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Editorial

Non-equilibrium quantum physics, many body systems, and foundations of quantum physics

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Abstract Presented is a brief summary of recent developments of topics addressed by the reviews and original papers of this volume related to non-equilibrium phenomena in various (especially mesoscopic) systems, the foundations of quantum physics, quantum optics and related fields of physics including biophysics, cosmology, gravitation and astrophysics.

1 Introduction

The volume summarizes advances in the understanding of the behavior of systems out of equilibrium and quantum thermodynamics, together with related themes of the foundation of quantum physics, astrophysics and cosmology. The original contributions are from top scientists of these fields (and their collaborators) who participated either in the online conference Frontiers of Quantum and Mesoscopic Thermodynamics (FQMT'21) or the regular one (FQMT'22). Both conferences were organized by the Institute of Physics of the Czech Academy of Sciences. The FQMT'21 was held online in July of 2021. The FQMT'22, which was held in Prague from July 31 till August 6, 2022, was a follow-up to the eight previous FQMT conferences (https://fqmt.fzu.cz/), see also references to the previous FQMT conferences [1–7].

The volume contains review papers and original papers which provide readers an orientation to the state-of-the-art of the following topics: Non-equilibrium quantum phenomena; Foundations of quantum physics; Quantum measurement, entanglement and coherence; Dissipation, dephasing, noise and decoherence; Many body physics, Quantum field theory; Quantum statistical physics and thermodynamics; Quantum optics; Quantum simulations; Physics of quantum information and computing; Topological states of quantum matter, quantum phase transitions; Macroscopic quantum behavior; Cold atoms and molecules, and Bose-Einstein condensates; Mesoscopic, nano-electromechanical and nano-optical systems; Biological systems, molecular motors and quantum biology; Cosmology, gravitation and astrophysics.

The articles in the volume are organized into the following sections:

◇ Non-equilibrium statistical physics and quantum thermodynamics;
◇ Foundations of quantum physics;
◇ Quantum optics, light-matter interactions;
◇ Quantum many body systems, quantum fluids;
◇ General physics.
◇ Non-equilibrium statistical physics and quantum thermodynamics:

1. Karol Białas, Jerzy Łuczka and Jakub Spiechowicz, Control of particle transport driven by active noise: strategy of amplification via a periodic potential [8].
2. Gerard Kennedy, Quantum torque on a non-reciprocal body out of thermal equilibrium and Induced by a magnetic field of arbitrary strength [9].
3. Meng Xu and Joachim Ankerhold, About the performance of perturbative treatments of the spin-boson dynamics within the hierarchical equations of motion approach [10].

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4. Malte Krug and Jürgen Stockburger, On stability issues of the HEOM method [11].
5. M. P. Liul, A. I. Ryzhov and S. N. Shevchenko, Interferometry of multi-level systems: rate-equation approach for a charge qu*d*it [12].
6. I. J. David, I. Sinayskiy and F. Petruccione, Benchmarking regularisation methods for quantum process tomography on NISQ devices [13].
7. Stephen M. Barnett, Vacuum representations of blackbody radiation [14].
8. Yasuhiro Utsumi, Dimitry Golubev and Ferdinand Peper, Thermodynamic cost of Brownian computers in the stochastic thermodynamics of resetting [15].
9. Juliette Monsel, Jens Schulenborg and Janine Splettstoesser, Non-geometric pumping effects on the performance of interacting quantum-dot heat engines [16].

Nowadays, experimental as well as theoretical investigations of time evolution of classical and quantum systems far from equilibrium are quickly developing. Various methods now allow investigation into time evolution of non-equilibrium systems at different time scales. To cope successfully with these challenges means seeking a more detailed understanding of phenomena, interactions and parameters which play key roles in determining system behavior, such as: proper determination of interactions strengths, influence of size and geometry of systems, quantum correlations, entanglement and their attendant dynamics; decoherence and dissipation; light-matter interactions; equilibration and thermalization of systems; roles of initial and boundary conditions; influence of the environment, strength of system–environment interactions, reservoirs and external fields on the time evolution of systems; quantum to classical transitions; dynamics of quantum phase transitions; and topological states of systems.

More detailed observations of non-equilibrium systems behavior bring also increasing pressure on attaining a better understanding and a more detailed description of equilibrium features of investigated systems, since their knowledge is requisite as a point of entry into deeper studies of non-equilibrium behavior. Thus, a better understanding of thermodynamics, which has ever played a central role in the understanding of phenomenological, macroscopic description of equilibrium systems, is critically important.

Classical thermodynamics has employed phenomenological treatments in order to introduce the concepts of “temperature”, “system”, “reservoir”, and “engine”. The central question nowadays is: under what conditions will thermodynamic behavior still manifest in various small systems. Due to the quantum aspects of small (molecular) systems, it is necessary to deal with quantum thermodynamics in order to properly discuss quantum pumps, quantum heat engines and quantum refrigerators. The task of quantum thermodynamics is to provide a suitable “phenomenological” framework, such as the “ergotropy”, for the “macroscopic” description of open systems, coming from more detailed studies of non-equilibrium quantum statistical physics of open systems and the foundations of quantum mechanics.

