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EDITORIAL

Focus on Active Colloids and Nanoparticles

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1. Introduction

The concept of 'active matter' has seen a tremendous development in recent years. Its constituents, ranging from birds to cells to phoretic particles and molecular motors, constantly convert available (free) energy into directed motion, which induces active stresses in their environment. These active stresses play an important role in living matter and might be harvested as useful work or to engineer novel properties in synthetic active materials. Moreover, in contrast with other non-equilibrium systems in which energy is injected at large scale, usually through the boundaries, active matter is characterized by a local energy injection at the level of the active agents themselves. Active particles need to break symmetry to acquire directed motion, a practical consideration that leads to use of Janus microswimmers—composite particles made from sections with different physical surface properties regarding catalysis, light absorption, etc—to sustain a local gradient that is harvested to propel the particle. This autonomous motion allows, for example, collective dynamic phenomena to arise from deceptively simple interaction rules. It is now accepted that this interplay of directed motion and interactions underpins a wealth of phenomena at the interface of physics, chemistry, and biology.

This focus issue has gathered 23 original research articles [1–23] in the field of synthetic active colloidal and nanoparticles that represent the breadth of current research. It combines theoretical work with new experiments and experimental techniques to realize directed motion through self-propulsion and study the properties of single and many-particle suspensions. In the following we summarize this work.

2. Single particle dynamics

Already the dynamics of single active particles is surprisingly rich. An important aspect is that their dynamics is strongly influenced by the environment, in particular geometric constraints and external flows. The combination of the latter two can be exploited to design microfluidic devices that focus active particles and bacteria [19]. Choudhury *et al* investigate how the dynamics of a single active particle is influenced by an underlying crystalline substrate, which can be seen as persistent random motion in a regular periodic potential [13]. A related question is tackled by Chamolly *et al*, who study the motion of a swimmer through a three-dimensional crystal taking into account hydrodynamic effects, showing the transition from localized states to random to straight motion [20]. In both studies, the passive particles of the substrate and crystal are of the same size as the active particle.

3. Novel collective phenomena

The arguably most exciting characteristic of active matter is the wealth of dynamic collective behaviors that can be realized. Particles can organize into dynamic spatial patterns such as clusters, flocks, and swarms that extend over distances much larger than the typical interparticle separation. These patterns break time-reversal symmetry and would thus be prohibited in thermal equilibrium. Breaking free from the constraints of detailed balance, novel collective phenomena can be realized.

In reference [2], Straube *et al* show how to arrange anisometric colloidal dimers into a 'colloidal mill', a persistent spiral pattern that exploits anchoring conditions of the liquid-crystal solvent. Janus particles can also assemble into one-dimensional chains, which 'buckle' and perform an undulatory motion that resembles that of flagella [8]. In both cases, directed motion is fueled by an alternating electric field perpendicular to the plane of motion. Moreover, a central task is to understand the microscopic pathways—and their kinetics—leading to dynamic structures, with the perspective to rationally design target structures. In this focus issue, Petroff and Libchaber elaborate on the first step in the formation of a crystal of hydrodynamically-bound rotating bacteria: the coalescence of two bacteria into a dimer, for which they present a simplified model [11]. The clustering of active particles due to short-range alignment interactions is studied by Nilsson and Volpe [18]. Moreover, they report that adding a few active particles with large orientational persistence to a passive suspension leads to the formation of extended metastable channels.

At high densities, active particles form regular structures (active crystals) not unlike passive systems. As an example, Delfau and coworkers explore how self-propulsion influences the properties of a special realization, cluster crystals, in which soft repulsive interactions allow a unit cell to be occupied by more than one particle [22]. They observe different cluster morphologies and eventually a melting of the crystal for large propulsion speeds. Reichardt and Reichardt, on the other hand, study many run-and-tumble particles moving in a heterogeneous environment, a disordered array of fixed obstacles, and driven by an external field [6]. They show that there is a transition between a jammed and a continuous flowing state as activity and density are varied. They rationalize their results through the self-clustering discussed next.

4. Phase-separating scalar active matter

Among the new behaviors displayed by active systems, their tendency to undergo clustering or phase-separation in the absence of attractive forces has attracted a lot of interest over the past ten years. In this context, Solon and collaborators have shown how a generalized thermodynamics can be built [3], which allows one to account quantitatively for the phase diagram of the so-called motility-induced phase separation (MIPS). The relevance of equilibrium concepts for MIPS thrusts a long-standing effort from the community. Paliwal and collaborators offer another contribution to this test of equilibrium concepts in active matter by proposing a construction of an effective chemical potential for active particles [12]. In particular, they study its relevance for a confined ideal gas, a sedimenting suspension and weakly self-propelled phase-separating particles.

