Multiple self-organized phases in cold atoms mediated by optical feedback

Giuseppe Baio, Gordon R. M. Robb, Alison M. Yao, Gian-Luca Oppo, Thorsten Ackemann
SUPA and Department of Physics, University of Strathclyde, Glasgow G4 0NG, Scotland, United Kingdom

Self-structuring via symmetry breaking is a prominent collective phenomenon occurring in cold and ultracold atoms coupled to optical fields [1]. Experimental realizations by means of trapped dipolar gases and optical cavities have shed light onto supersolidity and crystallization in out-of-equilibrium atomic systems [2, 3]. Recent work demonstrated the occurrence of structural transitions between supersolid phases in dipolar condensates [4]. In this work, we theoretically address 2D structural transitions occurring in an ensemble of cold thermal atoms with effective optomechanical interactions mediated by a coherent beam retro-reflected by means of a feedback mirror. The feedback loop scheme is represented in Fig. 1(a), where the dipole potential induces atomic density structures which, in turn, scatter photons into side-band modes enhancing the potential itself and leading to transverse light-atom self-structuring, sharing similarities with an effective-Kerr nonlinear medium [5].

The structural transitions above threshold are characterized in terms of three light-density crystalline phases, namely, hexagonal ($\mathbf{H}^+$), stripe ($\mathbf{S}$), and honeycomb ($\mathbf{H}^-$) (See Fig. 1(b)), in dependence on an interaction strength identified by the linear susceptibility of the cloud $\chi = b_0\Delta/2(1+\Delta)$, where b_0 is the on-resonance optical thickness and Δ the atomic detuning. Thus, within the space spanned by (b_0, Δ) with $\Delta > 0$, we identify phase boundaries in terms of a weakly nonlinear formalism, based on the real Ginzburg-Landau amplitude equations and corresponding free-energy functional. This leads to an analytical dependence of the free energy on χ for the different phases, where the corresponding minima determine the observed phase and theoretical boundaries in good agreement with numerical simulations (See Fig. 1(c)). An intriguing consequence of the structural landscape of our system, theoretically forbidden by the effective-Kerr picture, is given by the recovery of *inversion symmetry* in the $\mathbf{S}$ phase which results nontrivially from a self-tuning process, i.e., without recurring to externally imposed symmetry-breaking conditions.

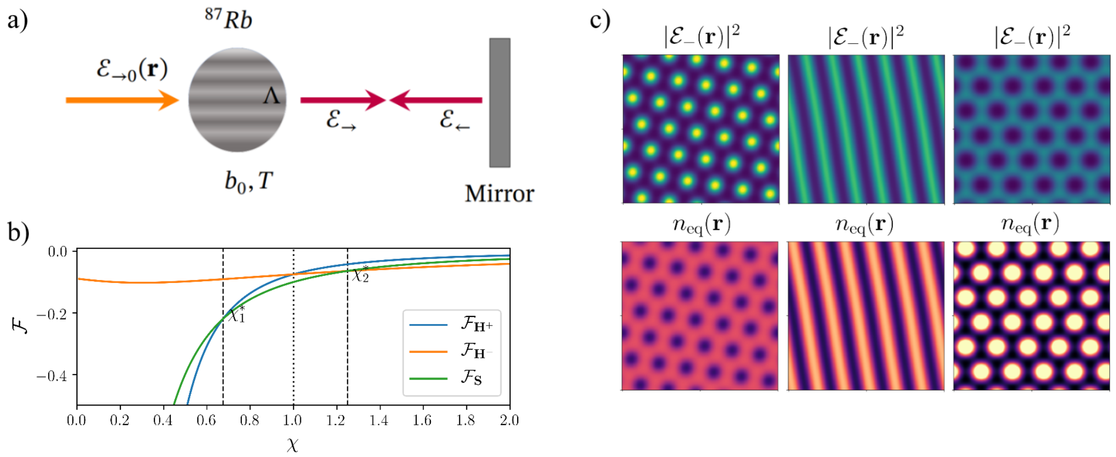

Fig. 1 a) Optomechanical single-feedback-mirror scheme. A far detuned beam of amplitude $\mathscr{E}_{\to 0}$ illuminates a cloud of atoms of optical density b_0 and temperature T. b) Multiple self-structured phases obtained at fixed b_0 and varying $\Delta > 0$ (blue detuning). Note the anti-correlated equilibrium intensity $|\mathscr{E}_{\leftarrow}|^2$ and density n_{eq} transverse profiles. c) Free-energy of the three phases above threshold. The minimum determines the observed phase while the intersections (dashed lines) identify the phase boundaries.

Moreover, we show that the stability of the $\mathbf{H}^+$ phases imply the existence of spatial feedback solitons that can be used as self-sustained atomic traps. Transverse motion of such feedback localized structures can be controlled by means of phase structured input $\mathscr{E}_{\to 0}(\mathbf{r})$, as demonstrated recently in [6].

References

[1] H. Ritsch, P. Domokos, F. Brennecke, and T. Esslinger. *Rev. Mod. Phys.* **85**, 553–601, 2013.

[2] F. Boettcher, J.-N. Schmidt, J. Hertkorn, K. Ng, S. Graham, M. Guo, T. Langen, and T. Pfau. *Rep. Progr. Phys.* , 2020.

[3] J. Léonard, A. Morales, P. Zupancic, T. Esslinger, and T. Donner. *Nature* **543**, 87, 2017.

[4] Y.C. Zhang, F. Maucher, and T. Pohl. *Phys. Rev. Lett.* **123**, 15301, 2019.

[5] G. Labeyrie, E. Tesio, P. M. Gomes, G.-L. Oppo, W. J. Firth, G. R. M. Robb, A. S. Arnold, R. Kaiser, and T. Ackemann. *Nat. Phot.* **8**, 321–325, 2014.

[6] G. Baio, G. R. M. Robb, A. M. Yao, and G.-L. Oppo. *Phys. Rev. Res.* **2**, 023126, 2020.

This is an accepted author manuscript of the following conference contribution: Baio G, Robb GRM, Yao AM, Oppo GL, Ackemann T. 2021. Structural phase transitions in cold atoms mediated by optical feedback. In 2021 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC). Piscataway, NJ.: IEEE. Article 9541765. https://doi.org/10.1109/CLEO/Europe-EQEC52157.2021.9541765