◇ Foundations of quantum physics:

1. Gregg Jaeger, Ontology and the foundations of quantum theory [17].
2. James K. Freericks, How to measure the momentum of single quanta [18].
3. Georgi Gary Rozenman, Denys I. Bondar, Wolfgang P. Schleich, Lev Shemer and Ady Arie, Bohmian mechanics of the three-slit experiment in the linear potential [19].
4. Arkady Plotnitsky, t is not time: reality, causality, and the arrow of events in quantum theory [20].
5. Michael Suleymanov and Eliahu Cohen, Quantum frames of reference and the relational flow of time [21].
6. A. M. Cetto, L. de la Peña and J. F. Pérez-Barragán, Revisiting canonical quantization of radiation: the role of the vacuum field [22].
7. Jacob M. Leamer, Wenlei Zhang, Nicholas J. Savino, Ravi K. Saripalli, Sanjaya Lohani, Ryan T. Glasser and Denys I. Bondar, Classical optical analogue of quantum discord [23].
8. Víctor H. Cervantes and Ehtibar N. Dzhafarov, Hypercyclic systems of measurements and patterns of contextuality [24].

Due to our increasing ability to prepare and measure various artificial structures which exhibit quantum behavior, it is inevitable to further improve our understanding of the foundations of quantum physics to be able to describe them. The relation is mutual: The artificially prepared structures can be studied by combined methods of condensed matter physics and quantum optics in such details that afford a deeper understanding of quantum physics, as represented by quantum interferences, entanglement, the uncertainty principle and quantum measurement processes.

Studies of various system parameters and their influence on the behavior of systems, together with investigations of related quantum and temperature fluctuations, quantum noise, dephasing and dissipation, create an essential part of the research which aims to better understand the performance and reliability of artificially created structures being studied, e.g., in the quickly developing field of quantum information and computing, or of small (nanoscale, classical or quantum) engines.

◇ Quantum optics, light-matter interactions:

1. Jacob Emerick, Colin Roy, Zorica Branković and Yuri Rostovtsev, Quantum control of quantum systems: from room-temperature masers to generation of entanglement photons [25].
2. Billie V. DeLuca and Anil K. Patnaik, Fourier transfer function for generic light pulse storage and retrieval using EIT [26].
3. Jeffrey Lee and Frank Narducci, Spatial magnetic field mapping with Raman spectra of laser cooled atoms in free-fall [27].
4. Luigi Giannelli, Giorgio Anfuso, Miroslav Grajcar, Gheorghe Sorin Paraoanu, Elisabetta Paladino and Giuseppe Falci, Integrated conversion and photodetection of virtual photons in an ultrastrongly coupled superconducting quantum circuit [28].

In addition, a deeper understanding of foundations of quantum physics is particularly essential for developing a suitable description of small (nanoscopic) quantum systems and their applications. This applies particularly to quantum optics and the physics of quantum information and computing, where detailed understanding of quantum interference, entanglement and decoherence processes, together with related knowledge of time scales governing the dynamics of the studied systems, are essential.

Recent advances in technologies, which have led to enormous improvements of measurement, imaging and observation techniques at microscopic, mesoscopic and macroscopic scales, have accelerated the mutual development of thermodynamics, non-equilibrium physics, foundations of quantum physics and quantum optics.

◇ Quantum many body systems, quantum fluids:

1. Aleksandr N. Mikheev, Ido Siovitz and Thomas Gasenzer, Universal dynamics and non-thermal fixed points in quantum fluids far from equilibrium [29].
2. K. Mukherjee, T. Arnone Cardinale, L. Chergui, P. Stürmer and S. M. Reimann, Droplets and supersolids in ultra-cold atomic quantum gases [30].
3. Joe Rowland Adams, Julian Newman and Aneta Stefanovska, Distinguishing between deterministic oscillations and noise [31].
4. T. R. Kirkpatrick and D. Belitz, Velocity-dependent forces and non-hydrodynamic initial conditions in quantum and classical fluids [32].
5. Franklin J. Vivanco, Amilson R. Fritsch, Arnol D. García-Orozco, Michelle A. Moreno-Armijos, Gustavo D. Telles, Pedro E. S. Tavares and Vanderlei S. Bagnato, Energy cascade in a far-from-equilibrium inhomogeneous trapped Bose gas obtained by power spectrum analysis [33].
6. Andrey Kudlis, Andrey Pikelner, Amnon Aharony and Ora Entin-Wohlman, Effective exponents near bicritical points [34].
7. Satoshi Ejima, Florian Lange and Holger Fehske, Entanglement analysis of photoinduced η-pairing states [35].
8. A. Churkin, I. Gabdank, A. L. Burin and M. Schechter, The strain gap in a system of weakly and strongly interacting two-level systems [36].
9. Nicklas Enenkel, Markus Garst and Peter Schmitteckert, Applicability and limitations of cluster perturbation theory for Hubbard models [37].

