Popular summary of the project *Nonequilibrium phase transitions, synchronization and chaos in thermodynamically consistent models*

Phase transitions are abrupt qualitative changes of the system properties that occur when some parameter (such as the temperature or pressure) crosses a certain threshold value. A common life example is the melting of ice into water when the temperature crosses 0°C. Phase transitions play a large role in nature and found many applications in technology. Consequently, much research has been devoted to study them. In particular, the theory of statistical physics provided an explanation of the mechanism of phase transitions. It showed that phase transitions are a result of interaction between many interacting units, such as atoms and molecules.

The studies thus far mostly focused on phase transitions that occur in thermodynamics equilibrium, that is, the situation when the state of the system does not change in time, and there are no constant flows of current (for example, the heat current). In such a case, phase transitions are determined only by thermodynamic parameters, such as the temperature. The situation becomes much more complex when the system is driven out of equilibrium. This happens, for example, when the system is connected to two media with different temperatures, which leads to the heat flow from the hot to the cold medium. In such a case, phase transitions are determined not only by temperatures, but also by details of the system dynamics. On the one hand, this makes a study of nonequilibrium phase transitions much more challenging. On the other hand, this leads to new physical phenomena, which are not observed at equilibrium. For example, the system may exhibit time-dependent oscillations even when the system parameters do not change in time. Such processes play a large role in regulation of biological rhythms in living organisms.

This project will employ modern methods of statistical physics to describe phase transitions that occur away from thermodynamic equilibrium. In particular, it will employ large deviation theory that describes probabilities of rare fluctuations, that is, deviations from the average behavior. Such fluctuations play an important role in nonequilibrium phase transitions. The description of phase transitions will be thermodynamically consistent, that is, the theoretical models used to describe them will obey the laws of thermodynamics. That is not always the case for the models presently used in the literature.

The first part of the project will be concerned with ***synchronization***, a process in which different oscillators align their frequencies and phases. It will be studied how transitions between phases with a different degree of synchronization manifest themselves in the changes of thermodynamic quantities. It will be also analyzed how the energy cost of synchronization may be optimized by playing with the details of the system dynamics, but without changing their thermodynamic parameters. Secondly, the project will generalize the methods of large deviation theory to describe ***nonequilibrium phase transitions in open quantum systems***. Such phase transitions are interesting, among others, from the perspective of applications for precise measurements. The developed methods will be used to determine probabilities of large events, which are crucial for phase transitions but cannot be easily characterized using currently existing methods. Finally, the project will investigate ***connections between thermodynamics and chaos***. The term “chaos” refers to a situation when the systems shows a very complex dynamics, strongly sensitive to initial conditions. It will be analyzed how fluctuations affect the dynamics of chaotic systems, and how chaos manifests itself in the thermodynamic behavior of the system. This will be relevant for the understanding of systems where interplay of chaos and fluctuations is important, such as chemical reactions or quantum systems interacting with the environment.