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EDITORIAL

Focus on quantum thermodynamics

Janet Anders[1] **and Massimiliano Esposito**[2]

[1] College of Engineering, Mathematics, and Physical Sciences, University of Exeter, Stocker Road, Exeter EX4 4QL, UK
[2] Complex Systems and Statistical Mechanics, University of Luxembourg, L-1511 Luxembourg, Luxembourg

E-mail: janet@qipc.org **and** massimiliano.esposito@uni.lu

Thermodynamics has been highly successful, impacting strongly on the natural sciences and enabling the development of technologies that have changed our lives, from fridges to jet planes. Until recently, it was applied to large systems described by the laws of classical physics. However, with modern technologies miniaturising down to the nanoscale and into the quantum regime, testing the applicability of thermodynamics in this new realm has become an exciting technological challenge.

As a result the field of quantum thermodynamics has recently started to blossom, fuelled by new, highly controlled quantum experiments, the availability of powerful numerical methods, and the development of novel theoretical tools, for instance in non-equilibrium thermodynamics and quantum information theory. Important goals of the field are, among others, a better understanding of thermalisation in quantum systems, the characterisation of non-equilibrium fluctuations in the quantum regime, and the design and realisation of new experiments exploring quantum thermodynamics using, for example, nuclear spins, cold atoms, trapped ions and optomechanic setups. Progress in the field of quantum thermodynamics and ultimately the resolution of technological challenges relies crucially on merging expertise from different fields, such as statistical physics, mesoscopic physics and quantum information theory. The aim of this 'Focus on' collection is to form an extensive open-access resource spanning across the different areas that today make up research in this exciting field.

This issue includes diverse approaches to quantum thermodynamics. The topic of thermalisation is covered by research papers that range from addressing fundamental questions such as 'When and how does an isolated quantum system thermalise?' [1, 2] to practical methods, such as 'How does one measure the temperature of small quantum systems?' for instance in ultracold lattice gases [3] or trapped ions [4].

Numerous contributions are concerned with a central question of thermodynamics—assessing the performance of energy conversion—but with a focus on small, quantum machines contrasting with traditional macroscopic machines. Research papers explore how fast and how efficiently quantum heat engines convert heat into work [5], and analyse the effect of friction [6] and the impact of strong system-reservoir interactions [7] on the performance of small thermal machines. The operation of quantum machines within a closed, clock-driven approach is contrasted with the externally controlled approach [8].

Practical considerations of quantum thermal machines include the determination of the maximum efficiency of energy conversion in a photovoltaic device [9], the full characterisation of out-of-equilibrium thermodynamics of an optomechanical system [10] and the construction of an optimal quantum engine realised with an optomechanical system [11]. The optimal finite-time operation of quantum thermal machines other than engines are investigated; including optimal cooling with a quantum refrigerator [12] and optimal charging of a quantum battery [13].

A large number of studies concern quantum fluctuations of thermodynamical quantities, such as work, heat and entropy, and a discussion of the meaning of fluctuations of non-commuting observables [14]. A derivation of single-shot values of work extraction and formation is presented [15], the link between single-shot work and non-equilibrium fluctuating work is discussed [16], and the limits to catalysis in single-shot thermodynamics are clarified [17]. Definitions of quantum work based on different measurements are compared in the Zeno limit of repeated measurements [18] and quantum non-equilibrium equalities are derived for irreversible driving protocols [19]. The entropy production for scattering processes of non-interacting bosons and fermions is determined [20] and the heat exchange of a driven quantum system is derived using a functional integral approach [21]. Floquet theory is used to calculate the transition rates and work exchange of a driven open quantum system [22] and to establish the full probability distribution of heat exchanged from a driven quantum system [23]. The accounting of entropy, heat and work of bipartite open quantum systems is also considered [24].

A number of proposals are made on how to measure such fluctuations in a wide range of mesoscopic systems. The measurement of stochastic energetic exchanges in quantum heat engines implemented with Cooper-pair boxes is considered [25], the experimental requirements for measuring temperature fluctuations in a single electron box are discussed [26] and the effect of incomplete measurement of photon exchange between a Cooper box with its baths is considered [27]. The direct measurement of heat and work in cold atomic setups is discussed [28] and a test of time-reversal symmetry through checking microreversibility in a superconducting artificial atom is proposed [29]. Further investigations consider the heat flow in small quantum devices, including the effect of finite and thus evolving reservoirs is addressed [30] and a heat diode and engine based on quantum Hall edge states is proposed [31]. The heat transfer in optomechanical arrays [32] and the dephasing of fluxonium qubits in superconducting devices [33] are also considered.

Last but not least the connection between thermodynamics and information theory in the quantum regime is explored, including the derivation of the thermodynamic cost of operating a feedback control protocol [34] and of creating correlations [35]. It is also discussed how to witness thermal entanglement in quantum many-body systems with the entropy [36] rather than energy or temperature [37].

The diversity of topics covered in this issue provides a glimpse into the rich field of quantum thermodynamics which evolves in diverse directions and is still full of open questions. A brief perspective of current research undertaken in quantum thermodynamics is provided in this focus issue [38]. Extensive review articles further expand on thermalisation [39], quantum engines [40], the link between information and thermodynamics [41], quantum information theoretic approaches to quantum thermodynamics [42] and on the general field of quantum thermodynamics [43].

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