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Physics at the FQMT'11 conference

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Abstract

This paper deals with the recent state of the art of the following topics presented at the FQMT'11 conference: foundations of quantum physics, quantum measurement; nonequilibrium quantum statistical physics; quantum thermodynamics; quantum measurement, entanglement and coherence; dissipation, dephasing, noise, and decoherence; quantum optics; macroscopic quantum behavior; e.g. cold atoms; Bose–Einstein condensates; physics of quantum computing and quantum information; mesoscopic, nano-electro-mechanical systems and nano-optical systems; spin systems and their dynamics; biological systems and molecular motors; and cosmology, gravitation and astrophysics. The lectures and discussions at the FQMT'11 conference, as well as the contributions to the related topical issue, reveal important themes for future development. The recent literature is included.

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I. Introduction

The FQMT'11 conference and the conference contributions to this topical issue have demonstrated many relations between concepts and methods used in such areas as foundation of quantum physics, non-equilibrium quantum statistical physics quantum thermodynamics, condensed matter physics, quantum optics and their applications to the physics of quantum computing, cold atoms, physics of mesoscopic systems, molecular motors and biological systems. There is also an increasing tendency for the merging of theoretical and experimental methods of quantum optics and condensed matter physics.

Similar to the previous FQMT conferences (FQMT'04 and FQMT'08), lectures and discussions during the FQMT'11 conference and contributions to this volume have also shown several quite challenging goals of the recent physics which are common to all these areas. From the time of the first FQMT conference in 2004 (FQMT'04), there have been some important partial successes on the way to solve tasks we formulated in the Proceedings from the FQMT'04 [1] and FQMT'08 [2] conferences, but we are still far from finding their final satisfactory solution. So, in some cases we will almost repeat the list of challenges from the conclusion of the FQMT'04 and FQMT'08 conferences, perhaps with a little different stress on their various aspects.

The FQMT'11 conference addressed foundations of quantum physics and non-equilibrium quantum statistical physics and focused on eight main problem areas:

- foundations of quantum mechanics,
- border between the classical and quantum systems,
- quantum interference, many body entanglement,
- non-equilibrium quantum systems,
- decoherence, noise, fluctuation and dissipation,
- measurements of small quantum systems,
- molecular motors, nanoscale biological systems.

These areas concern many physical situations studied by condensed matter physics (e.g. metals, semiconductors, superconductors and their various combinations, in artificially created structures), plasma physics, nuclear physics, elementary particle physics, chemistry and biology. Nowadays, all the above mentioned problems connect quantum theory, thermodynamics, statistical physics and physics of small systems not only from a theoretical, but also from an experimental point of view, at many levels.

II. Challenges

We now list ten goals which the lectures and discussions at the FQMT'11 conference and the contributions to this volume reveal to be important for future developments.

1. To improve our understanding of relation between classical and quantum physics.

The existence of quantum interference, confirmed experimentally at the microscopic level, brings the natural question of whether there can be of quantum interference of macroscopically distinct states. This question is the basis of the famous Schrödinger's cat thought experiment, which was formulated soon after another famous thought experiment, the Einstein–Podolsky–Rosen paradox, questioning the completeness and non-locality of quantum mechanics. Both thought experiments ask the question what is the relation between classical and quantum physics.

This leads to other questions:

- At which level can we still observe superposition of quantum states?
- Where is the borderline between the classical and quantum worlds?
- What does macroscopic and microscopic mean from this point of view?

With the possibility of more sophisticated quantum optics and solid state 'mesoscopic' experiments, the old questions have re-emerged together with many new questions related to the Copenhagen interpretation of quantum mechanics and other possible schemes for understanding the foundations of quantum mechanics. Nowadays, however, these questions can be discussed together with the relevant experimental results.

2. To get better insight into entanglement in various (microscopic–mesoscopic–macroscopic) systems.

Due to basic significance of quantum entanglement in behavior of quantum systems and increasing use of the idea of quantum entanglement in various experiments in many branches of physics it is necessary to improve our algorithms and methods for detecting and quantifying entanglement together with possibilities of how to prepare entangled states artificially in various systems. At the same time, we need to develop methods of how to properly describe the dynamics of entanglement depending on the system environment. This is needed not only from the point of view of final understanding of the transition from quantum to classical behavior and as to why macroscopic many body systems have a tendency to behave classically, but also to be able to develop possible real working schemes based on the physics of quantum entanglement, such as various teleportation protocols.

Since quantum entanglement has become a basic resource in quantum information science and other applications of quantum physics, it is really vital to understand how non-classical correlations decay in a real environment (and classical behavior of the system emerges). So, dynamics of entanglement is another challenging task of recent physics and we immediately see the connection of entanglement with non-equilibrium quantum statistical physics and quantum thermodynamics, especially with decoherence theory.

