Nonequilibrium thermodynamics of diffusion anomalies

Modern civilization has been built on the transformation of heat into work. Perfecting the heat engine was made possible by the development of thermodynamics, a phenomenological theory formulated to characterize monstrous machines of the Victorian industry. Fathers of thermodynamics introduced its fundamental laws by considering macroscopic systems in equilibrium. In contrast, a living cell is a microscopic system with a size of several micrometers. Its interior is viscoelastic, crowded, heterogeneous and strongly fluctuating environment. It is an open system that continuously exchanges matter and energy with its surroundings while maintaining a nonequilibrium steady state called homeostatis. One of the central challenges in modern physics is to put our understanding of macroscopic engines into the world of living cells.

Matter at the microscopic scale exhibits constant random motion known as diffusion which is a consequence of thermal agitation. Although diffusion is non-directional it can be an efficient transport method in cells, particularly over short distances. Recent years have seen impressive progress in experimental techniques such as microscopy or reconstruction of subcellular systems outside of living organisms allowing us to follow their dynamics in great detail. When tracking individual molecules in cells one routinely finds that diffusion is anomalous.

In addition to this non-directed diffusive movement, at the cost of energy input living cells also use active directed transport mechanism. It is powered by tiny proteins known as molecular motors (e.g. kinesin). Molecular motors move along the microtubules which are spatially periodic polymerized filaments and are immersed in the ubiquitous sea of thermal fluctuations that strongly affects their kinetics. Therefore molecular motors are isothermal engines working far away from thermodynamic equilibrium. They remarkably outperform any machine which we can manufacture.

The fascinating efficiency of molecular motors inspires the primary scientific goal of the proposed project. We want to apply the most recent developments in nonequilibrium thermodynamics and statistical physics to establish a link between the thermodynamics of molecular motors and diffusion anomalies such as anomalous diffusion and Brownian, yet non-Gaussian diffusion. In the project we want to address one of the most important missing puzzles in state of the art statistical mechanics: What are the thermodynamical consequences of diffusion anomalies? May diffusion anomalies be beneficial for living cell functioning?