CAPILLARY ACTION AND STATIONARY CURRENTS IN SCALAR ACTIVE MATTER

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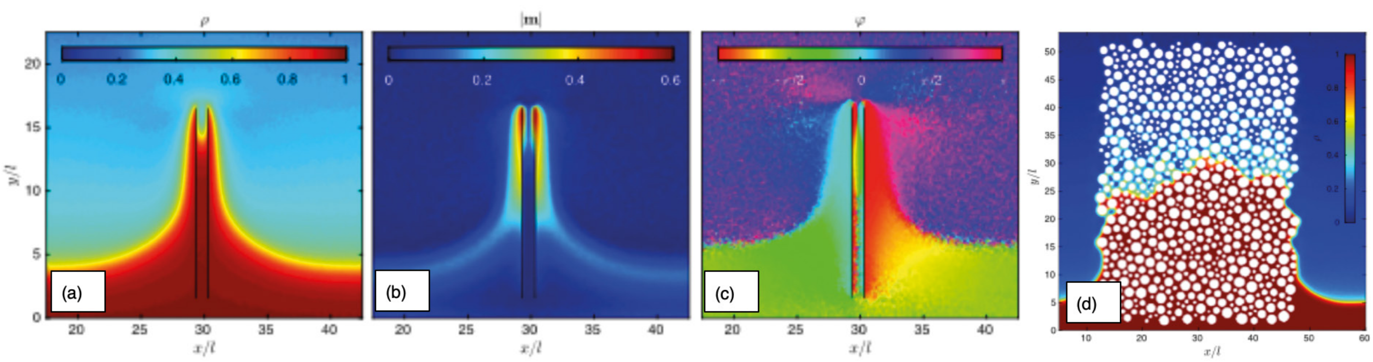
Active matter consists of particles (motile microorganism or active colloids) that consume nutrients or fuel and convert it into a persistent motion, has received a lot of attention due to its intrinsic out-of-equilibrium character on the microscale [1]. The simplest representatives of active matter are spherically symmetric, active Brownian particles (ABPs) [2] without alignment, however, with excluded volume interactions [3,4].

Further representatives of the same class, also called scalar active matter, are, for example, run-and-tumble particles and the active lattice gas. Such systems, although far from equilibrium, are in some sense reminiscent of a passive fluid with attractive interactions, since ABPs slow down during collisions and effectively attract each other. As a result, ABPs undergo a motility-induced phase separation (MIPS) into a coexisting dense and dilute phase [5], accumulate at walls [6], and in corners. Moreover, for a wide class of active systems, *e.g.* non-spherical ABPs, the pressure depends on the precise interactions between the active particles and the confining walls [7].

The investigation of capillary action, the ability of liquids to rise in thin tubes against gravity, has a long history and goes back to Leonardo da Vinci. Its origin is attractive interactions between the liquid molecules and the container walls and the attraction of the liquid molecules among each other causing surface tension. The height of the liquid column in the tube is governed by the balance between the gain in surface energy and the cost in gravitational energy. The classical picture seems to prohibit the appearance of capillarity in systems with purely repulsive interactions, but recently it was predicted that scalar active matter in a gravitational field will rise along vertical walls and inside capillaries [8]. Fig. 1a-c shows the stationary state of an active lattice gas model with repulsive particle-particle and particle-wall interactions, in a gravitational field in the presence of a thin pipe displaying a strongly elevated meniscus, whose height increases with the activity of the system, more precisely algebraically with the Péclet number. Fig. 1d shows how the same model predicts spontaneous imbibition in a porous medium.

These results have been confirmed for conventional sedimenting ABPs active Brownian particles (ABPs) in [9], where also the mechanism leading to the formation of a meniscus rising above the bulk of the sedimentation region has been elucidated. It turned out that the formation of the meniscus is determined by a stationary circular particle current, a vortex, centered at the base of the meniscus, c.f. Fig. 2a-b, whose size and strength • • •

▾ FIG. 1: (a–c) Capillary rise of an active lattice gas with capillary width δx/l=1 and capillary height δy/l=12.5. (a) Mean total density ρ(x,y). (b) Absolute value of the mean normalized polarization field. (c) Phase ϕ(x,y). ϕ=0 corresponds to a right-polarization, π/2 to up, - π/2 to down and +/-π to left. **(d)** Spontaneous imbibition of a porous medium, density plot. The white disks are regions of excluded volume representing the porous medium, the spaces in between represent the pores. From [8].



