



Mesoscopic thermoelectric phenomena / Phénomènes thermoélectriques mésoscopiques

Foreword



We (the coordinators) place in context the articles that appear in this dossier of the *Comptes rendus Physique* entitled *Mesoscopic Thermoelectric Phenomena* and we briefly mention some of our contributions to the subject.

1. Introduction

Thermoelectricity is a two-way process. Either a temperature gradient across a material can produce electricity (the Seebeck effect), or an electric current through the same material can create a temperature difference between its two sides (the Peltier effect). In other words, thermoelectric effects can be used either for harvesting useful energy from wasted heat (Seebeck) or for cooling things (Peltier) without the device having any moving parts.

The wasted heat yields a huge loss of energy in many domains. This is the case in the big industries (e.g. the power stations where electricity is produced), the engines of cars, trains, ships, planes, and the big data centres. Let us consider a car: only 30% of its gas consumption is used for its motion, while 70% produces heat, typically 40% disappearing through the exhaust pipe. This has led physicists to revisit thermoelectric effects. Could we use the Seebeck effect to convert the wasted heat into useful electrical power? At smaller scales, the laptops and cell phones also generate a lot of heat, using up the energy in the batteries in such a manner that they need to be charged very often. Could mesoscopic thermoelectric effects contribute to improving the heat management in nanostructures, converting the wasted heat in an useful energy supply? If so, this could be a route to saving a significant amount of energy in numerous applications. This could provide autonomous power supplies for the medical devices (pace-makers, etc.) or for the internet of things, by taking advantage of small temperature differences (such as those between the human body and its environment).

Another challenge is refrigeration, notably the cooling of hot spots in microprocessors. The last decades have been characterized by an exponential growth of the on-chip power densities. Values of the order of 100 W/cm^2 have become common [1], a power density which is similar to that emitted by the core of a nuclear reactor! For comparison, 7000 W/cm^2 characterizes the surface of the sun. Needless to say that a working chip will be damaged if one does not quickly extract the heat produced. Such problems of overheating are greatly increased by the introduction of ultra-small transistors and nanowire devices which conduct heat much less well than traditional information processing technologies (CMOS, etc.). More than our ability to reduce their sizes, the limitation of the performances of today microprocessors comes mainly from the difficulty of managing heat in ever-smaller integrated circuits, notably cooling the transistor drain areas. Progress could come from a more efficient use of the Peltier effect, notably for a local cooling of the hot spots. A better understanding of the thermoelectric effects, of the phonons and of the heat and entropy at scales going from the nanometer in molecules up to a few microns in quantum dots and nanowires might give the solution for these problems of overheating.

Since a few decades, the mesoscopic physics community has studied charge transport in nanostructures, considering the effect of a voltage difference at a uniform temperature, but more recently these investigations have been extended to the study of the combined effects of voltage and temperature gradients in nanostructures (for a very recent review, see [2]). This dossier contains contributions from this community. It is not intended as a review of all current progress in thermoelectrics, instead it draws attention to certain exciting topics in the thermoelectric and thermal response of mesoscopic systems. For a reader interested in the basics of thermoelectricity in bulk semiconductor materials, we recommend the textbooks [3–5] and the reviews [6–8]. We also note that exciting progress is being made using cobaltates [9] (correlated electron systems), ionic liquids [10], new semiconductor materials and polymers. A broad overview of the recent progress in thermoelectricity, notably using oxides, intermetallic compounds and small systems can be found in the lectures given by Antoine Georges at the Collège de France in 2012–2013 and 2013–2014 [11]. Other reviews on these subjects include [12–15].

Independently of the hope of making technological progresses, mesoscopic thermoelectric phenomena deserve to be studied from the point of view of fundamental physics. At a practical level, the thermoelectric response of a system gives us different information about that system than its electrical response, and this information can be crucial to understanding the physics of nanostructures. More fundamentally, the concept of heat and entropy at the nanoscale is different from

macroscopic systems, and this represents an important new domain of study. The second law of thermodynamics is at the heart of our understanding of irreversible processes in the macroscopic world. At smaller scales, this law can be violated by fluctuations. These fluctuations and the large deviations around the second law were the subject of the lectures given in 2016 by Bernard Derrida at the Collège de France [16]. In this dossier, the contribution of Koski and Pekola illustrates this new trend, showing how Maxwell's demons can be realized in nanoscale electronic circuits.

