Superfluidity versus thermalisation in non-linear wave systems

Mathias Albert, INPHYNI, Nice

Superfluidity is the ability of a fluid to move without dissipation through a possibibly complex environement. It is a property shared by many different systems ruled out by non-linear wave equations such as the non linear Schrodinger equation. On the other hand, wave thermalisation may soccur due to non linear interaction between waves.

During this talk, I will discuss the competition between these different phenonema in various physical systems such as, Bose-Einstein condensates, light propagating in non linear media or quantum chaotic systems (modified one dimensional kicked rotor).

Relaxation of phonons in the Lieb-Liniger gas by dynamical refermionization

Isabelle Bouchoule, Laboratoire Charles Fabry

Motivated by recent experiments, we investigate the Lieb-Liniger gas initially prepared in an out-of-equilibrium state that is Gaussian in terms of the phonons,
namely whose density matrix is the exponential of an operator quadratic in terms of phonons creation and anihilation operators. Because the phonons are not exact eigenstates of the Hamiltonian, the gas relaxes to a stationary state at very long times whose phonon population is a priori different from the initial one. Thanks to integrability, that stationary state needs not be a thermal state.
We completely characterize the stationary state of the gas after relaxation and compute its phonon population distribution. For this purpose, we use the mapping between the exact eigenstates of the Lieb-Liniger Hamiltonian and those of a gas of non-interacting Fermions, that we dub "Bethe fermions". We show that phonons are obtained by bosonization of the Bethe-fermions and we make extensive use of the powerfull bosonization techniques.
We apply our results to the case where the initial state is an excited coherent state for a single phonon mode, and we compare them to exact results obtained in the hard-core limit.

Magnetically mediated hole pairing in fermionic ladders of ultracold atoms

Thomas Chalopin, MPQ Munich

The Fermi-Hubbard model is an iconic model of solid state physics that is believed to capture the intricate physics of strongly correlated phases of matter such as High-Tc superconductivity. Such a state of matter is supposedly achieved upon doping a cold antiferromagnetic Mott insulator. Pairing of dopants (holes), in particular, is considered to be a key mechanism for the occurrence of unconventional superconductivity.

In this talk, I will present our recent experimental observation of hole pairing due to magnetic correlations in a Fermi-Hubbard-type system with a quantum-gas microscope. We realize the Fermi-Hubbard model using ultracold fermionic lithium atoms loaded in a 2D optical lattice, and measure the spin and density distributions of the many-body state with single site resolution.

We engineer mixed-dimensional Fermi-Hubbard two-leg ladders in which a potential offset between the legs suppresses the tunneling along the rungs, while enhancing spin exchange and singlet formation, thus drastically increasing the hole binding energy. We observe in particular that holes preferably sit on the same rung in order to maintain magnetic ordering, and we extract a binding energy on the order of the spin exchange energy.

ref: S. Hirthe et al, arXiv:2203.10027

Pre-thermalization and dynamical phase transition in non-equilibrium optical fluids

Nicolas Cherroret, CNRS, LKB, Sorbonne Université

The way isolated many-body systems return to equilibrium after a quench is an important question in statistical physics. In this context, near-integrable systems play a special role due to the dynamical emergence of a long-lived pre-thermal stage preceding the onset of thermalization. During this stage, the system evolves very slowly in time and exhibits universal features making it look almost thermal. Recently, the concept of pre-thermalization has been enriched by the discovery of a novel class of critical-like phenomena where a non-equilibrium system exhibits, before thermalization takes place, qualitatively different temporal behaviors in its correlation functions (`dynamical phases') around a critical value of a quench parameter. Such 'dynamical phase transition' has not yet been observed experimentally.

In this talk, I will discuss two simple optical-fluid systems where interesting pre-thermal phenomena can be observed. The first one is a weakly fluctuating fluid of light undergoing an effective interaction quench upon entering a Kerr medium and described by the nonlinear paraxial wave equation. In this configuration, I will describe the onset of a pre-thermal regime where the fluid exhibits a transient algebraic coherence and a light-cone spreading of correlations. The second one is a fluctuating fluid of light propagating in a dispersive Kerr material. Following a well chosen temporal quench, this system may display a dynamical phase transition separating two dynamical phases, respectively characterized by an exponential relaxation and a coarsening dynamics.