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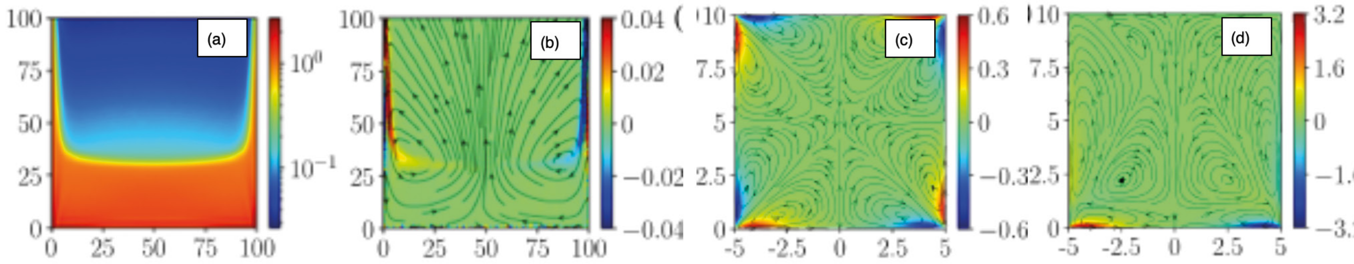
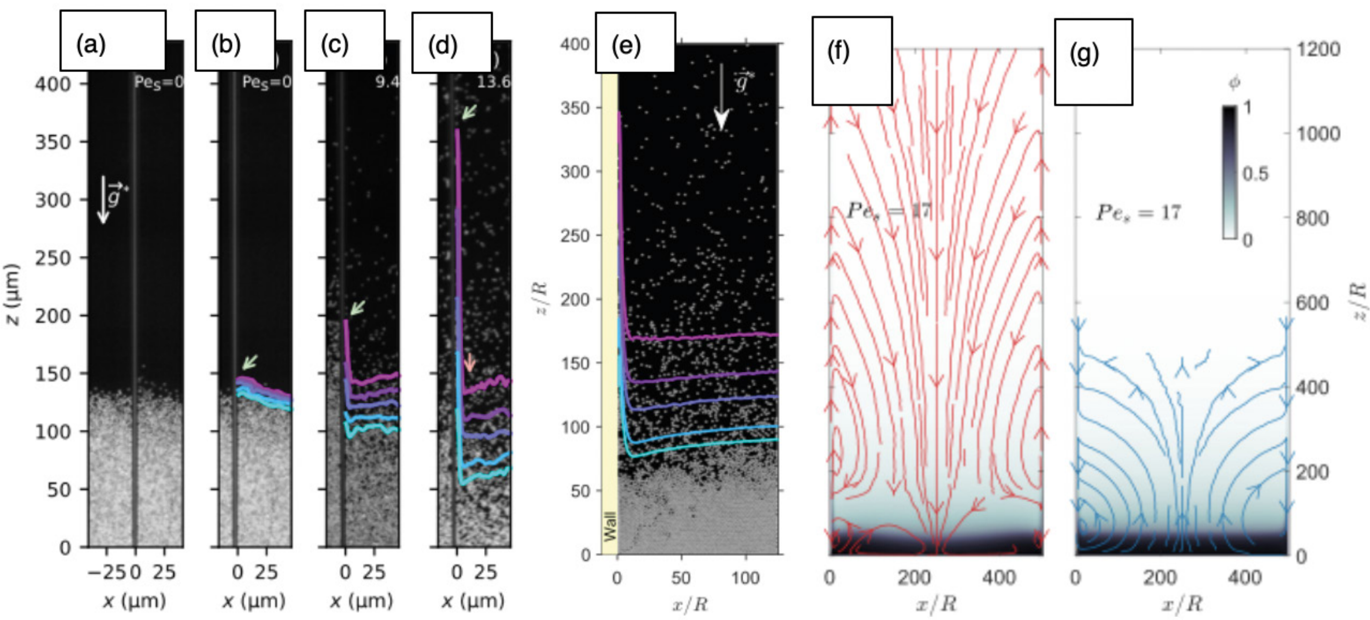


▲**FIG. 2: (a-b)** ABPs in a gravitational field with repulsive walls, (a) density profile, (b) flux lines of particle current J(r) together with modulus of the curl of J(r) (color code). **(c-d)** Flux lines of particle current for ideal ABPs in a box, (c) without gravitation, (d) with gravitation. From [9].

