Polariton quantum fluids of light in semiconductor lattices

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Many fascinating macroscopic physical properties emerge in condensed matter physics from ensembles of quantum particles: superfluidity, superconductivity, integer and fractional quantum Hall effects are a few examples. In absence of inter particle interactions, the lattice geometry and topology can profoundly modify transport and localization of quantum particles. For weak interactions, collective phenomena such as superfluidity or nucleation of quantized vortices emerge, while complex quantum correlations arise for strongly interacting particles.

The question we will discuss in this lecture is whether it is possible to simulate some of these condensed matter phenomena using a photonic system. In other word, can we reproduce with light some of these physical properties. A well controlled photonic platform would allow detailed investigations of these physical phenomena with full control of the parameters, the creation of new geometries which are unaccessible in nature and also permit the development of novel integrated photonic devices. On a longer term perspective, such photonic quantum simulation schemes will enable experimentally solving many body problems, which are impossible to calculate with a classical computer.

A large variety of photonic systems are currently envisioned for quantum simulation, such as coupled waveguides, ring resonators, microwave resonators or photonic crystals.

In this talk, we will describe recent advances in the use of semiconductor microcavities as a simulator platform. The confinement of both light and electronic excitations (excitons) within the cavity, enables reaching the so-called strong light matter coupling regime. The resulting mixed light-matter eigenstates, named cavity polaritons, behave as quantum fluids of light and can be manipulated in lattices.

- In the first part of the lecture, a detailed introduction to cavity polaritons will be provided. Particular emphasis will be given to experimental methods to generate polaritons and probe their quantum states. The physical properties resulting from their mixed light matter nature will be emphasized. We will also discuss how we can engineer the polariton band structure by designing lattices.

- The second part of the talk will be dedicated to polariton non-linearity in a regime where quantum correlations are negligible (mean-field approximation). Polariton quantum fluids show superfluid behavior, nucleation of quantized vortices and bistability. Some experiments which are now textbook references will be reviewed.

- The last part of the talk will be dedicated to the simulation of different systems using light : a benzene molecule with spin orbit coupling, a poly-acetilene chain with topological edge states or a graphene layer with Dirac cones. These examples illustrate not only the interest of such artificial lattices to unravel new physics but also for the design of interesting photonic devices.

We will conclude by addressing some methods which are currently explored to increase polariton interactions and reach a strong interaction regime with quantum correlations.

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Lecture I:
An introduction to Circuit QED: Quantum Optics with microwaves.
Lecture II:
Oscillators for Quantum Information: Bosonic quantum Error Correction

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Qubit Parity Measurement by Parametric Driving in Circuit QED

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Multi-qubit parity measurements are essential to quantum error correction. Current realizations of these measurements often rely on ancilla qubits, a method that is sensitive to faulty two-qubit gates and which requires significant experimental overhead. We propose a hardware-efficient multi-qubit parity measurement exploiting the bifurcation dynamics of a parametrically driven nonlinear oscillator. This approach takes advantage of the resonator's parametric oscillation threshold which depends on the joint parity of dispersively coupled qubits, leading to high-amplitude oscillations for one parity subspace and no oscillation for the other. We present analytical and numerical results for two- and four-qubit parity measurements with high-fidelity readout preserving the parity eigenpaces. Moreover, we discuss a possible realization which can be readily implemented with the current circuit QED experimental toolbox. These results could lead to significant simplifications in the experimental implementation of quantum error correction, and notably of the surface code.