Robin Corgier
LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Paris, France

"Delta-kick Squeezing enables Quantum-enhanced atom interferometry"

The possibility to overcome the standard quantum limit (SQL) by engineering specific quantum correlations between the atoms is attracting increasing interest in the field of atom interferometry. Recently, Bose-Einstein condensates (BECs) have been pinpointed as optimal candidates for the realization of entanglement-enhanced atom interferometers with spatially separated arms either in trapped [1] or free-fall [2] configurations. However, either due to the presence of residual interactions during the interferometer sequence or due to the fast expansion of the BEC during the state preparation, only a modest sub-SQL sensitivity gain is predicted.
To overcome these problems, we recently proposed a novel method we refer to as Delta-Kick Squeezing (DKS) [3]. This method involves the rapid action of an external trap focusing the matter-waves to significantly increase the atomic densities during a preparation stage. This method is explored in the two relevant cases of Raman or Bragg scattering light pulses. In the second case, we demonstrated the possibility to implement a non-linear readout scheme making the sub-SQL sensitivity highly robust against imperfect atom counting detection [4,5]. We predict more than 30 dB of sensitivity gain beyond the SQL, assuming realistic parameters and millions of atoms in the BEC.

In this colloquium, the main differences between Raman and Bragg interferometry sequences will be introduced as well as their respective impact in the generation of squeezing through the "One-axis twisting dynamiques". The advantages of the Delta-kick Squeezing method will then be discussed.

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Progress on a superradiant laser for time-and-frequency metrology
Marion Delehaye, Femto-ST Institute

Over the last years, superradiant lasers have emerged as a potentially powerful alternative to traditional optical atomic clocks. They are based on superradiance, a quantum phenomenon that leads an ensemble of atomic dipoles coupled to a single mode of the electromagnetic field to spontaneously emit collectively, producing a number of photons large enough for applications. The frequency of the emitted light can be very insensitive to external parameters, thus realizing an ultra-stable frequency reference. We are currently setting up an ytterbium-based superradiant laser experiment with metrological purposes at FEMTO-ST in Besançon, I will present its current status and perspectives.

A fast rotating superfluid on a curved surface

Romain Dubessy, Laboratoire de physique des lasers

Ultracold atom experiments enable the study of quantum systems in a very controlled and tunable environment. In this talk I will describe how atoms can be trapped onto a curved surface by using magnetic fields and radio-frequency photons. I will discuss the physics of rotating superfluid two dimensional systems, and report how thermal fluctuations can lead to the melting of the Abrikosov vortex lattice. Finally I will show that the curvature of the surface gives access to a regime of supersonic rotation, in which the atoms form a dynamical ring.

TBA
Quentin Fontaine,

Bogoliubov modes excited by thermal lattice phonons in a resonantly-driven exciton-polariton fluid

Irénée Frérot, Institut Néel

Probing quantum correlations and entanglement has become a major goal of experimental many-body physics, and remains largely uncharted in driven-dissipative systems. Exciton-polariton (EP) systems in semiconducting microcavities represent a driven-dissipative counterpart to trapped cold-atoms systems, and are a relevant platform to probe such beyond-mean-field quantum effects. Theoretically, it is expected that interactions among EP are well-captured by a driven-dissipative version of Bogoliubov theory, predicting the emission of correlated (k,-k) pairs of photons out of the cavity. Such correlated pairs have been observed in cold atom systems very recently, but not yet in EP systems. In this talk, I discuss a recent experiment where Bogoliubov collective modes are spontanously excited by thermal lattice vibrations of the solid-state material, which represent the last source of extrinsic noise to overcome before reaching a regime where quantum fluctuations alone would lead to the emission of correlated (and in fact, quantum-entangled) pairs.

Non-equilibirium physics and turbulence in a fluid of light

Quentin Glorieux, Laboratoire Kastler Brossel

Light propagating in a non-linear medium mimics the behavior of a superfluid and follows the Gross Pitaevskii equation.
We use this platform to simulate out-of-equilibirium physics and in particular I will report about recent results on 2D quantum turbulence in a superfluid.
I will present the emergence of isotropy after an isotropic forcing and the appearance of an inverse energy cascade evidenced by a Kolmogorov spectrum of the incompressible kinetic energy.

