CONDENSED MATTER PHYSICS

Meet Strange Metals: Where Electricity May Flow Without Electrons

By CHARLIE WOOD

November 27, 2023

For 50 years, physicists have understood current as a flow of charged particles. But a new experiment has found that in at least one strange material, this understanding falls apart.

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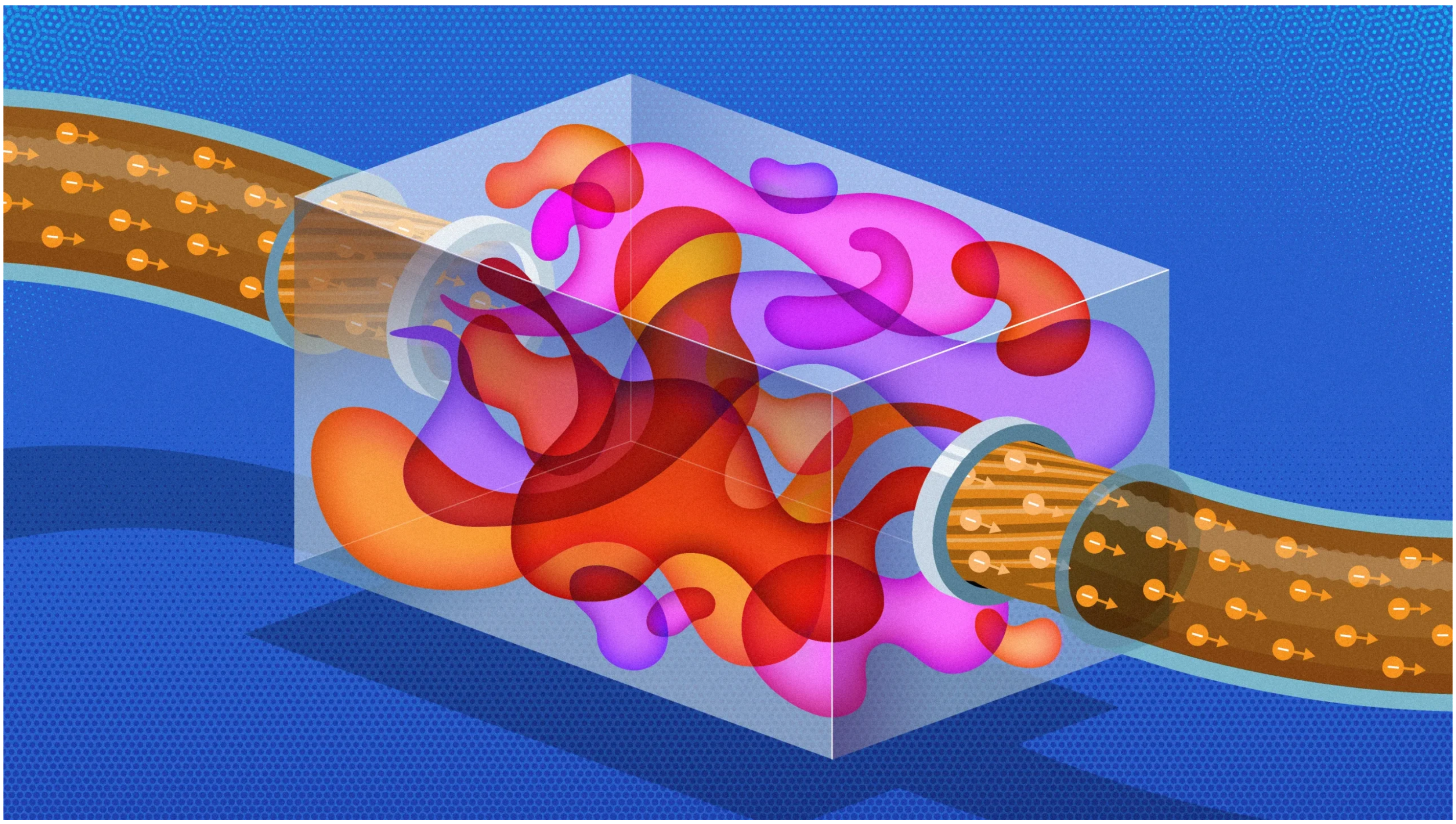

The unusual flow of electric current through a strange class of metals challenges our textbook understanding of charge-carrying particles — because whatever is shuttling current through these metals looks nothing like electrons.

