# Q 39: Photon BEC

Time: Wednesday 14:30–16:30 Location: HS V

Q 39.1 Wed 14:30 HS V

**Kardar-Parisi-Zhang Universality in a Two-Dimensional Photon Bose-Einstein Condensate** — •Joshua Krauss and Axel Pelster — Physics Department and Research Center OPTIMAS, RPTU Kaiserslautern-Landau, Germany

Recent experimental and numerical studies reveal that exciton-polariton condensates in an asymmetric Lieb lattice belong to the KPZ universality class [1]. However, achieving stable KPZ scaling requires a negative polariton mass, restricting experiments to one-dimensional lattices. Photon Bose-Einstein condensates offer offer a promising realization in two dimensions without a lattice.

We describe the dynamics of a photon BEC using a stochastic generalized Gross-Pitaevskii equation coupled to a stochastic rate equation for the bath of dye molecules [2]. Following Refs. [2,3], we incorporate a continuum analogue of incoherent hopping processes, which occur in photon BEC lattices. Using methods from exciton-polariton studies [1], we approximately map these dynamics to the KPZ equation. Additionally, we show that incoherent hopping significantly enhances effective photon-photon interactions for realistic experimental parameters.

[1] Q. Fontaine et alii, Nature **608**, 687 (2022).

[2] V. N. Gladilin and M. Wouters, Phys. Rev. A **101**, 043814 (2020).

[3] V. N. Gladilin and M. Wouters, Phys. Rev. Lett. **125**, 215301 (2020).

Q 39.2 Wed 14:45 HS V

**Dissipative dynamics and entanglement signatures of photon Bose-Einstein condensates in multiple microcavities** — •Aya Abouelela[1] and Johann Kroha[1,2] — [1]Univeristy of Bonn, Germany — [2]University of St. Andrews, UK

Quantum gases of photons have proven to be a versatile platform for investigating various quantum effects in many-body systems, including Bose-Einstein condensation, quantum coherence and entanglement. In this work, we investigate the driven-dissipative dynamics of open photon Bose-Einstein condensates (BEC) in a single-mode microcavity filled with dye molecules using the Lindblad master-equation approach. Two distinct types of dynamics are observed, a quasi-stationary condensate, which loses coherence after a sufficiently long time, and a lasing regime with finite condensate density in the steady state. We compute a phase diagram, which includes both the BEC and lasing regimes as a function of the experimentally tunable parameters, i.e., the external pumping power and the photon detuning frequency. We explore the possible entanglement signatures in a system of two coupled microcavities. The cavities are coupled via direct photon, as well as, molecule-assisted tunneling and the system can be proven to describe two-mode Gaussian states. We use the von Neumann entropy to quantify the degree of mutual information between the two states. Lastly, we utilize the covariance matrix to study the violation of the Peres-Horodecki criterion which implies inseparability of states, and consequently, entanglement.

Q 39.3 Wed 15:00 HS V

**Photon condensates in anisotropic traps: Dimensional crossover** — •Kirankumar Karkihalli Umesh[1], Julian Schulz[2], Sven Enns[2], Julian Schmitt[1], Martin Weitz[1], Georg von Freymann[2,3], and Frank Vewinger[1] — [1]Institut für Angewandte Physik, Universität Bonn, Wegelerstrasse 8, 53115 Bonn, Germany — [2]Physics Department and Research Center OPTIMAS, RPTU Kaiserslautern Landau, 67663 Kaiserslautern, Germany — [3]Fraunhofer Institute for Industrial Mathematics ITWM, Kaiserslautern, Germany

Recent advances in confinement technology based on 3D Direct Laser Writing (DLW) of nanostructures for dye-filled microcavities have allowed for an observation of a dimensional crossover in a bosonic system, namely non-interacting bosons (Nat. Phys. 20, 1810-1815 (2024)). In our system, photons are trapped in microscopic structures, and they thermalise by radiative coupling to a heat bath of dye molecules. In this system, we have observed the softening of the phase transition to a Bose-Einstein condensate when crossing from a harmonically trapped gas in a 2D to a 1D system. The technology used has the potential to realise arbitrary potentials for light, including lattice structures and traps with large trapping frequencies, allowing us to engineer interesting potential landscapes for photons to explore physics which has been inaccessible until now. We will present our latest results on lattice structures required to observe non-Hermitian dynamics-induced vortices in non-interacting bosons (Phys. Rev. Lett. 125, 215301 (2020)).

Q 39.4 Wed 15:15 HS V

**Field-theoretical description of driven-dissipative photon Bose-Einstein condensates** — •Roman Kramer[1], Michael Kajan[1], and Johann Kroha[1,2] — [1]Physikalisches Institut, Universität Bonn — [2]University of St. Andrews, United Kingdom

We formulate a Schwinger-Keldysh field theory to treat the non-Markovian dynamics of driven-dissipative quantum systems coupled to a reservoir. This is done by introduction of auxiliary particles, which assign an indiviual quantum field to each reservoir state, as developed in [1]. We apply the formalism to a driven-dissipative photon Bose-Einstein condensate (BEC) coupled to a reservoir of dye molecules with electronic and vibronic excitations in an optical microcavity, as observed experimentally in [2]. The emergence of a photon BEC is then achieved by inclusion of $U(1)$ symmetry-broken photon fields, which thermalize due to coupling to the molecules described by auxiliary particles. We find that the condensed parts of the photon modes dynamically synchronize and form a single BEC. This formalism can be extended to multiple coupled cavities.

References:

[1] T. Bode, M. Kajan et al. *Phys. Rev. Res.* **6**, 10.1103 (2024).

[2] J. Klaers, J. Schmitt, F. Vewinger et al. *Nature* **468**, 545 (2010).