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Quantum fluids of microwave photons in one-dimensional Josephson junction chains

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We will describe analog simulations of several models of strongly-interacting photons in one dimension. In one dimension, fermions and bosons is the same thing, and so these models are important because the cover a broad range of phenomena such as Kondo efect and superconductor-insulator transition. Our experimental system consists of a superconducting "telegraph" transmission line formed by two coupled chains of Josephson junctions. The photons in such a waveguide are similar to plain waves in vacuum but with a substantially lower velocity and higher wave impedance due to the large kinetic inductance of the junctions. The interactions originate from the Josephson non-linearity. In case of a high wave impedance, the non-linearity cannot be reduced to the simple Kerr effect, because of large quanum fluctuation of the phase difference across each junction. Furthermore, by making one of the junctions substantially different from the rest of the chain, we introduce a quantum impurity, which can disturb a large number of propagating photonic modes. In our experiment we can measure the spectrum of these photons, as well as their elastic and inelastic scattering as a function of frequency and impurity parameters. Such measurements provide an equilibrium probe of many-body dynamics of one-dimensional photonic systems and can give access to regimes both inaccessible in previous experiments and challenging for numerical simulations. We will describe results on three specific modes. (i) A strong multi-mode coupling circuit quantum electrodynamics using a large junction impurity as a transmon qubit. (ii) The quantum sin-Gordon model, describing a Bose glass transition in one dimensional superconductors. This is achieved using homogeneous chains with relatively weak junctions. (iii) The boundary sin-Gordon model, where only a single junction is weak – this model also describes back-scattering of interacting electrons in a one-dimensional quantum wire.

Equilibrium and out of equilibrium polariton superfluids

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Quantum fluids of exciton-polaritons have the peculiarity of showing very interesting coherent properties as well as possessing a spin dependent particle-particle interaction. Here we show phenomena of polariton condensates in different systems in which the polariton is formed by coupling optical, plasmonic and surface modes with inorganic, organic and hybrid 2D semiconductors. In particular we discuss the different response of a quantum fluid at equilibrium, in very long living polariton states [1, 2], and when strongly out of equilibrium [3]. Interestingly in both cases superfluidity is observed together with many correlated effects.

Thanks to the easy manipulation of the polariton state (density, phase, polarisation, etc.), in case of equilibrium fluids a wide range of dynamical responses of the condensate are shown when the phase is externally twisted, spanning from the formation of a long phase-slip line to the nucleation of Josephson vortices within the barrier, until the recovering of the superfluid behavior at high densities.

Curiously even in the worst case of out of equilibirum and very short polariton lifetime, superfluidity can still be observed by acting on the density of the condensate to increase its interaction.

Finally the value of the interaction constant of different polariton systems will be discussed. In particular in 2D nanostructured materials we have found very high inter-particle interactions that may lead to new perspective devices operating at room temperature [4].

Acknowledgements: the work presented in this invited talk has been done in collaboration with D. Caputo, G. Lerario, A. Gianfrate, A. Fieramosca, D. Suarez, L. De Marco, L. Polimeni, M. De Giorgi, L. Dominici and D. Ballarini.

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Spectral signatures of many-body localization with interacting photons

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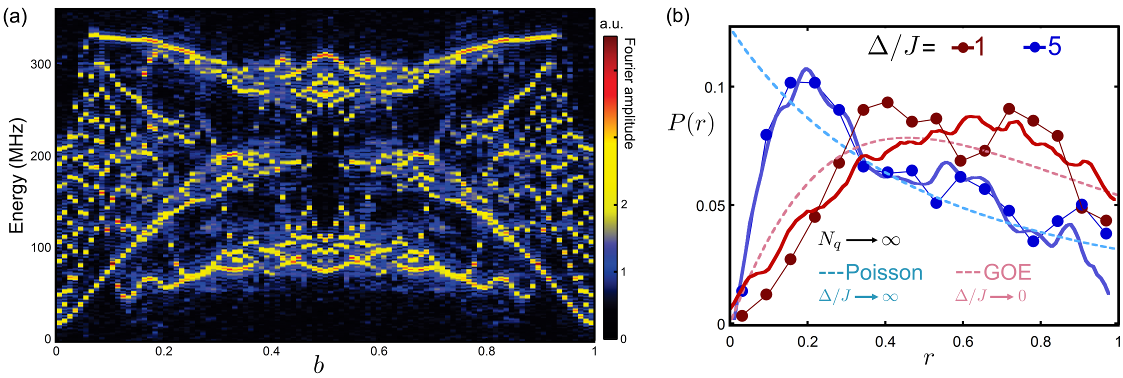
Statistical mechanics is founded on the assumption that a system can reach thermal equilibrium, regardless of the starting state. Interactions between particles facilitate thermalization, but, can interacting systems always equilibrate regardless of parameter values? The energy spectrum of a system can answer this question and reveal the nature of the underlying phases. However, most experimental techniques only indirectly probe the many-body energy spectrum. Using a chain of nine superconducting qubits, we implement a novel technique for directly resolving the energy levels of interacting photons. We benchmark this method by capturing the intricate energy spectrum predicted for 2D electrons in a magnetic field, the Hofstadter butterfly. By increasing disorder, the spatial extent of energy eigenstates at the edge of the energy band shrink, suggesting the formation of a mobility edge. At strong disorder, the energy levels cease to repel one another and their statistics approaches a Poisson distribution - the hallmark of transition from the thermalized to the many-body localized phase. Our work introduces a new many-body spectroscopy technique to study quantum phases of matter.
Acknowledgements: the work presented in this invited talk has been done in collaboration between Google and the Center for Quantum Technologies at the National University of Singapore.



