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Physics at the FQMT'04 conference

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Abstract

This paper summarizes the recent state of the art of the following topics presented at the FQMT'04 conference: quantum, mesoscopic and (partly) classical thermodynamics; quantum limits to the Second law of thermodynamics; quantum measurement; quantum decoherence and dephasing; mesoscopic and nano-electro-mechanical systems; classical molecular motors, ratchet systems and rectified motion; quantum Brownian motion and quantum motors; physics of quantum computing; and relevant experiments from the nanoscale to the macroscale. To all these subjects an introduction is given and the recent literature is broadly overviewed. The paper contains some 450 references in total.
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0. Introduction

The recent advancement of technology has enabled very sensitive experiments on natural and artificially prepared systems of molecular sizes. The possibility to shape such experiments provides many challenges from the point of view of understanding of basic concepts of physics related to these systems and development of methods for their description. There are two essential differences between these "mesoscopic" systems, we have in mind here, and large extended systems, such as crystals, described by the common thermodynamics and statistical physics theory. First of all, the typical "mesoscopic" system is of the intermediate size range between microscopic and macroscopic sizes. Second, the system can consist of only a relatively small amount of particles. The system is, however, very often connected via interactions with a macroscopic reservoir. This is very different from the situation which we use to describe by standard thermodynamics, where both, systems and reservoir, are large extended systems and the state of the system can be well characterized by macroscopic

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characteristics, like temperature. As for ‘‘mesoscopic’’ systems we definitely have to reconsider our concept related to the description of the system. In addition, due to their smallness, many of these ‘‘mesoscopic’’ systems can manifest quantum behaviour. Manifestations of quantum features like interference effects depend, of course, on the characteristic lengths of the system and temperature of the reservoir. Recent technology enables us to change very fine details of systems and conditions of measurements and to test various theoretical concepts experimentally. We are thus forced by technology and experiments to understand many essential concepts of the quantum theory, thermodynamics and statistical physics in this new context. It is not a trivial task at all to decide what characterizes such small systems and what information we can gain from our measurements. The characteristic phenomena for these ‘‘mesoscopic’’ systems are quantum coherence and decoherence, (‘‘thermal’’ and quantum) fluctuations and related noise in measured characteristics, tunnelling effects and dissipation. Under these conditions it is really hard to create a theory for the behaviour of the ‘‘mesoscopic’’ analogies of heat engines and motors, the themes opened by classical thermodynamics. Not surprising at all, the question of the validity of various formulations of the Second Law of thermodynamics in such systems has emerged. Apart from this, we are experimentally in touch not only with the basics of thermodynamics and statistical physics but also with quantum theory itself, since more and more precise experiments on these ‘‘mesoscopic’’ systems also challenge the interpretation of the quantum theory, its completeness and related theory of measurement. Many models and experimental systems have their classical and quantum version. Molecular motors and ratchets are considered as classical or quantum systems depending on the parameters of these systems and their surroundings. One of the main purposes of modelling and creating nano-electro-mechanical systems (NEMS) is to study the quantum features of both electronic and mechanical parts of these systems, their interplay and to observe and better understand the transition between classical and quantum behaviour. The proper understanding of classical and quantum features of microscopic and macroscopic states and their relation to the decoherence, dephasing, relaxation of systems, dissipation and quantum measurement problems is needed to understand behaviour of small ‘‘mesoscopic’’ systems. Since during measurements, systems can be very far from equilibrium we have to understand ‘‘arrow of time’’ problems, the emergence of non-equilibrium in these systems. To develop methods for the description of ‘‘mesoscopic’’ systems out of equilibrium and their relaxation to equilibrium is the absolutely necessary aim. It seems now that for the proper, coherent, operational behaviour of ‘‘qubits systems’’ which could lead to quantum computers in the future, the far from equilibrium regime could be the essential one. At the same time, solving the problem of how to read-out the information from these quantum qubits and not to disturb their coherence essentially, a deep understanding of the relaxation and dephasing processes is unavoidable.

Nowadays, all the above mentioned problems connect thermodynamics, statistical physics, quantum theory and physics of small systems not only from a theoretical, but also from an experimental point of view, at many levels. This recent state of the art motivated the organization of the FQMT’04 conference and the following choice of its main topics: quantum, mesoscopic and (partly) classical thermodynamics; quantum limits to the Second Law of thermodynamics; quantum measurement; quantum decoherence and dephasing; mesoscopic and NEMS; classical molecular motors, ratchet systems and rectified motion; quantum Brownian motion and quantum motors; physics of quantum computing; and relevant experiments from the nanoscale to the macroscale.

Many participants have submitted a contribution to these proceedings. These have been grouped in five sections:

1. Quantum thermodynamics.
2. Quantum and classical statistical physics.
3. Quantum measurements, entanglement, coherence and dissipation.
4. Physics of small quantum systems, and
5. Molecular motors, rectified motion, physics of nano-mechanical devices.

The grouping has been made as much as possible on objective criteria according to the prevailing orientation of the contributions. Due to the complexity and often general aspects of solved problems and their overlaps with many areas of physics, most contributions could be, however, placed into at least two sections and the division into sections is in the end, in some sense, a rather subjective and artificial one providing only the first, very rough, orientation between contributions.

0.1. A guide in the bibliography

The details of the recent development regarding the subjects of individual sections (altogether with some very recent development during a period of several months after the conference) can be found in the included literature (ordered mostly by years of publication):

1. Quantum thermodynamics: from Refs. [1–32].
2. Quantum and classical statistical physics: from Refs. [33–139].
3. Quantum measurements, entanglement, coherence and dissipation: from Refs. [140–336].
4. Physics of small quantum systems: from Refs. [337–395].
5. Molecular motors, rectified motion, physics of nanomechanical devices: from Refs. [396–455].

We note that, apart from some exceptions, only recent books and review articles 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 articles and leave up to the reader to find out the more detailed information from the variety of references offered in this article, which are roughly classified above. To help the reader, all references are given with their titles, not only books, but also all articles.

0.2. Contents

The aim of this article is to summarize the problems discussed at the conference, to introduce main topics of individual contributions and, last but not least, to point out relations between these topics.

The following five sections of this article correspond to the five groups of the contributions to these proceedings.

Each of these five sections consists of two parts: in the first part, the problem of the section is introduced. In the second part, called contributions to the conference, a short summary of all contributions to the proceeding section is given. Contributions are commented in the order in which they are published in the proceedings.

Due to many relations between discussed topics, texts in the following five sections partly overlap. The aim is, however, to show common themes from different points of view and levels of generality in different sections.

