

## Chapter 1

# Introduction (Why and how non-equilibrium?)

Nowadays most theorists working on condensed matter or statistical mechanics are involved with problems related to equilibrium. The interest is focused on different phase transitions. Many of them are spectacular, being candidates for technological applications too. On the other hand, the situation is very clear from a conceptual point of view. The object of mathematical interest is the statistical sum in the thermodynamic limit. However, one has to face a very intricate question - how equilibrium may be reached by physical systems obeying time reversal invariant (classical- or quantum-) mechanics? This is the central problem non-equilibrium theorists have to deal with, and the issue as such is getting a promising yet not satisfactory and exhaustive answer in the last decades only. Although Boltzmann formulated his famous and very successful equation for gases at the end of the 19th century, he was desperate about the lack of any sound foundation, neither was he able to defend it against the harsh criticism of Mach.

Beyond the conceptual problem of evolution versus equilibrium, one was interested in the past mostly in the description of stationary or slow non-equilibrium states, especially in the elaboration of procedures, to calculate on the basis of microscopical models the various phenomenological material parameters. This aspect had a serious motivation, also due to the technological applications based on the properties of metals and semiconductors.

However, the focus soon turned to non-linear phenomena, that proved to be extremely successful in technological applications. Here already one had to concentrate on behaviors and laws, resulting from the governing equations, rather than on a few phenomenological coefficients.

The last kick was given a decade ago by the use of extremely intense and ultrashort laser pulses (with wave-length corresponding to the gaps of

most important semiconductor materials). Here a new sort of experiments appeared under the name of “ultrashort-time spectroscopy”. In such an experiment one irradiates the material with two or more more ultrashort (in femtosecond domain) light pulses, and this way one is able to control the delay between the pulses too, which is also in the femtosecond range. This way, one gets a new control parameter which can give an insight into the rapid time evolution occurring in a many-body system.

The inventory of the theorist has improved in the past hundred years too. Until the late fifties of the past century a typical textbook on statistical mechanics described the Boltzmann equation as the unique topic of non-equilibrium. The Master equations themselves were treated in a rather marginal manner, since their modern applications seemed very limited.

Ever since then, the linear response theory- related mostly to the name of Kubo - made a breakthrough in the theoretical understanding of the kinetic coefficients, and found its way into the textbooks. The very last evolution in the theory occurred recently, due to the efforts to understand the new insight offered by the ultra-short spectroscopy. This implied the use of modern mathematical methods in treating interacting many-body systems, and tries to answer questions related to the very rapid microscopical changes in such a system. A new feature of the so called “quantum kinetics” is that one has to describe not just a parameter, which is independent on the way to measure it. The new sort of approach is to describe a definite experiment, and it can be formulated only by a close cooperation between the theorist and experimentalist. Although this approach proved to be very fruitful, also, unfortunately made the field less transparent, even if some monographs were already published on the subject [Haug and Jauho (1995); Bonitz (1998)]. Many theorists, however, are still reluctant to face the basic question: what has their calculation to do with the laboratory experiment? Are they calculating the same entity as the one measured in experiment *whether the calculated curves fit or not*?

This book tries a somewhat unconventional approach. It starts from analyzing some exactly solvable classical models, in order to illustrate the basic paradigms. Afterwards we sketch the approximative quantum-mechanical approach in a simplified way, showing its main features, while we discuss them later on a more sophisticated level. After this general glimpse, we will present the properties of the traditional equations of non-equilibrium statistical mechanics, such as the Master and rate equations as well as the Boltzmann equation. A relatively wide discussion of the scaling connection between the kinetic and hydrodynamic levels follows afterwards.

Several chapters are devoted to linear response theory and its applications. A careful discussion of non-relativistic quantum electrodynamics - as well as of its relationship to macroscopical electrodynamics - fits in this context. The second half of the book is devoted to the more modern aspects, on a more sophisticated level. The Markovian equations for the density operator (including its non-diagonal elements) and their deductions, are described in some detail. We also discuss the Bose-Einstein condensation in real time as an example for a better comprehension of spontaneous symmetry breaking. The last part is devoted to the presentation of the so called quantum kinetics, its mathematical tools (Keldysh-Green functions), properties of the approximations as well as the successes in explaining modern ultra-fast spectroscopy experiments.