3. To improve our understanding of decoherence in various (microscopic–mesoscopic–macroscopic) systems.

The central phenomenon which connects basic topics of the foundations of quantum physics as an interpretation of quantum mechanics, non-locality of quantum mechanics, quantum entanglement and quantum measurement problem with teleportation experiments, possible quantum qubits behavior and studies of various mesoscopic (nano)systems, is the phenomenon of quantum interference and its possible decay by various (decoherence) processes. The role of quantum interference and its erasing by decoherence processes is still not fully understood. This process seems to be important for our understanding of the border between the domains of classical and quantum physics; environmentally induced decoherence is one possible explanation of the collapse of the wave function and impossibility to observe macroscopic superposition of states.

There is now an increasing need to understand: (a) the relation between decoherence processes and the quantum measurement problem, (b) emergence of classical macroscopic world from the quantum world and (c) the physics of possible working qubit systems.

The central theme of 'qubits physics' is the theoretical description and measurement of five closely related phenomena: quantum entanglement, teleportation, decoherence, dissipation and noise. The most important task of all the investigations into various possible systems, which are candidates for qubits, is the fight between quantum coherence (needed for the proper function of qubit systems from the point of view of possible quantum computing algorithms) and decoherence coming naturally from the environment and being a natural obstacle to a realization of possible 'quantum processors' in the future, but is inevitable due to coupling to an environment which enables us to read out information from systems.

The most important questions (from many still unanswered ones) related to quantum decoherence and its understanding, at least as it seems now, are the following ones:

- What is the relation of decoherence processes with the transition between quantum and classical behavior?
- What are the dynamics of decoherence? In other words, how do the off-diagonal elements of the density matrix of the system evolve in time under various conditions, depending, e.g. on the initial state of the system and the reservoir, and on the strengths of coupling between the system and the reservoir? The realistic determination of decoherence times for various systems is a very useful, but sometimes difficult to fulfill, aim.
- What are possible mechanisms of decoherence in various systems?
- What is the relation of these mechanisms to other mechanisms in systems? In particular, quantum relaxation processes.
- How are decoherence processes related to quantum measurement processes? Namely, a natural question emerges as to whether decoherence can cause collapse

of the wave function in relation to the measurement processes. If yes, what is the difference between measurement of microscopic and possible macroscopic coherent states, if any? What is the relation to the possible irreversibility on the microscopic level caused by quantum measurement? In other words, can quantum decoherence satisfactorily solve the 'measurement problem' and related collapse of the wave function, if this really occurs?

4. To improve methods for measurements of small quantum systems.

Quantum systems exhibit many features different from classical ones and consequently their states are supposed to be described by wave functions and density matrices, these features being unknown in classical mechanics.

Natural questions thus emerge:

- What can we measure in quantum systems?
- Are information about systems based on non-commuting observables and the standard von Neumann approach to measurement is only possible and sufficient to characterize the quantum system?
- How do we perform measurements to gain relevant information about the system?
- Can we measure somehow the state of the system as represented by the wave function, i.e. to measure the wave function itself?
- Can we even ask: does the quantum wave function exist, and if so, does it have some real meaning or is it just our technical tool?

We can clearly see that these questions, which have nowadays a practical meaning, are closely related to the basic questions of the foundation of quantum mechanics and its various interpretations.

A good example of systems which are worth investigation to improve our knowledge of the foundation of quantum mechanics and the quantum statistical physics are nano-electro-mechanical systems (NEMS). NEMS represent a great hope for improving our understanding of many aspects of the behavior of small systems. Apart from providing ultra-sensitive measuring techniques and many other possible applications, NEMS also enable us to test basic ideas of quantum statistical physics and conceptual foundations of quantum mechanics. Taking into account 'mesoscopic' sizes, masses of both the nanomechanical resonator and coupled devices, temperatures involved and, in addition, coupling of the whole NEMS into its surroundings, we can see that we have the systems *par excellence* to study all essential questions of the quantum statistical physics of open systems: fluctuations, noise, dissipation and decoherence effects.

NEMS also offer a possible fascinating insight into the realm of the foundations of quantum physics, since their parameters approach now a possibility to measure not only the crossover between classical and quantum behavior of a nanomechanical resonator, but also to observe interference of macroscopically distinct quantum states and related decoherence times, due to environmentally induced decoherence. In addition, NEMS are promising from the point of view of detailed studies of decoherence theory and of observations of decoherence times which are important not only for the tuning of NEMS and, e.g. their possible use for quantum processor systems, but also for testing alternative approaches to quantum mechanics, where the decoherence times play an essential role.

