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Compressing a quantum gas of light and determining its equation of state

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Quantum gases of light, as photon or polariton condensates, can be realized in low-dimensional, mostly two-dimensional experimental settings. We have determined the mechanical compressibility of a photon Bose-Einstein condensate realized in a box potential and revealed its equation of state [1].

In our experiment, a photon Bose-Einstein condensate is realized in a dye-solution-filled optical microcavity, where the used small mirror-spacing in the wavelength regime introduces a low-frequency cutoff and photons thermalize by repeated absorption re-emission cycles to the rovibrational temperature of the dye, which is at room temperature. For the measurement of the mechanical compressibility of the optical quantum gas, a box potential was imprinted for cavity photons by microstructuring one of the cavity mirrors reflecting surface. We observe evidence for Bose-Einstein condensation of the photon gas above a critical photon number, as a saturation of the thermal photon cloud and a macroscopically populated condensate peak. These signatures of condensations in the finite size homogeneous two-dimensional system are well understood from the nearly vanishing small photon-photon interaction.

By mechanically tilting one of the cavity mirrors, a uniform force was exerted to the two-dimensional photon gas in the microcavity, which enables us to determine the mechanical compressibility of the optical quantum gas by monitoring the response to the force by camera imaging. While in the classical regime the compressibility reduces with density, as soon as the thermal de Broglie wavepackets spatially overlap and quantum degeneracy is reached, we observe an increase of the compressibility with density, as well understood from the at this point enhanced population of low-energy states due to quantum statistics. This confirms corresponding theory predictions and represents the first steps for quantum machines with light as the working medium. From the observed response of the optical quantum gas, we have also determined its equation of state.

In more recent measurements, we have carried out a novel test of the fluctuation-dissipation relation of the photon condensate coupled to the dye reservoir [2]. This confirms both the thermalized nature of the photon gas on a very fundamental level, as well as the picture of the dye electronic excitation providing an effective particle reservoir for the system photons in a grand canonical sense.

[1] E. Busley, L.E. Miranda, A. Redmann, C. Kurtscheid, K.Karkihalli Umesh, F. Vewinger, M. Weitz, and J. Schmitt, Science **375**, 1403 (2022).

[2] F. E. Öztürk, F. Vewinger, M. Weitz, and J. Schmitt, Phys. Rev. Lett. **130**, 033602 (2023).

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