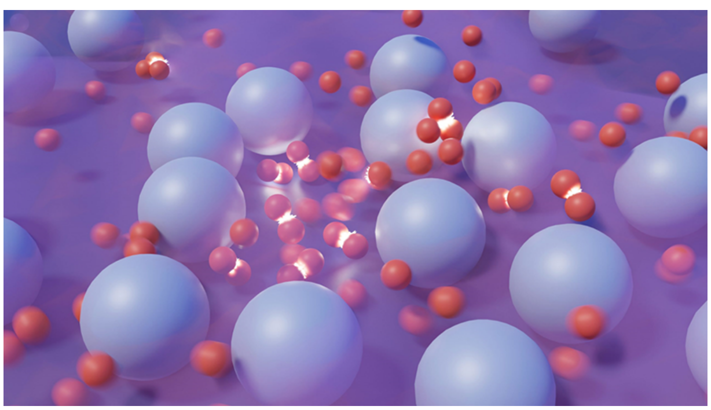
The Mystery of "Strange" Metals Explained

Some metals display an unusually high electrical resistance. Researchers now have an explanation for why.

By Katherine Wright

The current-carrying ability of so-called strange metals defies the known rules of electricity. Now Aavishkar Patel of the Flatiron Institute, New York, and his colleagues have an explanation for why [**1**]. They say that the result could help scientists find new materials that exhibit high-temperature superconductivity, of which strange metallicity is a precursor state.

If you heat a slab of copper, its electrical resistance—how much the material opposes the flow of an electrical current—will increase with the square of the temperature. But if you add some oxygen, lanthanum, and barium to that copper, the behavior suddenly changes. The resulting cuprate material has no electrical resistance at very low temperatures, but as it gets hotter the resistance increases linearly with temperature, making it a poorer conductor than a normal metal like copper. Other properties of the material are also abnormal, including its ability to absorb heat and to transport a rapidly oscillating electrical current. "But the resistivity change is the most striking," Patel says.



To explain the strangeness of strange metals, a new theory considers entanglement and randomness and finds that the combination of these two effects leads to nonuniform collisions between electrons. This collisional behavior produces the relatively large electrical resistance that is the hallmark of strange metals. **Credit: L. Reading-Ikkanda/Simons Foundation**

Scientists first uncovered these resistance oddities in 1986, but they have struggled to explain their origin. Last year, **experiments confirmed** a theory explaining the zero-resistance behavior (superconductivity) in cuprates. Now theorists have an explanation for the linear-resistance trend (strange metallicity) observed in cuprates and in other materials (see **Viewpoint: Graphene Reveals Its Strange Side**).

To understand why strange metals are poorer conductors than normal metals, Patel and his colleagues turned to the materials' electrons—the carriers of electrical current. For the material to have a larger resistance at lower temperatures, the team figured that the electrons must be moving more slowly. But why?

One possible cause the team considered was increased collisions among the electrons, which in theory should slow the particles down, leading to a resistance rise. Increased collisions can indeed change the momenta of individual electrons. But the team found that this change by itself does not affect the resistance, as the overall momentum—the so-called center of mass momentum—remains unaltered. Some electrons slow down, while others speed up, so "just increasing collisions doesn't do the trick," Patel says.

Another possibility that the team considered was an

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inhomogeneity in the potential energy landscape of the material. The team showed that traversing such a "bumpy terrain" alters the center of mass momentum of the electrons, regardless of whether or not they collide. But the temperature-dependent resistivity in this scenario matches that seen for normal metals, not strange ones. "We realized something else must be going on," Patel says.

That something else turned out to be entanglement. Modeling the electrons as being in a highly entangled state, the team found that in a bumpy terrain the strength of the electron entanglement varies depending on where in the material the entanglement took place. This entanglement inhomogeneity adds randomness to both the momenta of the electrons and the frequency with which they collide (the stronger the local entanglement, the more frequent the crashes).

Now instead of all flowing in one direction through the material, the electrons move in every direction. This irregularity induces a much larger center-of-mass-momentum drop than that found when the electrons move collectively. It also changes the temperature dependence of the corresponding resistance such that it follows the linear one seen in experiments. "This interplay of entanglement and nonuniformity is a new effect," Patel says. "It hadn't been considered before despite it being a relatively simple connection to make."

"This work provides a fresh and new perspective on a very important problem," says Rafael Fernandes, a condensed-matter theorist at the University of Minnesota who studies the collective behavior of electrons in disordered systems. "Not only do they find this universal mechanism for strange-metal behavior that doesn't depend on any material details, but they also provide a conceptual advance in how to think about electron interactions in strongly correlated materials. It's beautiful."

That sentiment is echoed by Yashar Komijani, a condensed-matter theorist at the University of Cincinnati who works on problems related to superconductivity. For Komijani, an important aspect of the model is its concrete prediction for the independence of the residual resistivity of a strange metal—the resistivity at zero kelvin—and the steepness of the gradient in the linear resistivity regime. "The prediction is something that experiments can easily check," he says.

Komaijini thinks that the new theory has a good chance of holding up to that experimental scrutiny, as well as to further theoretical investigation. But he notes that the theory doesn't yet answer all the open questions connected to strange-metal behavior. For example, while the new model predicts three of the anomalous behaviors of strange metals, it doesn't currently address a fourth, which relates to how the material deflects an electric current when it is subjected to a magnetic field. Patel and the team did not comment on this aspect of strange-metal behavior in this study.

Even with this caveat, Komaijini sees the work having an immediate impact on the search for strange metals that transition to superconductors at high temperatures. "To better understand high-temperature superconductors, we first need to understand strange metals," he says. "This work is a breakthrough in that direction."

Katherine Wright is the Deputy Editor of ***Physics Magazine***.

REFERENCES

1. A. A. Patel *et al.*, "Universal theory of strange metals from spatially random interactions," **Science 381, 790 (2023).**