Unveiling an anomalous electronic state opens a pathway to room-temperature superconductivity

Superconductive materials can conduct electricity with no resistance, but typically only at very low temperatures. Realizing superconductivity at room temperature could enable advanced, energy-efficient electronics and other technologies. Now, an international research team is one step closer to such an achievement. The researchers made the first observation of a special electronic state known as a "nodal metal," which provides more insight into electronic behavior at different temperatures, in a multilayer system comprising copper and oxygen.

The team, which includes researchers based in Japan, Taiwan and the United States, published their results on Oct. 27 in *Nature Communications*.

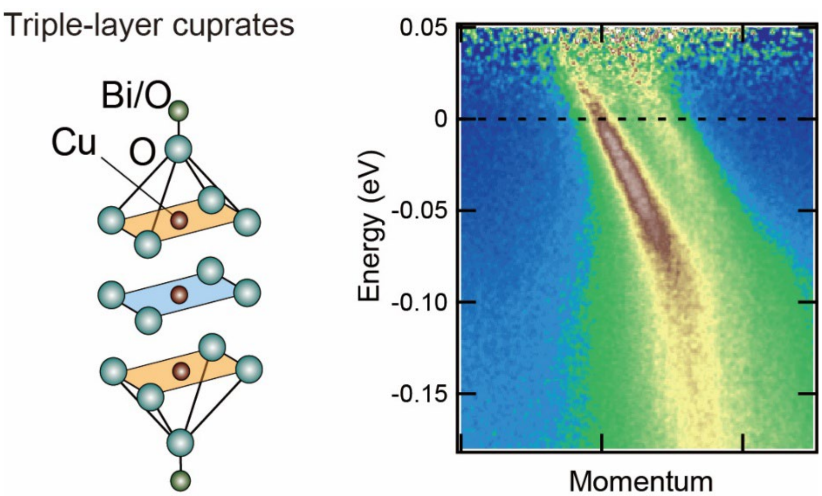

Image title: Crystal and electronic structures in the triple-layer cuprate superconductor
Image caption: Triple-layer cuprate superconductors have three copper oxide planes, two outer (orange) and one inner (blue) plane (left). These two types of copper (Cu)-oxygen (O) planes show two quasiparticle bands as observed in the high-resolution angle-resolved photoemission spectroscopy (right).
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"Superconductivity occurs when carriers — either holes or electrons — are doped into a two-dimensional copper oxide plane," said co-corresponding author Shin-ichiro Ideta, associate professor with the Hiroshima University Research Institute for Synchrotron Radiation Science.

This doping refers to introducing defects into the system, which can then be manipulated to achieve desired behaviors within specific parameters. Copper oxide superconductors have a multilayer system which shows different transition temperatures depending on the number of copper oxide layers, or planes, it has. It can undergo significant physical transitions — including converting into superconducting states, strange metal states and more.

“It is empirically known that the transition temperature is maximized in a triple-layer system with three copper oxide planes,” Ideta said. “However, it has been a long-standing mystery as to why the highest transition temperature is available and how the electrons behave at that temperature.”

To identify how different doping levels impact the electron behaviors at various transition temperatures, the researchers used an analysis method called high-resolution angle-resolved photoemission spectroscopy with synchrotron radiation. Intense beams of photons produced by a synchrotron, or particle accelerator, are used to excite electrons in a sample material — in this case, a triple-layer cuprate, or copper oxide, system. Researchers can measure how the excited electrons move, revealing the material’s electronic band structure — the relationship between the electrons’ energy and momentum. They can also directly measure an energy gap: when the material becomes superconducting, its electronic structure shows a kind of energy barrier, known as the superconducting energy gap, that keeps electrons stable and prevents them from being easily excited.

“Surprisingly, we found that superconducting electrons exist from temperatures much higher than the transition temperature in the inner copper oxide planes with very low hole concentration,” Ideta said, explaining that this low doping-high superconductivity region is the “nodal metal” that can reveal how even higher transition temperatures can induce superconductive electrons. “Furthermore, the superconducting energy gap that provides evidence of superconductivity in the system is significantly larger than in conventional superconductors.”

This nodal metal indicated that superconductivity is stabilized by the "proximity effect" between the two outer and one inner copper oxide planes, according to Ideta.

“This is the reason why the triple-layer cuprate superconductors show the highest superconducting transition temperature over other cuprate superconductors,” Ideta said. “This is a major advancement in our understanding of the mechanism for high-temperature cuprate superconductivity. In particular, the formation of superconducting electrons at high temperatures is expected to provide important guidance for the design and applied research of materials with high superconducting transition temperatures.”

Other collaborators on the paper include co-corresponding author Atsushi Fujimori and Shin-ichi Uchida, Department of Physics, University of Tokyo, Japan; Masashi Arita, Research Institute for Synchrotron Radiation Science, Hiroshima University, Japan; Kiyohisa Tanaka, UVSOR-III Synchrotron, Institute for Molecular Science, Japan; Shintaro Adachi, Shunpei Yamaguchi, Nae Sasaki and Takao Watanabe, Graduate School of Science and Technology, Hirosaki University, Japan; Takashi Noji, Graduate School of Engineering, Tohoku University, Japan; Shigeyuki Ishida, National Institute of Advanced Industrial Science and Technology,

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About the study

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