Q 20: Quantum Gases: Bosons II

Time: Tuesday 11:00–13:00 Location: F342

Q 20.1 Tue 11:00 F342

Bose-Einstein Condensation of Photons in a Four-Site Lattice Potential — •Niels Wolf, Andreas Redmann, Christian Kurtscheid, Frank Vewinger, Julian Schmitt, and Martin Weitz — Institut für Angewandte Physik, Universität Bonn, Deutschland

Bose-Einstein condensation can be observed with ultracold atomic gases, polaritons, and since about a decade ago also with low-dimensional photon gases. Cold atomic gases in lattice potentials are usually prepared following the creation of a condensate by transferring it into the periodic potential, while in recent work with photon gases direct condensation into a coherently split state of light has been realized [1]. Here we report on experimental work directed at realizing thermalized photon gases in periodic potentials of increased complexibility, i.e. beyond a double well.

Our experiments use a controlled mirror surface delamination technique to imprint variable potentials for light in a dye-filled optical microcavity environment. Photons thermalize by repeated absorption re-emission processes on the dye molecules in a four-site lattice potential superimposed by a weak harmonic trapping potential. We observe Bose-Einstein condensation of photons in the four-fold split coherent superposition of the localized microsites wave function representing the system ground state in the microcavity.

[1] C. Kurtscheid et al., Science 366, 894 (2019)

Q 20.2 Tue 11:15 F342

Many-body interference at the onset of chaos — •Eric Brunner[1,2], Lukas Pausch[1,2,3], Edoardo G. Carnio[1,2], Gabriel Dufour[1,2], Alberto Rodríguez[4], and Andreas Buchleitner[1,2] — [1]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, 79104, Freiburg, Germany — [2]EUCOR Centre for Quantum Science and Quantum Computing, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, 79104, Freiburg, Germany — [3]CESAM Research Unit, University of Liège, 4000 Liège, Belgium — [4]Departamento de Física Fundamental, Universidad de Salamanca, E-37008 Salamanca, Spain

We unveil the signature of many-body interference across dynamical regimes of the Bose-Hubbard model. Increasing the particles' indistinguishability enhances the temporal fluctuations of few-body observables, with a dramatic amplification at the onset of quantum chaos. By resolving the exchange symmetries of partially distinguishable particles, we explain this amplification as the fingerprint of the initial state's coherences in the energy eigenbasis. In the domain of fully developed quantum chaos, ergodic delocalisation of the eigenstates suppresses this fingerprint.

Q 20.3 Tue 11:30 F342

Dynamical characterization of the chaotic phase in the Bose-Hubbard model — David Peña Murillo and •Alberto Rodríguez — Departamento de Física Fundamental, Universidad de Salamanca, E-37008 Salamanca, Spain

We study the dynamical manifestation of the Bose-Hubbard model's chaotic phase [1] by analysing the temporal behaviour of connected two-point density correlations on experimentally accessible time scales up to a few hundred tunneling times. The time evolution of initial Mott states with unit density in systems including up to 17 bosons (Hilbert space dimension $\approx 10^9$) reveals that the chaotic phase can be unambiguously identified from the early time fluctuations of the considered observable around its equilibrium value [2]. The emergence of the chaotic phase is also seen to leave an imprint in the initial growth of the time signals. The possibility to discern specific features of this many-body chaotic phase, on top of the universal prediction of random-matrix theory, from these experimentally accessible measures is explored.

[1] L. Pausch *et al.*, Phys. Rev. Lett. 126, 150601 (2021)
[2] D. Peña Murillo, MSc Thesis, Universidad de Salamanca (2022)

Q 20.4 Tue 11:45 F342

Orbital dynamics of bosons in the second Bloch band of an optical lattice — •José Vargas[1,2], Marlon Nuske[1], Raphael Eichberger[1], Carl Hippler[1], Ludwig Mathey[1,2], and Andreas Hemmerich[1,2] — [1]Zentrum für Optische Quantentechnologien and Institut für Laser-Physik, Universität Hamburg, 22761 Hamburg, Germany — [2]The hamburg center for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany

We explore Josephson-like oscillations of a Bose-Einstein condensate populating the second Bloch band of a bipartite optical square lattice, which provides a double well structure with two inequivalent, degenerate energy minima. An oscillation of the relative population difference between the two energy minima of the second band is observed. The oscillation frequency depends on the ratio of two distinct collisions processes: the on-site collision term of atoms in either of the three local orbitals in shallow and deep wells of the lattice, and a flavour changing collision. The observations are compared to the predictions given by a full quantum model limited to only two single-particle modes neglecting dissipation, which reproduces the measured oscillations and show the correct dependency of the oscillation frequency on the ratio among the strength of the aforementioned collision terms.

