Researchers untangle the physics of high-temperature superconductors

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When some materials are cooled to a certain temperature, they lose electric resistance, becoming superconductors.

In this state, an electric charge can course through the material indefinitely, making superconductors a valuable resource for transmitting high volumes of electricity and other applications. Superconductors ferry electricity between Long Island and Manhattan. They're used in medical imaging devices such as MRI machines, in particle accelerators and in magnets such as those used in maglev trains. Even unexpected materials, such as certain ceramic materials, can become superconductors when cooled sufficiently.

But scientists previously have not understood what occurs in a material to make it a superconductor. Specifically, how high-temperature superconductivity, which occurs in some copper-oxide materials, works hasn't been previously understood. A 1966 theory examining a different type of superconductors posited that electrons which spin in opposite directions bind together to form what's called a Cooper pair and allow electric current to pass through the material freely.

A pair of University of Michigan-led studies examined how superconductivity works, and found, in the first paper, that about 50% of superconductivity can be attributed to the 1966 theory—but the reality, examined in the second paper, is a bit more complicated. The studies, led by recent U-M doctoral graduate Xinyang Dong and U-M physicist Emanuel Gull, are published in *Nature Physics* and the *Proceedings of the National Academy of Science.*

Electrons floating in a crystal need something to bind them together, Gull said. Once you have two electrons bound together, they build a superconducting state. But what ties these electrons together? Electrons typically repel each other, but the 1966 theory suggested that in a crystal with strong quantum effects, the electron-electron repulsion is being screened, or absorbed, by the crystals.

While the electron repulsion is absorbed by the crystal, an opposite attraction emerges from the spinning properties of the electrons—and causes the electrons to bind in Cooper pairs. This underlies the lack of electronic resistivity. However, the theory doesn't account for complex quantum effects in these crystals.

"That is a very simple theory and, you know, it's been around for a long time. It was basically the theoretical message of the 1980s, 1990s and 2000s," Gull said. "You could write down these theories but you couldn't really calculate anything—if you wanted to, you'd have to solve quantum systems that have many degrees of freedom. And now, my graduate student wrote codes that do exactly that."

For the paper published in *Nature Physics*, Dong probed this theory by using supercomputers to apply what's called the dynamical cluster method to a copper-oxide-based superconductor. In this method, the electrons and their spin fluctuations are computed together, allowing the researchers to do a quantitative analysis of the interactions between the electrons and their spin.

To do this, Dong peered into the regions where the material becomes a superconductor, and examined the main quantity of spin fluctuation called the magnetic spin susceptibility. She calculated the susceptibility and calculated the region and together with Gull and Andrew Mills, a physicist at Columbia University, analyzed the region.

With this spin susceptibility, the researchers could check the prediction of simple spin fluctuation theory. They found this theory was consistent with superconductivity activity—to about 50%. That is, about half of a material's superconductivity can be accounted for using the fluctuation theory.

"That's a big result because on one hand, we have shown that this theory works but also that it doesn't actually capture all that is happening," Gull said. "The question, of course, is what happens to the other half, and this is the place where the theoretical framework of the 1960s was too simple."

In a paper published in *PNAS*, Gull and Dong explored that other half. They returned to examine the electron systems within a simplified model of a superconducting crystal. In this copper-oxide crystal, there are layers of copper-oxygen bonds. The copper atoms build a square lattice, and in this configuration, each atom is missing a single electron.

When physicists add an element such as strontium, which will share an electron with the copper-oxygen layer, to the material the material becomes a conductor. In this case, strontium is called a dopant atom. Initially, the more charge carriers you add, the more superconducting the material will become. But if you add too many charge carriers, the superconducting property goes away.

Peering into this material, Gull and his co-authors examined not just the electrons' spin, but also their charge fluctuations.

Gull says the fluctuations that are convenient for understanding the system show up in two ways: the first is that the signal is at a single momentum point, and second is that the signal is at a low frequency. A single momentum low frequency excitation means there's a long-lived excitation that helps the researchers see and describe the system.

The researchers found that antiferromagnetic fluctuations—when electrons spin in the opposite direction—accounted for a majority of the superconductivity. However, they also saw ferromagnetic fluctuations that counteracted the antiferromagnetic fluctuations, which ultimately brought them back to the 50% finding.

"When you have a complicated many-electron system with many quantum particles, there's no reason why there should be a simple picture that explains everything," Gull said. "In fact, we find surprisingly that a scenario like the 1966 theory does capture quite a bit of stuff—but not everything."

Gull says next steps will be to see whether their findings can help them predict certain kinds of spectra, or the reflected light, involved in superconductors. He also hopes the results will allow physicists to understand how superconductors work, and with this knowledge, to design better superconductors.

More information: Xinyang Dong, Emanuel Gull & Andrew J. Millis, Quantifying the role of antiferromagnetic fluctuations in the superconductivity of the doped Hubbard model, *Nature Physics* (2022). DOI: 10.1038/s41567-022-01710-z.
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