Determination of the fine-structure constant using atom interferometry

Léo Morel[1], Zhibin Yao[1], P. Cladé[1] and S. Guellati-Khelifa[1,2]

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To test the standard model, we need to know the parameters that scale the fundamental interactions. Among them, the fine structure constant α which characterizes the strength of the electromagnetic interaction and thus plays a crucial role in quantum electrodynamics calculations. Using atom interferometry to measure the quotient $\hbar/m_{\mathrm{Rb}}$ of the reduced Planck's constant and the mass of a rubidium-87 atom, we obtained the most accurate determination of the fine structure constant $\alpha = 1/137.035999206(11)$ with a relative accuracy of 81 parts per trillion (ppt) [1]. This value differs by 5.6 σ from the one deduced from the cesium recoil measurement [3].

Combining Ramsey-Bordé interferometer based on Raman diffraction with Bloch oscillations in accelerated optical lattice and using an ultra-stable and robust experimental set-up, we achieved a record sensitivity of 4×10^{-11} to α in 48 h integration time. This allowed us to investigate experimentally several systematic effects, especially those related to wave-front distortions [2].

In this talk, I will present our experiment and I will discuss the impact of the new value of α on the test of the Standard Model based on the comparison between the theoretical and experimental values of the electron anomalous magnetic moment[5, 4].

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Observation of universal relaxation dynamics in disordered quantum spin systems

Clément Hainaut, Laboratoire PhLAM, Lille

A major goal toward understanding far-from-equilibrium dynamics of quantum many-body systems consists in finding indications of universality in the sense that the dynamic no longer depends on the microscopic details of the system. We realize a large range of many-body spin systems on a Rydberg atom quantum simulator by choosing appropriate Rydberg state combinations. We use this platform to compare the magnetization relaxation dynamics of disordered Heisenberg XX, XXZ, and Ising Hamiltonians in a scalable fashion. After appropriate rescaling of evolution time, the dynamics collapse onto a single curve. We develop simple integrable theoretical models, considering only local pairs of spins, that capture the observed universal behavior. This allows us to describe the temporal dynamics of the system in terms of an integrable model similar to systems featuring prethermalization. Since the dynamics of pairs are independent of the type of Hamiltonian up to a scaling factor, this integrable model explains the observed universal relaxation dynamics of disordered Heisenberg quantum spin systems.

Goldstone mode of a diffusive phase transition in a fluid of light

Maxime Jacquet, Laboratoire Kastler Brossel

Nambu-Goldstone (NG) modes of quantum fluids are low-energy collective excitations of the order parameter's phase that is related to the breaking of the U(1) symmetry of phase rotation.
Unlike in conservative systems that are characterized by propagating NG modes, out-of-equilibrium systems like quantum fluids of microcavity exciton-polaritons feature a diffusive NG mode of flat dispersion.
Using a recently developed coherent probe spectroscopy (CPS) method, we directly studied this mode in the transmission spectrum of a parametrically driven microcavity.
We evidenced spontaneous symmetry breaking by observing the disappearance of the NG mode when the phase of the idler mode was pinned, leaving a gap in the dispersion.
Besides the link it establishes between spectroscopic measurements and phase transitions, our experiment establishes CPS as a versatile method to study various field theories out of equilibrium.

Tunable interactions in driven two-component Bose-Einstein condensates: effective three-body interactions and beyond-mean-field effects

Lucas Lavoine, Laboratoire Charles Fabry

Mixtures of Bose-Einstein condensate offer situations where the usual mean-field interaction is reduced and higher-order terms may play a dominant role in the equation of state. In this context, the case of coherently coupled two component Bose-Einstein condensate will be addressed. First, we demonstrate a method to engineer large attractive three body interactions with striking consequences on the system properties [1]. Second, we measure the beyond-mean field equation of state and show that it is modified as compared to the uncoupled case [2].

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Two-body losses in one-dimensional quantum gases

Leonardo Mazza, LPTMS

The interplay between closed and open quantum dynamics is currently the object of an intense theoretical and experimental activity. In this talk I will consider one of the most natural open-quantum-system phenomena that take place in an ultracold gas, namely losses.

