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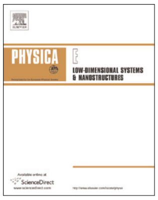

Thermoelectricity without absorbing energy from the heat sources

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HIGHLIGHTS

- Model of a quantum-dot energy-harvester: a quantum analogue of a thermocouple.
- Two thermal reservoirs (heat source and cold environment) and two electric contacts.
- Non-local Coulomb heat drag effects, non-locality of laws of thermodynamics.
- Finite power output without absorbing heat from the thermal reservoirs.
- Can beat a Carnot-efficient conventional thermocouple under equivalent conditions.

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ABSTRACT

We analyze the power output of a quantum dot machine coupled to two electronic reservoirs via thermoelectric contacts, and to two thermal reservoirs – one hot and one cold. This machine is a nanoscale analogue of a conventional thermocouple heat-engine, in which the *active* region being heated is unavoidably also exchanging heat with its cold environment. Heat exchange between the dot and the thermal reservoirs is treated as a capacitive coupling to electronic fluctuations in localized levels, modeled as two additional quantum dots. The resulting multiple-dot setup is described using a master equation approach. We observe an “exotic” power generation, which remains finite even when the heat absorbed from the thermal reservoirs is zero (in other words the heat coming from the hot reservoir all escapes into the cold environment). This effect can be understood in terms of a non-local effect in which the heat flow from heat source to the cold environment generates power via a mechanism which we refer to as *Coulomb heat drag*. It relies on the fact that there is no relaxation in the quantum dot system, so electrons within it have a non-thermal energy distribution. More poetically, one can say that we find a spatial separation of the first-law of thermodynamics (heat to work conversion) from the second-law of thermodynamics (generation of entropy). We present circumstances in which this *non-thermal* system can generate more power than any conventional macroscopic thermocouple (with local thermalization), even when the latter works with Carnot efficiency.

Dedicated to Markus Büttiker: In addition to his human qualities, we remember Markus fondly for the inspiring discussions we had. We think that this work would have led to another lively and enjoyable debate.

1. Introduction

There is great current interest in quantum and nanoscale systems that convert heat into electric current [1–3]. The simplest such systems are those that exhibit a thermoelectric effect [4,5]: they do the conversion in a steady-state (DC) manner, and so avoid the need for pumping cycles relying on time-dependent couplings. Quantum dots are particularly promising in this respect, and various applications have been proposed and (at least partially) realized experimentally, including thermoelectric engines [6–20], refrigerators [21–25], thermal rectifiers [26,27], and hybrid refrigerator power-sources [28]. In addition, the simplicity of these

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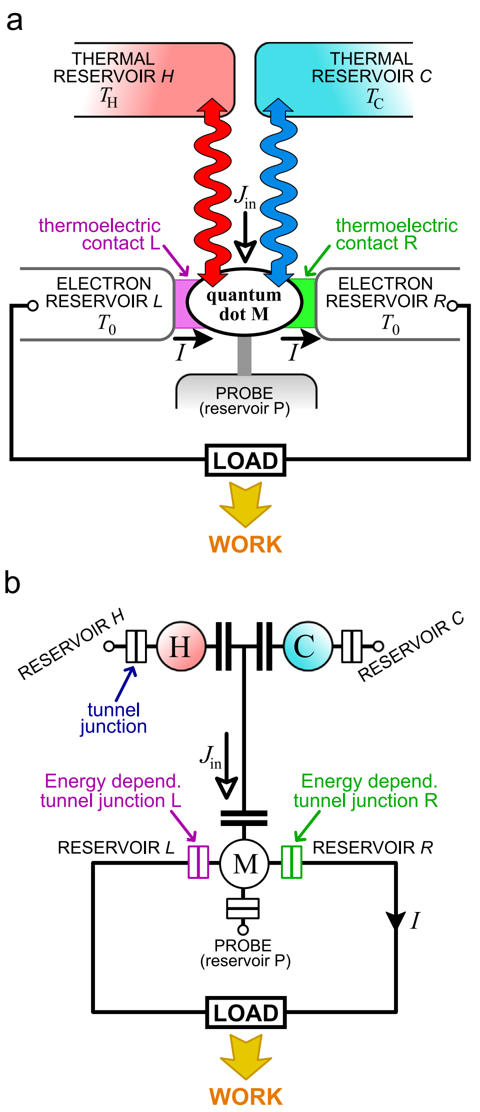