In general, mesoscopic thermoelectric transport involves considering a nanostructure connecting two electron baths (the hot and cold sources) characterized by Fermi–Dirac distributions of different temperatures and chemical potentials, and measuring the induced charge and energy currents through the nanostructure. In the limit where transport becomes inelastic and comes mainly from phonon-assisted hops, the nanostructure is not only coupled to two electron baths, but also to a third bath of phonons characterized by its own Bose–Einstein distribution. In other words, the investigation should be extended to setups contacting not only two electron baths, but also a third bath being a phonon bath (see the contribution of Jiang and Imry) or a third electron bath whose thermal fluctuations are coupled capacitively to the part of the nanostructure that carries electrical currents (see the contribution of Thierschmann, Sanchez, Sothmann, Buhmann and Molenkamp). Other similar thermoelectric ratchet effects in multiterminal setups are also described in Refs. [17–19]. Multiterminal thermoelectric transport is becoming an active field of research.

Experimentally, there have been works on thermoelectric phenomena in quantum systems since the beginning of the study of quantum transport through nanostructures [20,21]. However, they were limited by the lack of accurate thermometry at the nanoscale, without which one could only perform the most basic of analysis of these phenomena. In recent years this limit has increasingly disappeared as a number of thermometry techniques are being perfected, sometimes using thermoelectric effects [22]. We are now starting to get a quantitative picture of the thermoelectric responses of various quantum systems. In the theoretical physics community, the few pioneering early works on electronic thermal transport (Enquist–Anderson [23]) or thermoelectric effects (Sivan–Imry [24]) were appreciated, but little else was done due to the lack of experiments. However, now an increasing number of theorists are actively working on such problems. In addition to interactions between theorists and experimentalists with a background in mesoscopic physics, there are increasing fruitful contacts with the community of physicists working on the thermodynamics of small systems in other contexts.

2. Overview of the works in this dossier

This issue brings together the contributions from twelve groups, which review and place in context their recent works.

It begins by four theory papers. Paper 1 (Jiang and Imry) describes inelastic thermoelectric transport in mesoscopic systems coupling a source to a drain, while also being coupled to a phonon bath. It starts from the case of linear and nonlinear transport above a barrier before discussing more generally inelastic thermoelectric transport assisted by a heat bath. Rectification and transistor effects in the nonlinear regime for inelastic transport are considered.

Paper 2 (Sánchez and López) describes non-linear thermoelectric transport in nanostructures. This point is particularly important for many thermoelectric applications of nanostructures. The reason is that linear-response theory usually fails when the temperature drop on the scale of the electrons' relaxation length (typically given by the electron–electron or electron–phonon scattering length) is *not* small compared to the average temperature. In bulk materials the temperature drop happens over millimetres when the relaxation length is tens of nanometres, so the temperature drop on the scale of the relaxation length is tiny even when the hot and cold reservoirs have very different temperatures. In contrast, in a nanoscale thermoelectric, the hot and cold reservoirs are separated only by the nanostructure itself. In this case a large temperature difference immediately means one is outside the linear-response regime. Then the thermoelectric figure of merit, ZT , ceases to describe the thermoelectric's efficiency [25–30]. While the theoretical modelling of systems beyond the linear regime is difficult, it will certainly be important for many applications, and this paper gives crucial steps in this direction.

Paper 3 (Benenti, Ouerdane and Goupil) shows us the interest of being close to an electronic phase transition, notably near an Anderson transition. This work opens clear perspectives for the future, in which interacting solid-state systems near phase transitions could be candidates for efficient thermoelectrics (see also [31]). This clearly presents a challenge for theoretical physicists, since such systems are among the most difficult to understand. In addition, this paper discusses the case where the electrons interact in non-integrable systems with momentum conservation, where arguments corroborated by numerical simulations show us that the Carnot efficiency is achieved at the thermodynamic limit.

Paper 4 (Lambert, Sadeghi and Al-Galiby) gives a review of the thermoelectric properties of single molecules and porous nanoribbons. This is a crucial example of how one can calculate the transmission function of complicated molecular structures (typically using density functional theory), and thereby predict the structure of the thermoelectric response. This paper reviews works in which the authors have explored how a careful choice of the molecule would allow one to engineer a transmission function which changes rapidly with energy, thereby greatly enhancing the thermoelectric response.

Paper 5 (Svilans, Leijnse and Linke) gives a careful quantitative comparison between experiments and theories. Such a comparison is crucial for the development of better theoretical models. They describe experiments concerning low temperature thermoelectric transport in quantum dots, as one varies their properties with gates. They provide a general discussion concerning the devices and methods (energy scales, thermal bias, thermometry, thermoelectric measurement) and show how the electrical conductance g and thermopower S vary as a function of a gate voltage. They compare the results to both the predictions given by a Landauer theory and by a theory involving a single-electron tunnelling approximation.

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