Active suspensions with programmable interactions

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Status. Active colloidal particles (APs) are currently considered as model systems to mimic collective behavior under controlled conditions but may also find technical use as micro-robots to perform complex tasks in liquid environments [1]. In the meantime, a plethora of propulsion schemes has been developed which allows APs to harvest energy from their surrounding and convert it into translational motion. A key question in this field is to understand, how active particles are able to organize from random disperse into dense and highly organized collective structures (swarms, flocks) as known e.g. from birds, fish, insects or even bacteria [170]. Clearly, such behavior requires robust communication mechanisms between individual group members. Conversely to living systems where collective behavior is achieved by complex internal processes which are not always fully understood, the response of APs is much simpler. When user-defined interaction-rules were be applied to synthetic systems, this would provide a novel and versatile platform to gain a better understanding of the relationship between communication and self-organization.

A possible experimental route to impose user-controlled interactions to a suspension of APs is the use of a feed-back mechanism by which the propulsion of APs can be controlled on an individual level [171]. Recently, this idea has been experimentally demonstrated using Janus particles which are propelled by a light-induced mechanism [10, 172]. When such particles are illuminated with a focused laser beam, their propulsion motion can be controlled on a single particle level. Using a rapidly steered laser beam and a feedback mechanism, this allows to adjust the AP's motion depending on the surrounding particle configuration, the latter tracked in quasi real-time employing digital optical microscopy.

Current and future challenges. As a specific example for such user-defined interaction rule, we discuss how quorum sensing [173, 174] can be implemented in a suspension of synthetic ABPs. In bacterial systems, quorum sensing is achieved by the release and detection of diffusing signaling molecules which are characterized by a diffusion coefficient D_C, their production rate γ and their finite lifetime τ [175]. The concentration sensed by an individual i is then given by

$$c_i(t) = \tilde{c} \sum_{j \neq i} \frac{\sigma}{r_{ij}(t)} \exp(-r_{ij}(t)/\lambda) \tag{4}$$

where $r_{ij} = |\vec{r}_i - \vec{r}_j|$ is the distance to its neighbour j, σ the size of an individual, and λ the decay length $\lambda = \sqrt{D_c \tau}$ (being a measure of the range of communication). The prefactor $\tilde{c}$ is given by $\tilde{c} = \gamma / 4\pi D_c \sigma$. When the concentration sensed by an individual exceeds a sharp threshold value c_{th}, this triggers a sudden change in its behavior, e.g. in its motility leading to the efficient formation of bacterial colonies. To mimic such quorum sensing behavior, the motility of particle i is set by the following rule: when the concentration c_i (as determined from the experimentally measured particle configuration and the use of equation (4)) exceeds a user-defined threshold concentration $c_i > c_{th}$ the particle is non-motile, i.e. its propulsion velocity is zero. Otherwise it becomes motile and propels with velocity $v_i = v_0$, i.e. it is locally illuminated with the laser beam. Figure 27 shows how the normalized density distribution of a suspension of APs changes upon increasing the threshold c_{th}.

To understand, why cluster formation is supported by quorum sensing, it is important to recall that the propulsion of APs becomes zero in regions with high local particle density. Accordingly, particles can only diffusively escape dense regions which then facilitates their growth. On the other hand, particles in dilute regions are motile, which largely increases their probability leaving such areas. Accordingly, particles will permanently switch from a motile to a non-motile state. Indeed, it can be shown, that cluster formation becomes most enhanced when the switching rate (motile to non-motile and vice versa) becomes large and thus supports the idea, that quorum-sensing rules lead to enhanced clustering similar to living systems.

The above approach can be easily changed to other types of rules, e.g. including memory-effects or non-reciprocal interactions where the mutuals response of two individuals is not symmetric (opposed to the above example of quorum sensing). Non-reciprocal rules are relevant e.g. when the environmental sensing of individuals is based on vision. For finite vision cones, an individual A may see individual B but not otherwise which will largely affect their collective behavior.

It is important to realize that the above experimental approach does not aim towards modelling a specific collective state but imposes an interaction rule. Contrary to numerical simulations, all relevant particle interactions (phoretic, hydrodynamic) are fully contained within this approach and thus allows to observe collective behavior under realistic conditions. This apporach can be also extended to, for example, viscoelastic (opposed to Newtonian) swimming media which comprise the natural habitat of many living microorganisms. Such fluids are characterized by rather long stress-relaxation times which leads to a number of significant changes in their swimming motion [176, 177].

Concluding remarks. The possibility to impose user-defined interaction rules in systems of APs largely expands their use as model systems resemling the collective behavior of living systems. In addition to quorum-sensing rules, almost any other type of communication can be established,

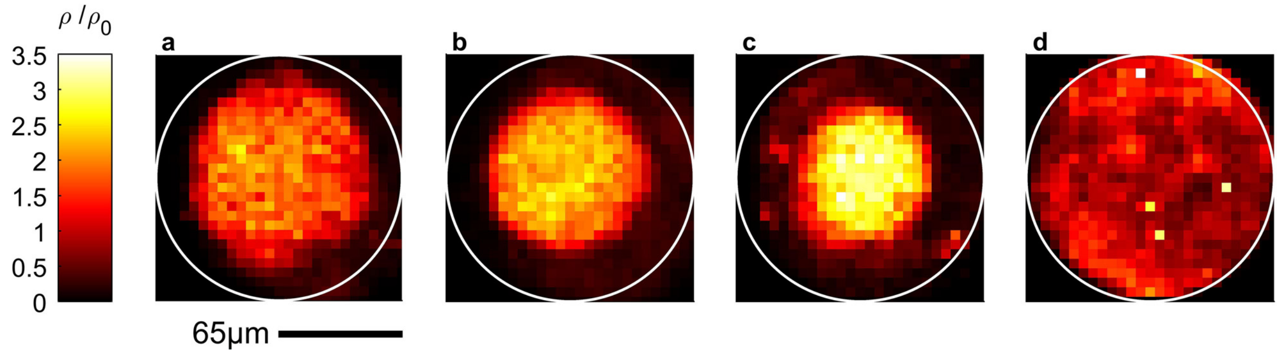

Figure 27. Density distribution of ABPs induced by quorum sensing with threshold values $c_{\text{th}} = 5.9,7.3,8.6$, c (a)and (d) and decay length = 10. With increasing cth the clusters become denser and smaller until cluster formation breaks down for a too large threshold (figure adapted from [10].

e.g. vision cones, time-delays, etc. Because mutual interactions in living systems are often not clear, comparison of the collective behavior with synthetic systems provides a promising route to uncover what type and over what distances information is exchanged between individuals to achieve a collective state.

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