Q 39.5 Wed 15:30 HS V

**Quantum gases of light in ring potentials** — •Patrick Gertz, Leon Espert Miranda, Andreas Redmann, Kirankumar Karkihalli Umesh, Frank Vewinger, and Martin Weitz — Institute for Applied Physics, University of Bonn, Wegelerstraße 8, 53115 Bonn, Germany

Optical quantum gases in material-filled microcavities provide exquisite experimental control over dimensionality, shape of the energy landscape or the coupling to reservoirs, which opens the door to investigate novel states of matter both in and out of equilibrium. Here we report on the experimental realization of a quantum gas of photons in ring-shaped potentials within a dye-filled optical microcavity. The trapping potential for the cavity photons is provided by imprinting static nanostructures on the surface of one of the cavity mirrors using a controlled laser-induced delamination of the dielectric mirror coating. We have achieved the quasi-1D, periodically closed confinement of photon gases in ring potentials and performed initial, characterizing measurements of spatial and spectral distributions. Prospects of this work include studies of both the Kibble-Zurek mechanism for photon condensates and of optical flux qubits.

Q 39.6 Wed 15:45 HS V

**Observation of Coherent oscillations in lattices for photon condensates** — •Peter Schnorrenberg[1], Daniel Ehrmanntraut[1], Nikolas Longen[1], Purbita Kole[1], Kevin Peters[1], and Julian Schmitt[1,2] — [1]Universität Bonn, IAP, Wegelerstr. 8, 53115 Bonn — [2]Universität Heidelberg, KIP, Im Neuenheimer Feld 227, 69120 Heidelberg

Exploring coherent dynamics of quantum gases trapped in periodic lattice potentials enables the microscopic study of fundamental phenomena, e.g., from condensed matter physics. Previous work with ultracold atoms or exciton-polaritons has focused on closed or far-from-equilibrium systems, respectively. Bose-Einstein condensates of photons in dye-filled microcavities, on the other hand, offer a new approach to access coherent dynamics of bosons in variable lattice potentials due to the possible coupling to the enviroment, e.g., from gain, loss, or reservoirs. Here we present measurements of the coherent dynamics of photon condensates trapped in periodic lattice potentials inside a dye-filled microcavity. By recording the time-resolved photon density, we observe Rabi oscillations in double well traps, which we validate by independent spectroscopic measurements, for variable tunneling rates. Moreover, we explore the emergence of Bloch oscillations in larger lattices, consisting of several sites. Our experimental scheme paves the way to investigate the crossover from coherent to incoherent dynamics in the presence of dephasing from reservoirs, which could provide new insights into quantum transport.

Q 39.7 Wed 16:00 HS V

**Imprinting reconfigurable topological states for photon condensates** — •Kevin Peters[1], Nikolas Longen[1], Purbita Kole[1], Daniel Ehrmanntraut[1], Peter Schnorrenberg[1], and Julian Schmitt[1,2] — [1]Universität Bonn, Institut für Angewandte Physik, Wegelerstrasse 8, 53115 Bonn, Germany — [2]Universität Heidelberg, Kirchhoff Institut für Physik, Im Neuenheimer Feld 227, 69120 Heidelberg

Previous studies in topological photonics have mostly focused on Hermitian engineering of the photonic band structure, with topological properties largely fixed in fabrication. However, recent theoretical work has proposed topological states of light arising solely from non-Hermiticity in a priori trivial lattices. Experimentally, such states have recently been observed in plasmonic waveguide arrays, although still predetermined in fabrication.

Here, I will present numerical evidence illustrating topological phases arising in 1D arrays of photon condensates through tunable gain and loss. Our system comprises dye-filled optical microcavities, coherently coupled by spatially uniform hopping. Tunable gain and loss are achieved by site-resolved pumping of dye molecule reservoirs. For suitable gain and loss, we observe a bulk band gap and spatially localized end states. Additionally, tunability of the lattice potential provides control over Hermitian properties of our system. Competing Hermitian and non-Hermitian effects lead to a rich phase diagram with various numbers of end states. Our approach allows for highly tunable and reconfigurable topological states of light.

Q 39.8 Wed 16:15 HS V

**Optically tuneable lattice potentials for Bose-Einstein condensates of photons** — •Nikolas Longen[1], Purbita Kole[1], Daniel Ehrmanntraut[1], Peter Schnorrenberg[1], Kevin Peters[1], and Julian Schmitt[1,2] — [1]Universität Bonn, IAP, Wegelerstr. 8, 53115 Bonn, Germany — [2]Universität Heidelberg, KIP, Im Neuenheimer Feld 227, 69120 Heidelberg

The concept of periodic potentials plays a key role in solid state physics, giving rise to emergent classical and quantum phases in materials with intricate system properties, such as topological band structures. Correspondingly, the precise control of lattice potentials for quantum gases of atoms, polaritons, or photons enables the simulation of a wide range of complex physical systems. Here, we present the realisation of tuneable lattice potentials for Bose-Einstein condensates of photons within dye-filled optical microcavities. A static lattice potential is created by imprinting localised indents on high-reflectivity cavity mirrors, in which the photons are trapped. By irradiating one of the cavity mirrors with a laser beam shaped by a spatial light modulator, we locally modulate the temperature of the dye medium. Exploiting the thermo-optic response of the dye solution, we demonstrate the reversible tunability of the potential energy of the photon condensates at individual lattice sites. The tunability is characterised by its spatial, temporal and power dependence on the heating laser pattern. Creating and tuning potentials for photon Bose-Einstein condensates in lattices using this method permits the reconfigurable creation of band structures for light, particularly those of topologically non-trivial character.