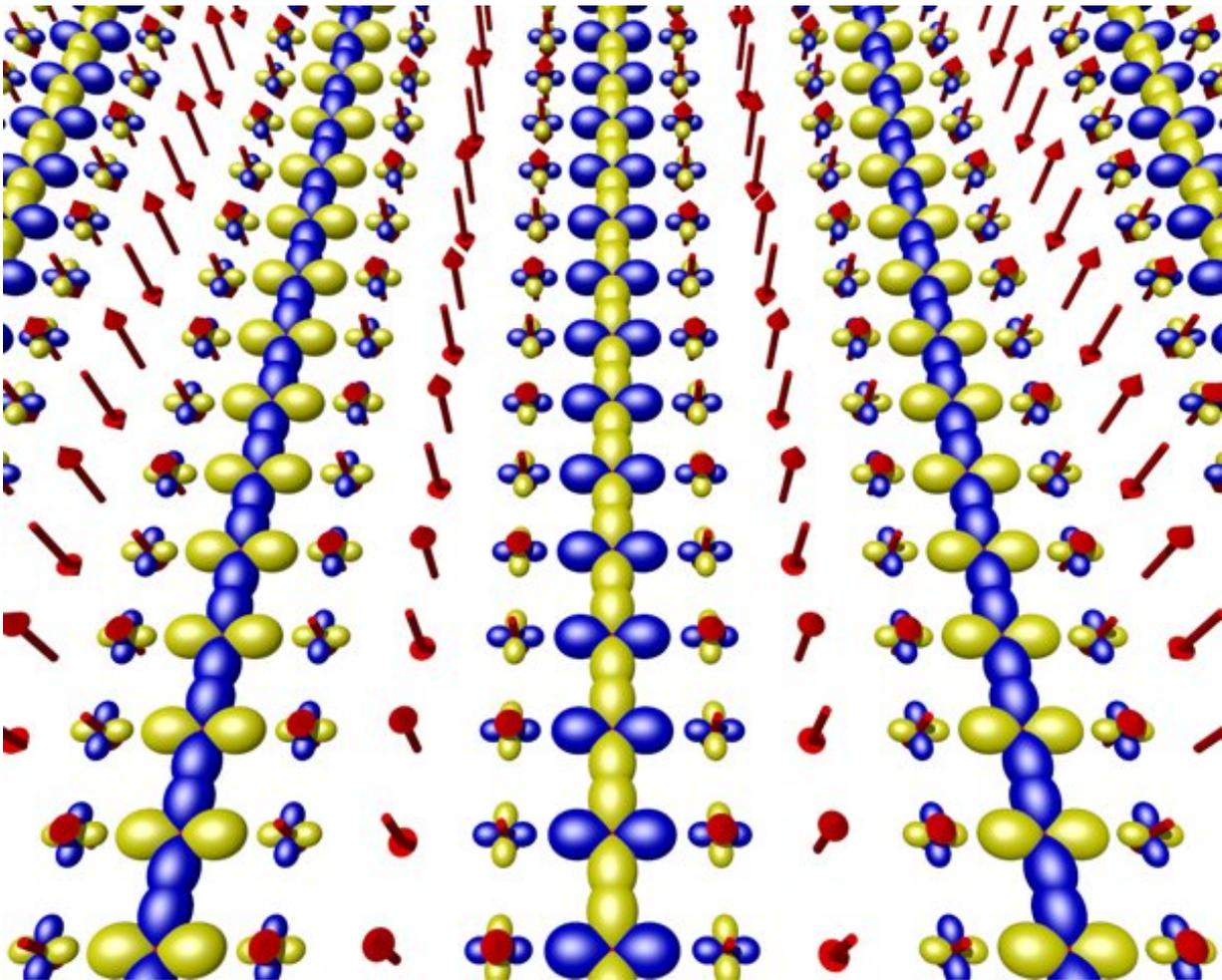


# Scientists see energy gap modulations in a cuprate superconductor

April 1 2020, by Karen McNulty Walsh



This schematic diagram maps out the binding energy (or superconducting energy gap) of individual electrons in a copper-oxide (cuprate) superconductor as measured by a sensitive microscope scanning across the surface. The size of the blue and yellow blobs surrounding individual atoms (red rods with arrowheads indicating their spin orientations) indicates the size of the energy gap (the larger

the blobs the bigger the gap and stronger the electron-pair binding at that location). Note how when scanning across horizontal rows, the pattern increases to a maximum, then decreases to a minimum (no blobs), increases to another maximum with the opposite orientation (yellow and blue blobs switched) and then a minimum again, repeating this pattern every eight rows. These modulations are the first direct evidence of a "pair density wave," a state of matter that coexists with superconductivity and may play a role in its emergence. Credit: Brookhaven National Laboratory

