Making magnetic monopoles, and other exotica, in the lab

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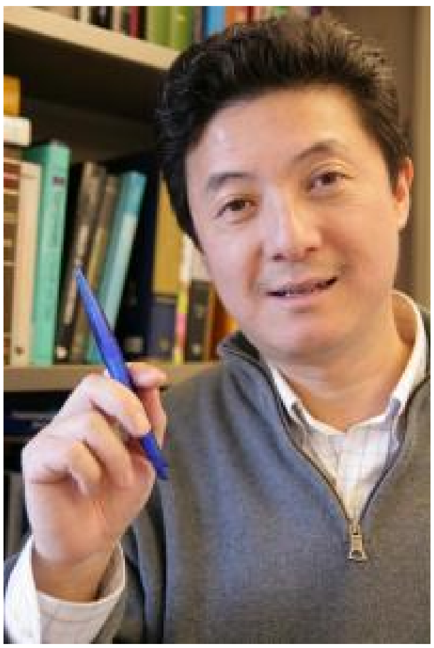

Physicist Shou-Cheng Zhang. Photo: Lauren Schenkman

Physicist Shou-Cheng Zhang has proposed a way to physically realize the magnetic monopole. In a paper published online in the January 29 issue of Science Express, Zhang and post-doctoral collaborator Xiao-Liang Qi predict the existence of a real-world material that acts as a magic mirror, in which the never-before-observed monopole appears as the image of an ordinary electron. If his prediction is confirmed by experiments, this could mean the opening of condensed matter as a new venue for observing the exotica of high-energy physics.

Zhang is a condensed-matter theorist at the Stanford Institute for Materials and Energy Science (SIMES), a joint institute of SLAC National Accelerator Laboratory and Stanford University. He studies solids that exhibit unusual electromagnetic and quantum behaviors, with an eye towards their use in information storage. But due to his training as a particle physicist, Zhang always keeps the big picture in mind. That's why it was so easy for him to see that the material he was already working on could behave like what theorists call a magnetic monopole, an isolated north or south magnetic pole.

The monopole is thought of as electric charge's magnetic cousin, but unlike positive or negative charges, north or south poles always occur together in what's called a dipole. A lone north or south pole simply doesn't show up in the real world. Even if you take a bar magnet and cut it in half down the middle, you won't get a separate north and south pole, but two new dipole magnets instead. For symmetry-minded theorists, however, it's natural that there should be a magnetic equivalent of charge. String theories and grand unified theories rely on its existence, and its absence undermines the mathematical feng-shui of the otherwise elegant Maxwell's equations that govern the behavior of electricity and magnetism. What's more, the existence of a magnetic monopole would explain another mystery of physics: why charge is quantized; that is, why it only seems to come in tidy packets of about 1.602×10^{-19} coulombs, the charge of an electron or proton.

For decades, scientists have kept their eyes peeled for the elusive monopole, but perhaps they were looking in the wrong place. "They were literally hoping it would fall from sky," Zhang says. The notion isn't as far-fetched as it seems—our world is constantly bombarded by weird particles showering from far-off cosmic events, and magnetic monopoles could very well show up as part of that rain. Some enterprising physicists installed loops of superconducting material on their rooftops. If anything remotely like a magnetic monopole fell through, the loops, being sensitive to magnetic fluctuations, would register it.

But in more than 30 years of searching, no one's been able to conclusively detect this particle. Accelerator experiments have been no more successful, leading scientists believe existing monopoles must be far too heavy to create in even the Large Hadron Collider.

Interestingly, Zhang's magnetic monopole didn't fall from the heavens; instead, it was leading a quiet life on the other side of a mirror, but a mirror made of a very special type of alloy. What's more, says Zhang, the math to prove the effect is very clear. "You could give the last part of the mathematical derivation as a final exam in a junior or senior year undergraduate physics class."

To understand how a material can act like a magnetic monopole, it helps to examine first how an ordinary metal acts when a charge—an electron, say—is brought close to the surface. Because like charges repel, the electrons at the surface retreat to the interior, leaving the previously neutral surface positively charged. The resulting electric field looks exactly like that of a particle with positive charge the same distance below the surface—it's the positive mirror image of the electron. In fact, from an observer's point of view, it's impossible to tell the difference.

The concept of an image charge is something undergraduate physics students encounter in their very first electricity and magnetism class, along with the idea that the magnetic monopole doesn't exist. But Zhang's "mirror" alloy is no ordinary material. It's what's called a topological insulator, a strange breed of solid Zhang specializes in, in which "the laws of electrodynamics are dramatically altered," he says. In fact, if an electron was brought close to the surface of a topological insulator, Zhang's paper demonstrates, something truly eerie would happen. Instead of an ordinary positive charge, Zhang says, “You would get what looks like a magnetic monopole in the ‘mirror.’”

To go back to the example of image charges, it’s important to emphasize that there isn’t actually half of a bar magnet somewhere inside this material. Instead, Zhang discovered, due to a peculiarity of the material called strong spin-orbit coupling, the nearby electron would induce a current in the surface that circulates constantly without dying out. This in turn—undergraduate physics majors, get out your pencils—would create a magnetic field that looks like that of a magnetic monopole. Experimentalists have tried to approximate this field before, for instance by arranging permanent magnets in certain ways. But to an outside observer, Zhang’s material would be completely indistinguishable from the monopole particle that physicists were hoping to catch in their superconducting detectors.

“We like to find things that don’t exist,” says Zhang. His work on the monopole has further ramifications; this could be a way to physically realize a number of particles that, until now, have only existed as mathematical loopholes in high-energy physics theories. For instance, Zhang has shown that the electron and image monopole together would act like a so-called “anyon” located at the solid’s surface. “The ‘any,’ in this case, is as in ‘anything,’” Zhang explains—they are particles that only exist in two dimensions, whose properties straddle those of the two classes of three-dimensional particles, fermions and bosons.

Although Zhang works as a theorist, he has close ties to experimental physics. In 2007, his prediction of the quantum spin Hall effect in mercury telluride was confirmed experimentally, earning his work praise in Science as a runner-up breakthrough of that year. “As a theorist you’re always motivated by the math, but it’s a testament to our understanding that we can predict real-world materials,” Zhang says. “Before, new materials were more or less found by accident.” Now other SIMES researchers will be using the Stanford Synchrotron Radiation Lightsource at SLAC to closely study two specific materials, bismuth selenide and bismuth telluride, that Zhang has predicted will exhibit this strange mirror behavior. They hope to confirm the prediction experimentally some time this year.

"Exotic particles such as the magnetic monopole, dyon, anyon, and the axion have played fundamental roles in our theoretical understanding of quantum physics," Zhang writes in the paper. "Experimental observation of these exotic particles in table-top condensed matter systems could finally reveal their deep mysteries." Topological insulators could provide a new experimental outlet for high-energy physicists. "You don't have to look towards the cosmos," Zhang says. "I think we'll see more of the beautiful mathematical structures of high-energy physics become realized in condensed matter physics."

Provided by SLAC National Accelerator Laboratory, By Lauren Schenkman