being a small laboratory, LPMMC is relatively sensitive to Threats and Weaknesses, especially to fluctuations on the funding and hiring level. On a national political level, LPMMC's visibility is limited. This, together with the consensus-based management strategy currently implemented at LPMMC makes it difficult to develop a well-defined, long-term scientific policy. At the same time, there is a clear political tendency to form larger and larger research facilities and laboratories, not only to face visibility issues but also to face management issues: administrational procedures become more and more

involved, human and financial resources more and more limited. The question as to the long-term viability of small structures such as LPMMC may become more and more relevant.
It is our strong conviction that small structures such as LPMMC are favorable to efficient, high-level research in theoretical physics at a relatively low cost. Since its creation, LPMMC has continuously provided substantial, high-level scientific output, with substantial local, national and international impact. It has successfully responded to the appearance of new challenges in the general area of condensed matter physics. It has played a significant role during the creation and operation of local computational platforms and federative research structures. Provided a relatively moderate amount of funding and hiring opportunities remain available, LPMMC will continue to do so in the near future.

ANNEXES

Annexe 1 : Présentation synthétique (*Executive Summary*)

On utilisera la "Présentation synthétique de l'entité – Unité de recherche" fournie avec les différents fichiers du dossier d'évaluation.

Ce document doit être rédigé en français (présentation synthétique) et en anglais (executive summary).

Annexe 2 : Lettre de mission contractuelle

Une copie de la lettre de mission adressée au directeur d'unité de recherche en début de contrat, si elle existe, sera jointe au dossier.

Annexe 3 : Équipements, plateformes

Une liste des équipements, des plateformes utilisés par l'unité de recherche sera jointe au dossier.

Annexe 4 : Organigramme fonctionnel

Une présentation schématique du mode d'organisation de l'unité de recherche sera jointe au dossier.

Annexe 5 : Règlement intérieur

S'il y a lieu, une copie du règlement intérieur de l'unité de recherche sera jointe au dossier.

Annexe 6 : Liste des réalisations et produits de la recherche

Cette liste sera répartie selon les trois rubriques indiquées dans le dossier : 1) la production scientifique ; 2) les indices de rayonnement et d'attractivité académiques ; 3) les produits destinés à des acteurs du monde social, économique et culturel.

On classera les réalisations selon la subdivision en équipes internes ou en thèmes, si l'unité de recherche est organisée de cette manière. Les produits communs à plusieurs équipes internes seront regroupés dans une rubrique spécifique.

Dans le cas de publications cosignées par plusieurs personnes, les noms des membres de l'unité de recherche, de l'équipe interne ou du thème seront soulignés dans la liste des co-auteurs.

Pour les personnels recrutés au cours des cinq dernières années, les produits réalisés dans leur unité de recherche d'origine seront mentionnés dans une liste séparée.

Annexe 7 : Liste des contrats

- contrats institutionnels sur financement public (par équipe ou par thème) ;
- brevets, contrats industriels, contrats sur financement privé… (par équipe ou par thème).

Annexe 8 : Document unique d'évaluation des risques - DUER (lorsqu'il existe)

Annexe 9 : Liste des personnels

Liste des personnels (chercheurs, enseignants-chercheurs et assimilés) de l'unité présents au 30 juin 2014 et qui le seront toujours au 1er janvier 2016.

Cette liste doit comprendre les noms, prénoms et ***signatures*** des personnels concernés.

On pourra utiliser la liste des personnels du fichier « Données du prochain contrat ».