Q 18: Photon BEC

Time: Tuesday 11:00–13:00 Location: P 4

Q 18.1 Tue 11:00 P 4

Using Direct Laser Writing to fabricate potential landscapes for photon gases in dye-filled microcavities — Julian Schulz[1], Kirankumar Karkihalli Umesh[2], •Sven Enns[1], Niklas Caspar[1], Frank Vewinger[2], and Georg von Freymann[1,3] — [1]Department of Physics and Research Center OPTIMAS, RPTU Kaiserslautern-Landau, 67663 Kaiserslautern, Germany — [2]Institute of Applied Physics, University of Bonn, 53115 Bonn, Germany — [3]Fraunhofer Institute for Industrial Mathematics ITWM, 67663 Kaiserslautern, Germany

We experimentally investigate photon gases and photon Bose-Einstein condensates in dye-filled microcavities. In order to achieve condensation in 2D systems and to investigate further phenomena such as incoherent transport [1], the creation of potential landscapes for the photon gas is necessary. We use the 3D laser lithography technology called Direct Laser Writing (DLW) to fabricate these potentials. Thereby, polymer structures can be printed onto the surface of the cavity mirrors. The refractive index contrast between the polymer structures and the dye-solution inside of the cavity create potential landscapes due to the modified optical path length. Using DLW allows for the creation of higher trapping frequencies and coupling rates between single potential sites in comparison to other techniques. We demonstrate these advantages by showing measurements of the photon gas in a SHH-chain and the dimensional crossover from 2D to 1D [2]. [1] L. Garbe et al., SciPost Phys. 16, 029 (2024). [2] K. Karkihalli Umesh et al., Nature Physics 20, 1810-1815 (2024).

Q 18.2 Tue 11:15 P 4

Observation of critical scaling in the Bose gas universality class — •Leon Kleebank[1], Frank Vewinger[1], Arturo Camacho-Guardian[2], Victor Romero-Rochin[2], Rosario Paredes[2], Martin Weitz[1], and Julian Schmitt[3] — [1]Institute of Applied Physics, Bonn, Germany — [2]Instituto de Fisica, Mexico City, Mexico — [3]Kirchhoff-Institut fur Physik, Heidelberg, Germany

Critical exponents characterize the divergent scaling of thermodynamic quantities near phase transitions and allow for the classification of physical systems into universality classes. While quantum gases thermalizing by interparticle interactions fall into the XY model universality class, the ideal Bose gas has been predicted to form a distinct universality class whose signatures have not yet been revealed experimentally. Here, we report the observation of critical scaling in a two-dimensional quantum gas of essentially noninteracting photons. We determine the critical exponent for the correlation length to be $\nu = 0.51(3)$.

Q 18.3 Tue 11:30 P 4

Kennard-Stepanov relation connecting absorption and emission in two-species xenon-noble gas mixtures — •Eric Boltersdorf, Thilo vom Hövel, Frank Vewinger, and Martin Weitz — Institute of Applied Physics, Bonn, Germany

Photons confined in a dye-filled microcavity can exhibit Bose-Einstein condensation upon thermalization through repeated absorption and (re-)emission processes on the dye molecules. This has been experimentally demonstrated for photons in the visible spectral regime in 2010. The most important prerequisite for the dye molecules to be a suitable thermalization mediator is the fulfillment of the so-called Kennard-Stepanov relation, a thermodynamic, Boltzmann-like scaling law connecting the absorption and emission lineshapes. In the present work, an experimental approach is investigated to realize Bose-Einstein condensation of vacuum-ultraviolet (100 nm - 200 nm; VUV) photons via repeated absorption and (re-)emission cycles between the $5p^6$ ground state and the $5p^5 6s$ (J = 1) excited state of xenon-noble gas excimer molecules in dense gaseous ensembles (pressure of up to 100 bar). Here, we present experimental data giving strong evidence for a Kennard-Stepanov scaling of photons in these dense xenon-noble gas ensembles.

Q 18.4 Tue 11:45 P 4

Limit Cycles Driven by non-Hermitian Interactions in Coupled Photon Condensates — •Kevin Peters[1], Peter Schnorrenberg[2], Daniel Ehrmanntraut[1,2], Nikolas Longen[1,2], and Julian Schmitt[2] — [1]Universität Bonn, Institut für Angewandte Physik, Wegelerstr. 8, 53115 Bonn, Germany — [2]Universität Heidelberg, Kirchhoff Institut für Physik, Im Neuenheimer Feld 227, 69120 Heidelberg

We report the first observation of limit cycle oscillations in photon condensates. In our experiments, photons were trapped in two coherently coupled, dye-filled optical microcavities forming a photonic dimer. Previous work has demonstrated Bose-Einstein condensation of the photons into the symmetric ground state of the dye-filled dimer above a critical photon number for the case of spatially uniform pumping. Here we report on the observation of emergent, self-sustained dynamics under inhomogeneous excitation. When only a single site of the dimer is pumped, we experimentally observe spontaneous oscillations in the photon number at both sites, appearing over a range of pump powers. We show that these oscillations are the result of stable limit cycles associated with a parametric instability predicted by theory. Unlike in Kerr and thermo-optical nonlinear cavities, the instability in the dye-microcavity system is driven by effective imaginary photon-photon interactions. These non-Hermitian interactions are mediated by the dye molecules, and their strength can be conveniently tuned via the cut-off frequency imposed by the cavity length.