For years physicists have been trying to decipher the electronic details of high-temperature superconductors. These materials could revolutionize energy transmission and electronics because of their ability to carry electric current with no energy loss when cooled below a certain temperature. Details of "high-Tc" superconductors' microscopic electronic structure could reveal how different phases (states of matter) compete or interact with superconductivity—a state in which like-charged electrons somehow overcome their repulsion to pair up and flow freely. The ultimate goal is to understand how to make these materials act as superconductors without the need for supercooling.

Now scientists studying high-Tc superconductors at the U.S. Department of Energy's Brookhaven National Laboratory have definitive evidence for the existence of a state of matter known as a [pair density wave](#)—first predicted by theorists some 50 years ago. Their results, published in the journal *Nature*, show that this phase coexists with superconductivity in a well-known bismuth-based copper-oxide superconductor.

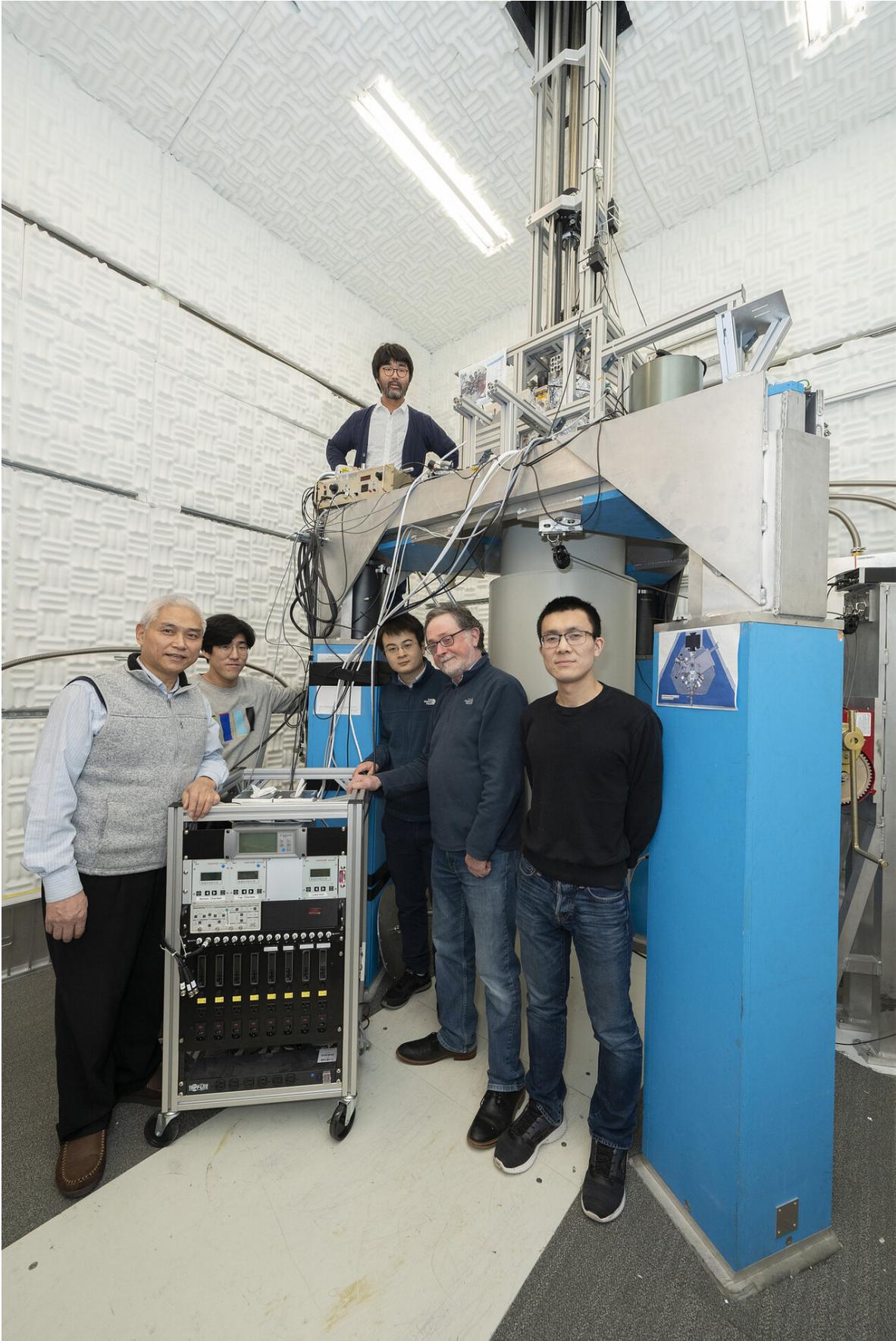
"This is the first direct spectroscopic evidence that the pair [density](#) wave exists at zero magnetic field," said Kazuhiro Fujita, the physicist who led the research at Brookhaven Lab. "We've identified that the pair density wave plays an important role in this material. Our results show that these two states of matter—pair density wave and superconductivity—coexist