1. Quantum thermodynamics

This was the subject that Vladislav Čápek worked on in the last decade or so of his life (see reference in his book with Daniel Sheehan [27]) and it was the original motivation for the conference. Its covering continues the line started in the conference *Quantum limits to the Second Law* organized (Organizing committee: V. Čápek, Th.M. Nieuwenhuizen, A.V. Nikulov, and D.P. Sheehan) at the University of San Diego (USA) in July 29–31, 2002 [15], where Vladislav was a co-organizer, and was continued in the Lorentz workshop (organized by Th.M. Nieuwenhuizen, M. Grifoni, and E. Paladino) *Hot Topics in Quantum Statistical Physics: q-Thermodynamics, q-Decoherence and q-motors*, that took place August 11–16, 2003, Leiden (the Netherlands).

Originally, thermodynamics developed as the phenomenological description of the macroscopic behaviour of macroscopic systems. It formulated the most general laws of the macroscopic world as the First and the Second Laws of thermodynamics and introduced such concepts as temperature, heat, entropy and state variables. Phenomenological theory of heat engines based on thermodynamical behaviour of macroscopic systems was also developed. Later on, Boltzmann and his followers created statistical thermodynamics. The concepts of micro-states and macro-states of a system were created and dynamics of systems at the microscopic level were connected to the averaged, macroscopic, behaviour of the system.

When quantum mechanics appeared, statistical thermodynamics had to take into account additional ingredients, but the overall structure of thermodynamics and its laws, and its meaning as the method of description of huge, macroscopic systems, remained unchanged since it was believed that quantum mechanics does not play a role at the macroscopic level.

The real challenge for thermodynamics came with the miniaturization of systems which were the objects of experiments. In addition, discussions about macroscopic quantum effects and possible interference of macroscopically distinct states also contributed to a new emerging view of thermodynamics. The question emerged under which conditions the thermodynamic behaviour still manifests. And, of course, whether the thermodynamic laws are still valid. Additional quantum mechanical ingredients as quantum interference effects, (coherent) tunnelling, quantum non-locality and entanglement, quantum (not only thermal) fluctuations and finite size systems (splitting to system and reservoir) together with possible reduced dimensionality of systems, started to play an important role. All old certainties, as the theory of heat engines, Maxwell's demon problem, its relation to information and thermodynamics laws, appeared suddenly in a new light. Discussions about what is the meaning of quantum thermodynamics started and continue up till today, together with a huge development in the related field of the quantum statistical and mesoscopic physics, see also Sections 3–5. The theoretical considerations have been complemented by more and more sophisticated and sensitive, sometimes really "crafty", experiments. In fact, there is the question up to which extent (size, parameters of systems) thermodynamics can provide unifying description of "macroscopic objects" based on the laws known from statistical physics (discussed in the next Section 2) and quantum mechanics (Section 3). Especially, the use of the concept of temperature and its limits were questioned in connection with small quantum systems. The validity of the Second Law of thermodynamics was questioned, too. New suggestions of "heat" engines on the molecular level have been discussed. In addition, concepts developed in these three inter-related disciplines (discussed in Sections 1–3 of this article) are nowadays intensively tested and their possible limitations manifested by experiments on small quantum (mesoscopic) systems (Section 4), which special cases as molecular motors and NEMS are discussed in Section 5.

1.1. Contributions in the proceedings

The main players in this field present their contributions. First, there is the Scully group (Texas A&M; Princeton University) that focuses, in a series of papers on quantum optical engines, their fight against the Maxwell demon, and explain this old paradox on the basis of quantum thermodynamics.

Next, there is the Mahler group (Stuttgart), which, together with Gemmer (Osnabrück), presents a long argument for the emergence of thermodynamic behaviour in small quantum systems by introducing random quantum states. Closely related is the clarification of the question of when the notion of temperature applies to small quantum systems.

In his opening talk of the session, Nieuwenhuizen started out from the First and Second Laws as they apply to finite and nanoscale systems, integrating it with the work of Čápek. He stressed that some formulations of the Second Law can be violated, though no case is known where they are all violated. A new part of the material, referring to non-optimality of adiabatic work processes, is presented here; overviews of the further material of the talk are mentioned.

Then there are contributions of other long time players in the field: Ford and O'Connell discuss properties of the fine-grained entropy; Sheehan works out experimental setups which can be tested; Berger works out a description for the Chernogolovka experiment on power production by inhomogeneous mesoscopic rings. Keefe describes how a conventional superconductor may have an unexpected efficiency when cycling it across the transition line.

Patnaik and other members of the Scully group also clarify the role of injection times in certain lasers without inversion.

2. Quantum and classical statistical physics

Statistical physics is the powerful approach to study macroscopic properties of systems for which the dynamics is far too difficult to study otherwise than numerically. It has provided a theoretical basis of the laws of thermodynamics due to its recognition of the molecular structure of matter, and has applications to a diversity of systems with many elements, also outside the range of condensed matter physics, such as star clusters, granular materials, traffic problems, econophysics, risk management, etc.

The basic task of statistical physics is to relate microscopic characteristics of the systems, like interactions and dynamics of their many microscopic parts, with their macroscopically observed properties. It connects the level of description of the dynamics of individual particles, such as electrons, with macroscopic behaviour of such complicated structure, such as metals. Special attention must be paid to the description of the systems when the amount of particles involved is somewhere between microscopic and macroscopic, e.g. it has mesoscopic features, see also Section 4 and references there. Statistical mechanics is our tool to understand at least partly (in general non-equilibrium) many particle interacting systems and phenomena related to these systems as are various transient, relaxation, transport and dissipation processes, (thermal) fluctuations and corresponding noise during measurements on systems—in summary to understand all (generally non-linear and non-equilibrium) stochastic processes, linear or non-linear effects, short and long time behaviour of systems and dependency of the behaviour of an individual system on its initial state, structure, size and dimensionality. This is accompanied by better understanding of the reversibility of phenomena at the microscopic level and the general irreversibility at the macroscopic level. All the above discussion is common for both classical and quantum statistical physics. The properties of systems where quantum mechanics plays an important role, can be, however, in addition to classical behaviour, strongly influenced mainly by the three essential manifestations of quantum mechanics: the Pauli exclusion principle, quantum interference effects and quantum fluctuations. We will discuss in more detail mainly quantum interference and its relation to quantum decoherence and dissipation in the next Section 3. Quantum interference effects also play an essential role in the mesoscopic structured discussed in Section 4. In the following discussion we will take quantum mechanics into account.

