Thermodynamics of active matter

Recommended with commentary by Aparna Baskaran, Brandeis University

Introduction : Non-equilibrium steady states of materials are achieved by energy input into the system and dissipation into a heat reservoir. For example a colloidal system subject to oscillatory shear has input in the form of the driving of the boundary while dissipation occurs due to the frictional interaction with the solvent. A particular subset of non-equilibrium steady states that have been the focus of intense research in the recent past have been those that occur in active matter. Active materials are systems that are driven at the microscopic scale. The paradigm encompasses diverse systems on many length scales ranging from the cell cytoskeleton and bacterial colonies to herds of animals. Theoretically, an active material is a system composed of "molecules" that are "engines" that are locally coupled to a driving source and a dissipative sink that are performing work on the environment and each other. Contrast this to the sheared colloid case mentioned above to note that in such cases, the driving is macroscopic, i.e., on the scale of the system and only the dissipation is local. So, an understanding of emergent behavior in active materials requires us to understand the consequences of the microscopic work being produced to dynamics on length scales of the system size.

Context and Overview : When thinking about work and dissipation or heat, the theoretical starting point is thermodynamics. Let us consider the thermodynamics of a system as given by an appropriate free energy that acts as the thermodynamic potential that determines the macroscopic steady state of the system. A particular phenomenology that is well described by such a framework is phase separation kinetics and phase equilibria. Active fluids exhibit an inherently out of equilibirum phase separation phenomenon that has been dubbed "motility induced phase separation", that arises due to the microscopic work done by the individual entities acting as an effective attractive interaction between them. In the context of this phenomenon, extensive use has been made of the mathematical analogy to the thermodynamics of equilibrium phase separation to construct an effective thermodynamic description for active materials. A couple of recent examples are [1] and [2].

Another approach that could be taken is to consider the thermodynamics of an active system at the level of the first law of thermodynamics. The nonequilibirum steady state of the system is accomplished when the sum of all the microscopic work done by the active units is balanced by the dissipative mechanisms at play. Formulated this way, one can use the framework of thermodynamics that has extensively been used in the context of other non-equilibrium steady states [3]. This is the approach taken in the featured paper.

Results : This paper formulates the consequences of the configurational kinetics of a generic active material in terms of work fluctuations. Using this framework in the context of inhomogeneous systems, the author is able to formalize the notion of an interface energy. Then, using a specific and well studied microscopic model for an active fluid, namely one of active Brownian particles, it is shown that the surface tension between interfaces in the phase separated regime is negative, even though the phenomenology of the system does not show any proliferation of these interfaces.

References :

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2. GS Redner, CG Wagner, A Baskaran, MF Hagan "Classical nucleation theory description of active colloid assembly" Phys. Rev. Lett. **117**, 148002 (2016).
3. U Seifert "Stochastic thermodynamics, fluctuation theorems and molecular machines." *Reports on Progress in Physics* **75** 126001 (2012).