5. To improve our understanding of quantum systems far from equilibrium.

The need for improvement in this field is being driven by a growing demand to understand details of quick switching-on processes during experiments on nano-size systems which must be, due to their contacts, understood as open systems. These transients, switching-on or off processes, generally start from highly non-equilibrium quantum initial states.

The proper understanding of formulation of the initial state (i.e. the preparation period of systems before their measurement) and its time development (its measurement) is important not only from the point of view of basic science (theory of quantum measurement, quantum transport theory) but this is also crucial for possible applications. This is in fact an interdisciplinary field where many fundamental questions and possible applications meet: as it was mentioned at various places in previous sections, non-equilibrium theory of open systems relates, via decoherence theory, to all branches of physics discussed at the conference, from the foundations of quantum mechanics, to measurements on quantum systems, to the physics of quantum computing and mesoscopic systems.

There is an increasing need for improvements of advanced methods of how to deal in practice with very difficult tasks related to the proper description of many-body effects in quantum systems far from equilibrium. Recently, we are witnessing growing interest in improvements and use of methods such as time-dependent density functional theory, dynamical mean-field theory and density matrix renormalization group. These methods often combine advantages of both basic approaches, non-equilibrium Green's functions and density matrix methods.

To summarize, we need to develop a non-equilibrium theory which will be able to describe (open) systems with various numbers of particles (e.g. from individual electron systems up to many-electron systems) with sufficient accuracy in all time ranges, e.g. covering processes and dynamics of the system from short-time to long-time scales. To this end, we need to find a proper description of initial conditions, interactions in the system, and efficient methods of how to find dynamics beyond both Markovian and linear approximations.

6. To connect methods of statistical physics to cosmology and the nature of dark matter.

In a separate session, subjects such as observational aspects of black holes, microlensing of stars by planetary objects, fundamental issues of the Wilkinson Microwave Anisotropy Probe (WMAP) data and new theories of dark matter, were discussed. These subjects flourish by implementing techniques of statistical physics, but are each too vast to expand on here. Nevertheless, we can say that the combination of astrophysics, cosmology research and methods of statistical physics is very much needed, and just now it is the right time for this direction of the research. Of course, both improvements of methods of statistical physics and observations of matter on large scales are very much desirable. In the future, these investigations can lead even to a better understanding of certain aspects of the foundations of quantum mechanics (e.g. they can be related to research in the field of Stochastic electrodynamics) and can be closely related to other topics, which were discussed at the FQMT'11 conference.

7. To develop more complex models for dissipation processes.

In 'small systems', such as NEMS, complicated couplings can be created between various parts of the system and their surroundings. There is a possibility that, e.g. the resonator can be damped via excitations of internal modes of the system. The dissipation can also be mediated via a strong electron–phonon interaction when an adiabatic (Born–Oppenheimer) approach is not sufficient. In other words, we have to study dissipation mechanisms in these new systems and to develop methods for including them in the dynamical description, so that these mechanisms will be still practically treatable within the generalized master equations (GME) framework.

The description of the decoherence processes for various systems is a highly non-trivial task which is far from being satisfactorily fulfilled. Many highly successful models have already been introduced for the description of systems with dissipation, e.g. variants of the central spin model (both, system and reservoir are represented by spins), spin–boson model (system composed by spins, reservoir by bosons) not to mention the celebrated Caldeira–Leggett model. However, as the conference talks and discussions revealed, new, more complex and more realistic models are needed to describe the dissipation processes together with improvement of the general theory of open systems.

8. To create new methods to analyze noise spectra and to thereby extract useful information from small systems.

There is continuing need to gain more information about 'mesoscopic' systems from transport studies as opposed to only from studies of the mean current, which measures the total charge transported via the system. Full counting statistics (FCS), i.e. the knowledge of the whole distribution of transmitted charge through a small system provides more information about the system than just the first cumulant of the FCS (mean current). Already the second cumulant, the current noise, can help us to distinguish between the different transport mechanisms which lead to the same mean current. The problem, however, is how to coordinate the choice of a model of the measured small system with a method of how to calculate reliable several first cumulants; calculations heavily depend on an approximation of a GME. Due to technical difficulties, calculations are up to now limited.

9. To study intensively physical processes in 'small' biological systems, i.e. on the level of cells and their organelles.

Recent nano-technologies enable us to construct 'biomimetic' systems, which mimic at least some features of complicated biological systems and mechanisms in living cells. Apart from the investigation of mimetic systems, nano-devices (e.g. NEMS) provide us a possibility to 'follow individual molecules' in cells and manipulate them. This increases the possibility of a 'symbiosis' between biology and physics. We can improve our knowledge of how cells work by using physics, but also physics research can be motivated by studies of cellular mechanisms. Molecular motors is the field where physics and biology already mutually cooperate. It is assumed nowadays, that every directed motion in living cells (such as transport of ions through cells' membranes, and kinesin walking along cytoskeletal filaments) is governed by molecular motors. These 'microscopic engines' probably operate in the overdamped Brownian motion regime and for a better understanding of their roles in cells, a further development of methods of statistical physics is essential: we deal not only with individual motors in cells, but our challenge is to understand highly cooperative behavior of many molecular motors, filaments of the cytoskeleton system, transport through membranes, and organelles of the cell. We can encounter such phenomena as traffic flows, traffic jams and pattern formation in cells.