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Samuel Velasco/ *Quanta Magazine*

After a year of trial and error, Liyang Chen had managed to whittle down a metallic wire into a microscopic strand half the width of an *E.coli* bacterium — just thin enough to allow a trickle of electric current to pass through. The drips of that current might, Chen hoped, help settle a

Chen, then a graduate student, and his collaborators at Rice University measured the current flowing through their atoms-thin strand of metal. And they found that it flowed smoothly and evenly. So evenly, in fact, that it defied physicists' standard conception of electricity in metals.

Canonically, electric current results from the collective movement of electrons, each carrying one indivisible chunk of electric charge. But the dead steadiness of Chen's current implied that it wasn't made of units at all. It was like finding a liquid that somehow lacked individually recognizable molecules.

While that might sound outlandish, it's exactly what some physicists expected from the metal the group tested, which along with its unusual kin has beguiled and bewildered physicists since the 1980s. "It's a very beautiful piece of work," said Subir Sachdev, a theoretical physicist at Harvard University who specializes in strange metals.

The observation, reported last week in the journal *Science*, is one of the most straightforward indications yet that whatever carries current through these unusual metals doesn't look anything like electrons. The new experiment strengthens suspicions that a new quantum phenomenon is arising within strange metals. It also provides new grist for theoretical physicists attempting to understand what it might be.

"Strange metals, no one has any earthly idea where they're coming from," said Peter Abbamonte, a physicist at the University of Illinois, Urbana-Champaign. "It used to be considered an inconvenience, but now we realize it's really a different phase of matter living in these things."

A Cuprate Wrench

The first challenge to the conventional understanding of metals came in 1986, when Georg Bednorz and Karl Alex Müller rocked the physics world with their discovery of high-temperature superconductors — materials that perfectly carry an electric current even at relatively warm temperatures. Familiar metals like tin and mercury become superconductors only when chilled to within a few degrees of absolute zero. Bednorz and Müller measured the electrical resistance in a copper-based ("cuprate") material and saw that it vanished at a relatively balmy 35 kelvins. (For their breakthrough discovery, Bednorz and Müller pocketed a Nobel Prize just a year later.)

To begin to understand the bizarre electric current flowing through strange metals, Douglas Natelson and his colleagues needed to figure out what units of charge were carrying the current.

Jeff Fitlow/Rice University

Physicists soon realized that high-temperature superconductivity was only the beginning of the mysterious behavior of the cuprates.

The cuprates got really weird when they stopped superconducting and started resisting. As all metals warm, resistance increases. Warmer temperatures mean atoms and electrons jiggle more, creating more resistance-inducing collisions as electrons shuttle current through a material. In normal metals, such as nickel, resistance rises quadratically at low temperatures — slowly at first and then faster and faster. But in the cuprates, it rose linearly: Each degree of warming brought the same increase in resistance — a bizarre pattern that continued over hundreds of degrees and, in terms of strangeness, overshadowed the material's superconducting ability. The cuprates were the strangest metals researchers had ever seen.

The linear rise in resistance threatened a celebrated explanation of how electric charge moves through metals. Proposed in 1956, Lev Landau's "Fermi liquid" theory placed electrons at the center of it all. It built upon earlier theories that, for simplicity, assumed that electrons carry electric current, and that the electrons move through a metal like a gas; they flit freely between atoms without interacting with each other.