Considering the huge variety of properties and phenomena related to various systems to find the most feasible methods of their description, statistical physics has developed many methods. Here, we will mention only some which are the most relevant to the conference contributions.

One of the most important concepts for various systems descriptions is the concept of closed and open systems.

2.1. Closed systems

The theoretical microscopic description of any quantum system starts from the Hamiltonian of the isolated system which can be, however, driven by some external time-dependent field described by the additional time-dependent part of the Hamiltonian. Such an isolated externally driven system is then called a closed system. The dynamics of a closed system are governed by the unitary evolution which is described either by the Schrödinger equation for the wave function or the Liouville equation for the density matrix of the system. Very often the needed (relevant) observables are single particle ones and, in this case, a one particle reduced density matrix description is used to find these observables. This reduced one particle matrix is found from approximations of the famous BBGKY chain of equations for reduced density matrices [38,122].

From the point of view of formulation of an approximation scheme, it is often advantageous not to calculate directly the single particle reduced density matrix, but to formulate dynamics within the Non-equilibrium Green's function (NGF) method [103–138]. This method was extensively used for investigations of many extended systems such as metals, semiconductors, plasma physics and nuclear matter physics systems when the closed system description appears as the natural one and, in consequence, it leads to a solvable description of the system. Similarly to the closed equation for a single particle reduced density matrix obtained by approximations within the BBGKY hierarchy, the irreversibility of the description and the related description of the dissipation phenomena emerge in this description when the asymptotical (approximal) equations are closed either for the single particle Green's functions or related single particle distribution function, as is in the case of the Boltzmann equation.

There are many identities and relations which help to solve the dynamical equations written for closed systems. One special identity, which is worth mentioning here, is the famous fluctuation–dissipation theorem, which, as its name implies, relates fluctuations with the effect of dissipation. This theorem is at the heart of linear response theory and enables us to formulate Kubo–Greenwood formulas for solution of various linear response problems. As an identity, which must be fulfilled in any linear response theory, the fluctuation–dissipation theorem can also serve us as the control for models involving dissipation. The study of glasses has taught us, however, that it applies only to systems where the largest timescale is less then the observation time [54,56].

For better description of molecular, mesoscopic and quantum optical systems, it can be, however, advantageous (from the point of view of the possibility to find the solution of the dynamics) to introduce the concept of an open system, which can be also useful from the point of view of a more natural description of quantum mechanics itself, due to its principal non-locality, see the following Section 3.

2.2. Open systems

Supposing there is a small part of a total system T, which we are preferably interested in. In this case, we divide the total closed system $T = S + B$, which is always governed by unitary evolution, to a so-called (relevant for us) open system S and (irrelevant for us) a bath B named sometimes also a reservoir. The dynamics of the open system S is then governed by the non-unitary dynamics for the reduced density matrix of the system S obtained by projection of the total density matrix to the subspace S and the Liouville equation for the total system T only to the subspace S, too. As a result of a projection technique, e.g. Nakajima-Zwanzig, we will have a generalized master equation (GME) for the reduced density matrix of the open system S [87–102]. Formally, this scheme works pretty well. The first important problem, however, emerges just at the level of this step. There are no essential problems to find a reasonable approximation of the resulting equations when the coupling between the open system S and the bath B is weak, so the separation seems to be quite natural. In this case of weak coupling, we have the very well-formulated Davies theory. As soon as the coupling is very strong, problems start and even today no really satisfactory approximations are known. In this respect, it is interesting to recall the breakdown of the Landauer inequality for the amount of work to be dispersed in order to erase one bit of information, occurring exactly in this regime [11,12].

Generally, the GME has a very complicated structure, and to find its solution for different systems and conditions is one of the tasks of recent quantum statistical physics. Similar to the situation in the description based on the closed systems, the basic approximation, which essentially simplifies the GME, is the Markovian approximation which removes all memory effects and introduces a local time structure of the equation. In such a case, the memory effects are important for the description of the system, and much more complicated non-Markovian approximations are used. From the point of view of behaviour of systems we can also formulate the GME in the so-called Brownian motion or quantum optics limit—the names of approximations and their use are self-explanatory.

Apart from methods based on the density matrix description and related Liouville equation for the quantum mechanical density matrix, there are also methods using the path integral formulation. Especially, the Feynman–Vernon formulation is often used. The path integral formulation is especially advantageous for formulation of problems with dissipation. On the other hand, we can solve a dissipative quantum dynamical problem with a path integral approach, the GME, or even via a generalized quantum Langevin equation. Special attention to various models with dissipation will be paid in the next section.

There are also recent attempts to combine the advantages of NGFs, originally developed within the concept of the closed systems, with the concept of open systems by generalization the NGF method for open systems [101,102]. This approach needs, however, still some time to be developed into a practical working scheme.

2.3. Contributions in the proceedings

First, there is a very elegant approach by Skála and Kapsa who derive the laws of quantum theory, and the limit to classical mechanics, on the basis of probability theory.

The section continues with contributions from the Stuttgart/Osnabrück groups (represented by Gemmer, Mahler and Michel) on quantum heat transport and a relation between Schrödinger and statistical dynamics. Next, there is a contribution by a Prague group centered around Mareš on a classical problem put forward by the celebrated Prague scientist Fürth. They investigate a possibility to find the difference between classical and quantum Brownian motion in systems with periodic chemical reactions. The criterion for the experimental accessibility of Fürth quantum diffusion limit is formulated in the article. Experimental data show that the quantum nature of Brownian motion in the investigated systems is very likely.

Menšík shows how to increase chances to solve complicated integro-differential dynamical structure of Nakajima–Zwanzig equations for the density matrix by transformation into the linear algebra system.

In a series of three papers, Špička et al. discuss long and short time quantum dynamics within the NGF approach. Reconstruction theorems for Green's function, which enable construction of single time quantum transport equations either of Landau–Boltzmann equation type for the quasiparticle distribution function or GMEs for the single particle density matrix, is discussed in detail.

After this there comes a contribution by Mareš et al. on a method, called stochastic electrodynamics, that might underlie the well known but poorly understood zero point fluctuations and zero point energy of quantum mechanics.

The article of de Haan deals with a resummation approach in classical physics that avoids infinities such as the infinite self-energy of a point charge.

The follow up paper Khrennikov attacks the claim that probabilities of quantum theory cannot be explained from classical probability theory; he explicitly shows that they follow directly, provided the context (measurement setup) is specified first.

Next, there are contributions by Klotins on a symplectic integration approach in ferroelectrics and by Patriarca on the Feynman–Vernon model for a moving thermal environment.