(a) Experimental realization of Hofstadter butterfly with a chain of 9 superconducting qubits. We simulate the problem of Bloch electrons on a 2D lattice subject to a perpendicularly applied magnetic field. We directly measure the energy spectrum of the system which resembles a butterfly.(b) The distribution of the energy levels in an interacting system. When there are two photons in the system, for small disorder, the measured histogram of levels shows GOE distributions, which is predicted when the energy eigenstate repel each other. For large disorder, the histogram tends toward a Poisson distribution, which is the signatory of transition to the many-body localized phase.

Lattices of Spin-polarised Interacting Polariton Condensates: A novel quantum simulator platform

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While ultracold atoms have been very successful in probing closed equilibrium condensed matter phenomena, open non-equilibrium quantum systems have attracted a strong and growing interest recently because of their rich dynamics and nontrivial steady states. Exciton-polaritons have emerged as a prime candidate for the non-equilibrium system of interacting bosons. Polaritons are mixed light-matter bosons resulting from the strong coupling of photons in a microcavity and excitons in a quantum well which can condense into macroscopically coherent many-body states. As a prime example of the non-equilibrium nature of polariton condensates, we have shown recently that polariton condensates can spontaneously magnetize [1], and we can control their spin optically and electronically [2]. Interestingly, the coupling of the spin of two coupled condensates can be also controllably aligned (or anti-aligned) [3]. Hence, a lattice of polariton condensates is expected to model a non-equilibrium interacting spin system with unusual properties [4].

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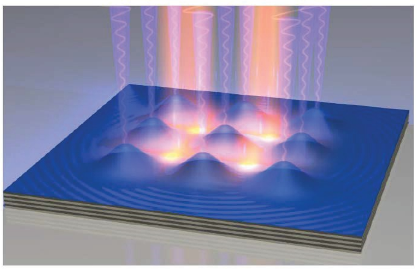

Figure 1: Optically controlled magnetized polariton lattices.

Topological photonics and quantum Hall effects with light

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Topological photonics is a rapidly-emerging field of research in which geometrical and topological ideas are exploited to design and control the behavior of light. Drawing inspiration from the discovery of the quantum Hall effects and topological insulators in condensed matter, recent advances have shown how to engineer analogous effects also for photons, leading to remarkable phenomena such as the robust unidirectional propagation of light, which hold great promise for applications. Thanks to the flexibility and diversity of photonics systems, this field is also opening up new opportunities to realise exotic topological models and to probe and exploit topological effects in new ways.

In this lectures, I will review experimental and theoretical developments in topological photonics across a wide-range of experimental platforms, including photonic crystals, arrays of cavities in silicon photonics and circuit-QED, and twisted optical resonators. After a brief introduction to the general geometrical and topological concepts that have been developed in the study of solid-state electronic systems, I will give a general overview of the specific features that characterize photonic systems in contrast to electronic topological insulators. A special attention will be paid to light propagation in topologically protected edge states which has provided the first smoking gun of topological photonics effects. The physical meaning of the Berry curvature of a band will also be highlighted in connection to recent experimental observation of an anomalous Hall effect with light. I will conclude with a discussion of the most exciting perspectives in the direction of fractional quantum Hall fluids of light when the non-trivial topology is associated to strong optical nonlinearities. The latest advances in the generation and detection of such strongly correlated states of light will be presented, as well as their promise in view of quantum technological applications.

