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Collective behaviours of active mixtures

Active matter describes systems whose fundamental constituents dissipate energy to exert self-propelling forces on the environment. The study of this broad class of systems was initially motivated by the biological worlds in which activity is the rule rather than the exception. Over the past twenty years, a wealth of synthetic active systems have been engineered, which now pave the way toward the development of synthetic active materials (See Figure 1). A number of fundamental questions however need to be adressed before one can reach the level of complexity relevant for material design.

This project aims at addressing the fate of active-matter phenomenology when one moves away from the idealized, single-component systems which have been the workhorse of the community so far. Take a system comprising N identical interacting active particles. Pairwise forces and torques already lead to collective behaviours without counterparts in passive systems: particles may start moving collectively (See [1, 2] and Fig. 2-a) or form cohesive phases in the absence of cohesive forces (See [3] and Fig. 2-b). Recently, it has become increasingly clear that mixtures can lead to even richer behaviours. For instance, colocalization or demixing of species have been observed in bacterial suspensions (See [4] and Fig. 2-c&d).

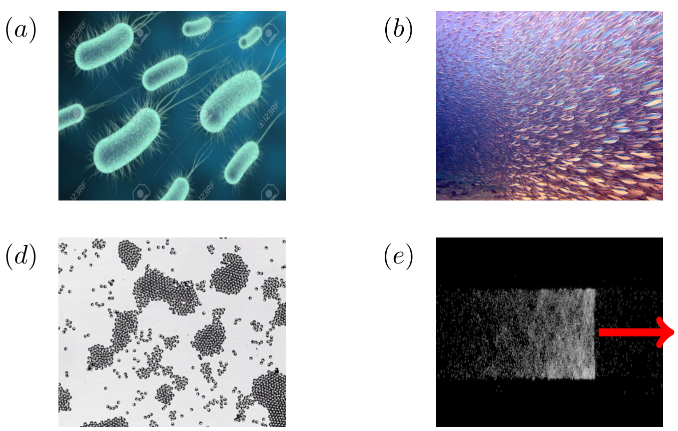

FIG. 1. From bacteria (a) to animals (b) to crawling cells (c), biology is filled with active entities whose physical properties need to be part of any quantitative description of the biological world. Over the past twenty years, physicists and chemists have developed a large variety of synthetic active particles by ‘motorizing’ colloidal particles (d & e) or droplets (f). From clusters in the absence of cohesive forces [5] to traveling solitary waves [6] to dynamic lane formation and breaking [7], their phenomenology is without counter part in the passive world.

In practice, we will start from microscopic descriptions of active mixtures and build analytically their coarse-grained descriptions, using field-theoretical methods and stochastic calculus. Numerical simulations at the microscopic and macroscopic scales will complement non-linear analysis to decipher the collective behaviors these systems may exhibit. Building explicitly coarse-grained descriptions will require the derivation of closure schemes that can be worked out exactly in the high-dimension limit (collab. with F. van Wijland and A. Altieri [8]) or on simpler lattice models [9]. Beyond the type of phase transitions that can be observed in these systems, a whole range of questions await: What controls the dynamics of interfaces between coexisting phases? And how can one define surface tension in such systems [10]? In the presence of chemical reactions, population dynamics, or reservoirs, can the concept of chemical potential be extended to active systems? How does the presence of disorder [11], boundaries [12], or external potentials impact the bulk behaviours of active systems [13]? Finally, effective equilibrium descriptions have sometime been derived to describe single-component systems [14]. How do they generalize to mixtures?

Answering these questions using the tools of non-equilibrium statistical mechanics and field theory will be the goal of this project & thesis. This project is aimed at students with a solid background and taste for statistical mechanics, and will involve both analytical computations and numerical simulations. The references below to some of our previous works can give you a taste of the type of approaches that are developed in the group.

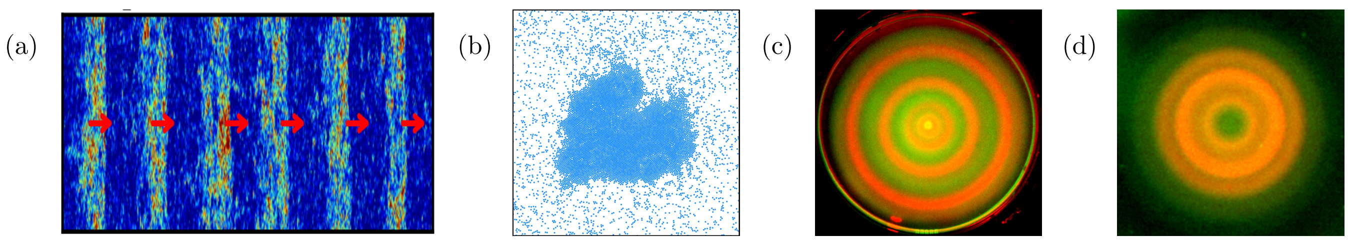

FIG. 2. **(a)** Self-propelled particles experiencing aligning torques may undergo a transition to collective motion characterized by the emergence of inhomogeneous travelling structures, akin to those reported in Fig. 1-e. **(b)** Self-propelled particles interacting via purely repulsive forces may undergo phase-separation and lead to cohesive phases. This explains the phenomenology reported in Fig. 1-d. **(c & d)** Mixtures of two strains of bacteria mutually enhancing (c) or inhibiting (d) their motilities undergo pattern formation with demixing or co-localization, respectively [4].

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