SYMPOSIUMS ET DÉBATS

Polish-French (mini)Symposium: Development in the Physics of Ultracold Matter

1–3 juillet 2021
Centre Scientifique de l'Académie Polonaise des Sciences à Paris
(en présence)

The symposium addresses the physics of ultracold gases and their applications in quantum technology.

Research on ultracold matter has been honored with 14 Nobel prizes in the last 25 years. The field is developing very dynamically in both theoretical and experimental basic research, and also in the field of applications in the emerging quantum technology.

Currently, clouds of atomic gas can be cooled to picokelvin temperatures. It is also possible to manipulate a single atom or a group of several atoms on demand. Therefore, observation of characteristic quantities, previously impossible to measure, is now available. Interesting novel directions of theoretical research emerge inspired by the advances in experimental techniques and unexpected results. They allow understanding the quantum effects occurring in the observed systems and how they affect the key properties of the systems under investigations.

The main topics of the mini-symposium are: new phases of matter arising from nonlocal interactions, nonlinear phenomena, computational methods used in modeling of quantum many-body systems, research on quantum coherence of ultracold atoms, time crystals as well as creation of entangled states of ultracold atoms.

Abstracts

Kazimierz Rzążewski

Centrum Fizyki Teoretycznej PAN, Warszawa

Fluctuations of Bose-Einstein condensate

Particle fluctuations of a number of condensed atoms is one of fundamental problems of quantum gases physics. In the last two years it is not only a theoretical, but also the experimental problem. I will review nearly a quarter century of our own efforts. I will explain our new method of the Fock states sampling.

Alice Sinatra

Laboratoire Kastler Brossel, UPMC, Paris

Nuclear spin-squeezing by continuous measurement

The nuclear spin of helium-3 is very well isolated from the environment and has coherence times measured to be hundreds of hours. We propose a method to manipulate at the quantum level the collective nuclear spin of a helium gas in a cell at room temperature, by means of a continuous quantum non demolition measurement. A discharge is temporarily switched-on in the gas which populates the metastable state of helium. The nuclear collective spin then slightly hybridizes with the collective spin of metastable atoms thanks to metastability exchange collisions. The metastable atoms interact with light in an optical cavity, and the field leaking out from the cavity is continuously measured. Nuclear spin squeezing provides a metrological gain for nuclear-spin based sensors such as miniaturized magnetometers and gyrometers whose sensitivity will ultimately reach the limits imposed by quantum mechanics. It also opens up fascinating perspectives on the possibility of creating and maintaining a macroscopic quantum state over very long periods of time.

Krzysztof Sacha
Uniwersytet Jagielloński, Kraków

Time Crystal Phenomena

Time crystals are quantum many-body systems which due to interactions between particles can spontaneously self-organize in time and start moving periodically. It will be shown that such a phenomenon can be observed in closed periodically driven systems. It will be also presented that condensed matter phenomena, like Anderson or many-body localization, topological phases or Mott-insulating phase, can be realized in crystalline structures in time.

Dmitry Petrov

LPTMS, Universite Paris-sud XI, Paris

Higher-order effective interactions for bosons near a two-body zero crossing

We develop the perturbation theory for bosons interacting via a weak two-body potential V, attractive and repulsive parts of which cancel each other. We find that the leading nonpairwise contribution to the energy emerges in the third order in V and represents an effective three-body interaction, the sign of which in most cases (although not in general) is anticorrelated with the sign of the long-range tail of V. We calculate the leading two-body and three-body interaction corrections for tilted dipoles in quasi-low-dimensional geometries.

