1.3.12 Quantum thermal machines

The interest in study quantum thermal machines has its roots in the need to understand the relations between thermodynamics and quantum mechanics [1, 2]. The progress in this field has also important applications in the control of heat transport in nano-devices [3]. The fundamental limits to the dimensions of a quantum refrigerator have been found in series of recent works [4-6]. It has been further demonstrated that these machines could still attain Carnot-efficiency [5] thus launching the call for the implementation of the smallest possible quantum refrigerator.

We theoretically designed an electronic quantum refrigerator based on four quantum dots arranged in a square configuration, in contact with as many thermal reservoirs [7]. The system implements the minimal mechanism for acting as a self-contained quantum refrigerator, by operating without the requirement of external time-dependent work and demonstrating heat extraction from the coldest reservoir and the cooling of the nearby quantum-dot. We also discuss the operational nature of the definition of local temperatures in systems out of equilibrium and how important is to discuss reference experimental regimes to define the regime of operation of small quantum thermal machines.

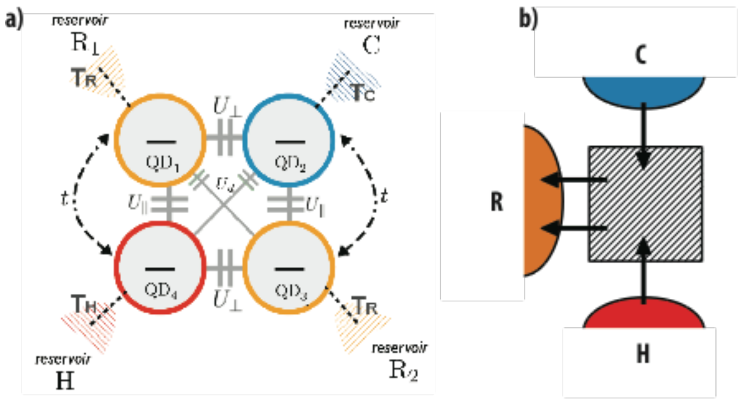

Figure 1: a) The quadridot. Vertical and Horizontal interdot capacitances are considered to be the highest energy scales among those in the figure. Their values are determined by the arrangement of the top gates over the QDs, which are not shown. The four quantum dots are weakly tunnel coupled to the electronic reservoirs H, C, R1, and R2, respectively, which are all grounded but maintained at equilibrium at a well-defined temperatures. No tunneling is possible between dot 1 (orange) and dot 2 (blue), and between dot 4 (red) and dot 3 (orange). b) schematic representation of the heat flux.

Minimal self-contained thermal machines are theoretical systems that perform a cycle based only on the steady-state heat transfer from thermal reservoirs at different temperatures, utilizing as few degree of freedom as possible. In our work we design an implementation of these machines operating by quantum mechanical tunneling, consisting of four quantum dots in a planar square array (named a “quadridot”) coupled to independent electron reservoirs as shown in Fig. 1. The couplings and the electrostatics interactions has been carefully chosen so that the quadridot could pump energy from the high temperature reservoir H and the low temperature reservoir C to the intermediate temperature reservoirs, thereby acting as a "quantum refrigerator" (Fig 1). To show this effect, we explicitly solve the open dynamics of the quadridot and study its asymptotic behavior. In the Born-Markov-Secular limit we write a Lindblad equation for the reduced density matrix of the quadridot, which describes the effective dissipative and coherent interaction between the low-energy states of the system obtained after a Schrieffer-Wolff transformation. Solving numerically the steady state equation we observe that for each TC < TR, there exists a minimal threshold value for TH above which the quadridot extracts heat from the cold reservoir C. This is shown in Fig. 2-a for TR=2 and different values of Ud, the quadridot works as a refrigerator in the blue region. For given TH > TR, there is a minimal temperature (whose approximate value is obtained analytically) for the cold reservoir under which the effect cannot work. Interestingly for large values of TH/TR this value asymptotically converges toward a finite non-zero temperature which can be interpreted as the emergent absolute zero of the model. This refrigeration effect is also accompanied with a cooling of QD2, namely its effective local temperature T(eff)C decreases as TH increases, for sufficiently high TH. However, being the quadridot a nanoscale system out-of-equilibrium, the definition of the local temperature is must be operational. In Fig. 2 we show an example of operation showing that depending on how the refrigeration effect is "switched on" we can achieve very different operational regimes. The QD2 might be either colder (in region I) or hotter (in region II) when the device extract heat from the C reservoir. Conversely, we might achieve a colder QD2 also when the quadridot pumps heat into the colder bath (III).

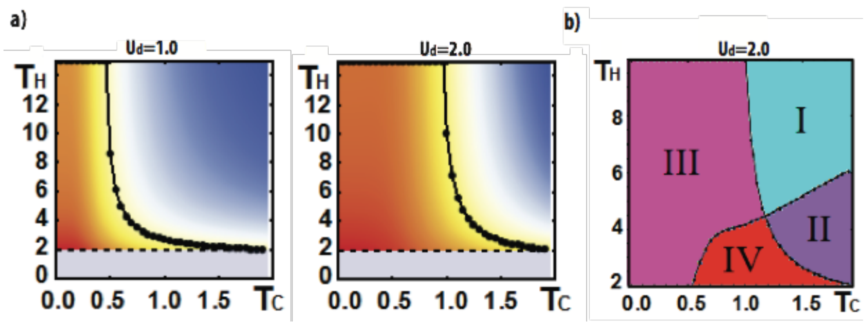

Figure 2: a) Working conditions of the refrigerator. Panels refer to Ud = 1 (left), Ud = 2 (right). The change of sign in the heat flow occurs at a value of TH indicated by the black line. Above this line (blue region) the machine works as a proper refrigerator extracting heat from the C,H-reservoirs and pumping it into R. Black dashed line above the grey region indicates TH = TR=2. Blue/Red background color intensity is proportional to the actual heat pumped to/extracted from C- reservoir. b) Possible temperature regimes for Ud = 2. In regions I/II the refrigerator is working (heat is extracted from C) while in regions III/IV the C bath receives heat. In regions I/III we have an effective decrease of single particle occupation number (i.e. nC < n0C).

In Ref. [8] a completely different approach to quantum thermodynamics was proposed. Specifically in this work, we define thermodynamic configurations and identify two primitives of discrete quantum processes between configurations for which heat and work can be defined in a natural way. This allows us to uncover a general second law for any discrete trajectory that consists of a sequence of these primitives, linking both equilibrium and non-equilibrium configurations. Moreover, in the limit of a discrete trajectory that passes through an infinite number of configurations, i.e. in the reversible limit, we recover the saturation of the second law. Finally, we show that for a discrete Carnot cycle operating between four configurations one recovers Carnot's thermal efficiency.

References

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