The section ends with a microcanonical approach to the foundations of thermodynamics by Gross.

3. Quantum measurement, entanglement, coherence and dissipation

This section deals with some core problems of recent physics, as the foundations of quantum physics, mechanisms of decoherence and dissipation and emergence of the classical world from the quantum one, as well as macroscopic irreversibility from microscopic reversibility. These are, nowadays, contrary to past thinking, not only posed as theoretical, academic problems, but they are now more than in the past reflected in recent experiments and even suggested applications.

The central phenomenon which connects such topics as the quantum measurement problem, interpretation of quantum mechanics, non-locality of quantum mechanics, quantum entanglement and teleportation, measurements on quantum systems with possible quantum qubits behaviour and studies of various mesoscopic systems, is the phenomenon of quantum interference.

The existence of quantum interference, confirmed experimentally at the microscopic level, brings the natural question about a possibility of quantum interference of macroscopically distinct states. This question is the basis of the famous Schrödinger's cat thought experiment [148], which was formulated soon after another famous thought experiment, the Einstein–Podolsky–Rosen (EPR) paradox [140,148], 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: Where is the border line between the classical and quantum worlds? What does macroscopic and microscopic mean from this point of view? At which level can we still observe superposition of quantum states? The standard Copenhagen interpretation of quantum mechanics just states that microscopic quantum objects are measured by classical macroscopic apparatus. The collapse of the wave function (by some "stochastic" unknown process) occurs in the relation with the measurement and we will receive an "unpredictable" measured value. At the time of its formulation, experiments, which would enable measurement of the transition between the micro- and macroworlds under well-defined conditions, were not accessible. 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.

The above mentioned problems were thoroughly discussed at the conference. Lively, discussions about the foundations of quantum mechanics and related experiments followed talks of leading experts in this area, R. Balian, A.J. Leggett and A. Zeilinger. They gave talks with the very fitting and self-explanatory titles:

R. Balian: "Solvable model of quantum measurement",

A.J. Leggett: "Does the everyday world really obey quantum mechanics?",

A. Zeilinger: "Exploring the boundary between the quantum and classical worlds".

Later on, K. Schwab give a talk about NEMS (see also Section 5) "Quantum electro-mechanical devices: our recent success to approach the uncertainty principle", which documented the very real and fruitful relations between fundamental questions of quantum physics, possibilities of the recent technologies and experimental physics dealing with small quantum systems (Sections 4 and 5).

All these lectures and the following discussions showed that the role of quantum interference and its erasing by decoherence processes is still not fully understood, but we are gradually getting better insights in many problems of quantum physics of the micro-worlds and macro-worlds. In addition, we see the old problems, represented by EPR and Schrödinger's cat paradox in a new light. The emerging landscape of foundations of quantum physics and relevant experiments is more and more complex. After pivotal experiments of Alain Aspects and his group [144–147,205] investigating the non-locality of quantum theory and Bell's inequalities from the late seventies and early eighties of the last century, we have witnessed a wave of important experiments, coming from two fields: quantum optics and solid state physics.

Many experiments have attempted to test non-locality of quantum mechanics as well as the quantum complementarity principle. Since interference effects are often seen as the manifestation of non-local behaviour, there is sometimes believed to be a direct relationship between tests of quantum non-locality, entanglement and complementarity. After Aspect's experiments (which tested directly validity of Bell's inequality) other independent experiments testing quantum non-locality appeared. In 1989, Franson [153] suggested an experiment with energy-time entangled photons to compare "standard" quantum mechanics with local hidden variable theories based on different degrees of interference in these groups of theories. The corresponding experiments were realized about ten years later [199–201]. These experiments confirmed independently the results of Aspect's group, i.e. strong violations of Bell's inequality. Another experimental scheme to test non-locality (using the idea of three-photon entanglement states, nowadays called GHZ states) was developed by Greenberger, Horne and Zeilinger [158] and improved by Mermin [159]. The first experiments with GHZ states were reported in 1999 [206] and quantum non-locality was tested via three-photon GHZ states [215] without direct use of Bell's inequality. Recently, the question of a single photon non-locality has reappeared. For a recent and "extreme" discussion for a single photon non-locality, see Ref. [244]; it is interesting to compare this paper to the local interpretation by Vaidman [178] and the related discussion [174,179,180].

The complementarity principle, which is in contradiction with local theories, was tested via "which-way" double slit-type experiments. A Gedanken which-way experiment using micromaser cavities was suggested and gradually improved upon by Englert, Rempe, Scully, and Walter [160,161,175,207]. Ideas related to the so-called quantum eraser thought experiments reported in the articles above were experimentally realized in 1995 [186]. The quantum eraser principle was also lively discussed at the FQMT'04 conference after the lecture of Marlan Scully: "Quantum Controversy: From Maxwell's Demon and Quantum Eraser to Black Hole Radiation".

All experimental tests of non-locality and complementarity up to now support non-locality of the quantum mechanical picture and seem to exclude the idea of local reality. This is still a heavily debated subject, however, and there are opposing view points as well, which argue that locality cannot be excluded, see e.g. Refs. [219–222,245]. Non-locality is also strongly advocated on the basis of teleportation experiments using the entangled states. For the first time the possibility to teleport a photon was discussed in Ref. [168]. Teleportation was then experimentally realized in 1997 [193].

Another group of experiments related strongly to both foundations of quantum physics, and even possible applications, are experiments dealing with the physics of quantum computing, i.e. physics of qubits. Several leading experts in this field delivered their lectures at the conference speaking about various aspects of the physics involved, both from the theoretical and experimental point of views. Namely, participants heard (in addition to the contributions included in these proceedings) the following lectures:

B. Altshuler: "Non-Gaussian low-frequency noise as a source of decoherence of qubits",

T. Brandes: "Shot noise spectrum of open dissipative quantum two level systems",

A. Caldeira: "Dissipative dynamics of spins in quantum dots",

H. Mooij: "Coherence and decoherence in superconducting flux qubits",

G. Schön: "Dephasing at symmetry points",

U. Weiss: "Non-equilibrium quantum transport, noise and decoherence: quantum impurity systems and qubits".

Again, as we can see even from the titles of these lectures, the central theme of "qubits physics" is the theoretical description and measurement of three closely related phenomena: dissipation, noise and decoherence.

There are nowadays several ideas being put forward as how to realize quantum qubit systems practically. The most active work is mainly on these systems: quantum optical systems (and cavity quantum electrodynamics based on systems), ion traps, liquid state NMR and spin systems in semiconductors. During the conference special attention was paid to superconducting circuit systems which use the Josephson junction effect. The common central theme of all the investigations into these various systems 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).

