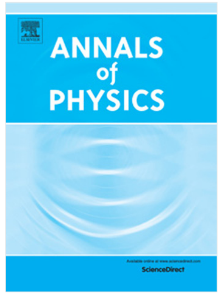
Accepted Manuscript



Classical information driven quantum dot thermal machines

Abhin Shah, Sai Vinjanampathy, Bhaskaran Muralidharan

PII: S0003-4916(18)30203-3
DOI: https://doi.org/10.1016/j.aop.2018.07.032
Reference: YAPHY 67727

To appear in: *Annals of Physics*

Received date : 25 April 2018
Accepted date : 26 July 2018

Classical information driven quantum dot thermal machines

Abhin Shah,[1] Sai Vinjanampathy,[2,3] and Bhaskaran Muralidharan[1]

[1] Department of Electrical Engineering, Indian Institute of Technology Bombay, Powai, Mumbai-400076, India.
[2] Department of Physics, Indian Institute of Technology Bombay, Powai, Mumbai-400076, India.
[3] Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543.

(Dated: July 23, 2018)

We analyze the transient response of quantum dot thermal machines that can be driven by hyperfine interaction acting as a source of classical information. Our setup comprises a quantum dot coupled to two contacts that drive heat flow while coupled to a nuclear spin bath. The quantum dot thermal machines operate both as batteries and as engines, depending on the parameter range. The electrons in the quantum dot interact with the nuclear spins via hyperfine spin-flip processes as typically seen in solid state systems such as GaAs quantum dots. The hyperfine interaction in such systems, which is often treated as a deterrent for quantum information processing, can favorably be regarded as a driving agent for classical information flow into a heat engine setup. We relate this information flow to Landauer's erasure of the nuclear spin bath, leading to a battery operation. We further demonstrate that the setup can perform as a transient power source even under a voltage bias across the dot. Focusing on the transient thermoelectric operation, our analysis clearly indicates the role of Landauer's erasure to deliver a higher output power than a conventional quantum dot thermoelectric setup and an efficiency greater than that of an identical Carnot cycle in steady state, which is consistent with recently proposed bounds on efficiency for systems subject to a feedback controller. The role of nuclear spin relaxation processes on these aspects is also studied. Finally, we introduce the Coulomb interaction in the dot and analyze the transient thermoelectric response of the system. Our results elaborate on the effective use of somewhat undesirable scattering processes as a non-equilibrium source of Shannon information flow in thermal machines and the possibilities that may arise from the use of a quantum information source.

I. INTRODUCTION

Fundamental thermoelectric transport studies aimed at probing the physics of heat flow in the nanoscale [1–14] have been very actively pursued in recent times. In this context, the quantum dot thermoelectric setup [3, 6, 13, 15–20] is an ideal test bed and a minimal model to understand advanced concepts related to the microscopics of heat flow. In recent times, there is also considerable interest in understanding the intricate connection between information and thermodynamics [21–30]. It has also been shown [21, 26, 27, 31, 32] that "demon" assisted transport setups can be devised to work as a battery. These setups typically involve the active channel being coupled to ancillary systems that act as demons [21]. The action of the demon ancilla may also be thought of as a feedback controller on the channel, which is the quantum dot in our case. In such cases, important bounds on the thermodynamic efficiencies have been proposed [26, 33–36].

At the same time, the action of the demon ancilla may also be thought of in terms of a flow in Shannon information into the active channel which may be viewed as the reverse process of Landauer's erasure [21, 28–30]. While there has been a lot of recent attention to improve quantum thermal machines using quantum coherence and entanglement [37, 38], somewhat less attention has been given to improving *quantum* thermal machines with classical information. In this manuscript, we analyze in detail such a quantum thermal machine that features a hyperfine mediated quantum dot setup and demonstrate an enhancement in the performance of quantum thermal machines driven by classical information.

A schematic of our thermal machine is depicted in Fig. 1(a). The setup we analyze comprises a quantum dot coupled to two contacts that drive heat flow, while coupled to a nuclear spin bath as schematized in Fig. 1(b). The electrons in the quantum dot interact with the nuclear spins via hyperfine spin-flip processes, which, in turn, acts as the driving agent for classical information flow into the heat engine setup. There has been sufficient theoretical and experimental research in the area of nuclear spintronics concerning the manipulation of nuclear spins by means of hyperfine interaction between the host nuclei and the itinerant electrons in the quantum transport setup [32, 39–44], specifically with the aim of controlling the undesired effects of hyperfine interaction on the electronic qubit system. This specifically involves the study of dynamic nuclear polarization by transferring spin polarization from electrons to the nuclear spin system [39]. The so-called detrimental hyperfine spin-flip processes, we demonstrate, sets the stage to develop information driven quantum dot thermal machines, specifically using the well developed GaAs setups. We demonstrate that the act of nuclear spin assisted spin-flip scattering, can be cast as a flow of classical information source. The polarization of the nucleus serves as the information content, and the rate of change of Shannon entropy of the bath or the erasure rate is the information current.

We simulate the fast dynamics of electronic transport self-consistently with the slow dynamics of the nuclei [43, 45] and analyze the characteristics of the thermal