I will first discuss the regime of strong losses in a one-dimensional bosonic gas and give quantitative predictions on the dynamics in the quantum Zeno regime. I will then move to the case of fermionic gases with SU(N) spin and show that the interplay between losses and symmetries drives the system in Dicke states or generalisations thereof. A dynamical theory will be presented that is based on the spin-charge separation, with coupled evolution equations. Charge correlations build up in time while the spin is cooled down to the ground-state of an Heisenberg ferromagnet.

Characterization of cold atom gravimeters for field applications

V. Ménoret, iXblue

High precision gravity measurements using cold atom interferometers have been demonstrated since several years, and these quantum instruments can now outperform their classical counterparts. In particular, accuracy and long-term stability of atomic gravimeters have been intensively studied in laboratories. However, these characterizations remain a challenge for highly portable devices because design constraints reduce the number of adjustable parameters. We will discuss results obtained with the Absolute Quantum Gravimeters developed by iXblue, and the recent progress towards a consolidated accuracy budget. We will also show the relevance of quantum gravimeter for field applications in geophysics, with a focus on volcano monitoring.

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Creating Wigner-negative photonic qubits with an intracavity Rydberg superatom

Alexei Ourjoumtsev, Collège de France

I will describe the first fully deterministic preparation of non-Gaussian Wigner-negative free-propagating states of light, obtained by mapping the internal state of an intracavity Rydberg superatom onto an optical qubit encoded as a superposition of 0 and 1 photons. This approach allows us to reach a 60% photon generation efficiency in a well-controlled spatio-temporal mode, while maintaining a strong photon antibunching. By changing the qubit rotation angle, we observe an evolution from quadrature squeezing to Wigner negativity. Our experiment sets this new technique as a viable method to deterministically generate non-Gaussian photonic resources, lifting several major roadblocks in optical quantum engineering.

Optimal control of Bose-Einstein condensates in an optical lattice: state shaping and reconstruction

Bruno Peaudecerf, LCAR, Toulouse

I will present our latest results on applying quantum optimal control to shape the phase-space distribution of Bose-Einstein condensates in a one-dimensional optical lattice. Through an optimised time-dependent modulation of the lattice position, we can tailor the collective wavefunction of the condensate [1]. Using this tool, we can prepare, in the phase space of each lattice site, a variety of translated and squeezed Gaussian states, and superpositions of Gaussian states.
Complete reconstruction of these non-trivial states is performed through maximum likelihood state tomography, demonstrating an efficient preparation. As a practical application of our method to quantum simulations, we initialize the atomic wavefunction in an optimal Floquet-state superposition to enhance dynamical tunnelling signals.

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Light thermalization and condensation in multimode fibers: Experiments and wave turbulence theory

A. Picozzi, Université de Bourgogne

Different studies on wave turbulence revealed that purely classical waves can exhibit a process of condensation that originates from the thermalization of the waves toward the Rayleigh-Jeans (RJ) equilibrium distribution [1]. Although condensation of classical waves differs from the quantum Bose-Einstein condensation, the underlying mathematical origin is analogous because of the common singular behavior (vanishing denominator) of the Bose and RJ distributions. The experiment is based on light propagation in multimode fibers, which is known to be affected by a structural disorder of the material. We have developed a wave turbulence description of the random waves accounting for the presence of disorder. The theory unveils a significant acceleration of the rate of thermalization and condensation that is induced by the disorder [2-3]. Our experiments in multimode fibers evidence the transition to light condensation: By decreasing the kinetic energy ('temperature') below the critical value, we observe a transition from the incoherent thermal RJ distribution to wave condensation [4].

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The rise and fall, and slow rise again, of operator entanglement under dephasing

Johannes Schachenmayer, Institut de Science et d'Ingénierie Supramoléculaires

Entanglement entropies (EEs) are an indicator for the complexity of quantum states and of their "approximability" on classical computers. In the context of cold atom "quantum simulation" prospects, studies of EE dynamics, and the fundamentally interesting interplay between coherent Hamiltonian dynamics (building up EEs) and dissipation (destroying EEs), are crucial. In this talk I will discuss a recently discovered effect in generic spin models subjected to dephasing: There, the operator entanglement (OE), an EE-equivalent for density matrices, initially exhibits an expected rise and fall behavior. However, at long times we find that the OE can rise again, following a universal logarithmic increase. In this talk I will explain this behavior using a combination of exact numerical simulations and analytical arguments valid for strong dephasing.