The understanding of many body systems is far from complete. However, nowadays the specific arrangements and the control of the number of constituent particles in systems featuring cold atoms and molecules can reveal macroscopic quantum effects and can be used for testing and perturbative methods of quantum many-body theory and foundations of quantum physics.

Fast developing nanoscale technologies enable us to prepare an enormously diverse range of nanoscopic systems with well defined inner parameters with good control of their interactions with the external environment and time-dependent fields. Nanoscale structures include not only very small artificially prepared structures, but also structures occurring in living cells, as for example complex molecules, proteins and molecular motors. Such systems are on the borderline between different disciplines (i.e., physics, chemistry, and biology) where the dynamic behavior of these systems and corresponding various methods of their description (individual or statistical, microscopic or macroscopic, classical or quantum) meet. These (often open) systems are commonly dominated by quantum effects, by topology of their structures and states, and by strong interactions with their environment. Due to their position between the macro and micro world, these systems exhibit many surprising phenomena which can lead to a better understanding of quantum mechanics, many-body physics, quantum computing, and the relation between classical and quantum behaviors by sensitive choice of parameters. The development of theoretical concepts for their description and reliable experimental methods is of great importance for investigating these systems, testing theories and designing new nanostructures with well defined, desired behavior.

◇ General physics:

1. Giorgio Torrieri, The equivalence principle and inertial-gravitational quantum backreaction [38].
2. Theodorus Maria Nieuwenhuizen, The smeared-horizon observer of a black hole [39].
3. Jiří J. Mareš, Václav Špička and Pavel Hubík, Thought experiments in electromagnetic theory and the ordinary Hall effect [40].
4. Shohei Watabe, Michael Zach Serikow, Shiro Kawabata and Alexandre Zagoskin, Continuous percolation in a Hilbert space for a large system of qubits [41].
5. Till Dolejsky, Erik Fitzke, Lucas Bialowons, Maximilian Tippmann, Oleg Nikiforov and Thomas Walther, Flexible reconfigurable entanglement-based quantum key distribution network [42].
6. Jiří J. Mareš, Václav Špička and Pavel Hubík, On physical processes controlling nerve signalling [43].

Studies of mesoscopic (mostly nanoscopic) systems can shed the new light on long-standing and extremely important problems for better understanding of observed phenomena in many fields of the natural sciences, such as: dynamics of measurement processes; relations between system parameters, system–environment interactions, external fields and time scales of system evolution; irreversible behavior of real systems in comparison with reversible microscopic laws; emergence of classical macroscopic behavior from microscopic quantum behavior; limits to "phenomenological" thermodynamic descriptions, the problem of how to describe open quantum systems far from equilibrium, especially in the case of a strong interaction between a small system and reservoirs; stochastic behavior of systems, which can be caused either by innate features of the studied systems or by the fact that the studied systems are open.

A better knowledge and insight into the foundations of quantum and non-equilibrium statistical physics is also essential for a proper formulation of the fundamental laws of physics, astrophysics and cosmology.

It is now also evident that the performance of living cells is based on (in general) far from equilibrium states and that non-equilibrium processes play a decisive role in the proper performance of various structures which are essential for life. One of the key features of complex organisms is their ability to reach homeostasis. Accordingly, a proper understanding of relaxation, equilibration, steady state and local (in time and space) equilibrium states of various complex systems in cells and their interactions with the environment is critical. Thus, non-equilibrium statistical physics and thermodynamics can help on the way to understanding life processes. Another essential aspect of living organisms involves networks (as for example neural or immune systems), which depend on synchronization of the inner structures of various cells and their mutual interactions. Therefore, the volume contains manuscripts which deal with these aspects of life from the point of view of the involved physical mechanisms.

The above-mentioned challenges occur not only in many fields of physics, but also in astrophysics, chemistry, and biology. Thus this volume includes several papers which are at the border of physics and other natural sciences.

To summarize: From the point of view of experimental and observational possibilities, the understanding of few body systems, as well as many body systems, microscopic, mesoscopic and macroscopic systems, both in and out of equilibrium, is far from complete. The increasing ability to study subtle details of equilibrium features and, at the same time, the dynamics of systems, creates new challenges in many fields of equilibrium as well as non-equilibrium physics and foundations of quantum physics.

The contributions to this topical issue have been grouped in five sections, as indicated above, and in the contents of the volume. Details of recent developments regarding the subjects of the individual sections can be found in the included reviews and papers, and references therewith. Additional information can also be found in journal volumes dedicated to the previous FQMT conferences [1–7]. We trust that in this way the reader has been provided a working orientation to the topics contained in this volume.

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