Microswimmers capped with carbon on one side can be propelled and steered by light

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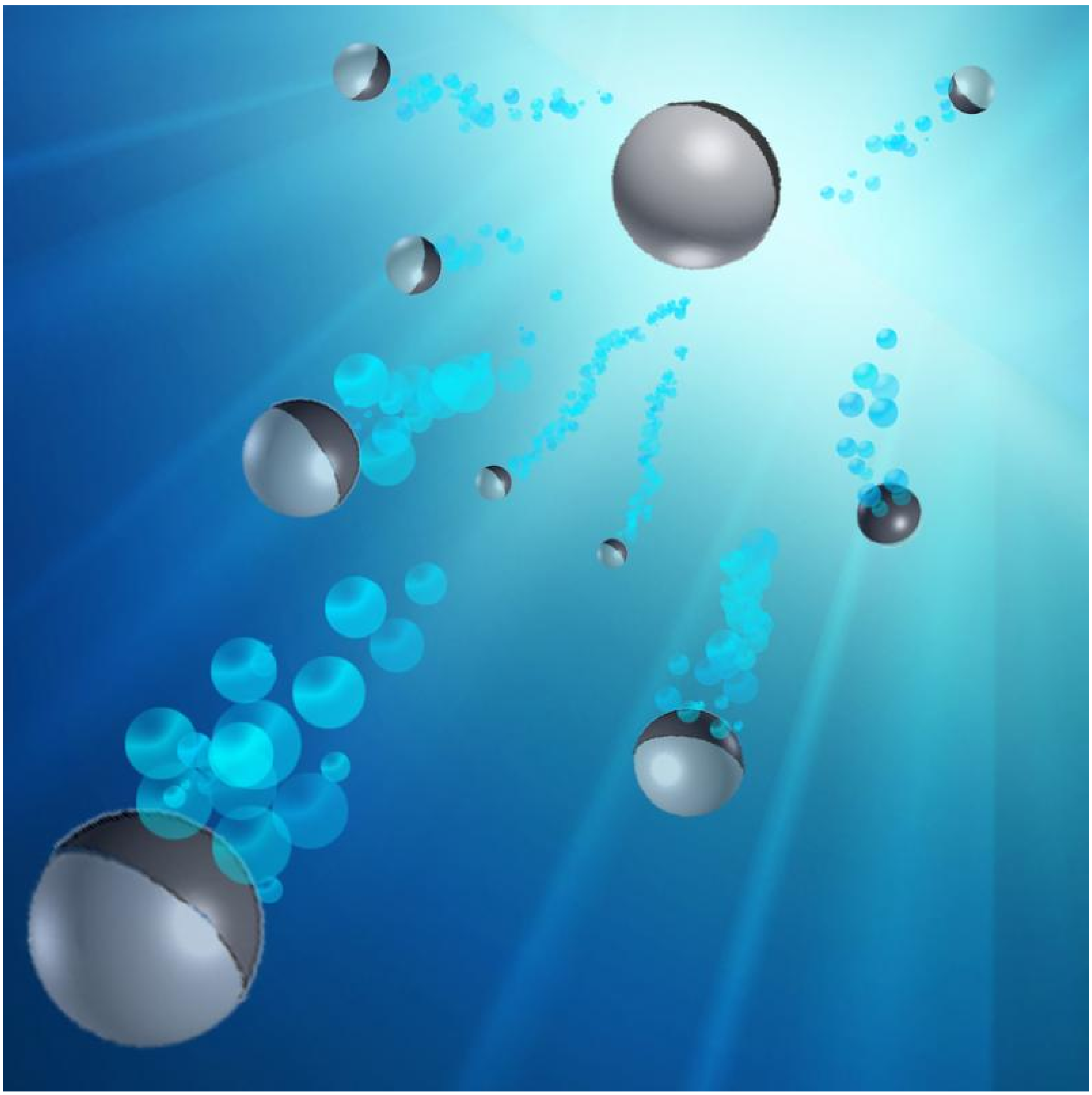

Travel into the darkness: Half-coated Janus particles, named after the roman double-faced godness, are autonomously navigating towards a light source. Researchers based in Stuttgart find such phototactic behaviour, also known from living microorganisms, also in synthetically fabricated microswimmers. Credit: Celia Lozano (MPI for Intelligent Systems/University of Stuttgart)

Phototactic behaviour directs some bacteria towards light and others into darkness: This enables them to utilize solar energy as efficiently as possible for their metabolism, or, otherwise, protects them from excessive light intensity. A team of researchers headed by Clemens Bechinger from the Max Planck Institute for Intelligent Systems and the University of Stuttgart, as well as colleagues from the University of Düsseldorf have now found a surprisingly simple way to direct synthetic microswimmers towards light or darkness. Their findings could eventually lead to minuscule robots that seek out and treat lesions in the human body.