Piotr Deuar

Instytut Fizyki PAN, Warszawa

Scalable full quantum dynamics of dissipative Bose-Hubbard systems and multi-time correlations

Methods for numerically simulating large driven-dissipative quantum systems are of increasing importance due to ongoing experimental progress in a number of platforms such as polariton condensates, nanopillars, photonic lattices, or transmon qubits. We demonstrate the positive-P method known otherwise from quantum optics to be ideal for this purpose across a wide range of parameters, focusing on the archetypal driven-dissipative Bose-Hubbard model. For example, full quantum dynamics of a nonuniform 256x256 lattice of sites is demonstrated. Accessible parameters include those where interactions and dissipation are significant, occupations low and common semiclassical approximations can break down. Antibunching or strong two-particle interference such as in the anomalous photon blockade can be simulated. The presence of dissipation alleviates instabilities in the positive-P method that were known to occur for closed systems, allowing the simulation of full quantum dynamics up to and including the steady state. In the accessible regime, numerical effort scales linearly with the number of sites, quadratically with the precision, and doesn't care about symmetry or its lack. We also find that the regions of applicability of the positive-P, and truncated Wigner approaches are mutually complementary. Together these approaches cover the majority of parameter space in the dissipative Bose-Hubbard model. The positive-P approach also provides a simple and physically intuitive way to calculate many unequal time correlations, allowing their investigation in a non-perturbative and scalable way.

Felix Werner

École Normale Supérieure, Paris

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

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 of various key models of interacting fermions, mostly in the normal phase. We obtained first results inside a superfluid/superducting phase, namely the s-wave superfluid phase of attractive Hubbard model in 3D [1]. Spontaneous symmetry breaking is realized by expanding around a BCS Hamiltonian. All diagrams up to order ~12 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 sign problem) we observe a first-order superfluid-to-normal phase transition, and a thermally activated polarization of the superconducting phase. We also discuss the large-order behavior of the expansion and its relation to Goldstone and instanton singularities.

Yvan Castin

École Normale Supérieure, Paris

Une quasi-particule massive dans un gaz de phonons / A massive quasiparticle in a phonon gas

We consider in dimension 3 a very low temperature homogeneous superfluid exhibiting two types of excitations, (i) gapless acoustic phonons of linear dispersion relation at low wavenumber, and (ii) gapped gamma quasiparticles of quadratic (massive) dispersion relation in the vicinity of its extrema. Recent work [Nicolis and Penco (2018), Castin, Sinatra, and Kurkjian (2017, 2019)], extending the historical study of Landau and Khalatnikov on the phonon-roton interaction in liquid helium-4, has explicitly determined the scattering amplitude of a thermal phonon on a quasiparticle at rest at the temperature leading order. We generalize this calculation to the case of a quasiparticle of arbitrary subsonic group velocity, with a rigorous construction of the S-matrix between exact asymptotic states, taking into account the incessant phonon-phonon and phonon-gamma interaction, which dresses up the incident or emerging phonon and quasiparticle with virtual phonons; this sheds new physical light on the Feynman diagrams of phonon-gamma scattering. In the whole parameter space (wave number, interaction strength, etc.) where the gamma quasiparticle is energetically stable with respect to the emission of phonons of arbitrary wave vectors, we can then characterize the erratic motion it performs in the superfluid as a result of its incessant collisions with the thermal phonons, through the average force and the longitudinal and transverse diffusion coefficients involved in a Fokker-Planck equation, and then, at long times when the quasiparticle has thermalized, through the spatial diffusion coefficient.

Tomasz Karpiuk

Uniwersytet w Białymstoku

Disruption of a Bose-Fermi droplet by an artificial black hole

We study the evolution of a binary system consisting of an artificial black hole and a white dwarf. We implement the quantum hydrodynamic equations and carry out numerical simulations. As a model of a white dwarf star we consider a zero temperature droplet of attractively interacting degenerate atomic bosons and spin-polarized atomic fermions. Such mixtures are investigated experimentally nowadays.

