The science that stumped Einstein

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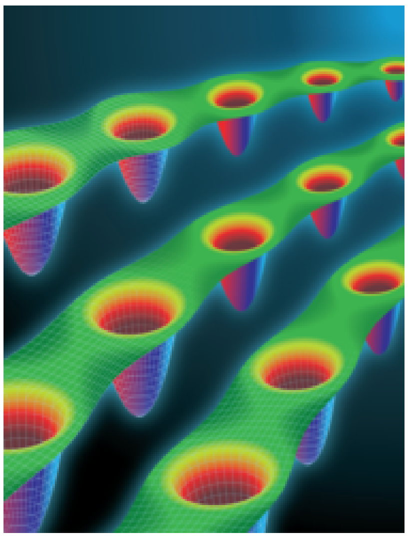

These vortices appear on certain types of superconductors when they're exposed to magnetic fields. Under very cold conditions, superconductors can conduct electricity with virtually no losses - which could make them invaluable for energy; but they have limitations that make them hard to work with. Scientists are figuring out ways to make them more adaptable, such as above: slicing the superconductor into very, very thin strips that can only hold one vortex across. This helps "pin" the vortexes down so they don't interfere with superconductivity (shown in green) as much.

In 1908, the physics world woke up to a puzzle whose layers have continued to stump the greatest scientists of the century ever since. That year, Dutch physicist Kamerlingh Onnes cooled mercury down to -450° Fahrenheit and discovered—to his astonishment—that it could conduct electricity perfectly. And then for the next 50 years, no one could explain why.

Ordinary wires, even really good ones like copper, lose up to a third of the electricity they carry over long distances. But these materials, called superconductors, don't lose any energy. Ever. You could start a current in a loop of superconducting wire and it would circle around, theoretically, forever.

This phenomenon confounded the greatest minds in physics. From papers, lectures, and the reports of former students, we know that Einstein spent a lot of time thinking about it. Everyone did; it was one of the great unanswered questions, even as scientists unraveled other mysteries like the structure of atoms and the age of the universe.

But Einstein never came up with an answer. Neither did the great quantum physicist Richard Feynman, or any of the other luminaries: Niels Bohr, Lev Landau, Werner Heisenberg, Maria Goeppert Mayer. Physicist Felix Bloch crankily suggested a new theory: "Superconductivity is impossible."

In their labs, scientists continued to discover more and more superconductors, but the new materials didn't seem to follow a pattern. Some were pure elements; some were alloys. Even more oddly, it turned out that normally good conductors, like copper, were worthless as superconductors. And why did they all have to be cooled down to near absolute zero to work?

"All of the great minds had a go at figuring out the theory behind superconductors," said Argonne Distinguished Fellow and materials scientist Mike Norman. "But no one had anything good until 1957."

That year, a trio of University of Illinois physicists published an explanation called BCS theory (for Bardeen, Cooper, and Schrieffer) that explained the odd behaviors. Satisfied, scientists shelved it away under "solved mysteries."

That's why no one was prepared when, in 1986, a team from a Swiss laboratory announced it had found a superconductor that worked at much warmer temperatures —up to -280°F. Although to most of us that number sounds positively frigid, for scientists studying superconductors it was a thunderclap.

BCS theory did not explain this phenomenon. Physicists were stunned. They went back to the drawing board, and that's where they still are today, a quarter-century later. In the meantime, we've explained why the universe is expanding, documented what we're made up of down to the tiniest subatomic particles, and landed a robot on Mars; but we can't explain why these new superconductors work.

This hasn't been for lack of trying—after all, superconductors are enormously useful. Their unique properties let scientists invent technologies we'd never have otherwise. So far, they've given us cell phone tower signals, Maglev trains, and an unprecedented window into how our bodies work: they are an integral part of MRI scans to diagnose and study everything from cancer and multiple sclerosis to depression and schizophrenia.

As useful as superconductors are, they have a lot of limitations, which is why it remains important to figure out how they work. The biggest problem is that superconductors still have to be extremely cold to work. That means that if you want to put one in, say, an MRI machine or an engine, you also have to build in complex, expensive ways to cool it down. The -280° F superconductors were a big deal because you can cool them down to that temperature with liquid air, which is much less expensive than liquid helium.

But if we could craft a material that would superconduct at close to room temperature, the possibilities strain the imaginations of a roomful of engineers. Room-temperature superconductors would represent an unbelievable advance for energy: imagine wires stretching across America without ever losing any electricity, or engines that are close to 100% efficient because they lose much less energy as heat. (Ordinary engines are at best about 50% efficient—that's why they get so hot.) Superconductors could make windmills cheaper by reducing the turbines' weight. They could form the basis of ultrafast computer processors.

All this is a small taste of what superconductivity could promise us, if we could master it.

While BCS theory explains the behavior of the original low-temperature superconductors, the theory behind the so-called "high-temperature superconductors" remains stubbornly elusive, and developing one is still one of the Holy Grails of physics.