In general, decoherence is a process of a loss of quantum interference (coherence) due to non-unitary dynamics of the system, which is a consequence of a coupling between the system and the environment (in terms of theory of open systems discussed in Section 2, due to interaction between the open system S and the reservoir B). Since technically quantum interference is described by the off-diagonal elements of the density matrix of the system, correspondingly the decay of these elements (their possible time development towards their zero values limit) describes the decoherence processes. When all off-diagonal density matrix elements are zero, the system is in a fully decoherent (classical) state. Phenomenologically, the transition in time from the quantum (coherent) state into the classical (decoherent) state can be described by a decoherence factor $e^{-t/\tau}$, where τ is the decoherence time. Generally, the decoherence, of course, includes both dephasing and dissipative contributions (and not only), sometimes denoted as T_2 and T_1 processes. Dephasing is related to processes randomizing the relative phases of the quantum states. Dissipation corresponds to interaction processes which are changing the populations of quantum states.

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, see also Section 2. There are still many unanswered questions related to quantum coherence, the most important, at least as it seems now, are the following ones:

1. *What is 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, 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.

2. *What are possible mechanisms of decoherence in various systems*? Apart from this, what is the relation of these mechanisms to other mechanisms in systems, e.g. namely to quantum relaxation processes?

3. *What is the relation of decoherence processes with the transition between the quantum and classical behaviour?*

4. *How are decoherence processes related to quantum measurement processes?* Namely, a natural question emerges as to whether the decoherence can cause collapse of the wave function in relation to the measurement process? If yes, what is the difference between measurement on 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?

Investigation of various manifestations of quantum interference, dissipation, dephasing and decoherence, in general, is a very active area of recent research, since we need to understand decoherence at microscopic, mesoscopic and macroscopic scales to be able to deal with recent experimental systems, see also Sections 4 and 5. On the other hand, nowadays a huge diversity of investigated systems, with often well-controlled parameters, provide us an enormous amount of experimental data to build up a gradually more and more satisfactory picture of decoherence processes and related theories of their description. Apart from providing a practical solution for every-day problems encountered when analysing behaviour of experimentally tested systems, this progress in knowledge about interference effects and decoherence processes also helps us to improve our understanding of quantum physics at its most fundamental level. As already partially discussed above, interference and decoherence play a crucial role in interpretation of quantum mechanics and possible alternative theories.

Apart from the Copenhagen interpretation of quantum mechanics and its small variations, there are many other interpretations between which it is difficult to distinguish since they provide, at least in principle, the same description of nature and the same results when applied to concrete physical situations. Here, we name only some important representatives of these alternatives of the Copenhagen interpretation:

1. Statistical interpretation as it is represented by the approach of Ballentine [141], and embraced by Balian on the basis of his solution of the quantum measurement problem [223,237].
2. The de Broglie-Bohm interpretation with de Broglie's idea of pilot waves and Bohm's idea of quantum potentials [152,166,171,330].
3. Many world interpretation as represented by Everett's approach [142,148].
4. Macroscopic realism as represented by Leggett's contributions [143,150,164,171,185,225,259].
5. GRWP (spontaneous collapse models) theory as represented by the works of Ghiradi, Rimini, Weber and Pearle [149,155,233,234], and by the recent development in this field [254], and
6. Penrose theory combining quantum mechanics with the geometry of space and time [154].

We will not discuss these theories in detail here, see many references to this section at the end of this article. We will just briefly comment that the problem of the collapse of the wave function, measurement of microscopic versus macroscopic states and decoherence processes, are related in some of the above-mentioned interpretations of quantum mechanics. Environmentally induced decoherence is one of possible explanations for the collapse of the wave function and non-possibility to observe macroscopic superposition of states.

Generally, decoherence can be a candidate for explaining most of the difference between the microscopic world of quantum physics and the macroscopic (classical) world we directly observe. From this point of view, the idea of decoherence can help us in the end to understand, even at the very fundamental level, the relation between quantum statistical physics and thermodynamics. Since the decoherence time is very sensitive to the parameters of the system and to the reservoir with which the system is coupled, its values can change over many orders from the very small (non-measurable nowadays) values for macroscopic objects to the very large values for almost isolated elementary particles. The small, "mesoscopic" systems, see also Section 4, however, provide a possibility to make measurements of decoherence in the time range which is observable by recent techniques.

3.1. *Contributions in the proceedings*

First, Balian et al. contribute to the "perennial", but still not satisfactorily closed, discussion of the measurement of quantum systems. The quantum measurement problem has long suffered from a lack of models with enough relevant physics, which has led to desperate views as being unsolvable, being a matter of philosophy, and so on. In his talk, Balian presented a simple, yet sufficiently rich model for the measurement of a spin-$\frac{1}{2}$. Based on the macroscopic size of the apparatus, he connects the irreversibility of the measurement with the general problem of irreversibility in statistical physics, where the paradox of microscopic reversibility plays no role in practice, because it relates to unrealistically long times. Balian also touched upon questions related to decoherence (see points 1–4 above). In the model he considered, the Schrödinger cat terms vanish by dephasing and are, being hidden but still present, in a subsequent step erased by decoherence (the situation is similar to spin-echo setups, when no echo is made). The registration of the measurement takes place on a still longer timescale and has classical features. The whole setup, before, during and after the measurement, has a natural look within the statistical interpretation of quantum mechanics.

One of the surprising features of quantum mechanics is its coherence and entanglement. This leads to processes that, even though possible in the physics of classical Brownian motion, are rather unexpected. This theme is represented by works of Büttiker and Jordan on ground-state entanglement energetics, of Aharony, Entin–Wohlman and Imry on phase measurements in Aharonov–Bohm interferometers of Schulman and Gaveau on quantum coherence in Carnot engines, of D'Arrigo et al. on quantum control in Josephson qubits, and by Cohen on quantum pumping and dissipation.

