Nonequilibrium quantum phase transitions in a hybrid atom-optomechanical system

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We consider a hybrid quantum many-body system formed by a vibrational mode of a nanomechanical membrane, which interacts optomechanically with light in a cavity, and an ultracold atom gas in the optical lattice of the out-coupled light [1]. A competition occurs between the force localizing the motional state of the atoms in the optical lattice and the membrane displacement. At a critical atom-membrane interaction, we find a nonequilibrium quantum phase transition from a localized symmetric state of the atom cloud to a shifted symmetry-broken state. A strong atom-membrane entanglement arises. The effect occurs when the atoms and the membrane are non-resonantly coupled.

In addition, also the internal degrees of freedom of the atoms can be addressed [2,3]. We show that this hybrid atom-optomechanical system not only undergoes a nonequilibrium quantum phase transition between phases of different collective behavior, but also that the order of the phase transition can be tuned. The coupling between atoms and membrane can tuned by changing the intensity of a common laser. The order of the phase transition is determined by the imbalance of the population of internal atomic states and the transition frequency. Moreover, hysteresis is found by adiabatically tuning the coupling strength in the regime of a first-order phase transition. Finally, we show [3] that the mechanical mode can be squeezed by the backaction of internal excitations of the atoms in the gas. A Bogoliubov approach reveals that these internal excitations form a fluctuating environment of quasiparticle excitations for the mechanical mode with a gaped spectral density. Nanomechanical squeezing arises due to quasiparticle excitations in the interacting atom gas when the mechanical frequency is close to resonance with the internal atomic transitions. Interestingly, nanomechanical squeezing is enhanced by atom-atom interactions.

[1] N. Mann, M. R. Bakhtiari, A. Pelster, and M. Thorwart, Phys. Rev. Lett. 120, 063605 (2018).

[2] N. Mann, A. Pelster, and M. Thorwart, submitted (2019).

[3] N. Mann and M. Thorwart, Phys. Rev. A 98, 063804 (2018).