• • • increase with the ABP activity. The origin of these vortices can be traced back to the confinement of the ABPs in a box: already the stationary state of ideal (non-interacting) ABPs without gravitation displays circular currents that arrange in a highly symmetric way in the eight octants of the box, see Fig. 2c. Gravitation distorts this vortex configuration downward, leaving two major vortices at the two side walls, with a strong downward flow along the walls, see Fig. 2d. Repulsive interactions between the ABPs change this situation only as soon as motility induced phase separation (MIPS) sets in and forms a dense, sedimented liquid region at the bottom, which pushes the center of the vortex upwards towards the liquid-gas interface. Self-propelled particles therefore represent an impressive realization of scalar active matter that forms stationary particle currents - reminiscent of emergent probability fluxes in confined microbial navigation [10] - being able to perform visible work against gravity or any other external field. Somewhat counterintuitively the circular current at the left wall rotates counter-clockwise (and the one at the right wall clockwise), see. Fig. 2b and d, such that particles are not actively pushed upwards along the wall, but instead slide downwards under the influence of gravity. In some distance from the wall, towards the center of the box, the activity elevates the particles again from the sedimented layer into the gas region, where they are then again driven towards wall.

These theoretical predictions [8,9] should be experimentally observable experimentally in active colloids under gravitation. They constitute a class of materials composed of colloidal-scale particles locally converting chemical energy into motility, mimicking micro-organisms. Several new phases of active matter have been observed experimentally in synthetic self-propelled colloids, reminiscent of the aforementioned phenomenology of ensembles of ABPs. An experimental setup that is relevant for the above model predictions is the gravitational sedimentation of gold-platinum Janus colloids immersed in a hydrogen-peroxide bath, which are self-propelled by phoretic effects [11]. Using this

▼**FIG. 3:** Active Janus colloids climb a wall. **(a)** Experimental set-up: glass wall dipped into a sedimented monolayer of passive colloidal particles at Peclet number Pe=0 under a gravity g. **(b-d)** Iso-density maps of the colloids at Pe=0 (passive case) and for two activities Pe = 9.4 and Pes= 13.6. The iso-density values ϕ are from top to bottom 0.08, 0.12, 0.16, 0.24, and 0.3. The pale green arrow highlights the maximum height of the iso-density curve ϕ = 0.08 at the adsorption layer. The pale red arrow indicates the small depression of the density close to the wall. **(e)** Snapshot of a numerical simulation of an assembly of ABPs under gravity near a wall with alignment Γ~ = 26 and adhesion strength ~ε = 3:25, respectively, at an activity Pe = 13. F) Numerical streamlines of a velocity field v = J/ρ together with the packing fraction φ for a simultaneously attracting and aligning wall **(f)** and for a neutral wall **(g)**. From [11].



experimental setup, it was demonstrated that active colloids show active capillary rise, see Fig. 3. A dynamic absorption layer at the wall was observed, which roses with increasing activity, c.f. Fig. 3a-d. Due to the absence of MIPS the wetting layer is much thinner and the particle fluxes are reversed, which could be explained by the following additional wall-particle interaction: Fig. 3f shows the flux lines resulting from a simulation for an ABP system in the gaseous phase in a gravitational field and with wall alignment and -adhesion, and Fig. 3g the same system for a neutral wall. Thus, active colloids can actually climb up a wall. Gravity is essential to generate a polarization in the bulk, that is then enhanced by wall-alignment. This polarization, together with activity-dependent wall-adhesion, is most likely responsible for the persistent vertical pumping observed in the system.

These results demonstrate that a vertical wall effectively harvests energy from the microscopic scale to produce a macroscopic work. More generally, a side wall can act as a pump against a force parallel to it, generating a net steady-state flux in the system. These results pave the way for active microfluidic systems, where even a basic config- uration involving walls and gravity could play a role analogous to a generator in an electric circuit. ■

About the authors

Heiko Rieger is Professor for Theoretical Physics at the Saarland University in Saarbrücken, Germany. His research focuses on statistical physics and biological physics and he presently concentrates on understanding collective effects in active matter and living systems.

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