Landau added a way of handling the crucial but complicated fact that electrons interact. They are negatively charged, which means they constantly repel each other. Considering this interaction between the particles transformed the electron gas into something of an ocean — now, as one electron moved through the fluid of electrons, it disturbed the nearby electrons. Through a complicated series of interactions involving mutual repulsion, these now gently interacting electrons ended up traveling in crowds — in clumps known as quasiparticles.

The miracle of Fermi liquid theory was that each quasiparticle behaved almost exactly as if it were a single, fundamental electron. One major difference, though, was that these blobs moved more sluggishly or more nimbly (depending on the material) than a bare electron, effectively acting heavier or lighter. Now, just by adjusting the mass terms in their equations, physicists could continue to treat current as the movement of electrons, only with an asterisk specifying that each electron was really a quasiparticle clump.

A major triumph of Landau's framework was that in normal metals, it nailed the complicated way in which resistance rises quadratically with temperature. Electron-like quasiparticles became the standard way of understanding metals. "It's in every textbook," Sachdev said.

But in the cuprates, Landau's theory failed dramatically. Resistance rose in an immaculate line rather than the standard quadratic curve. Physicists have long interpreted this line as a sign that cuprates are home to a new physical phenomenon.

"You pretty much have to believe that nature is either giving you a clue or nature is incredibly cruel," said Gregory Boebinger, a physicist at Florida State University who has spent much of his career studying the cuprates' linear response. "To put up such a terribly simple and beguiling signature and to have it not be physically important would just be too much to bear."

As a graduate student, Liyang Chen spent a year working out how to make a metallic wire that's thinner than a single bacterial cell.

Courtesy of Liyang Chen

And the cuprates were just the beginning. Researchers have since discovered a host of disparate materials with the same alluring linear resistance, including organic "Bechgaard salts" and misaligned sheets of graphene. As these "strange metals" proliferated, scientists wondered why Landau's Fermi fluid theory seemed to break down in all these different materials. Some came to suspect that it was because there were no quasiparticles at all; the electrons were somehow organizing themselves in a strange new way that obscured any individuality, much as the discrete nature of grapes gets lost in a bottle of wine.

"It's a phase of matter where an electron really has no identity," Abbamonte said. "Nevertheless, [a strange metal] is a metal; it somehow carries current."

thesis adviser, Douglas Natelson of Rice University, along with his colleague Qimiao Si, to consider how they might more directly scrutinize the anatomy of the charge moving through a strange metal.

"What could I measure that would actually tell me what's going on?" Natelson wondered.

