Periodic Energy Transport and Entropy Production in Quantum Systems

David Sánchez[1]

[1]Institute for Cross-Disciplinary Physics and Complex Systems IFISC (UIB-CSIC),
Campus Universitat Illes Balears, E-07122 Palma de Mallorca, Spain

The understanding of the energy transfer in nonequilibrium open quantum systems is a fundamental problem in physics. The separation of energy in heat and useful work and dissipation is the key for a thermodynamical description. In quantum systems under ac driving, the identification of these different components of energy is a nontrivial task which is paramount to cold atoms, nanomechanical, nanoscale optoelectronical, and mesoscopic electron systems. Typically, the central piece of these systems contains a small number of particles and are driven out of equilibrium, which renders a usual thermodynamical description unreliable. Yet, they are in contact to one or more macroscopic reservoirs with well defined thermodynamical intensive parameters.

Most of the recent literature on quantum thermodynamics focuses on static fields and the resulting stationary transport effects. However, there is a growing interest in analyzing thermodynamic properties of quantum conductors in the presence of time-dependent potentials [1]. In this case, dynamics is the main objective of the theory as fluxes and responses depend explicitly on time. In addition to the interest on fundamental aspects, it is of paramount importance for potential applications to discriminate which portion of the energy invested to operate quantum devices is amenable to be used and which one is wasted by dissipation. This distinction is at the heart of thermodynamics and is conventionally addressed in quasistationary processes where the system under study is very weakly coupled to the reservoirs. In quantum electronics, nevertheless, the generic situation is to have the driven structure strongly coupled to the rest of the circuit, which plays the role of reservoir. On the other hand, we are typically interested on the generation of currents, which implies nonequilibrium situations.

In this talk, I will discuss in detail the energy transfer in out-of-equilibrium systems coupled to external baths. The analysis is based on a phase-coherent mesoscopic sample (a confined system with discrete energy levels) attached to fermionic reservoirs held at a given temperature. In Fig. 1 we schematically show the two terminal case. The energies of the sample evolve with time due to the coupling with nearby ac gate terminals. Deep inside the reservoirs, electrons relax their excess energy and the baths can thus be considered in local thermal equilibrium. We will also consider the entropy production in the whole system and will identify the different terms arising in the redistributed energy and heat [2, 3]. Importantly, when the energies shift slowly with time the response is adiabatic and an exact Joule law can be demonstrated for the time domain. [2] In addition, we will briefly discuss the nonadiabatic regime [4] in which case the ac frequency is larger or of the order of the inverse dwell time inside the conductor. Our analysis is completely general and does not rely on the particular approach followed to evaluate the relevant dynamical quantities, like the charge and energy fluxes and the rate of entropy production.

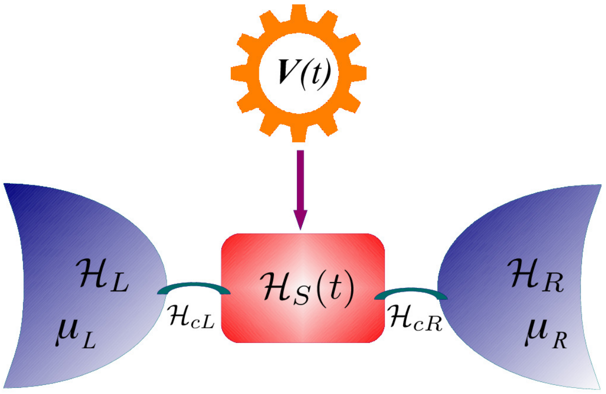

Figure 1: Sketch of the system under consideration. A quantum conductor (described by the Hamiltonian H_S), is coupled to two reservoirs (H_L and H_R) kept at the same temperature T, but with different chemical potentials μ_L and μ_R. The conductor is also driven out of the equilibrium by the application of ac local power sources, which are all collected in the vector $\mathbf{V}(t)$. The Hamiltonians representing the left and right contact regions are H_{cL} and H_{cR}, respectively.

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