Weyl nodes in polaritonic Josephson junctions

Dmitry Solnyshkov, Institut Pascal

An optical microcavity driven by quasi-resonant pumping can reach a gapped superfluid regime. In this case, the spectrum of elementary excitations exhibits a gap, as in the superconductors. Furthermore, it is possible to create an interface between normal and superfluid regions, similar to normal/superconductor interface. Solving the Gross-Pitaevskii equation analytically, we have shown that a polaritonic analogue of Andreev reflection can occur at such interfaces.

We have also shown that a normal region surrounded by two superfluids represents an analogue of a Josephson junction hosting topological states (close to Andreev bound states) forming synthetic bands. This configuration can be extended to an analogue of a multi-terminal Josephson junction. We study bands formed by the p-like states of a pentagonal 5-terminal junction (4D parameter space). We numerically demonstrate the presence of 4 Weyl points in a specific 3D subspace, with 2D subspaces exhibiting non-zero Chern numbers. Finally, we derive an effective Hamiltonian encoding the full 4D parameter space, studying the trajectories of the Weyl points and their creation and annihilation. The 4D space is shown to contain 3D subspaces with broken time-reversal symmetry hosting 6 Weyl points.

Non-equilibrium quantum dynamics: numerical approaches challenging quantum complexity

Tommaso Roscilde, Laboratoire de Physique, ENS de Lyon

A central theme of quantum simulation using ultracold atoms — as well as any other platform — is the coherent control of quantum many-body state, and in particular of its entanglement features. This should ideally occur in a scalable fashion: namely for ever bigger systems and for ever longer coherence times. The perspective of scalable quantum simulations poses a grand challenge to theoretical studies, since the computational resources required for a reliable simulation of quantum dynamics are generically expected to scale exponentially with size and time, exposing the fundamental complexity of the quantum many-body problem.

In this talk I will review several approaches that we have been devising recently in order to overcome this exponential complexity, and to offer an "information-compact" representation of quantum many-body states prepared by a coherent unitary dynamics. Our general approach is to use a "variational Ansatz", namely to postulate that the quantum state can be described via a drastically reduced amount of information with respect to its exponentially many coefficients on a given basis, hopefully retaining the essential physical traits of the exact state. We shall focus specifically on lattice spin models (describing e.g. Mott insulators of spinor gases, trapped ions or arrays of Rydberg atoms), as well as more generic lattice gases, and discuss the effectiveness and limitations of several approaches to their dynamics, ranging from Gaussian Ansätze; truncation of cumulant hierarchies; and entangled (pair-product) variational states. In particular the latter approach turns out to be most effective, allowing us to unveil a seemingly universal paradigm of entanglement dynamics for long-range interacting spin systems.

High-order diagrammatic expansion around BCS: polarized superfluid phase of the attractive Hubbard model

Félix Werner, Laboratoire Kastler Brossel

In contrast to conventional QMC methods, expansions of intensive quantities in series of connected Feynman diagrams can be formulated directly in the thermodynamic limit. Over the last decade, diagrammatic Monte Carlo algorithms made it possible to reach large expansion orders and to obtain state-of-the-art results for various models of interacting fermions in 2 and 3 dimensions, mostly in the normal phase.

We obtained first results inside a superconducting phase, for the 3D attractive Hubbard model [1]. Spontaneous symmetry breaking is implemented by expanding around a BCS Hamiltonian. All diagrams up to 12 loops are summed thanks to the connected determinant algorithm [2] with anomalous propagators. Working on the BCS side of the strongly correlated regime, we observe convergence of the expansion, and benchmark the results against determinant diagrammatic Monte Carlo [3]. In presence of a polarizing Zeeman field (where unbiased benchmarks are unavailable due to the fermion sign problem) we observe a first-order superconducting-to-normal phase transition, and a thermally activated polarization of the superconducting phase well captured by a quasiparticle description. We also discuss the large-order behavior of the expansion and its relation to Goldstone and instanton singularities.

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