Giuliano Orso

Paris Diderot University

Effects of disorder in interacting quantum systems: from two-body Anderson transitions to disorder quenches

In this talk I review our recent numerical work on the field of disordered systems in the presence of interactions. I first discuss the problem of the mobility edge for a system of two interacting particles, tracing out the complete phase diagram in the space of energy, interaction and disorder. Next, we use the Gross-Pitaevskii equation to simulate a recent experiment, studying the relaxation dynamics of a three-dimensional Bose-Einstein condensate after switching on or off a disorder potential generated by a laser speckle.

Dominique Delande

Laboratoire Kastler-Brossel, CNRS, Sorbonne Université,
Ecole Normale Supérieure, Collège de France, Paris

The Quantum Boomerang Effect

When a wavepacket is launched with a finite velocity in free space, it follows a ballistic motion, both in classical and quantum mechanics. In the presence of a disordered potential, the generic classical behavior, described by the Boltzman equation, is a random walk whose characteristic length is the mean free path. The center of mass of the classical "wavepacket" first drifts ballistically in the direction of the initial velocity, slows down and ends up at long time displaced by one mean free path. The quantum dynamics is drastically different: the center of mass first drifts ballistically, but rapidly performs a U-turn and slowly returns to its initial position. I will describe this "Quantum Boomerang" effect both numerically and analytically in dimension 1, discuss the importance of symmetry properties and show that it is partially destroyed by weak particle interactions.

Jakub Zakrzewski

Uniwersytet Jagielloński, Kraków

Many body localization without disorder

I will discuss recent experimental and theoretical studies of non-ergodic dynamics and localization in tilted one-dimensional systems such as e.g. fermions in tilted optical lattices.

Bruno Laburthe-Tolra

Universite Paris 13, Villetaneuse, Paris

Measuring the growth of correlations in an array of dipolar particles

We investigated the spin dynamics and quantum thermalization of a macroscopic ensemble of S = 3 spins initially prepared in a pure coherent spin state. The experiment uses a unit-filled array of 10 thousand chromium atoms in a three dimensional optical lattice. Atoms interact at long distance under the effect of magnetic dipole-dipole interactions, realizing the spin-3 XXZ Heisenberg model with long-range couplings. We investigated the build-up of quantum correlations in this many-body system. For this, we measured collective properties such as the total population in the seven different Zeeman states or the collective spin length. We also found that the measurement of magnetization fluctuations and of the covariance between the measured populations in different Zeeman states provide direct quantitative estimates for two-body correlations.

Anna Minguzzi
LPMMC, Grenoble

Josephson effect(s) for strongly correlated gases in one dimension

We study Josephson oscillations of two strongly correlated one-dimensional bosonic clouds separated by a localized barrier. Using a quantum-Langevin approach and the exact Tonks-Girardeau solution in the impenetrable-boson limit, we determine the dynamical evolution of the particle-number imbalance, displaying an effective damping of the Josephson oscillations which depends on barrier height, interaction strength and temperature. We show that the damping originates from the quantum and thermal fluctuations intrinsically present in the strongly correlated gas. Thanks to the density-phase duality of the model, the same results apply to particle-current oscillations in a one-dimensional ring where a weak barrier couples different angular momentum states. In the latter case, depending on interaction strength and temperature, we identify various dynamical regimes where the current oscillates, is self-trapped or decays with time and involve phase slips of thermal or quantum nature.

Krzysztof Pawłowski

Centrum Fizyki Teoretycznej PAN

LL-GPE and Quantum Droplets in 1D

Describing the properties of a strongly interacting quantum many-body system poses a serious challenge. I will discuss an approximation, called here LLGPE, useful to study a 1D gas in the regime of any interaction strength. The LLGPE is a generalization of the Gross-Pitaevskii equation that may be deduced from a hydrodynamical description. I show that the linearization of LLGPE leads to dispersion relations of the elementary excitations that stay in good agreement with the exact results of the Lieb-Liniger model, for any strength of the contact interactions. I will briefly discuss the solitonic solutions of LLGPE and their correspondence to the so-called type II excitations. In the second part of my talk, I will move to LLGPE with the dipolar interactions included. In this case, one finds solutions resembling the quantum droplets, even though the celebrated Lee-Huang-Yang term is not applicable in the discussed cases. I will discuss the origin and properties of the quantum droplets and preliminary results concerning their dynamics and excitations.