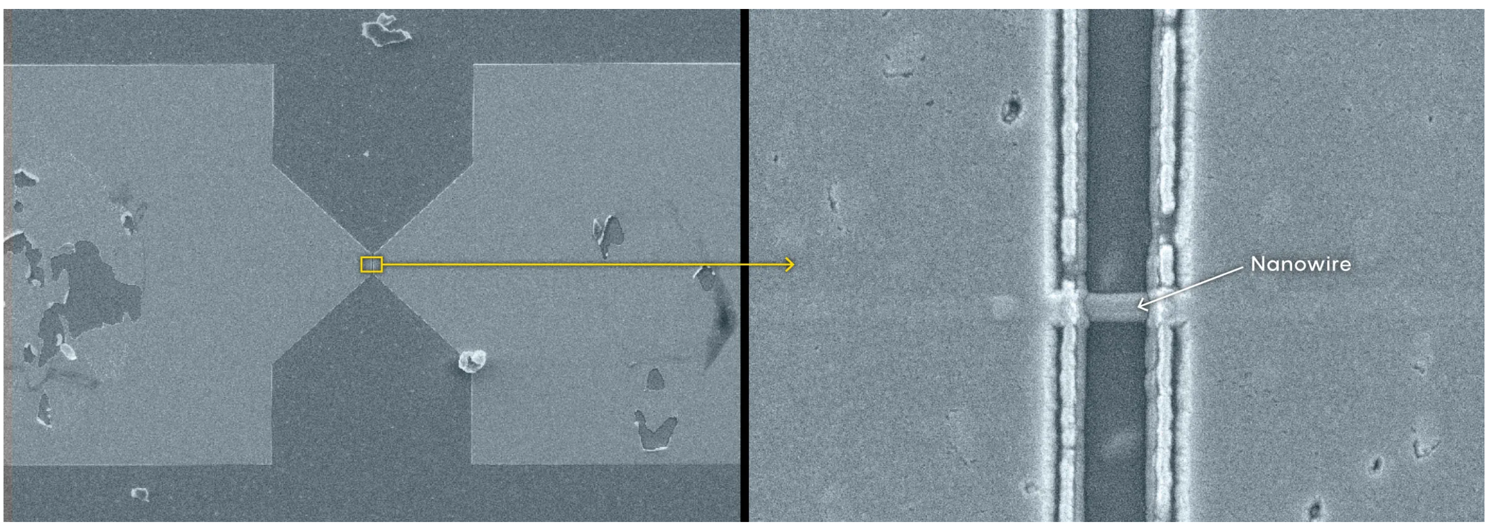
The Anatomy of Electricity

The team's goal was to dissect the current in a strange metal. Did it come in electron-size chunks of charge? Did it come in chunks at all? To find out, they took inspiration from a classic way of measuring fluctuations in a flow — the "shot noise" — a phenomenon that can be understood if we think of the ways that rain might fall during a rainstorm.

Imagine you're sitting in your car, and you know from a trustworthy weather forecast that 5 millimeters of rain will fall over the next hour. Those 5 millimeters are like the total electrical current. If that rain is parceled into a handful of giant drops, the variation in when those drops hit your roof will be high; sometimes drops will splatter back to back, and at other times they will be spaced out. In this case, the shot noise is high. But if the same 5 millimeters of rain is spread into a constant mist of tiny droplets, the variation in arrival time — and therefore the shot noise — will be low. The mist will smoothly deliver almost the same amount of water from moment to moment. In this way, shot noise reveals the size of the drops.

"Just measuring the rate at which water shows up doesn't tell you the whole picture," Natelson said. "Measuring the fluctuations [in that rate] tells you a lot more."

Similarly, listening to the crackle in electric current can tell you about the chunks of charge that make it up. Those chunks are normally Landau's electron-like quasiparticles. Indeed, recording the shot noise in a normal metal is a common way of measuring the fundamental charge of the electron — 1.6×10^{-19} coulombs.



The strange-metal device (left) that Natelson and his colleagues used to measure shot noise, along with a zoomed-in image of the wire Chen fashioned, which spans just hundreds of nanometers and connects the two larger sections. The damaged spots in those sections are where wires were attached to drive a current.

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influence the electrons. These wires need to be nanoscopic in scale.

The group chose to work with a particular strange metal made of ytterbium, rhodium and silicon because Natelson and Si's longtime collaborator, Silke Bühler-Paschen of the Vienna University of Technology, had worked out how to grow the material in films just dozens of nanometers thick. That took care of one spatial dimension.

It then fell to Chen to work out how to take those films and carve out a wire measuring mere nanometers in length and width.

Over the course of about a year, Chen tested different ways of whittling down the metal by effectively sandblasting it with atoms. But in trial after trial, he found that the resulting nanowires suffered atomic-scale damage that destroyed the strange metal's characteristic linear resistance. After dozens of attempts, he landed on a process that worked: He plated the metal with chromium, used a stream of argon gas to blast away all but a thin line of the chromium-protected strange metal, then stripped off the chromium with a bath of hydrochloric acid.

In the end, Chen, who successfully earned his doctorate in the spring and has since gone to work in finance, crafted a handful of nearly flawless nanowires. Each was roughly 600 nanometers long by 200 nanometers wide — about 50 times narrower than a red blood cell.