All the material of these lectures (and much more) can be found in the recent review articles on *Quantum Fluids of Light* [1] and on *Topological Photonics* [2], as well as on my personal webpage [3].

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[3] `http://www.science.unitn.it/~carusott`

Few and many-body physics of slow-light and Rydberg polaritons

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Hybridizing light and matter allows to create quasi-particles with tunable properties and strong interactions between photons. I will give an introduction to an important class of such quasi-particles, slow-light polaritons. They emerge when photons are resonantly coupled to an atomic transition in a two-photon process by a coherent control laser. When the atomic transition has a small intrinsic two-photon linewidth, absorption losses are highly suppressed due to the formation of light-matter dark states. Properties of these slow-light or dark-state polaritons [1] such as group velocity, transverse- and longitudinal effective mass and spatial profile can be tuned by the control field. This makes them ideal for applications in quantum information e.g. for storage of photonic qubits. One can create effective scalar or gauge potentials for slow-light polaritons. Finally spin-degrees of freedom emerge when multi-component probe fields of different polarization or color are coupled in parallel to different two-photon transitions.

While interactions between photons are typically very weak, they can be made large for slow-light polaritons due to their matter component. For example, if the final state of the two-photon transition is a Rydberg state, the polaritons inherit the strong and nonlocal dipole-dipole interaction between atoms excited to Rydberg states. I will introduce Rydberg polaritons and discuss their two-body physics in the two different regimes of dissipative and dispersive coupling. The latter correspond to either a resonant or an off-resonant coupling to the intermediate state. In the dissipative case, the low-energy physics of Rydberg polaritons is equivalent to a hard-sphere gas, while in the dispersive regime two- and multi-particle bound states exist.

The long-range and non-trivial interaction potential between Rydberg polaritons gives rise to rich and interesting many-body effects. I will give a (non-exhaustive) overview of these. E.g., the hard-sphere character of Rydberg polaritons in the low-energy regime allows to create crystalline structures of slow or stored photons and may give rise to a super-solid behavior. The flat-top character of the effective interaction potential can lead to unconventional Luttinger-liquids in one spatial dimension and exotic fractional quantum Hall states in two dimensional systems in the presence of an effective homogeneous magnetic field.

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Quantum aspects of topological photonics

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The application of topology in optics has led to a new paradigm in developing photonic devices with robust properties against disorder. Although significant progress on topological phenomena has been achieved in the classical domain, the quantum regime has remains largely unexplored. In this talk, I discuss in recent developments in the quantum regime:

First, we demonstrate a strong interface between single quantum emitters and topological photonic states [1]. Our approach creates robust counter-propagating edge states at the boundary of two distinct topological photonic crystals [2]. We demonstrate the chiral emission of a quantum emitter into these modes and establish their robustness against sharp bends. This approach may enable the development of quantum optics devices with built-in protection, with potential applications in quantum simulation and sensing.

Second, spontaneous parametric processes such as down-conversion (SPDC) and four-wave mixing (SFWM) have long been the common sources of quantum light, for instance, correlated photon pairs and heralded single photon. These spontaneous processes are mediated by vacuum fluctuations of the electromagnetic field. Therefore, by manipulating the electromagnetic mode structure, for example, using nanophotonic systems, one can engineer the spectrum of generated photons. However, such manipulations are susceptible to fabrication disorders which are ubiquitously present in nanophotonic systems. We demonstrate a topological source of correlated photon pairs where the spectrum of generated photons is robust against fabrication disorder [3].

In the end, I discuss how light can take a different role as a probing and manipulating tool for *electronic* topological states [4, 5].

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Physics simulations in photon superfluids and gases.