Q 20.5 Tue 12:00 F342

Stability of vortices in dipolar droplets — Milan Radonjić[1,2], •Antun Balaž[2], and Axel Pelster[3] — [1]I. Institute of Theoretical Physics, University of Hamburg, Germany — [2]Center for the Study of Complex Systems, Institute of Physics Belgrade, University of Belgrade, Serbia — [3]Physics Department and Research Center OPTIMAS, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, Germany

Vortices in dipolar Bose-Einstein condensates have been studied theoretically and numerically for a long time, but have proved to be elusive and were experimentally observed only very recently [1]. Based on variational calculations, it was suggested [2] that vortices may also exist in dipolar droplets [3], exotic quantum states that emerge due to quantum fluctuations [4]. Here we investigate if self-bound dipolar droplets can support vortices using numerical approach based on the extended Gross-Pitaevskii equation, which includes quantum depletion and finite-size corrections. We also study dynamical stability of such vortex states for experimentally relevant values of system parameters.

[1] L. Klaus et al., In press, Nat. Phys. (2022).
[2] A. Cidrim et al., Phys. Rev. A **98**, 023618 (2018).
[3] H. Kadau et al., Nature **530**, 194 (2016).
[4] A. R. P. Lima and A. Pelster, Phys. Rev. A **84**, 041604(R) (2011); Phys. Rev. A **86**, 063609 (2012).

Q 20.6 Tue 12:15 F342

Optimal route to quantum chaos in the Bose-Hubbard Hamiltonian — •Lukas Pausch[1,2], Edoardo G. Carnio[2,3], Alberto Rodríguez[4], and Andreas Buchleitner[2,3] — [1]Département de Physique, Université de Liège, Belgium — [2]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Germany — [3]EUCOR Centre for Quantum Science and Quantum Computing, Albert-Ludwigs-Universität Freiburg, Germany — [4]Departamento de Física Fundamental, Universidad de Salamanca, Spain

The dependence of the chaotic phase of the Bose-Hubbard Hamiltonian [1,2] on particle number, system size and particle density is investigated in terms of spectral and eigenstate features. Within the energy and parameter range where chaos fully unfolds, the expectation value and the eigenstate-to-eigenstate fluctuations of the fractal dimensions of Bose-Hubbard eigenstates show clear signatures of ergodicity and are well described by random-matrix theory (RMT) [1,2]. As the limit of infinite Hilbert space dimension is approached along different directions, the fastest convergence to the random-matrix predictions is achieved at fixed particle density $\lesssim 1$ [3]. Despite the agreement on the level of low-order statistical moments, the model is ever more distinguishable from RMT in terms of its full fractal dimension distributions as Hilbert space grows. These results provide evidence of a way to discriminate among different many-body Hamiltonians in the chaotic regime.

[1] L. Pausch et al., Phys. Rev. Lett. 126, 150601 (2021)
[2] L. Pausch et al., New J. Phys. 23, 123036 (2021)
[3] L. Pausch et al., J. Phys. A 55, 324002 (2022)

Q 20.7 Tue 12:30 F342

Full quantum simulations of Bose gases with the complex Langevin method — •Philipp Heinen and Thomas Gasenzer — Kirchhoff-Institut für Physik, Universität Heidelberg, Im Neuenheimer

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While path integrals can be straightforwardly evaluated by standard Monte Carlo methods in the case of a real action, these are not applicable for a complex action because the interpretation of the integrand as a probability density is lost in this case, a fact that is commonly known as sign problem. This hinders ab initio simulations of the interacting Bose gas in the field-theoretic framework, since the purely imaginary Berry phase term in its action causes a sign problem even in thermal equilibrium. The complex Langevin (CL) algorithm is a generic, model-independent approach to tackle the sign problem by recasting the path integral into a stochastic Langevin equation and by complexifying the originally real degrees of freedom of the problem. While it has a long-standing history in high energy physics, its application to ultracold atoms is rather recent. In my talk I want to demonstrate that CL is able to simulate interacting bosons from first principles and show applications to the BKT transition and the physics of dipolar Bose gases.

Q 20.8 Tue 12:45 F342

An Atomic Mode Parametric Amplifier Mediated by Cavity Photons — •Fabian Finger, Rodrigo Rosa-Medina, Nicola Reiter, Panagiotis Christodoulou, Tobias Donner, and Tilman Esslinger — Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland

Parametric amplification is a fundamental concept of nonlinear dynamics, occurring in fields so diverse as mechanics, electronics, and atomic physics. In the past, ultracold quantum gases exhibiting short-range contact interactions have been used to demonstrate parametric amplification of atomic modes. Here, we make use of global-range interactions in an optical cavity to realize a fast parametric amplifier producing atomic pairs in specific spin and momentum modes. Our implementation relies on Raman scattering between spin levels in a spinor Bose-Einstein condensate, induced by the interplay of a running-wave transverse laser and the vacuum field of the cavity. Detuned from Raman resonance, a four-photon process gives rise to effective spin-mixing dynamics. We observe pair production of signal and idler atoms in tens of microseconds and demonstrate its nonlinear character by varying the number of atoms in the pump reservoir. We extend our results to a regime exhibiting two concurring pair production channels and observe correlated momenta between the highly fluctuating signal and idler modes, verifying the phase matching condition of the parametric amplifier. Our results demonstrate a new experimental platform for fast atomic parametric amplification and provide prospects for matter-wave interferometry using entangled motional states.