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Controlling Living Matter using Ferrofluids

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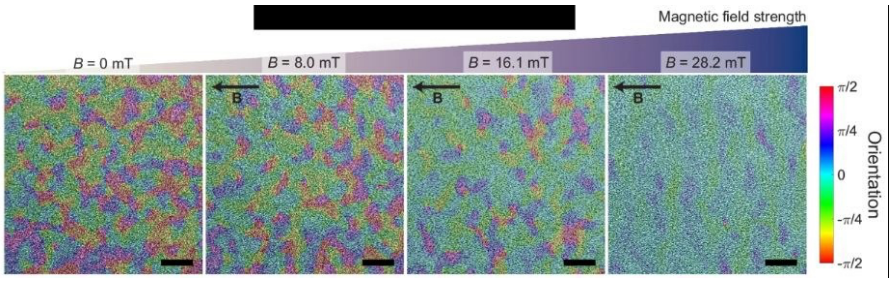
Non-magnetic microscopic particles can be manipulated using magnetic fields when dispersed in a magnetizable medium such as a ferrofluid. As demonstrated by Arne Skjeltorp in 1980s [1], the non-magnetic particles form regions of vanishing magnetic susceptibility and magnetization within the ferrofluid known as "magnetic holes". Magnetic holes are associated with an apparent magnetic moment that gives rise to typical orientation-dependent attractive and repulsive magnetic interactions. More recently, it has been shown that non-spherical microscopic magnetic holes, such as those formed by silica microrods in a ferrofluid, experience magnetic torque that aligns the holes with the external field [2].

Here, we demonstrate that the concept of magnetic holes can be applied also to living microscopic matter to control their active behavior, such as swimming direction. Specifically, we demonstrate this for swimming rod-shaped *Bacillus subtilis* bacteria using a standard culturing medium (Terrific Broth) that we dope with PEG-coated iron oxide nanoparticles that do not adhere to the bacteria [3]. The bacteria in the ferrofluid respond to magnetic field by aligning with the field, forcing them to swim parallel and antiparallel with the external field. The alignment is reversible and vanishes when the magnetic field is turned off.

At higher bacterial concentrations the suspension exhibits active turbulence. Application of a uniform magnetic field on the turbulent-like suspension leads to gradual transition from the active turbulence into a nematically aligned state (Fig. 1). The nematic state exhibits minute undulations and transverse flows - first signs of the emerging hydrodynamic instability towards active turbulence. Releasing the aligning magnetic torque allows direct visualization of the hydrodynamic instability leading to full active turbulence [3].

Our findings show that magnetic torque mediated by a ferrofluid on living microscopic objects can be a powerful tool for controlling both single particle dynamics as well as collective states. One major advantage is generality: special magnetic microorganisms are not needed. At the end, we highlight opportunities for manipulating other microscopic organisms beyond the *B. subtilis* bacteria.



References

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