Q 18.5 Tue 12:00 P 4

Two-Dimensional Photon Gases in a Silver-Mirror Based Optical Dye-Microcavity — •Niels Wolf, Leon Kleebank, Andreas Redmann, Frank Vewinger, and Martin Weitz — University of Bonn

While the thermalization of radiation through contact with matter is a well-established concept, it has been shown only relatively recently that, when applying this concept to low-dimensional photon gases, optical quantum gases with a tunable chemical potential can be realized, allowing for the formation of Bose-Einstein condensates of photons [1]. Thermalization is in this system reached by repeated absorption and emission processes on dye molecules, which act as a thermal reservoir for the photon gas. In principle one can expect that this photon gas thermalization mechanism should allow for a phase-space build-up of light, although microcavity systems based on dielectric mirrors have not shown this effect, as understood from the large angle-dependence of the dielectric mirror reflectivities, which result in photon loss [2]. We have set up a dye-filled microcavity apparatus based on metallic mirrors, which offer a much wider angular acceptance range than dielectric mirrors. The aim of this ongoing experiment is the observation of phase-space build-up of light. The current status of the experimental results, which include observations of the microcavity emission spectra of a two-dimensional photon gas in the metallic mirror setup, will be reported.

[1] J. Klaers, J. Schmitt, F. Vewinger, and M. Weitz, Nature 468, 545-548 (2010) [2] E. Busley et al., Phys. Rev. A 107, 052204 (2023)

Q 18.6 Tue 12:15 P 4

On vortices in photon Bose–Einstein condensates: Open-dissipative effects on size and stability — •Joshua Krauss and Axel Pelster — Physics Department and Research Center OPTIMAS, RPTU Kaiserslautern-Landau, Kaiserslautern, Germany

Open-dissipative quantum fluids have been extensively studied numerically [1,2]. In view of a complementary analytical description, a recent study [3] introduced the projection optimization method, generalizing the standard optimization method for closed condensates [4] to open-dissipative systems. We apply this method to a complex Gross–Pitaevskii equation [6] that heuristically models a photon Bose–Einstein condensate, which is harmonically trapped. Together with established methods from hydrodynamics, we obtain an approximate dynamical vortex solution and demonstrate how open-dissipative parameters affect vortex both size and stability.

[1] V.N. Gladilin and M. Wouters, *Phys. Rev. Lett.* **125**, 215301 (2020)
[2] V.N. Gladilin and M. Wouters, *New J. Phys.* **19**, 105005 (2017)
[3] J. Krauß *et alii*, *Phys. Rev. Res.* **7**, 033007 (2025)
[4] V.M. Perez-Garcia *et alii*, *Phys. Rev. Lett.* **77**, 5320 (1996)
[5] J. Keeling and N.G. Berloff, *Phys. Rev. Lett.* **100**, 250401 (2008)

Q 18.7 Tue 12:30 P 4

Steady-state behavior and symmetry breaking of photon

BECs — •Milan Radonjić[1,2], Axel Pelster[3], and Michael Thorwart[1] — [1]I. Institut für Theoretische Physik, Universität Hamburg, Germany — [2]Institute of Physics Belgrade, University of Belgrade, Serbia — [3]Physics Department, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, Germany

We revisit the dynamics of open, driven-dissipative photon Bose-Einstein condensates (phBECs) in a dye-filled microcavity using a cumulant expansion approach within the Lindblad formalism [1,2]. Motivated by a recent study [3], we extend our previous work [2] by considering, in addition to U(1)-invariant operator averages, the condensate amplitude and other U(1)-symmetry breaking amplitudes as non-zero. Specifically, we analyze the possible steady states of the dynamics using a method typically employed in laser theory. This allows us to critically examine the emergence of the ghost attractor and its impact on the long-time behavior of phBECs.

[1] P. Kirton and J. Keeling, Phys. Rev. Lett. 111, 100404 (2013).
[2] M. Radonjić et al., New J. Phys. 20, 055014 (2018).
[3] A. Abouelela et al., Phys. Rev. Lett. 135, 053402 (2025).

Q 18.8 Tue 12:45 P 4

Ring Potentials for Photons in Dye-Filled Optical Microcavities — •Patrick Gertz, Leon Kleebank, Andreas Redmann, Kirankumar Karkihalli Umesh, Frank Vewinger, and Martin Weitz — Institute for Applied Physics, University of Bonn, Wegelerstraße 8, 53111 Bonn

Nanostructured dye-filled optical microcavities permit the study of quantum gases of light, while allowing precise experimental control over dimensionality, shape of the energy landscape and coupling to reservoirs. This enables the investigation of novel states of matter both in and out of equilibrium.

Here we report on the experimental implementation of a quantum gas of photons confined to a ring-shaped potential within such a material-filled microcavity, where the trapping potential is provided by static nanostructures, achieved by controlled laser-induced delamination of the dielectric coating of one of the cavity mirrors. We have achieved quasi-1D, periodically closed confinement of photon gases in ring potentials and performed measurements of the spatial and spectral distributions. Also, we observe macroscopic ground state occupation, giving preliminary evidence for Bose-Einstein condensation of photons in the system.