After cooling them to frigid, single-digit Kelvin temperatures, the researchers ran electric current through the strange metal nanowires. They also ran current through nanowires made of normal gold. The current in the gold wire crackled in the familiar way that currents made of charged quasiparticles do — like fat raindrops splattering on the car roof. But in the strange metal, current slipped quietly through the nanowire, an effect akin to the nearly silent hiss of mist. The most straightforward interpretation of the experiment is that charge in this strange metal does not flow in electron-size chunks.

"The experimental data provide strong evidence that quasiparticles are lost in the strange metal," Si said.

Not all physicists, however, are fully convinced that the experiment kills Landau's quasiparticles. "It's a very bold claim," said Brad Ramshaw, a physicist at Cornell University. "So you need bold data."

One limitation of the experiment is that the group tested only one material. Just because shot noise is low in Chen's ytterbium, rhodium and silicon blend, that doesn't guarantee that it's low in other strange metals. And a one-off anomaly can always be ascribed to some poorly understood detail about that material.

Ramshaw also pointed out that metals ring with all manner of strange vibrations that might distort shot noise in the current. Chen and his colleagues ruled out interference from the more common vibrations, but it's possible that some exotic ripple evaded their notice.

Nevertheless, Ramshaw finds the experiment compelling. "It's strongly motivating for people to try to do other things to see if they are also consistent with no electrons," he said.

put into precise mathematical terms. "What's the right vocabulary to use," Natelson said, "if you're not going to talk about quasiparticles?"

When pressed, physicists respond to this question with a quiver of metaphors for what appears when individual electrons disappear: They meld into an entangled quantum soup; they congeal into a jelly; they form a frothy mess of charge sloshing around. Philip Phillips of Urbana-Champaign likens a strange metal's electrons to the rubber in a tire. When rubber comes out of a tree, its molecules line up in individual strings. But during the vulcanization process, these strings transform into a rugged net. A new substance emerges from the collection of individuals. "You're getting something that's bigger than the sum of its parts," he said. "The electrons themselves have no integrity."

Silke Paschen of Vienna University of Technology and Qimiao Si of Rice University have spent nearly 20 years studying the notion that quasiparticles disappear when two quantum states compete for dominance in a metal.

Tommy LaVergne/Rice University

to do with real materials made of a real grid of atoms. For one thing, it had no space; all electrons sit at a single point where they randomly interact and become entangled with all other electrons.

Over the last couple of years, Sachdev, Aavishkar Patel of the Flatiron Institute, and their collaborators have been working on bringing space into the SYK model. They spread electron interactions across space by considering the effects of flaws in the atomic lattice — spots where atoms have gone missing or extra atoms have appeared. This dusting of atomic imperfections causes random variations in how pairs of electrons interact and become entangled. The resulting tapestry of entangled electrons has a linearly rising resistance — the hallmark of a strange metal. They recently used their framework to calculate shot noise as well. The numbers don't quite match Chen's observations, but they form the same qualitative pattern. "All the trends are right," Sachdev said.

Other researchers emphasize that the theoretical situation remains fluid — it isn't clear to some whether materials as distinct from one another as sheets of graphene and cuprate superconductors could all share a similar enough slate of flaws to produce the shared strange-metal properties in the way required by Sachdev and Patel's theory. And alternative theories abound. Phillips, for example, suspects that strange metals call for an emergent form of electromagnetism that doesn't rely on whole electrons. Si and Bühler-Paschen, meanwhile, have spent almost 20 years developing and exploring a theory for how quasiparticles dissolve when a system sits at a "quantum critical point," where two different quantum mechanical states struggle for the upper hand. In the shot-noise experiment, they brought their nanowires to just such a critical point.

While physicists don't yet agree on why electric charges appear to dissolve inside strange metals, or even if they truly do dissolve, they are determined to find out.

"If we really think there's a whole category of metals out there that we don't understand," Natelson said, "it's important to understand those."

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