Symmetry-breaking motility in disordered nematic active fluids

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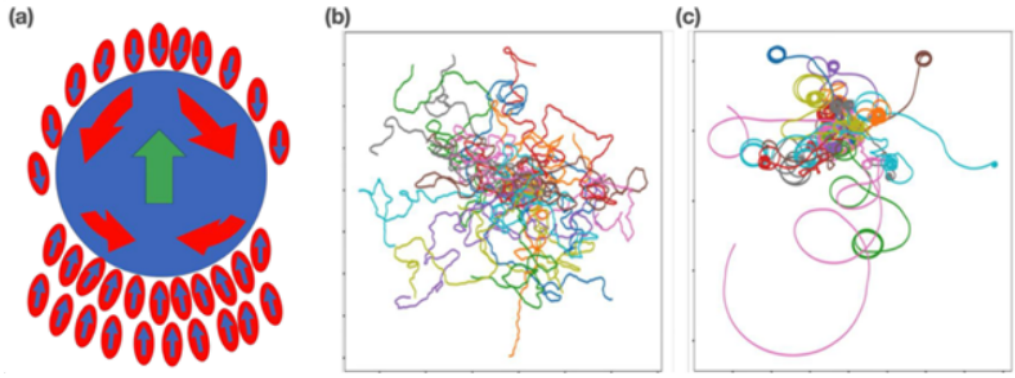
In active systems, microscopic violation of time-reversal symmetry can give rise to spontaneous currents, a unique out-of-equilibrium phenomenon. A central question of statistical physics on this is how such current emerge and are controlled coupled to slow degrees of freedom. In particular, recent developments in stochastic thermodynamics have emphasized the role of effective forces and induced friction in probe dynamics driven far from equilibrium[1,2].

In our previous work, we showed that motion of an object immersed in dilute and disordered active fluids can induce currents that enhance its own motion, leading to a ratchet-like mechanism which we call 'symmetry-breaking motility'[3]. In that setting, the bath particles do not interact, and the mechanism can be understood simply in terms of asymmetric effective interaction between the front and the back.

Here, we extend the scope of symmetry-breaking motility to a more realistic and strongly interacting regime: a bath of self-propelled elongated particles with volume exclusion. We consider a symmetric, non-penetrable tracer and investigate its response under both externally imposed motion and free evolution. We find that the system exhibits two distinct symmetry-breaking mechanisms controlled by particle shape and microscopic interaction parameters. At intermediate aspect ratios, the tracer undergoes spontaneous directed motion driven by a rear-stabilized cluster of aligned rods, while at larger aspect ratios the same mechanism becomes unstable, leading instead to chiral spinning motion, as can be seen in figure (b) and (c).

Furthermore, we develop a hydrodynamic description by deriving a Boltzmann equation with nematically aligning collisions, and analyze how the resulting eigenmodes and their growth rates control the stability of translational versus chiral motion. In particular, we show that particle anisotropy and interaction details selectively amplify different modes, which in turn determine whether the tracer exhibits persistent propulsion or rotational instability.

This establishes a direct link between microscopic geometry and macroscopic response: the active medium reorganizes into anisotropic structures whose symmetry and stability depend on the tracer's motion and shape. In this sense, the medium effectively "senses" geometry through its non-equilibrium response, encoding it in the induced forces and collective modes acting on the tracer.



References:

[1] J-H. Pei and C. Maes, Induced friction on a probe moving in a nonequilibrium medium, Phys. Rev. E 111, L032101 (2025)

[2] J-H. Pei and C. Maes, Transfer of Active Motion from Medium to Probe via the Induced Friction and Noise, Phys. Rev. Lett. 136, 038301 (2026)

[3] K. Kim, Y. Choe and Y. Baek, Symmetry-breaking motility of penetrable objects in active fluids, Phys. Rev. E 107 014614 (2024).