While most of the studies of interacting active particles consider the single-component 'pure-body' limit, Wittkowski *et al* propose a systematic study of multi-component systems comprising active and passive particles [21]. They first derive, at mean-field level, linear instabilities of these systems and propose coarse-grained descriptions that should, in principle, allow one to characterize the full phase diagrams of such mixtures. Finally, phase-separation is a collective behavior which is observed at moderate densities. The physics of dense active matter has received little attention so far but the interplay between self-propulsion and the glass transition is now the focus of intensive research. Berthier and collaborators show that the fate of the glass transition as self-propulsion drives a system away from its equilibrium limit is highly non-trivial, with activity sometimes enhancing and sometimes depressing the glassiness of the system [14].

5. Active particles in external potentials

The Boltzmann distribution states that the probability of finding a passive particle at a given position in an external potential is simply connected to the energy it would have at this position. This simple relationship between energetics and statistics is lost in active systems. This both grants active matter under external potential a rich phenomenology and limits our ability to engineer active systems. Ginot *et al* [1] propose a detailed study of sedimenting active particles. They measure experimentally the steady-state distribution of a dilute system of self-propelled Janus colloids and they show that it can be described quantitatively by sedimenting active Brownian particles. In addition to a quantitative agreement between experiments and theory, they characterize the local ordering of the particles induced by the gravity field and discuss how to characterize the osmotic pressure of such a suspension.

The converse limit, in which gravity maintains particles in the vicinity of the bottom end of their container is the topic of an article by Rühle and co-workers [5]. A detailed modeling of the hydrodynamic interactions between a swimmer and the confining wall reveals rich phenomenologies, ranging from particles 'levitating' above the bottom wall thanks to hydrodynamic forces to intermittent dynamics split between the close vicinity of the wall and a more distal region. The physics of an active particle close to a confining wall is also a matter of interest for dry active matter, as illustrated by an article by Das and co-workers, who compare the predictions of two types of active dynamics [9].

6. Theory and computation

Constructing simple yet accurate models is a challenge on all scales, from the underlying microscopic mechanisms of self-propulsion to the modeling of effective interactions that can explain the emerging large-scale behavior. Self-propulsion is typically the result of rather complex mechanisms involving hydrodynamic flows, and providing analytical insights remains a daunting task. An example of this avenue is provided by Majee and Würger in reference [7] exploiting the nanoscale Seebeck effect, where the temperature gradient of a single illuminated Janus particle in an electrolyte drives a creep flow along the particle surface.

Two papers in this focus issue address the interacting many-body challenge beyond short-range pairwise forces using complementary approaches. Huang *et al* study numerically active Janus particles driven by a chemical reaction on one hemisphere, taking into account explicitly the ensuing phoretic and hydrodynamic interactions due to the non-uniform concentration of the involved chemicals [15]. Hoell *et al* deploy dynamic density functional theory to model suspensions of circle swimmers [16]. Swimmers are modeled as force dipoles and hydrodynamic interactions are again taken into account. The authors apply their theory to the situation of an harmonic trap and observe different aggregation patterns.

Finally, Woodhouse *et al* study the propagation of information in an idealized network model of spontaneous active flows [4]. It connects active matter to more general aspects of non-equilibrium statistical physics such as information and entropy production, but also the topology of the network plays an important role for the propagation of information.

7. Experimental

The experimental contributions to this special issue highlight the broad potential of active microparticles. Niu *et al* [17] present a facile micro-photometric method for monitoring pH gradients, achieving a pH resolution of 0.05 with a spatial resolution of a few microns. Such a technique will allow for the measurement of quantitative concentration fields surrounding chemical swimmers, indispensable to the development of quantitative models accurately predicting osmotic and phoretic interactions present in the experiment.

The refining of our conceptual frame is crucial as experimental facts demonstrate drastic changes in the individual behavior of microswimmers induced by changes in their environment. Dietrich *et al* [23] show that the dynamics of self-propelled microswimmers in 3D is qualitatively and quantitatively different from that of similar particles trapped at a 2D fluid–fluid interface. Lozano *et al* [10] show that the microswimmers trade their continuous persistent random-walk in water for a run-and-tumble like behavior when immersed in a visco-elastic fluid as a result of a recoil from the elastic stress of the medium. Those results deepen our understanding of the dynamics of individual microswimmers in complex or confined environments. How they can provide original strategies to steer synthetic microswimmers at the individual level and control their collective behavior remains to be addressed and demonstrates that much is still to be done.

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