and interact."

The team's results come from measurements of single electrons' tunneling spectra using a state-of-the-art spectroscopic-imaging scanning tunneling microscope (SI-STM) in Brookhaven's OASIS laboratory.

"What we measure is how many electrons at a given location 'tunnel' from the sample surface to the superconducting electrode tip of the SI-STM and vice versa as we vary the energy (voltage) between the sample and the tip," Fujita said. "With those measurements we can map out the crystalline lattice and the electron density of states—as well as the number of electrons we have at a given location."

When the material is not superconducting, electrons exist over a continuous spectrum of energies, each propagating at its own unique wavelength. But when the temperature goes down, the electrons start to interact—pairing up as the material enters the superconducting state. When this happens, scientists observe a gap in the energy spectrum, created by an absence of electrons within that particular energy range.



Kazuhiro Fujita (top) with other members of the research team (left to right: Genda Gu, Sang Hyun Joo, Zengyi Du, Peter Johnson, and Hui Li) at the spectroscopic-imaging scanning tunneling microscope (SI-STM) in Brookhaven's OASIS laboratory. Credit: Brookhaven National Laboratory

"The energy of the gap is equal to the energy it takes to break the electron pairs apart (which tells you how tightly bound they were)," Fujita said.

As the scientists scanned across the surface of the material, they detected spatially modulating energy gap structures. These modulations in the energy gap revealed that the strength of electrons' binding varies—increasing to a maximum, then dipping to a minimum—with this pattern repeating every eight atoms across the surface of the regularly arrayed crystal lattice.

This work built on [previous measurements](#) showing that the current created by pairs of electrons tunneling into the microscope also varied in the same periodic way. Those modulations in current were the first evidence, though somewhat circumstantial, that the pair density wave was present.

"Modulations in the current of the paired electrons is an indicator that there are modulations in how strongly paired the electrons are across the surface. But this time, by measuring the energy spectrum of individual [electrons](#), we succeeded in directly measuring the modulating gap in the spectra where pairing occurs. The modulations in the size of those gaps is direct spectroscopic evidence that the pair density wave state exists," Fujita said.

The new results also included evidence of other key signatures of the pair density wave—including defects called "half-vortices"—as well as its interactions with the superconducting phase.

In addition, the [energy](#) gap modulations mirror other Brookhaven Lab research indicating the existence of modulating patterns of electronic and magnetic characteristics—sometimes referred to as "stripes"—that also occur with an eight-unit-cell periodicity in certain high-T<sub>c</sub> cuprate superconductors.

"Together these findings indicate that the pair density wave plays a significant role in these materials' superconducting properties. Understanding this state may help us make sense of the complex phase diagram that maps out how superconducting properties emerge under different conditions, including temperature, magnetic field, and charge-carrier density," Fujita said.

**More information:** Imaging the energy gap modulations of the cuprate pair-density-wave state, *Nature* (2020). [DOI: 10.1038/s41586-020-2143-x](#) , [nature.com/articles/s41586-020-2143-x](https://www.nature.com/articles/s41586-020-2143-x)

Provided by Brookhaven National Laboratory

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