Constraint-Dependent Physical Quantities in Active Baths

Peng Liu

School of Physics, Beijing Institute of Technology, Beijing 100081, China

Email: liupeng@bit.edu.cn

Abstract: We have developed a method to measure active depletion forces, directly determining the active depletion force between two colloidal particles through optical tweezer experiments and computer simulations. Our study further explores related phenomena such as active noise, active pressure, and the mean potential energy of colloidal particles in an optical trap, all of which are closely related to the degree of constraint applied to the particles. This work represents a significant extension of physical concepts and relationships from equilibrium thermal baths to nonequilibrium systems. [Phys. Rev. Lett. 124, 158001 (2020).]

In equilibrium, the entropic force (also known as the depletion force) refers to an effective attractive interaction between large particles suspended in a thermal bath composed of many smaller particles. The origin of this force lies in the fact that the proximity of the large particles reduces their configurational space, thereby increasing the configurational space available to the smaller particles, ultimately leading to an increase in the system's total entropy. In equilibrium thermal baths, the entropic force is independent of external constraints on the particles, meaning that it can be determined either by the radial distribution function of freely moving large particles or by direct measurement through a scheme where the large particles are fixed. Similarly, in equilibrium, the noise experienced by suspended particles is white noise, the pressure exerted on them can be expressed as a state function independent of external constraints, and the energy equipartition relation is also unaffected by the strength of the constraints. This invariance with respect to external constraints is a fundamental result of equilibrium statistical physics. However, it remains unclear whether this invariance holds in nonequilibrium active baths, and even the correct method to measure active depletion forces is not well understood.

We first propose a correct method for measuring active depletion forces and directly determine the active depletion force between two colloidal particles by constraining them with optical tweezers. We find that this depletion force is highly sensitive to the external constraints applied; neither the radial distribution function of free particles nor the fixed particle scheme can provide the correct active depletion force. Subsequently, we extended our research to a series of thermodynamic properties of active matter, measuring the pressure [J. Phys.: Condens. Matter 35, 445102 (2023)], noise characteristics [Soft Matter 16, 4655 (2020)], and potential energy in an optical trap [Chin. Phys. B 29, 058201 (2020)] for colloidal particles in a nonequilibrium active bath. We discovered that these physical quantities or relationships are highly dependent on the external constraints imposed on the inert colloidal particles, in stark contrast to the situation in equilibrium thermal baths. At a microscopic level, this constraint dependence originates from the impact of colloidal particle relaxation dynamics on the distribution of active particles and the intensity of their collisions. These studies demonstrate that the physical concepts in active baths are far more complex than those in thermal baths and cannot be treated using equilibrium methods.