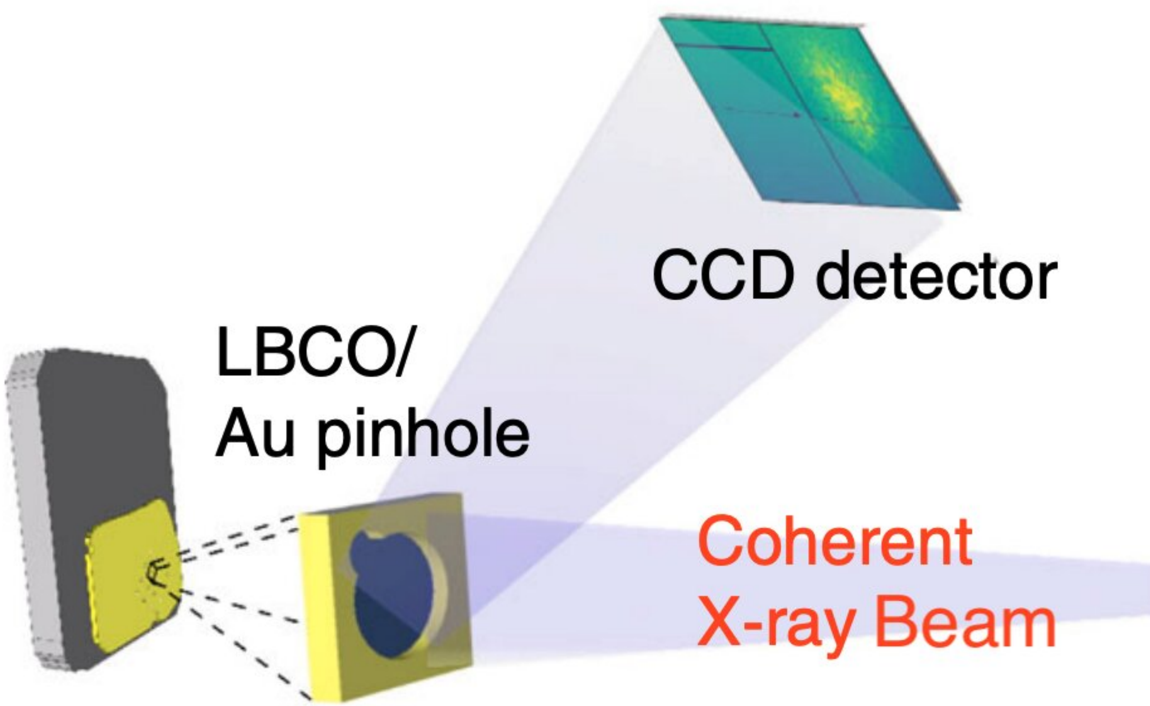
A superconductor that 'remembers' its electronic charge arrangement

October 30 2019, by Laura Mgrdichian



The schematic shows how a speckle pattern is measured: first the coherent x-ray beam delivered by the beamline is focused onto the sample, then the x-rays are scattered by the sample at a specific angle (sensitive to the charge density wave presence)and captured by the CCD detector. The pinhole provides a mask, allowing the researchers to illuminate only a small, specific area of the sample. Credit: Brookhaven National Laboratory

In the field of superconductivity—the ability of a material to conduct electricity with virtually zero resistance—the so-called high-temperature superconductors (HTSCs) are possible candidates for a new generation of advanced technologies. One subset of these, the "cuprates," which are crystalline materials based on planes of copper oxide, are particularly promising. But scientists still need to learn much more about these materials before mainstream, room-temperature applications are possible. Currently, even the "high-temperature" superconductors must be chilled to very, very cold temperatures by everyday standards.

Working at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory, researchers from Brookhaven and University College London recently discovered something new and very surprising about one type of periodic electric charge arrangement, which coexists with superconductivity in cuprates, known as a charge density wave (CDW). They found that the specific CDW order within their sample was "remembered" when the sample was repeatedly heated past the temperature where the CDW disappears. This discovery opens a new avenue of research into how these intriguing materials work, bringing scientists one step closer to a complete picture of electronic behavior in cuprates.