"I've met people from all kinds of specialties, from string theorists to metallurgists, who all have their own pet theories about what will really prove to be the key," Norman said. Superconductivity has such high practical potential that the U.S. Department of Energy established a special institute to study it called the Center for Emergent Superconductivity, an Energy Frontier Research Center headed by Brookhaven National Laboratory with Argonne and the University of Illinois at Urbana-Champaign as partners. The program studies superconductivity with the triple goal of studying superconductor theory, making new superconductors, and improving current superconductor technology.

The reason the field is so obsessed with theory is that it's difficult to make breakthroughs without a fundamental understanding of how the electrons in a superconductor behave. "A lot of it is still serendipity," Norman said, "which is not where we want to be."

"It's become clear that superconductors involve a highly correlated electron system," said Argonne physicist Wai Kwok. "It's what we call a many-body problem, which makes it hard to model. We don't have the math to do this yet."

We do have the theory more or less worked out for the first wave of superconductors, called conventional superconductors. Electricity is really just electrons moving around, so scientists had to figure out why they got around so easily in these particular materials.

The next few paragraphs contain more than Einstein ever knew about superconductors.

You probably know that as the temperature rises, atoms get more and more excited and bounce around all over the place. But at close to absolute zero, atoms get very, very still.

At these very cold temperatures, the atoms in the superconductor form a stiff lattice. An electric current sends electrons running through the lattice. As they sail through, the positive protons in the lattice are a tiny bit attracted to the negative electrons, so they move slightly toward the electron. The resulting increased positive charge pulls the next electron forward a little faster. Imagine dolphins riding the wave created by the wake of a ship. In ordinary materials, electrons bounce off the lattice and are lost as heat. But the wake effect helps the electrons move along in an orderly fashion.

Unfortunately, this fragile effect breaks down very easily as the material gets warmer. So we know this phenomenon can't explain unconventional superconductors, the kind that work at much higher temperatures and thus are used for most practical superconductor applications.

Besides needing to be very cold, two other properties make superconductors hard to work with. First, if you bend them too much, the internal grains and crystals become so misaligned that they won't superconduct anymore.

Scientists hope to find a superconducting material that is isotropic—which means that it will continue to superconduct even when it's twisted into a coil, a necessary condition for use in engines and other tight spaces. "All kinds of cables and electromagnets are made by twisting," Norman said.

The problem is that magnetic fields affect the performance of a superconductor. If a scientist tries to apply a magnetic field, the superconductor will repel it by creating its own field that runs exactly counter to it. If the magnetic field is too strong, the superconductor will throw up its hands and stop being a superconductor altogether.

Furthermore, the superconductor's capacity changes depending on whether the magnetic field is parallel or perpendicular to it. This is particularly problematic when trying to use superconductors in engines, since the magnetic field orientation can change with each turn of the motor. So researchers want to figure out a way to keep a superconductor working smoothly even while there's a magnetic field in the vicinity.

One of Argonne's principal superconductivity studies focuses on the reason why magnetic fields impair the functioning of superconductors. "When you apply a magnetic field to a high-temperature superconductor, these little pockets of non-superconductivity called vortices form," said Kwok. "They start out as just a few nanometers across, but get bigger as the temperature increases. Eventually, these vortices overlap and eliminate superconductivity altogether."

Likewise, when you increase the magnetic field, the number of vortices increases. When you apply an electric current to such a superconductor, it pushes the vortices around.

The moving vortices create a voltage across the superconductor, causing electrical resistance and energy loss. The more the vortices move, the worse the problem gets. So Argonne scientists want to pin them down.

Kwok and his team knew that vortices like to sit at defects in the material. So they created artificial defects by bombarding the superconductor with lead ions. "The lead ions act like cannonballs, punching through the superconductor and leaving column-shaped defects behind," Kwok said. "These attract the vortices and help make them stay put, which significantly improves the superconductor's current capacity."

Elsewhere at Argonne, Distinguished Fellow Valerii Vinokour took a different approach. He and his colleagues worked with extremely thin superconducting wires that are just 50 nanometers across. (For scale, your fingernails grow at the rate of one nanometer per second.) They are so thin that only one row of vortices can fit on them.

Then they applied an external magnetic field—and found that the material stayed superconducting at temperatures and field strengths where no one had been able to pin vortices before.

These advances are useful for several industry applications—for instance, Kwok and his team work directly with industrial partners to improve their superconductivity-based products, such as superconducting wire.

Kwok and others at Argonne, along with their industrial partners, are continuing to explore a variety of approaches. One interesting angle involves exploring nanoparticles as a way of creating customizable defects. Nanoparticles are good at self-assembling, so one idea is to have them assemble into columns that would serve as defects to pin the vortices.

The science that stumped Einstein is now 112 years old and counting, and the Holy Grail is still waiting for someone to claim it. But the physics world thrives on challenges, and our modern world relies on the technology that physics creates to solve those challenges; handy things like MRIs, the web, and GPS satellites all owe their gears and genes to physicists and other scientists studying fundamental properties. Superconductors no doubt have a lot more to give the world—if we can tease out their secrets.

Provided by Argonne National Laboratory