Mariusz Gajda

Instytut Fizyki PAN, Warszawa

Coherent collisions of two Bose-Bose droplets

I will discuss coherent dynamics of two interacting Bose-Bose droplets. Their relative motion can be understood in terms of the evolution of zero-energy modes recovering symmetries spontaneously broken by the mean field solution. A phase-dependent interaction potential and Josephson-junction-like equations are introduced to explain the observed behaviour. I will show that the evolution of the droplets is a macroscopic manifestation of the hidden dynamics of their phases.

Mirosław Brewczyk

Uniwersytet w Białymstoku

Berezinskii-Kosterlitz-Thouless phase induced by dissipating quasisolitons

We theoretically study the sound propagation in a two-dimensional weakly interacting uniform Bose gas. Using the classical fields approximation we analyze in detail the properties of density waves generated both in a weak and strong perturbation regimes. While in the former case density excitations can be described in terms of hydrodynamic or collisionless sound, the strong disturbance of the system results in a qualitatively different response. We identify observed structures as quasisolitons and uncover their internal complexity for strong perturbation case. For this regime quasisolitons break into vortex pairs as time progresses, eventually reaching an equilibrium state. We find this state, characterized by only fluctuating in time averaged number of pairs of opposite charge vortices and by appearance of a quasi-long-range order, as the Berezinskii–Kosterlitz–Thouless (BKT) phase.

Hadrien Kurkjian

CNRS, Laboratoire de Physique Théorique, Touluse

Collective modes as precursors of the phase transition in superfluid Fermi gases

I will discuss the collective excitation spectrum of a superfluid Fermi gases at and around the critical temperature. In this regime, the response of the system to a driving pairing field is dominated by a collective mode with a quadratic dispersion. Still visible above Tc, this mode acts as a precursor of the phase transition. It evolves from a relaxation mode (of pure imaginary frequency) to a propagating mode as a function of the interaction strength, and it can be observed by coupling the gas to a reservoir of Cooper pairs.

Emilia Witkowska

Instytut Fizyki PAN, Warszawa

Criticality-enhanced quantum sensing with spin-1 condensates

We theoretically investigate estimation of the control parameter in a spin-1 Bose-Einstein condensate near quantum phase transitions in a transverse magnetic field with a fixed macroscopic magnetization. We quantify sensitivity by quantum and classical Fisher information. For these different metrics, we find the same, beyond-standard-quantum-limit (SQL) scaling with atom number near critical points, and SQL scaling away from critical points. In the particular case of antiferromagnetic condensates, the system exhibits the first- and second-order phase transition depending on the value of magnetization. We exploit both types of system criticality as a resource in the precise estimation of control parameter value. We demonstrate supersensitivity and show that the precision scales with the number of atoms up to N4 around critically.

In addition, we study the precision based on the error-propagation formula providing the simple-to-measure signal which coincides with its scaling with the quantum Fisher information. We find that both depletion of the mF=0 Zeeman sub-level and transverse magnetization provide signals of sufficient quality to saturate the sensitivity scaling. To explore the effect of experimental imperfections, we study the scaling around criticality at nonzero temperature and with nonzero detection noise. Our results suggest the feasibility of sub-SQL sensing in spin-1 condensates with current experimental capabilities.

Youcef Baamara

Laboratoire Kastler Brossel

Scaling laws for the sensitivity enhancement of non-Gaussian spin states

We identify the large-N scaling of the quantum gain offered by over-squeezed spin states, that are accessible by one-axis-twisting, as a function of the preparation time. We further determine how the scaling is modified by relevant decoherence processes and predict a discontinuous change of the quantum gain at a critical preparation time that depends on the noise. Our analytical results for arbitrary N provide recipes for optimal and feasible implementations of quantum enhancements with non-Gaussian spin states in existing atomic experiments, well beyond the reach of spin squeezing.