The theoretical and experimental study of both classical and quantum molecular motors enables us to develop a better stochastic method of systems description which is, in some sense, complementary to a fully microscopic description, starting from deterministic Newton or Schrödinger equations. Similarly, as Langevin and Fokker–Planck equations are complementary to the reversible, deterministic Newton equation and irreversible statistical mechanics based on it, the quantum Langevin equation and other quantum stochastic equations are complementary to the irreversible quantum statistical description starting from the 'reversible, deterministic' Schrödinger equation. In the end, both approaches, either the one starting from the deterministic description or the one starting from the stochastic description, must provide the same results. Again, natural questions in relation with classical and quantum molecular motors, are:

- How the irreversibility is emerging?
- Where is the crossover between the classical and quantum worlds?

It is generally agreed that chemistry of biomolecules is governed by the laws of quantum mechanics. It is, however, up to now completely unclear whether quantum mechanics plays any significant role in the essential processes which lead to life; the possible role of quantum coherence, entanglement and of decoherence processes in living organisms remains uncertain, together with questions relating to at which levels transition from quantum to classical takes place. Any existence of macroscopic quantum phenomena in living organisms is not supported by any evidence up to now.

Thus, biological systems offer physics many fascinating possibilities to investigate these systems at various levels of their complexity and present challenging tasks on the way to understanding how the laws of physics work in such complex systems. To understand these living systems at least partially, we have to combine many fields of physics. It is impossible to name all fields of biophysics and biological physics which are nowadays quickly developing, but we can mention modeling brain functions, immune system, structure, solvation and folding of biomolecules, electron and proton transfer in bioenergetics and enzyme catalysis, ultrafast quantum dynamics in photosynthesis and physics of cell membranes. Thus, there are many problems where physics can help biology and vice versa. For example, recent investigations show that statistical physics can help us understand biological information processing: the effect of stochastic resonance can explain how weak biological signals are amplified by random fluctuations.

10. To further improve systems which we can study experimentally, to suggest new experiments for small systems and to investigate various combinations of systems and parameters we have under our control.

There are many promising areas of research, such as quantum optics, cold atoms and Bose–Einstein condensates, physics of quantum computing, nano-electro-mechanical and opto-mechanical systems, spin systems, quantum Brownian motion and molecular motors, which provide us a possibility to test experimentally the developed models and basic theories (as for example the theory of decoherence) in greater detail.

III. Conclusion

There is hope that by working on the above mentioned problems in the future we will understand how and when a possible quantum thermodynamic description will appear as a special limit to quantum statistical physics. We will have better explanation for the irreversibility not only from the point of view of how it appears in the macroscopic world when a microscopic description is in principle based on a reversible description, but also in relation to the quantum measurement process which is an irreversible process itself. At the same time, we will understand better when and how the classical macroscopic world which we daily observe is emerging from our quantum statistical picture of the microworld.

Even small experimental systems (generally far from equilibrium states) are still complicated from the point of view of theoretical description and the interpretation of experiments.

In other words, we need to develop theoretical methods and models we are able to solve, and from which it is possible to extract information comparable with experimental data. At the same time, the model has to be able to describe the actual complexity of the experiment.

To conclude, we can again, as already after the FQMT'04 and FQMT'08 conferences, say that the depth and the diversity of the questions addressed at the FQMT'11 conference were very profound and are reflected in this topical issue.

IV. Structure of the volume and a guide in the bibliography

Many participants have submitted a contribution to this topical issue. These have been grouped in eight sections. The details of the recent developments regarding to the subjects of individual sections can be found in the included literature (ordered mostly by year of publication):

- Foundations of quantum mechanics [3–100].
- Quantum measurement, entanglement, decoherence and noise [101–202].
- Quantum thermodynamics [203–231].
- Non-equilibrium quantum statistical physics [232–340].
- Physics of small quantum systems [341–433].
- Cold atoms, quantum optics [434–477]
- Molecular motors, biological systems [478–539].
- General physics [540–578].

We note that, apart from some exceptions, only recent books and review papers are referred to. We suppose that the reader will find all other important articles in these books and reviews. Apart from this, we often do not refer in the text to specific books or review papers and leave the reader to find out the more detailed information from the variety of references offered in this paper, which are roughly classified above.

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