The ability to move in a directed way instead of swimming willy-nilly in a random direction is vital for many microorganisms. "Evolution has taken enormous efforts to endow motile bacteria with the ability to orient themselves," says Clemens Bechinger. Sperm cells are a good example. They have an efficient propulsive system in the form of a flagellum. However, this would do them little good without a way to navigate towards the ovum, as their chance of fertilizing the ovum would otherwise be very slim. Chemical attractants released by the ovum point the way. The spermatozoa simply follow the concentration gradient of those substances.

Bacteria are also propelled by flagella and have even developed a whole range of control systems – some based on increasing or decreasing concentrations of nutrients, others on gravitation, the earth's magnetic field or sources of light.

Clemens Bechinger's team has endowed synthetically produced particles with both: a motility system and a sense of direction, for example along a magnetic field or towards light. This results in tiny robots that can be steered through a liquid by means of simple external signals.

The black half of a Janus particle heats up more strongly

However, it is almost hopeless to copy nature directly. The perception apparatus and motility systems that living organisms use to move in a preferred direction are far too complex. "Instead, we are developing microswimmers that are capable of phototaxis with minimal effort," Bechinger explains.

The team headed by the Max Planck Fellow has now achieved that goal. Its microswimmers are surprisingly simple in design. They are transparent glass beads measuring a few thousandths of a millimetre in diameter whose motility system also serves as a compass. The researchers provide the microswimmers with both functions by capping one half with a black carbon layer, making the particles reminiscent of crescent moons.

When illuminated uniformly, such simply constructed so-called Janus particles move through a mixture of water and a soluble organic substance because the light heats the black-coloured half of the particle more strongly than the other side. The heat separates the water and the organic substance, resulting in a difference in solute concentration between the two sides of the bead. The concentration gradient is balanced by liquid flowing along the spherical surface of the transparent half to the black side. Much like a rowing boat, which moves in the opposite direction of the oar strokes, the particles swim through the liquid with their transparent side facing forward.

A light-dark transition results in directed motion

The synthetic microswimmers move, however, in a random direction; in other words, they have a motility system but no sense of direction. The researchers solved that problem by letting the Janus particles swim along a light gradient, i.e. in the direction perpendicular to a gradual light-dark transition. The microparticles then actually move in a directed manner towards the less strongly illuminated part of the liquid.

The scientists have thus endowed this relatively simple system with phototaxis abilities. This is explained by the fact that the side of the bead located in the more brightly illuminated part heats up more strongly than the side in the darker region. The flow of liquid which compensates for the difference in concentration between the two halves of the Janus particle moves faster on the side exposed to more light than on the side of the particle in the darker part of the light-dark transition. This situation is analogous to a rowing boat when the oars are not moving at the same speed on both sides: it rotates.

Exactly the same effect is observed with the Janus particles. They rotate until the black cap is facing towards the light. In this position, the entire interface between the cap and the transparent part are in uniform brightness, so that the compensatory liquid flow is equally strong everywhere. The Janus particle then moves straight toward the darker side. "By means of simple modifications of the sphere we're also able to produce movement towards the brighter side," says Celia Lozano, who works as a postdoc on Bechinger's institute. The researchers have thus created an incredibly simple model of phototaxis.

Robots as medical patrollers are within reach

However, if the light intensity falls below a certain value, this mechanism no longer works. After just a tenth of a millimetre or so, the particles begin to deviate increasingly from their course. To solve this problem and to navigate the microswimmers reliably over long distances, Celia Lozano uses a system consisting of a laser, lenses and mirrors to generate a light field with a saw tooth profile with areas of decreasing and increasing brightness.

The areas of increasing and decreasing brightness are, however, not uniformly wide. In the comparatively wide areas with decreasing light intensity, the particles move toward the darker region in a directed manner. By contrast, in the areas with increasing intensity, they swim from darkness into light, holding their original course as they do so. "This is because the areas of increasing brightness are so narrow that the particles have no time to reverse their direction during their passage," explains Borge ten Hagen, who has confirmed this effect in computer simulations. Overall, the microswimmers therefore move continuously in one direction.

The fact that the system as a whole is very simple makes it interesting for applications. "Millions of these microswimmers can be produced with ease," Bechinger says. Such an armada of reliably controllable microparticles can be used to model the swarming behaviour of various species. And because the orientation mechanism developed by the researchers works not only in a light-dark transition but also in a chemical concentration gradient, for example in the proximity of tumours, the vision of producing robots the size of blood cells that patrol blood vessels to detect and treat lesions, such as tumours, has also moved within reach.

More information: Celia Lozano et al. Phototaxis of synthetic

microswimmers in optical landscapes, *Nature Communications* (2016).
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