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Editorial

# Non-equilibrium dynamics: quantum systems and foundations of quantum mechanics

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**Abstract.** This text presents a brief overview of the recent development of topics addressed by the original papers of this volume related to non-equilibrium phenomena in various (especially mesoscopic) systems and the foundations of quantum physics. A selection of relevant literature is included.

## 1 Introduction

The volume summarizes advances in the understanding of the behavior of quantum systems out of equilibrium, together with related themes of the foundation of quantum physics and quantum thermodynamics. The original contributions are from top scientists of these fields (and their collaborators) who participated in the conference Frontiers of Quantum and Mesoscopic Thermodynamics (FQMT'17), which was organized by the Institute of Physics of the Czech Academy of Sciences and was held in Prague in July 2017 as a follow up to the six previous FQMT conferences (https://fqmt.fzu.cz/) [1–5].

The volume contains several mini-review papers and tutorials which provide readers an excellent orientation into the state-of-the-art of the following topics: Non-equilibrium statistical physics and quantum transport, Quantum thermodynamics and molecular engines, Foundations of quantum physics, Disordered and quantum many body systems, superfluidity, and superconductivity, and Biophysics and chemical physics. These reviews are accompanied by original research papers dealing with more detailed aspects of these fields. We believe this set of papers provides useful insights into recent developments in the above mentioned fields and at the same time the volume documents important relations between related topics.

Further development of all these fields is needed to deal with an increasing requirement for more detailed understanding and use of such phenomena as quantum correlations, entanglement and their dynamics; decoherence and dissipation; light-matter interactions; behavior of closed and open quantum systems far from equilibrium; equilibration and thermalization of systems; roles of initial and boundary conditions; influences of environment, reservoirs and external fields on the

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time evolution of systems; quantum to classical transitions; dynamics of quantum phase transitions; and topological states of systems. The above mentioned phenomena, related problems and challenges occur in many fields of physics, astrophysics, chemistry, and biology.

As for systems, which enable study of various related questions, mesoscopic systems are especially suitable for this purpose due to their vast variety of structures and parameters. Various systems, of natural and artificial origin, can exhibit mesoscopic features depending on inner parameters of those systems and interactions with their environment. Typical mesoscopic systems can be of nanoscale size, composed from atoms (molecules). Nanoscale structures include not only very small physical structures, but also structures occurring in living cells, as for example complex molecules, proteins and molecular motors. At the same time, nanoscale technologies enable the preparation of well-defined artificial structures composed of between a few to hundreds of atoms (molecules) to create an enormous diversity of systems with well-defined inner parameters which can be influenced by external fields. These structures can be studied by methods of condensed matter physics and quantum optics in such detail that affords a deeper understanding of quantum physics, as represented by quantum interference, entanglement, the uncertainty principle, quantum measurement and what is often termed "non-locality". Of particular interest are carbon allotropes, quantum wires and dots, microcavities, single molecule nanomagnets, molecular motors and active gels, various structures in living cells, as well as specific arrangements featuring cold atoms and molecules which can exhibit macroscopic quantum effects and which can be used for testing methods of quantum many-body theory.

Recent advances in technologies have led to enormous improvements of measurement, imaging and observation techniques at microscopic, mesoscopic and macroscopic scales. At the same time, various methods allow investigation into not only equilibrium features, but also time evolution of classical and quantum systems (which are in general far from equilibrium) at different time scales. This increasing ability to study subtle details of the dynamics of systems yields new versions of old questions and creates new challenges in many fields of physics.

A good understanding of the time evolution of both classical and quantum systems is essential for an explanation of many observations and experiments of contemporary physics. Observed systems must often be treated as non-equilibrium, open systems in which their behavior is influenced not only by their inner parameters, but also by properties of their environment and time dependent external fields. The theory of non-equilibrium behavior of quantum many-body systems is, however, far from complete. There are lasting and extremely important problems related to modern technologies, including questions of irreversible behavior of real systems in comparison with reversible microscopic laws, emergence of classical macroscopic behavior from microscopic quantum behavior, charge (electron), spin and heat transport, limits to "phenomenological" thermodynamic descriptions, and the problem of how to describe properly open quantum systems far from equilibrium, especially in the case of strong interaction between a small system and reservoirs.

Another challenging problem is stochastic behavior of systems caused either by innate features of the systems or by noise related to the fact that the studied systems are open. Studies of quantum and temperature fluctuations, as well as quantum noise, dephasing and dissipation create an essential part of the research in this direction. Recently, various versions of non-equilibrium fluctuation and fluctuation-dissipation theorems for quantum systems have been discussed. These studies are of key importance since the fluctuations, dissipation and noise are closely related to the performance and the reliability of both artificially created nano-devices as well as natural "engines", as are for example molecular motors in cells.

This theme brings us to the field of biophysics. Non-equilibrium processes and the system's environment play a decisive role in the behavior of small structures of living organisms and there are many important questions to be answered before we fully understand the laws which govern the performance of the nanoscopic structures that are essential for life. In this regard, it appears one of the necessary conditions for the proper performance of cells is that their dynamics be based on far from equilibrium states and related nonlinear, non-equilibrium transport.

Behavior of molecular motors and the field of biomimetics are associated with more general considerations related to thermodynamics and the use of various mesoscopic structures. Among the central themes of classical thermodynamics are the concepts of "temperature", "system", "reservoir", and "engine". Due to the quantum aspects of mesoscopic (molecular) systems, it is necessary to deal with quantum thermodynamics to discuss possible quantum pumps, heat engines and refrigerators. The task of quantum thermodynamics is to provide a good "phenomenological" frame for the "macroscopic" description of open mesoscopic systems coming from more detailed studies of non-equilibrium quantum statistical physics of open systems and the foundations of quantum mechanics. The central question is: under which conditions will the thermodynamic behavior still manifest in various small systems.

In general, the above mentioned problems arise in dissipation, dephasing and decoherence processes, and, on a very basic level, the foundations of quantum mechanics and related theories of quantum measurement. A better knowledge and insight into the foundations of quantum physics is essential for a proper formulation of the fundamental laws of physics with regard to Bell inequalities and quantum gravity. It is also essential for developing a suitable description of small quantum systems and their applications. This applies particularly to quantum optics and the physics of quantum information and computing, where questions of quantum interference, entanglement and decoherence processes, together with knowledge of time scales governing the dynamics of the studied systems, are essential and mutually beneficial.

The contributions to this topical issue have been grouped in five sections, as indicated in the contents of the volume. Additional details of recent developments regarding the subjects of individual sections can be found in the short list of books and review articles (ordered mostly by years of publication):

- Non-equilibrium statistical physics and quantum transport:
  from references [6–65],
- Quantum thermodynamics and molecular engines:
  from references [66–88],
- Foundations of quantum physics:
  from references [89–149],
- Disordered and quantum many body systems, superfluidity, and superconductivity:
  from references [150–187],
- Biophysics and chemical physics:
  from references [188–227].

We note that only recent books and review articles are referred to. Our choice is, of course, rather subjective and far from complete. Nevertheless, we trust the reader has been provided a basic orientation to the fields and topics contained in this volume.

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