Fig. 1. (a) A sketch of a quantum dot thermocouple in which the electrons in the central part of the thermocouple (the quantum dot) exchange heat with its cold environment (Reservoir C) as well as the heat source (Reservoir H). The couplings of the dot to reservoirs L and R have an energy dependence chosen to ensure that each one has the opposite thermoelectric response. As a result they form a thermocouple, which can be used to generate electrical power. The load is taken to be a device that converts the electrical power into some other form of useful work (it could be a motor converting the electrical work into mechanical work). (b) A circuit picture of the set-up in (a), in which the exchange of energy with the heat source and the environment are modeled by a capacitive coupling to electronic fluctuations in those reservoirs, which we take to be thermally activated hopping of electrons between the bulk and a localized state, indicated by the two upper circles (H and C). Thus each of the three circles represents a two-state system, with occupations 0 or 1.

thermoelectric quantum dots makes them ideal model systems for the study of quantum thermodynamics.

The most developed theory of non-equilibrium thermodynamics, known as irreversible thermodynamics [29], assumes that the shortest lengthscale in the system is that on which the particles thermalize (the inelastic scattering length). Then, any system coupled between two reservoirs at very different temperatures has a well-defined local temperature everywhere within it. However, as we reduce the size of the circuit elements into the nanoscale regime, this ceases to be the case. A system that is much smaller than the electron thermalization length will be in a *non-thermal state* whenever it is coupled to reservoirs that are at significantly different temperatures or electrochemical potentials. In other words, the distribution of the excitations in the system cannot be described in terms of a thermal distribution.

In general, we wish to answer the question: what new physics can emerge in a quantum system operating in this non-thermal regime? This work presents a first response to this question, in the context of the thermoelectric quantum dot system sketched in Fig. 1(a). This can be considered as a miniaturized version of the usual macroscopic thermocouple power generator, in which the macroscopic metal reservoir between the two thermoelectrics has been replaced by the quantum dot M. Our system is similar to three-terminal energy harvesters considered in Refs. [8,30], which separate the conductor from a heat source with which it exchanges energy but no particles. See also Refs. [31–33,9], which consider related models with bosonic heat sources. However, instead of the dot being coupled only to the heat source (reservoir H), we consider the case when it is also coupled to the cold environment (reservoir C). Since the environment coupling is never negligible, we argue that this is the generic case. It is certainly the case in conventional thermocouples, where it is well-known that the region between the two thermoelectrics is not as hot as the heat-source, because it also exchanges heat with the cold environment. With this in mind, the simplest case would be when the temperature of the cold environment C is the same as the temperature T_0 of the electrical circuit in which the thermocouple is inserted (reservoirs L and R). However, we consider the more general case where T_C is different from T_0, for example due to Joule heating in the wires or load $(T_0 > T_C)$. Following what is known about conventional thermocouples, one would expect the energy available to produce electricity to be equal to the heat that flows in from reservoir H minus the heat that is lost as it flows out into reservoir C. We call this quantity J_{in}, and study how the power generated by a quantum dot thermocouple, P_{gen}, depends on it.

In this work, we show that the quantum-dot thermocouple can generate power even when the total heat absorbed from the thermal reservoirs (H and C) is zero ($J_{in}=0$). Instead, the dot extracts heat from the electronic reservoirs (L and R) and converts it into electrical power. It might appear that this "exotic" power generation violates the laws of thermodynamics (since the thermal reservoirs provide no energy to allow the dot to convert heat into work), but we show that this is not the case. It can be explained in terms of a non-local heat drag effect, in which the heat flow from H to C can induce heat and charge currents in the circuit (i.e. through the thermoelectric contacts to reservoirs R and L) even when $J_{in}=0$. We show that this exotic power generation only arises because no thermalization occurs within the quantum dot, meaning that the dot is maintained in a non-thermal state by its contact with the hot and cold reservoirs. As such it has no analogue in conventional thermocouples. We argue that as a result a quantum-dot thermocouple can achieve power outputs larger than any conventional thermocouple (even one working with Carnot efficiency) over a broad range of parameters. This is not because our device has an efficiency higher than Carnot efficiency (this is forbidden by the laws of thermodynamics), but because it can also extract useful work from the non-local drag effect. This is something a conventional thermocouple cannot do, irrespective of how efficient it is.

This work is organized as follows. In Section 2, we introduce our model of the quantum dot thermocouple. Section 3 discusses the basic mechanisms behind the rectification of heat fluctuations in our device, in the simpler case where it generates no power. Section 4 gives results for the power generation, which Section 5 explains in terms of non-local heat drag, shows that it obeys the laws of thermodynamics, and discusses potential experimental implementation. Section 6 shows that the effect is suppressed if relaxation processes cause the state of dot M to become thermal.