4. Physics of small quantum systems

In the context of this section, systems are understood to be small (often also called mesoscopic) when their parameters enable us to observe quantum interference effects manifested, for instance, in the transport characteristics of electrons. Usually, these systems are artificially created structures which combine metal, semiconductor or superconductor materials [338,341,343, 346–348,352–357,362,363]. Various characteristics related to electrons in these structures are studied. The "small" size of the system is not the only one decisive parameter which determines whether quantum interference will be manifested. In fact, what is small from the point of view of manifestations of quantum interference effects depends also on the interactions in the systems. For instance, the quantum coherence of an electron which moves in the sample ballistically without scattering events can be disturbed by its scattering with phonons; of course, with decreasing sample size there is a bigger probability that the electron flows through the sample without any inelastic scattering which disturbs its quantum coherence. On the other hand, the increasing temperature drastically increases the probability of electron–phonon scattering. So, when temperature is lower, the size of the sample can be bigger to observe interference effects related to the electron moving without scattering through the sample. Of course, the concentration of electrons is another parameter which influence the quantum behaviour because of its relation with the electron–electron interaction.

Physics of "small" (mesoscopic) systems has been a very active area of research already for many years, which brings further and further motivation for investigations due to ever improving technologies [377,382,389,390,392–395,419]. These enable the preparation of more and more interesting samples with really well-defined parameters and to measure more and more, in the past inaccessible, details. Nowadays, experiments can measure quantum interference effects in a system and their dependence on various parameters as, for example: dimensionality of the sample (quantum dots, quantum wires and various two dimensional systems are common), size of the sample and its geometry, concentration of impurities (the number of scattering events can be varied), concentration of electrons, temperature of the sample and its environment, and strengths of electric and magnetic fields.

These artificially prepared systems enable us to test various hypotheses, methods and theories developed in the above discussed areas of Quantum thermodynamics (Section 1), Statistical physics (Section 2) and Physics of quantum measurement, entanglement, coherence and dissipation (Section 3).

In these small systems, many quantum interference and fluctuation phenomena are studied under various conditions, among others, weak electron localization, universal conductance fluctuations, persistent currents, and tunnelling (resonant tunnelling). Special attention is also paid to the Aharonov–Bohm effect, quantum Hall effects, and quantum chaos [58,341,348,352,353,362,363, 384].

An especially fast developing area is "quantum dots" physics [386,389,390]. Nowadays, quantum dots can be fabricated with a few levels, thus constituting artificial atoms. As their parameters can be manipulated, this yields unprecedented tools to study the dynamics of few level open systems and dissipative processes in a controlled way. Quantum dots systems, as mentioned already in Section 3, are also candidates for creating working qubit systems.

Another very active area of research is dealing with molecular systems and molecular electronics [382,391,392].

"Mesoscopic" systems also contributed to the development of some special theoretical methods of quantum statistical physics. To describe very effectively linear transport of electrons in mesoscopic systems, the Landauer–Büttiker method was introduced [58,338,348,352,353,359]. This formalism, based on the idea of transport as a scattering problem, is suitable for the description of transport through samples where only elastic scattering (on impurities) takes place. Transport channels are then well described by transmission and reflection coefficients, and we have a simple recipe of how to calculate transport characteristics. In this case, this efficient method is equivalent to the Kubo–Greenwood formula which has to be, however, used when inelastic scatterings must be taken into account [339,340,342]. To describe various transport regimes in the case of disordered systems, random matrix theory [66] and non-linear sigma models [55] are also in use. Many techniques, originally used for the description of bulk (extended) systems, as, for example, Green's functions [112–114,129,339,342,360,367,368,373,374] or the path integral approach [58], have been also adapted to describe the physics of small systems.

4.1. Contributions in the proceedings

This section contains papers by Hohenester and Stadler on quantum control of the electron–phonon scattering in artificial atoms, of Kuzmenko, Kikoin, and Avishai on symmetries of the Kondo effect in triangular quantum dots, by Rotter et al. on Fano resonances and decoherence in transport through quantum dots, by Král and Zdeňek on the stationary-state electronic distribution in quantum dots.

Further, there is a contribution by Kamenetskii on mesoscopic quantum effects of symmetry breaking for magnetic-dipolar oscillating modes, of Sharov and Zaikin on parity effects and spontaneous currents in superconducting nanorings and by Sadgrove et al. on noise on the quantum and diffusion resonances of an optics kicked atomic rotor.

The section ends with a contribution from Mareš et al. which deals with the weak localization from point of view of stochastic electrodynamics.

5. Molecular motors, rectified motion, physics of nanomechanical devices

Physics of molecular motors and nanomechanical systems create special branches of physics of small ("mesoscopic") systems. Contrary to the preceding section, this section deals with classical as well as quantum systems.

Contributions in the proceedings deal with many aspects of molecular motors and rectified motion (classical and quantum versions of ratchet systems) and discuss various aspects of molecular and nano-mechanical devices.

5.1. Molecular motors and rectified motion

The basic feature of ratchet systems is the existence of a periodic, but asymmetric potential in the presence of an AC driving field. In addition, a system with a ratchet effect must have such parameters that thermal and quantum (in the case of quantum motors) fluctuations play an important role in its dynamics. Under these conditions, directed transport can appear both in classical and quantum systems. Due to the essential role that Brownian motion plays in the ratchet effect, systems manifesting this effect are called either ratchet, or equivalently, Brownian motor systems. Due to the importance of fluctuations, ratchet effects appear generally in small systems [403–406,417].

The ratchet effect occurs naturally in biological systems, where it creates a base for functioning of so-called molecular motors. These are proteins that take care of transport and muscle contraction in living organisms [397,399,401,402,408,409,413,416]. Apart from these naturally created systems, molecular motors are also studied in artificially shaped systems which, in some sense, mimic functions of molecular motors in living cells [404,417].

There were several very interesting lectures at the FQMT'04 conference which covered Brownian motion and molecular motors in both classical and quantum variants together with relevant experiments and possible applications. This can be demonstrated by the following lectures presented at the conference:

H. Grabert: "Quantum Brownian motion with large friction",

M. Grifoni: "Duality transformation for quantum ratchets",

P. Hänggi: "Brownian motors",

H. Linke: "Nano-machines: from biology to quantum heat engines",

T. Seideman: "Current-driven dynamics in molecular scale electronics. From surface nanochemistry to new forms of molecular machines",

S. Klumpp: " Movements of molecular motors: random walks and traffic phenomena".

Klumpp discussed a less studied aspect of these motors, namely their large-scale motion, which of course is the thing that makes them so relevant in our bodies.

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?" and "Where is the crossover between classical and quantum worlds?".

5.2. Nanomechanical systems

In this subsection, we will briefly comment on two categories of small mechanical systems, opto-mechanical and NEMS.

The central part of both systems is the mechanical resonator of nanometer to micrometer size scale which is coupled to a specially shaped "environment". This coupling enables us to detect vibrational modes of the resonator and also enables these systems to work as "devices".