Filip Gampel

Instytut Fizyki PAN

Continuous observation of a few-body quantum system

We study the influence of frequent observation on the temporal evolution of a single or several quantum particles. To this end we introduce a model of detectors on a grid measuring position and momentum. Using the Monte Carlo wavefuntion (MCWF) method allows us to develop a framework to predict single possible trajectories of the particle(s).

Tanausú Hernández

Instytut Fizyki PAN

Spin squeezing for several spin-orbit coupled fermions in an optical lattice

We investigate the dynamical formation of spin squeezing in the system composed of several ultra-cold fermions in a one-dimensional optical lattice from the initial spin coherent state. As the basic Fermi Hubbard model is unable to generate spin squeezing, we include the spin-orbit coupling to induce the production of spin-squeezed states. The corresponding Fermi-Hubbard Hamiltonian is analyzed in the transformed frame to obtain a relevant spin model which explains squeezing generation. An exact numerical analysis of the model for a small number of lattice sites was performed in different scenarios to probe the influence of spin-orbit coupling. Since we are working with a small number of particles, a special focus on boundary conditions was necessary to obtain accurate results. Finally, we show how the squeezing generation can be understood with the help of the OAT model under a certain regime of parameters.

Piotr Grochowski

Centrum Fizyki Teoretycznej PAN

Many-body molecule formation at a domain wall in a one-dimensional strongly interacting ultracold Fermi gas

We analyze how the presence of the bound state on top of strong inter component contact repulsion affects the dynamics of a two-component ultracold Fermi gas confined in a one-dimensional harmonic trap. By performing full many-body numerical calculations, we retrieve dynamics of an initially phase separated state that has been utilized to excite the spin-dipole mode in experimental settings. We observe an appearance of pairing correlations at the domain wall, heralding the onset of a molecular fraction at the interlayer between the components. We find that such a mechanism can be responsible for the stabilization of the phase separation.

Jakub Kopyciński
Centrum Fizyki Teoretycznej PAN

Solitons and phonons in 1D. Beyond the limit of weak interactions

The usefulness of the widely-known Gross-Pitaevskii equation (GPE) falls down as soon as gas enters the strongly repulsive interaction regime. In this regime, one can still invoke hydrodynamics combined with the exact solution of the Lieb-Liniger (LL) model. This approach results in the modification of the GPE, which we call LLGPE. We put our main focus on the LLGPE and study type-I and type-II excitations within this model. We use the linearization to obtain the dyspersion relation of type-I excitaions. The phononic spectra turn out to be consistent with the LL model for a wider range of interactions than GPE. We also find out the dark soliton energies have a qualitative agreement with type-II excitation energies. We point out there is no many-body approach we can compare to as they are either highly model-dependent or unsuitable in the strongly interacting case. We argue the LLGPE has a broader range of applicability than the GPE with a constraint of slowly varying density.

Maciej Kruk

Instytut Fizyki PAN

Fock State Sampling Method for BEC Fluctuations

I will present the details of our new method for sampling statistical ensembles of Bose gases, and our results for 1D harmonic and ring traps.