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Photon fluids are nonlinear optical systems in which small perturbations in the transverse plane of a beam propagating in a nonlinear defocusing medium are described by the hydrodynamical Euler equations [1–3]. These equations contain an additional term due to diffraction and that is completely analogous to the quantum pressure term that arises in the same equations describing a two-dimensional Bose-Einstein-Condensate (BEC). Photon fluids therefore form part of the larger family of so-called "quantum fluids of light", that also include polariton fluids and recent experiments on photon condensation [4].

The photon fluid density, which defines the speed of linear excitations (referred to as "sound" waves, in analogy to their BEC counterpart) is determined by the laser intensity while the overall flow is controlled via the gradient of the spatial phase profile. This last aspect makes these systems extremely versatile as the spatial profile of a laser beam can be readily manipulated in amplitude and phase, thus enabling recent studies investigating for example superfluidity and vortex instabilities [5] and proposals for the study of curved spacetime physics [6, 7]

Recently, these studies have led to the experimental realization of a 2+1D vortex flow with the identification of both a horizon and ergosphere [8]. These experiments follow recent work using draining water tanks showed that waves entering a hydrodynamic vortex may be scattered and amplified [9], effectively extracting rotational energy. This effect is related to a particle scattering effect first predicted by Penrose in 1969 [10] referred to as the Penrose process. A remarkably similar phenomenon, the Zel'dovich effect, appears in the context of electromagnetic waves incident on rotating conducting or absorbing cylinders [11].

Generalising, when the photon-photon interactions are attractive one may still refer to a photon gas. Although this will in general be unstable to perturbations and speed of sound can no longer be identified, these interacting gases may be used for a wide range of studies and are particularly relevant for quantum simulations of effects such as the dynamical Casimir effect (spontaneous production of photon pairs from a periodically varying boundary condition), the Schrödinger-Newton Equation [12] (first introduced by Penrose to describe the interaction between a quantum wave-function and Newtonian gravity) and photon pair creation from expanding spacetimes [13].

Acknowledgements: the work presented in this invited talk has been done in collaboration with A. Prain, F. Marino, I. Carusotto, E. Wright, D. Vocke, C. Maitland, S. Vezzoli, K. Wilson, P. Ohberg.

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Calorimetry of a Bose-Einstein-condensed photon gas

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Bose-Einstein condensation has been observed with cold atomic gases, quasiparticles in solid state systems as polaritons, and more recently also with photons in a dye-filled microcavity. I will here report on recent measurements of our Bonn group determining the heat capacity of the two-dimensional photon gas in the dye-filled microcavity system. Thermalization of photons is achieved in a number-conserving way by repeated absorption re-emission cycles on the dye molecules, and the cavity mirrors provide both an effective photon mass and a confining potential. For the here reported measurements, we first determine the internal energy of the trapped photon gas by analyzing spectra of the microcavity emission at different ratios of photon number and critical photon number, from which after differentiation the heat capacity can be derived. At the Bose-Einstein phase transition, the determined heat capacity of the optical quantum gas shows a cusp-like singularity, similar as in the -transition of liquid helium, illustrating critical behaviour. From the optical spectra also the entropy per photon of the trapped photon gas could be determined. In more recent work, we have realized lattice potentials for the photon gas, and observed both tunneling and effective photon interactions in a double-well system.

Experimental many-body physics using arrays of individual atoms

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This talk will present our on-going effort to control the dipole-dipole interaction between cold Rydberg atoms in order to implement spin Hamiltonians that may be useful for quantum simulation of condensed matter problems. In our experiment, we trap individual atoms in two-dimensional arrays of optical tweezers [1] separated by few micrometers and excite them to Rydberg states using lasers. The arrays are produced by a spatial light modulator, which shapes the dipole trap beam. We can create almost arbitrary, two-dimensional geometries of the arrays with near unit filling [2].