Due to advances in microfabrication techniques, nanomechanical devices have a great potential, not only in applications, as e.g. ultrasensitive mass and force detectors at the molecular level, high-speed optical signal processing devices, and electrometers, (e.g. when coupled to a Cooper-pair box) but also in investigations of fundamental concepts of quantum mechanics.

Opto-mechanical systems consist of a resonator coupled to a radiation field by radiation pressure effects. A radiation field serves as a probe to read out information about the state of the resonator (oscillator's frequency and position).

At the FQMT'04 conference, the lecture of P. Tombesi: "Macroscopic entanglement for high-precision measurements" was devoted to applications of opto-mechanical systems of high-precision measurements [424,442].

In the following, brief summary of nanomechanical systems we will concentrate on the discussion of NEMS since they were, in comparison to opto-mechanical systems, far more discussed at the conference. In addition, contrary to opto-mechanical devices, contributions related to NEMS are presented in these proceedings.

The overview of recent developments in the physics of NEMS was contained in the following three lectures:

M. Blencowe: "Semiclassical Dynamics of Nanoelectromechanical systems"

A. MacKinnon: "Theory of some NEMS"

K. Schwab: "Quantum electro-mechanical devices: our recent success to approach the uncertainty principle"

Nano-electro-mechanical systems (*NEMS*) are nanometer to micrometer scale mechanical resonators coupled electrostatically to electronic (mesoscopic) devices of comparable size. In other words, NEMS are micro-electro-mechanical systems (MEMS) scaled to submicron size. As a central part of NEMS, the mechanical resonator, very simple structures, such as a cantilever or a bridge, are commonly used [434,445,455]. A mechanical resonator having submicron size and small mass can vibrate at frequencies from a few megahertz up to around a gigahertz. There is a possibility to detect the displacement of the vibrating part of the resonator (e.g. cantilever) by ultrasensitive displacement detectors. Several working schemes have been suggested [435,445,453]. One of the possibilities for the extremely sensitive motion detectors for the nanomechanical resonator is a single-electron transistor (SET) [432,449,448].

There are plenty of suggested and even experimentally realized schemes for devices using electromechanical coupling to the submicron resonator.

Mass spectrometer: When a small particle (molecule) attaches itself to a resonator, its mass can be determined from the resulting vibrational frequency shift of the resonator [440,441].

Electro-mechanical which-way interferometer: The resonator (cantilever) is electrostatically coupled to a quantum dot situated in one of two arms of an Aharonov–Bohm ring. The vibrating cantilever decides which way the individual electron goes from the dot. At very low temperature a submicron cantilever can be represented by a single quantum mechanical oscillator [425,433].

Quantum shuttle: This is a model device suggested originally by Gorelik et al. [420]. In this model, a movable dot, coupled to a quantum harmonic oscillator, is situated between two contacts. Electrons are shuttled from one contact to the other on the dot. In the vicinity of the contacts, the electron can tunnel from the dot to the respective contact. There are variants of this model (single or triple dot arrangements). In addition, not only shuttling of electrons but also of Cooper pairs has been studied [431]. All the suggested models have been intensively investigated from the point of view of what are the proper observables which can decide between quantum and classical shuttling processes [428,437–439]. Recently, even full counting statistics (FCS) of the quantum shuttle model have been calculated [451]. Even though there have been recent attempts to make quantum shuttles, it seems now that these devices are still too large to be able to manifest quantum effects.

Systems for solid-state quantum information processors: There is a chance that NEMS will play an important role in the development of quantum computer systems, see also Section 3. The task of fabricating physical qubit elements in such a network that will reach sufficiently long quantum decoherence decay times and at the same time will be able to control entanglement of individual elements, is one of obstacles on our way to a quantum computer. Recently, a promising scheme has been suggested: high-frequency nanomechanical resonators could be used to coherently couple two or more current-biased Josephson junction devices to make a solid-state quantum information processing architecture [446,452].

Nanomechanical resonators coupled to a Cooper-pair box: The system of a nanomechanical resonator which is electrostatically coupled to a Cooper-pair box has been studied both theoretically and experimentally [429,436,445,455]. There has been a hope that these systems can be used to test some ideas from the decoherence theory and questions related to the foundation of quantum physics, see the text below.

BioNEMS: With advancing technologies and huge sensitivity of NEMS to detect small inertial masses (even of individual molecules) and at the same time forces (chemical forces), there is an increasing chance that NEMS will be effectively used to improve our knowledge of macromolecules existing in living cells by measuring their masses and binding forces. Questions of the type: "Can one realize a nanoscale assay for a single cell?" have already been seriously asked. Biochips involving nanoscale mechanical systems could be quite helpful in biochemistry studies [421].

NEMS systems represent a great hope for improving our understanding of many aspects of the behaviour of small systems. Apart from providing ultra-sensitive measuring techniques and many other possible applications, this also enables us to test basic ideas of quantum statistical physics and conceptual foundations of quantum mechanics mentioned in Sections 2 and 3.

5.2.1. *NEMS, statistical physics and foundations of quantum mechanics*

Taking into account "mesoscopic" sizes, masses of both the nanomechanical resonator and coupled devices, temperatures involved (NEMS systems operate at very low temperatures) 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. For example, the analysis of the current noise spectrum can help to distinguish between possible mechanisms of transport of electrons between two contacts of a quantum shuttle device. Suggested models and approximation schemes can be tested experimentally.

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 behaviour 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, see also Section 3.

A possibility to use NEMS for which-way experiments, one of the essential tests of interference behaviour and non-locality nature of quantum mechanics, was already mentioned above.

Testing the Heisenberg Uncertainty Principle is another choice. There is an increasing effort to approach the quantum limit for position detection. The recent [447] ultra-sensitive measurements of positions of a resonator (effectively represented by an oscillator) at very low temperature were made on the NEMS system. The positions of a nanomechanical resonator, a vibrating mechanical beam (with the frequency of about 20 MHz) which was about a hundredth of a millimeter long and cooled down to about 60 mK, were measured by a single-electron transistor coupled electrostatically to the resonator. It is fascinating to realize that this test of the Uncertainty Principle used a mechanical beam, very small from the point of view of human senses, but still macroscopic from the point of view of common conception of micro-world and macro-world of quantum mechanics. The beam consists of about 10^{12} atoms. Such a many-particle object definitely is not considered to be microscopic. This experiment is not only trying to approach the Heisenberg Uncertainty limit for a position measurement, but it tries to approach it for a macroscopic object. In other words, this type of experiment aims to find a crossover not only between the quantum and classical worlds but also to find out how this crossover is related to the possible distinction between the micro-world and macro-world.

