Optomechanical Systems as Quantum Heat Engines

Miika Rasola[1]
Mikko Möttönen[1]

1. QCD Labs, Department of Applied Physics, Aalto University, Espoo, Finland

miika.rasola@aalto.fi

While new quantum technologies [1] are being developed at an accelerating pace, the field of quantum thermodynamics (QTD) [2] is attracting a lot of attention, as researches find themselves wondering, how do these new quantum devices interact with heat. QTD attempts to answer that question by investigating the relationship between two fundamental theories: quantum mechanics and thermodynamics. From such considerations, a completely new type of device can be envisioned. A quantum heat engine [2][3] is a device operating at the quantum level, specifically designed to interact with heat reservoirs and extract coherent work from heat flow. Here we propose to utilize a well-know quantum device in a novel manner in order to realize such a quantum heat engine.

An optomechanical cavity is an interesting type of quantum system where various quantum phenomena are regularly investigated [4]. In an optomechanical system, two oscillator modes are coupled with a non-linear coupling, described by the following Hamiltonian:

$$H_I = -\hbar g_0 \hat{a}\hat{a}^T (\hat{b} + \hat{b}^T)$$

The mode related to the operator $\hat{a}$ is the optical cavity mode and the mode related to $\hat{b}$ is the mechanical mode.

The optical mode in an optomechanical system is typically driven by a coherent laser. Here, we present a new scheme of utilizing an optomechanical system by coupling the optical mode to two heat baths separated in temperature. The heat baths are given Lorentzian line shapes centred at different frequencies, so that the hot bath has a higher characteristic frequency. As heat flows from the hot to the cold bath through the optical cavity, some of that energy is transferred to the mechanical mode due to the difference in average photon energies between the baths.

The rather intricate dynamics of this system can be relatively well captured (in a certain parameter regime) by a Heisenberg-Langevin (HL) stochastic equation. Here, we derive and numerically solve the HL equations for a system described above. In figure 1. we present an example of the time evolution of expected photon occupations in the optical and mechanical modes.

There are numerous ways of realizing the system described here physically. One viable candidate is circuit quantum electrodynamics (cQED) [5], where heat conduction studies are already being performed, and optomechanical coupling can be achieved [6].

Figures

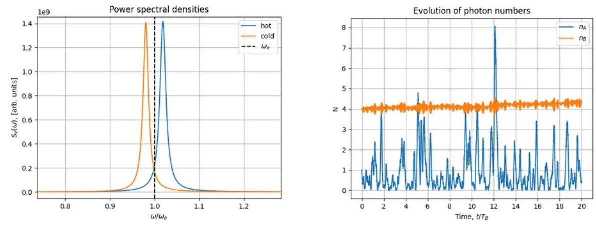

Figure 1: Left: Spectral densities of the heat baths. Right: Example evolution of the optical (blue) and mechanical (orange) modes.

References

[1] W. P. Schleich et al, Appl. Phys. B 122:130 (2016)

[2] S. Deffner and S. Campbell, Morgan and Claypool Publishers 2053-2571 (2019)

[3] Q. Bouton et al, Nat Com. 12 2063 (2021)

[4] M. Aspelmeyer et al, Rev. Mod. Phys. 86 1391 (2014)

[5] A. Blais et al, Rev. Mod. Phys. 93 025005 (2021)

[6] J. R. Johansson et al, Phys. Rev. A 90 053833 (2014)