Symmetry-reversals in chiral active matter

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Visiting the Aquarium in Monterey, California one can see splendid examples of fluid dynamics in action: the high Reynolds number flows that surround you in the Splash Pool, or the fluid-structure interactions that allow jellyfish to propel themselves in subtle and elegant ways. Imagine the fluid dynamics of oxygen absorbing gills where an intricate balance between diffusion and flow speed is maintained. One amazing fluid dynamics aspect can also be viewed, even though it is not traditionally included in fluid dynamics textbooks. The “Open Sea” exhibit displays a school of fish that continuously swirls as a fluid in a fluid, sometimes quickly responding to external stimuli (sharks) while also slowly setting its own pace, wandering like a ghostly cloud through the entire tank. Amazing videos can be watched live \cite{2}, for a still see Figure 1.

Figure 1: Still from webcam watching the Open Sea exhibition in the Monterey Bay Aquarium
The collective behavior of schools of fish, but also flocks of birds, swarms of bacteria and crowds of people has gained substantial attention in the last two decades, as there is surprising and deep physics in these systems, often referred to as “active materials”. These materials are composed of components with some source of internal energy that propels them. Computer modelling of flocking dates back to Reynolds [3], but one of the earliest insights of statistical mechanics hiding in the collective behavior of these active materials is the modelling by Vicsek et al. [4]. They showed that even the simplest model system of an active material shows a phase transition between collective aligned dynamics and disordered motion. In the same year, the Toner-Tu equation [5] was developed as a Navier-Stokes equivalent for such “fluids”. Theoreticians flocked to the field and have amassed a tremendous understanding of active materials and their rich phase behavior [6, 7].

Experimental studies of the behavior of active matter systems can be done in an aquarium on live animals; one can even do oscillatory rheology on a swarm of small flies [8] that turn out to display negative storage moduli associated with inertia. However, living systems can be challenging to get into a steady state. Living systems do not allow for easy adaptation to test the microscopic ingredients that generate collective dynamics. The search for model systems has produced systems at various length scales: cars in a circle [9], robots that can be programmed [10] and even self-propelling droplets [11] and colloidal systems [12] are being explored as ways to study active materials in the lab. It is evident that even these systems present their own level of complexity and inadaptability. We therefore resorted [1] to a system of simple 3D printed, “self-propelling” particles or disks levitated by a layer of forced air; see Figure 2. The particles are not truly self-propelling: they receive their energy from the stream of air they are floating on. The particles are designed such that a small part of the supporting air gives them a torque via their asymmetric “exhausts”. The torque makes the particles spin, while small fluctuations from the turbulent air surrounding the particles makes them bounce into each other. We studied the collective dynamics of a collection of such floating, spinning and bouncing disks. This simple system allows one to answer questions about how the emergent behavior of the disks depends on the way the particles interact with each other.

Figure 2: Motion blur visible in the rotating spinners from [1]. The arena measures about 13cm in diameter. The spinners are marked with different colors to facilitate tracking. Airflow through the small holes in the base levitates the spinners and drives their rotation.
The twist here is that the torque pushes energy into the rotational degree of freedom of every particle, while the particle collisions transfer this energy to the two translational degrees of freedom. We showed that the translational degrees of freedom have almost perfect Maxwell-Boltzmann distributions, even though the system is highly dissipative. An almost identical spinner system published back-to-back in the same Soft Matter volume 14 (2018) did not show such ideal gas behavior. We believe that the coupled set of Langevin equations that determine the microscopics of these active spinners [13] have the answer: the coupling between the driving torque and translational degrees of freedom depend on four factors: the moments of inertia and the transfer of energy between particles and among their degrees of freedom. The former are different in the two studies; the latter are set by the interparticle friction. The ratio of these prefactors decides what kind of collision statistics emerges.

When one packs more “spinners” per unit volume, the gas turns into a solid, slowing all dynamics. Yet we found that there is a less trivial way the volume fraction of particles controls the collective behavior of the spinners. Friction also matters here. We find that the spinner swarm swirls counterclockwise when few particles are bouncing around, while the swarm spins clockwise when density increases. We attribute this to the asymmetry in scattering dynamics of particles with an intrinsic spin. Note that all particles spin counterclockwise. A left-sided collision essentially slows down a particle, while a right collision accelerates a particle. With more particles in the arena, the ratio of left versus right sided collisions changes, changing direction in swarming. Indeed, enhancing friction among the particles or between particles gives the ability to control the swarming to great extent.

Active materials display all the beauty and depth that traditional fluid dynamics systems show, while also presenting a whole new set of challenges and opportunities. In the arena of active materials, there is ample space for experimental model system analysis. We have found that these model systems give new scientific insights and are even simple enough to serve as teaching material for advanced laboratory classes.

REFERENCES