Interference of macroscopically distinct states and measurement of decoherence times: At the end of the discussion of NEMS and foundations of quantum mechanics, we will return to the nanomechanical resonator coupled to Cooper-pair box NEMS already introduced above. This NEMS offers a working scheme to produce superpositions of distinct position states and measure their decay due to environmentally induced decoherence [429,436,445]. This scheme is based on the idea of coupling a nanomechanical resonator to a Cooper-pair box to gain an advantage of coupling the resonator to a well-defined two-level system (spin-down and spin-up states; a Cooper-pair box consists of a small superconducting island which is linked through a Josephson junction to a superconducting reservoir). The aim is to produce entangled states of a mechanical resonator and a Cooper-pair box: as soon as the Cooper-pair box is in a linear superposition of charge states (prepared by using an external gate) the resonator is (due to entanglement) driven in a superposition of spatially separated states. Under some circumstances, the separation of these states is large enough so that these states can be described as distinct states. Since the used resonator (cantilever) contains about 10^{10}–10^{11} atoms, we can suppose these states are macroscopically distinct states. There is a possibility to observe decoherence times related to this superposition of macroscopically distinct position states due to their coupling to the "well-defined" environment.

5.2.2. *A guide in the bibliography*

The recent development in nano-electromechanical studies is well documented in the book from Cleland [430] and several review articles [421,426,431,445,455].

5.3. *Contributions in the proceedings*

First of all, large scale motion of molecular motors is reviewed by Klumpp et al. They use lattice models to deal with well-known traffic problems, in their case in the context of motion of unbound molecular motors. In this way, they model behaviour of molecular motors in living cells which are responsible for driving the transport in organelles.

Quantum heat engines based on particle-exchange are discussed by Humphrey and Linke. They thoroughly discuss properties and differences in the thermodynamics underlying the three-level amplifier (a quantum engine based on a thermally pumped laser) and two-level quantum heat engines.

An overview of theoretical problems related to some nanomechanical systems (NMS) and NEMS is given by MacKinnon. He explicitly deals with two models of NEMS: (1) a system of gears in which he investigates the effects of quantization of angular momentum and (2) a quantum shuttle. In the discussion based on properties of these two models he shows essential problems of NEMS models as for their understanding and their experimentally observable realizations: (1) to create a model of experimentally detectable quantum effects related to both mechanical and electronic degrees of freedom and (2) to describe properly the dissipation of mechanical energy.

The quantum shuttle, as a representation of NEMS, is studied in the article of Flindt et al. They present a method for calculating the current noise spectrum for NEMS that can be described by a Markovian generalized master equation (GME). The analysis of the gained noise spectrum shows two possible mechanisms beyond the current through the quantum shuttle device: depending on parameters, either shuttling or sequential tunnelling will prevail.

Rekker et al. investigate the classical Brownian motion of particles under some specific constraints. They consider the noise-flatness-induced hypersensitive transport of overdamped Brownian particles in a tilted sawtooth potential drive by multiplicative non-equilibrium three-level noise and additive white noise.

The following paper of Chvosta and Šubrt is by its theme closely related to the paper of Rekker et al. Chvosta and Šubrt model the one-dimensional diffusion dynamics of the Brownian particle in piecewise linear time-dependent potentials. They study two model potential profiles: W-shaped double well and a periodic array sawtooth. In both cases, the potential is superimposed on a step of harmonically oscillating height.

The section ends with a study of a quantum version of molecular motors. Zueco and García-Palacios solve the Caldeira–Leggett master equation in the phase-space representation to describe the behaviour of quantum ratchets. They discuss the transition between the classical and quantum behaviour of ratchets (in terms of methods using Fokker–Planck as a classical version of the Langevin equation and Caldeira–Legget as a quantum version of the quantum Langevin equation) and the related decoherence processes.

6. Summary

The FQMT'04 conference and the conference contributions to these proceedings have demonstrated many relations between such areas as quantum thermodynamics, statistical physics, quantum measurement theory, decoherence theory, physics of small systems, molecular motors and NEMS. Apparently, there is also an increasing tendency for merging theoretical and experimental methods of quantum optics and solid state physics. Lectures, contributions and discussions during the conference have also shown several really challenging goals of the recent physics, which are common to all these areas:

1. *To improve methods for the description of (open) systems far from equilibrium*: We need to develop 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. A really challenging problem is to develop a theory which describes proper dynamics of the system when the interaction between the system and the reservoir is a strong

one, and weak coupling theories are not working properly.

2. *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 the 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 would be still practically treatable within the GMEs framework.

3. *To improve our understanding of decoherence in various (microscopic–mesoscopic–macroscopic) systems*: There is 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. As to the first item, some progress was discussed at the meeting by presenting an explicit, solvable model for a quantum measurement. It would be interesting to see more research along these lines.

4. *To create new methods to analyse noise spectra and to thereby extract useful information for systems such as NEMS*: There is also an increasing need to gain more information about "mesoscopic" systems from transport studies as opposed to only the mean current, which measures the total charge transported via the system. The full counting statistics (FCS), i.e. the knowledge of the whole distribution of transmitted charge through the small system, of course, provides more information about the system than just only 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, more or less, to Markovian approximations of GME of used models.

5. *To study intensively physical processes in "small" biological systems, i.e. on the level of cells and their organelles*: Recent nanotechnologies enable us to construct (biomimetic) systems, which mimic at least some features of complicated biological systems and mechanisms in living cells. Apart from investigation of mimetic systems, nanodevices (e.g. NEMS) provide us a possibility to "follow individual molecules" in cells and manipulate them. This increases a possibility of "symbiosis" between biology and physics: we can improve our knowledge of how cells work 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 do not deal only with individual motors in cells but our challenge is to understand highly cooperative behaviour 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. In fact, 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.

6. *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 Brownian motion and

molecular motors, opto-mechanical and NEMS, quantum optics and physics of quantum computing, which provide us a possibility to test experimentally the developed models and basic theories (as, for example, the theory of decoherence) in greater detail.

There is hope that working on the above-mentioned problems we will in future understand how and when a possible quantum thermodynamic description will appear as a special limit of 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 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. The task to understand the phenomena discussed at the FQMT'04 conference is to navigate in between *Scylla* and *Charibda*, the opposing rocks, which are created on one side by theoretical models and on the other side by experiments. 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 real complexity of the experiment.

To conclude, we can say that the depth and the diversity of the questions addressed at the FQMT'04 conference were very profound and this is reflected in these proceedings.

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