The talk will present our demonstration of the coherent energy exchange in small chains of Rydberg atoms resulting from their dipole-dipole interaction [3]. This exchange can be controlled by addressable lasers [4]. This interaction realizes the XY spin model. We have also implemented the quantum Ising model [5]. The spin Hamiltonian is mapped onto a system of Rydberg atoms excited by lasers and interacting by the van der Waals Rydberg interaction. We study various configurations such as one-dimensional chains of atoms with periodic boundary conditions, rings, or two-dimensional arrays containing up to about 50 atoms. We measure the dynamics of the excitation for various strengths of the interactions between atoms. We compare the data with numerical simulations of this many-body system and found excellent agreement.

This good control of an ensemble of interacting Rydberg atoms thus demonstrates a new promising platform for quantum simulation using neutral atoms, which is complementary to the other platforms based on ions, magnetic atoms or dipolar molecules.

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Photon Mott Insulator, etc...

Jonathan Simon[1]
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I will highlight progress on two fronts: building strongly-correlated lattice materials out of microwave photons and strongly-correlated bulk materials out of optical photons. We (in collaboration with the Schuster Lab) have dissipatively stabilized a Mott insulator of microwave photons implemented in a lattice of capacitively coupled transmon qubits. I will describe the state-of-the-experimental-art, plus challenges/opportunities arising from cross-thermalization between the dilution-refrigerator and the Mott insulator, and prospects to integrate these ideas with our recently demonstrated photon Chern insulator. In parallel, we have also observed collisions between individual optical photons in a multi-mode Fabry-Perot cavity: I will describe these results and their direct connection to upcoming experiments investigating FQH physics of cavity polaritons in twisted resonators.

Interfacing Spins with Photons for Quantum Simulation

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Coupling many atoms to a single mode of light provides an efficient means of spreading quantum information across an extended many-body system. I will report on experiments in which we harness photons in an optical cavity to mediate "flip-flop" interactions among distant spins in a millimeter-long cloud of atoms. We characterize the spin-exchange interactions via quench dynamics and imaging of the local magnetization, demonstrating optical control of the interactions' strength and sign (ferromagnetic *vs* antiferromagnetic). Furthermore, we observe signatures of correlated pair creation in the $m = \pm 1$ Zeeman states of a spin-1 system, a process analogous to spontaneous parametric down-conversion or to collisional spin mixing in Bose-Einstein condensates. In contrast to direct collisional interactions, non-local light-mediated interactions offer unprecedented opportunities for engineering the spatial structure of spin-spin couplings and correlations. I will describe prospects for tailoring the interactions to enable new directions in quantum simulation [1]—including realizing toy models of quantum gravity—and to generate new resources for quantum-enhanced sensing [2].

Acknowledgements: E. Davis, G. Bentsen, L. Homeier, and T. Li conducted the experiments presented in this invited talk. The outlook in quantum simulation draws on theory collaborations with E. Altman, A. Daley, S. Gubser, and B. Swingle.

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Non-Equilibrium Thermodynamics of Quantum Processes

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Thermodynamics is an inherently macroscopic theory that describes energy-exchange processes between a system and its environment, and the extraction of work from a driven system. Its traditional formulation requires processes that are quasi-static: at every instant of time, the system should be close to its thermodynamic equilibrium, so that macroscopic thermodynamic quantities (such as pressure, volume, and temperature) could be meaningfully defined.

Yet, the current management of microscopic systems evolving according to the theory of quantum mechanics extends up to the viability of observations of individual trajectories. This opens up the possibility to study non-equilibrium processes that are strongly affected by non-classical (i.e. non-thermal) fluctuations. Which are the implications for thermodynamics? Is it still possible to define and study thermodynamic quantities when we address non-equilibrium processes at the quantum level?

In this talk I will introduce the field of stochastic thermodynamics of quantum processes, illustrating recent theoretical developments, inspired by an information-theoretic approach, and the experimental progresses that have resulted from them. I will address both theoretical proposals (aimed, for instance, at sharpening the fundamental Landauer principle), and experimental endeavours in NMR, optomechanics, and intra-cavity ultra-cold atoms.