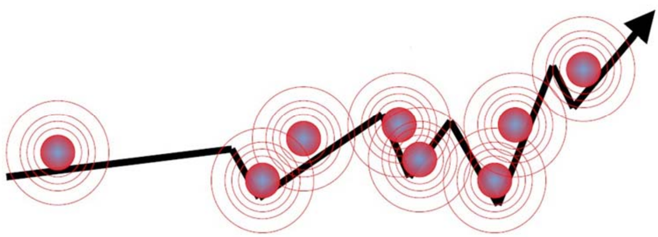
Maciej Łebek

Centrum Fizyki Teoretycznej PAN

Repulsive dynamics of strongly attractive one-dimensional quantum gases

We analyze the dynamics of one-dimensional quantum gases with strongly attractive contact interactions. We specify a class of initial states where attractive forces effectively act as strongly repulsive ones during the time evolution. Our findings extend the theoretical results connected with super-Tonks-Girardeau gas to highly non-equilibrium dynamics. The mechanism is illustrated on the prototypical problem of the domain stability in two-component Fermi gas. We discuss non-local interactions and analyze the universality of the presented results.

Polish-French (mini)Symposium: Development in the Physics of Ultracold Matter



July 1-2, 2021

Paris

ACADEMIE POLONAISE DES SCIENCES
Centre Scientifique à Paris

L'affiche préparée par Centre de physique théorique de l'Académie Polonaise des Sciences à Paris

PROGRAMME

1st July 2021

11:50	Opening
12:00 – 13:30	1st Session (chairman Krzysztof Pawłowski) Kazimierz Rzążewski “*Fluctuations of Bose-Einstein condensate*” Alice Sinatra *“Nuclear spin-squeezing by continuous measurement”* Krzysztof Sacha *“Time Crystal Phenomena”*
15:00 – 16:30	2nd Session (chairman Krzysztof Sacha) Dmitry Petrov *“Higher-order effective interactions for bosons near a two-body zero crossing”* Piotr Deuar *“Scalable full quantum dynamics of dissipative Bose-Hubbard systems and multi-time correlations”* Felix Werner *“High-order diagrammatic expansion around BCS: Polarized superfluid phase of the attractive Hubbard model“*
17:00 – 18:30	3rd Session (chairman Anna Minguzzi) Yvan Castin *«Une quasi-particule massive dans un gaz de phonons / A massive quasiparticle in a phonon gas”* Tomasz Karpiuk *“Disruption of a Bose-Fermi droplet by an artificial black hole”* Giuliano Orso *“Effects of disorder in interacting quantum systems: from two-body Anderson transitions to disorder quenches”*

18:30 – 19:30 Mini Poster Session

Youcef Baamara *"Scaling laws for the sensitivity enhancement of non-Gaussian spin states"*

Filip Gampel *"Continuous observation of a few-body quantum system"*

Piotr Grochowski *"Many-body molecule formation at a domain wall in a one-dimensional strongly interacting ultracold Fermi gas"*

Jakub Kopyciński *"Solitons and phonons in 1D. Beyond the limit of weak interactions"*

Maciej Kruk *"Fock State Sampling Method for BEC Fluctuations"*

Maciej Łebek *"Repulsive dynamics of strongly attractive one-dimensional quantum gases"*

Tanausú Hernández *"Spin squeezing for several spin-orbit coupled fermions in an optical lattice"*

2nd July 2021

9:30 – 11:00 4th Session chairman Rzążewski

Jakub Zakrzewski *"Many body localization without disorder"*

Dominique Delande *"The Quantum Boomerang Effect"*

11:30 – 13:00 5th session (chairman Piotr Deuar)

Bruno Laburthe-Tolra *"Measuring the growth of correlations in an array of dipolar particles"*

Anna Minguzzi *"Josephson effect(s) for strongly correlated gases in one dimension"*

Krzysztof Pawłowski *"LL-GPE and Quantum Droplets in 1D"*

15:00 – 17:00 6th Session (chairman Alice Sinatra) - hybrid

Mariusz Gajda *"Coherent collisions of two Bose-Bose droplets"* (online)

Mirosław Brewczyk *"Berezinskii-Kosterlitz-Thouless phase induced by dissipating quasisolitons"* (online)

Hadrien Kurkjian *"Collective modes as precursors of the phase transition in superfluid Fermi gases*"

Emilia Witkowska *"Criticality-enhanced quantum sensing with spin-1 condensates"*