Superfluid light in dense atomic vapor

Murad Abuzarli[1*], Wei Liu[1], Quentin Fontaine[1], Tom Bienaimé[1], Elisabeth Giacobino[1], Alberto Bramati[1], Quentin Glorieux[1]

[1] *Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-PSL Research University, Collège de France, 4 place Jussieu, 75005 Paris, France*

*E-mail: murad.abuzarli@lkb.upmc.fr

We study quantum fluids of light by engineering experimental setups that realize effective photon-photon interactions and probing the evolution of such systems in different environments.

We use a hot Rb vapor as an optically non-linear medium to produce a self defocusing beam which can be interpreted as a flux of repulsing photons in the transverse plane. Unlike the commonly used cavity configuration where light trapped in a 2D plane is strongly coupled to the matter inside it and acquires thus matter-mediated interactions [3], in our paraxial geometry the propagation is analogous to the temporal evolution of a 2D fluid (Figure 1). This analogy is apparent if one compares the non-linear propagation equation for the electric field amplitude (equation (2)) to the Gross-Pitaevskii equation (GPE, 1), the time coordinate is replaced by the axial direction:

$$i\hbar\partial_t\Psi(\mathbf{r},t) = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r}) + g|\Psi(\mathbf{r},t)|^2\right]\Psi(\mathbf{r},t), \quad (1)$$

$$i\partial_z\mathcal{E}(\mathbf{r}_\perp,z) = \left[-\frac{1}{2k}\nabla_\perp^2 + V_\perp(\mathbf{r}_\perp) + g'|\mathcal{E}(\mathbf{r}_\perp,z)|^2\right]\mathcal{E}(\mathbf{r}_\perp,z), \quad (2)$$

where Ψ stands for the macroscopic wavefunction, $\mathcal{E}$ for the electric field amplitude, $\hbar$ for the reduced Planck constant, m the boson mass, $k = n\omega/c$ for the laser wavevector magnitude, V and $V_\perp$ for the external potentials, finally g and $g' = -k\chi^{(3)}/(2n^2)$ the interaction constants. The GPE (equation 1) is a mean-field description of a superfluid (SF) [2]. The key ingredients required for superfluidity, namely macroscopic coherence of the wavefunction and interaction between particles are readily available in our setup with the optical coherence of the laser and the optical non-linearity g' induced by Rb atoms, respectively. Hence our research addresses the question: can one observe experimentally signatures of superfluidity for light?

We measured the propagation of small density perturbation (optical intensity modulation) on top of a fluid of light [1]. The measured dispersion relation is analogous to that of the Bogoliubov quasiparticles in a superfluid. In our case the wavenumber is given by the transverse spatial frequency of the intensity modulation. The generalized frequency is inferred from the measurement of the pertubation wavepacket's group velocity. The latter, in turn, scales as the square root of the fluid density, similar to the speed of sound of the Bogoliubov modes in a superfluid.

Current investigations aim at adding two new features to the setup: the first one consists in confining the fluid of light in an external potential $V_\perp$. This can be achieved by creating transverse variation of the refractive index with the help of an auxiliary beam and multi-level structure of Rb atoms. With this tool our setup will be able to simulate quantum fluids in ordered lattices or disordered external potentials. The second one aims at experimentally reaching long evolution times. In fact, current limitation of probing fluid's dynamics resides in finite cell length. Even if using longer vapor cells partially solves this problem, in order to access arbitrarily long evolution times we will implement the state recycling procedure [4] by reinjecting the final state of the field back into the vapour cell entrance.

On the long term, the aim of our research project is to provide an experimental platform for simulation of quantum many-body systems relevant for quantum technologies.

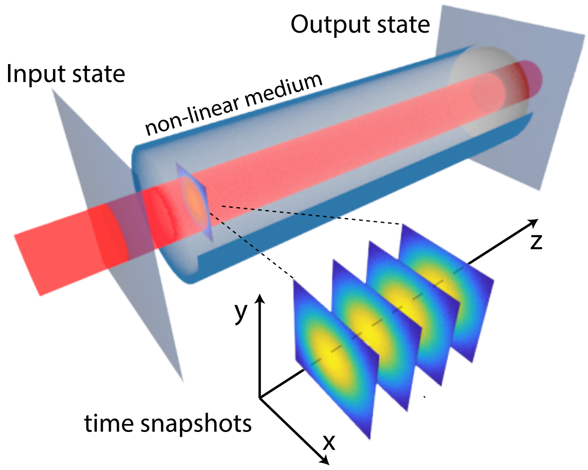

Figure 1: Schematic visualization of the experiment.

Acknowledgement

Research conducted within the PhoQuS (Photons for Quantum Simulation) project funded by the European Commission (Grant agreement ID: 820392).

References

[1] *Q. Fontaine, T. Bienaimé, S. Pigeon, E. Giacobino, A. Bramati, and Q. Glorieux*, Observation of the Bogoliubov Dispersion in a Fluid of Light. Phys. Rev. Lett. **121**, 183604 (2018)

[2] *I. Carusotto*, Superfluid light in bulk nonlinear media. **470** Proc. R. Soc. A (2014)

[3] *Iacopo Carusotto and Cristiano Ciuti*, Quantum fluids of light Rev. Mod. Phys. **85**, 299 (2013).

[4] *S. Mukherjee, H.K. Chandrasekharan, P. Öhberg, N. Goldman and R.R.Thomson* State-recycling and time-resolved imaging in topological photonic lattices. Nat Commun **9**, 4209 (2018)