Mag-Neato: Team Advances Understanding, Control of Magnetic Droplets

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Drop by drop, magnetism is entering a new phase — one that may point the way to liquid, morphing robotics and other fluid technologies that can do what their solid, static counterparts cannot.

Until a couple of years ago, only solid materials had demonstrated ferromagnetism: the strongest, permanent type commonly known for sticking photos to refrigerators, which it can do without the aid of an external magnetic field. Then, in 2019, a team led by the University of Massachusetts Amherst's Thomas Russell reported the creation of liquid droplets that also featured ferromagnetism.

To do it, the team deposited millimeter-sized water droplets into oil. The suspended droplets each housed tens of billions of iron oxide nanoparticles that, by themselves, exhibit paramagnetism: a weaker, temporary type that responds to the magnetic fields produced by other magnets. The oil, meanwhile, was laced with molecules that drew the iron oxide nanoparticles to the surface of the water droplets, where they jammed together and essentially formed a shell.

After applying and removing an external magnetic field, the team found that the nanoparticle jamming had endowed the water droplets with permanent magnetism. And there was more: The researchers showed they could morph and lock the "structured liquid" magnets into non-spherical shapes, including ellipsoids and cylinders.

Robert Streubel, now an assistant professor of physics and astronomy at the University of Nebraska–Lincoln, was among the members of that original team.

"It's pretty exciting," Streubel said. "Because whatever we've done so far, we're always surprised by something."

But those surprises also meant that there was plenty Russell and his fellow researchers didn't yet comprehend about the nature and potential of their creation. So they embarked on a series of theory-backed experiments and simulations that they recently detailed in the journal Proceedings of the National Academy of Sciences.

The researchers were especially interested in learning how to tailor the magnetic properties of the droplets and, by extension, gain greater control over their movement. In one experiment, they changed their nanoparticle recipe, mixing some non-magnetic nanoparticles in with the original, paramagnetic iron oxide variety. When they did, they found that lower concentrations of the iron oxide nanoparticles actually lent the droplets stronger magnetism than expected.

More importantly, the mixture ended up coating the droplet surfaces with discrete patches of ferromagnetism, not the randomly distributed and oriented magnetism that arose when embedding the droplets with only the iron oxide nanoparticles. Those patches — especially when combined with non-spherical shells — could be used to tune a droplet so that it produces stronger or more responsive magnetism in some directions than others, Streubel said.

Refining control over the size and distribution of those patches might eventually allow for, say, the design of miniature liquid robots whose droplet-composed components could be independently, magnetically manipulated. It might also lend itself to adaptive lenses or mirrors, Streubel said, allowing engineers to modify the refraction or reflection of light on the fly by magnetically altering the opacity or location of individual droplets.

The ability to rotate the droplets by exposing them to a rotating magnetic field, as the researchers have demonstrated multiple times, only adds to their potential versatility. The team confirmed that the magnetic precision needed to rotate the droplets is possible thanks to the dynamics of the nanoparticles that migrate to their surface. Those nanoparticles are still paramagnetic when floating near the center of a droplet, where their electrostatic repulsion forces them to maintain some distance from one another.

It’s only when the nanoparticles begin jamming near the surface, Streubel said, that they become ferromagnetic, with the magnetic poles of their atoms all locking in to the same orientation — and yielding a magnetic field that then attracts more nanoparticles from the center.

“So there is this particle-dependent absorption, so to speak,” he said. “And because of that, they accumulate at the interface. They locally behave like a system which is completely ferromagnetic.”

The characteristics of a water droplet itself also influence the emergence of the ferromagnetism. Nanoparticles tend to jam faster and more easily at the surface in droplets with lower pH, or more acidity. Higher pH impedes that jamming by allowing the nanoparticles’ repulsive electrostatic charges to keep them apart, the team found, contributing to less stable magnetization and shell integrity. That susceptibility to pH might eventually prove useful, for instance, in designing drug-carrying transports that can passively target cancerous cells, whose pH often differs from their healthy counterparts.

All of those potential applications, and others yet to be conceived, will require greater understanding and control of a technology that is very much in its infancy, Streubel said. Varying the nanoparticle compounds, mixtures, concentrations and sizes, then carefully measuring the magnetic outcomes, should help it mature.

“It is highly interesting to look into this, because up to now, it was always: We focus on crystalline structures, highly ordered materials, and use those,” Streubel said. “Those are, by definition, the most pure and perfect. But if you then really consider (certain) applications, you can never rely on anything like those. So if we can do this, it would help.”

In the meantime, Streubel said the researchers are enjoying the process of uncovering and investigating each surprise that the ferromagnetic droplets have in store.

“Right now,” he said, “it’s really almost like a toy — a playground to try stuff.”

Russell and Streubel authored the recent PNAS study with researchers from the University of California, Santa Cruz, the Lawrence Berkeley National Laboratory, the Beijing University of Chemical Technology, the Chinese Academy of Sciences, the City University of Hong Kong, the University of Science and Technology of China, and the World Premier Institute’s Advanced Institute for Materials Research.

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