Electric field correlation measurements on a vacuum field state in the THz

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The electric field temporal correlations are conventionally performed using an interferometer such as a Mach-Zehnder followed by an intensity detector, as the output of the latter will yield an intensity as a function of the delay between both arms proportional to the real part of the normalized autocorrelation function $g^{(1)}(\tau)$. We have recently investigated an alternative way to infer the statistics of Terahertz fields using electro-optic sampling. In the latter, the pulse from a femtosecond laser is propagated in a non-linear crystal along with the Terahertz field to be measured. A measurement of the polarization rotation of the near-infrared laser pulse, performed using a balanced detector, yields an instantaneous measurement of the electric field [1]. Recently, we have modified this technique by co-propagating *two* femtosecond laser pulses in the same crystal with a variable delay. As a result, the measurement of the field at two variable delay times $E(t)$ and $E(t+\tau)$ can be performed and the time averages $\langle E(t)E(t+\tau)\rangle$. In a first set of measurements, classical sources such as quantum cascade laser [2] or quantum cascade laser combs [3] were investigated, and the classical correlation functions g^1 and $g^{(2)}$ evaluated. These measurements enabled to observe the increase in the second-order correlation function $g^{(2)}(0)$ as the laser was driven with a current from above to below threshold as well as give a direct indication of the temporal profile of the output of THz quantum cascade laser combs, showing that the emission has a short time structure with a quasi constant background.

In recent experiments, we have applied this technique to thermal fields, down to the limit of zero temperature. In order to achieve this, we have to immerse the experiment in a cryostat cooled at 4K in order to supress efficiently the blackbody radiation in the bandbass of the detection system, spanning roughly 200GHz to 2.5THz. The striking result is that correlations measurement yield still a result even when performed onto vacuum. In one picture, it can be understood as resulting from the successive evalutation of the field operators $\hat{a}(t) + \hat{a}^{\dagger}(t)$ at two different times, which will yield a term proportional to $\langle \hat{a}(t)\hat{a}^{\dagger}(t)\rangle$ that will yield a non-zero value even applied onto the vacuum state. Using the formal analogy between a single mode of the field and a harmonic oscillator, it is actually a well-known result that the two-time correlator of the position is non-zero even in the ground state [4]. However, in contrast to most of the measurements performed on harmonic oscillators, we are not measuring the spectral density function but directly the two-time correlator. Our measurement can be interpreted as a non-continuous weak measurement of the position of the oscillator.

We will also discuss recent measurements in which transport properties of two-dimensional electron gases were probe while the system was in the ultra-strong coupling regime.

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Polaritons for Chemistry and Materials Science

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Exciton transport plays a crucial rule in natural phenomena such as photosynthesis and in artificial devices such as organic solar cells, but is inefficient in many organic materials. We will discuss how the formation of collective polaritonic modes can dramatically enhance the efficiency of exciton transport when the molecules are strongly coupled to an electromagnetic mode [1]. This effect can be exploited to either harvest and direct excitations to specific positions by tuning the spatial distribution of the EM mode [2] or to extend the spatial range of the Forster energy transfer process [3]. We then show that in systems with a discrete EM mode spectrum, strong-coupling-enhanced exciton transport can proceed through *dark* modes that have no photonic component, but which nonetheless acquire a delocalized character in the strong-coupling regime [4].

In the second part, we discuss the influence of strong coupling on internal molecular structure and chemical reactions [5]. While most models of strong coupling are based on simple two-level models, pioneering experiments have shown modifications of chemical reaction rates under strong coupling [6]. In order to address this mismatch, we have developed a first-principles model that fully takes into account both electronic and nuclear degrees of freedom [7]. We will first discuss the applicability of the Born-Oppenheimer approximation, which is challenged by the introduction of the new intermediate timescale of energy exchange between the molecule and the field. Based on these findings, we then show how photochemical reactions such as photo-isomerization can be almost completely suppressed under strong coupling [8]. Finally, we show how polaritons can also lead to the formation of a polaritonic "supermolecule" involving the degrees of freedom of all molecules, opening a reaction path on which all involved molecules undergo a chemical transformation [9].

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