"It would be like melting a pile of ice cubes and then refreezing them—and discovering that they refroze into an identical pile of cubes, even down at the microscopic level," explained Brookhaven Lab physicist Claudio Mazzoli, one of the researchers involved in the study. "Nobody would expect to see that."

Mazzoli and his co-researchers describe their work in the March 29, 2019 online edition of Nature Communications.

The electronic behavior of the cuprates, as with all HTSCs, is quite complex. As the name implies, the electrons that make up a CDW form a periodic standing-wave pattern. CDWs have been observed in nearly all the cuprates, but their role in superconductivity is still not fully understood. Do they compete with superconductivity? Do they participate in it? Do they hinder superconductivity in certain ways and possibly add to it in others? Scientists are still working this out.

"In the HTSCs, any arrangement of electrons is of interest to researchers," said Brookhaven physicist Mark Dean, another of the paper's authors. "The goal is to investigate these arrangements and tune them—or perhaps remove them—so that the superconducting transition temperature of the material can approach, or maybe surpass, room temperature. To do this, we must learn as much as we can about the electrons' behavior and their structures in HTSCs."

One thing that researchers do know is that cuprates containing the same copper oxide planes—but arranged in a slightly different way—may have CDWs with dramatically different properties. It seems, then, that the part of the crystal lattice that hosts the CDW has an effect on the CDW.

Here, the group set out to learn more about the relationship between the material's lattice structure and CDW behavior. Their model system was a cuprate known as LBCO for the compounds it contains: lanthanum, barium, copper, and oxygen. LBCO has a transition temperature—the temperature below which it displays the CDW, and above which it does not—of 54 degrees Kelvin (K) (although equivalent to about -360 degrees Fahrenheit, this temperature is still relatively high in the superconductor world).

The group wanted to find out how imperfections in the LBCO crystal lattice can stabilize the CDW. They were interested in a well-known lattice distortion that occurs in the material: a tilt in the octahedral shape formed by bound copper and oxygen atoms. This tilt tends to anchor the

CDW to the lattice such that it orients in a certain direction; it appears that the CDW may be sensitive to the spatial inhomogeneities, or domains, of the lattice. This relationship between the CDW and the domains, as suggested by the temperature behavior uncovered in this study, may be unique to LBCO. It will be very important to understand whether this is a general feature of the cuprates.

The group cycled their LBCO sample through a range of temperatures, repeatedly heating and cooling it, while probing it with X-rays at Brookhaven's National Synchrotron Light Source II (NSLS-II), a DOE Office of Science User Facility. At the Coherent Soft X-Ray Scattering (CSX) beamline, they used a technique known as coherent resonant X-ray diffraction, in which X-rays scatter from different domains in the CDW spatial arrangement, interfere with each other, and form a "speckle" pattern that is captured by a special camera. Analyzing this pattern yields information on the CDW's features.

This task—directly observing a CDW while tracking its changes, over a range of temperatures—is collectively very challenging, in large part due to the very short distances that characterize the features of a CDW. NSLS-II is uniquely suited to this type of investigation due to the coherent nature of the light it produces, meaning the light waves travel in unison rather than out-of-sync and jumbled. Older light sources do not have such highly coherent beams.

The speckle analysis revealed that the specific CDW order present below 54 K returned even when the sample was repeatedly cycled through much higher temperatures, up to about 240 K (about -28 °F). The researchers think that the structural changes that take place in the crystal below 240 K create a "pinning landscape" that anchors the CDW to the lattice.

"Our work opens a new route for studying the complex interplay between charge and lattice degrees of freedom in superconducting cuprates," said the paper's lead author, Xiaoqian Chen, a researcher in Brookhaven's Condensed Matter Physics and Materials Science Department at the time this study was performed (she is now working at Lawrence Berkeley National Laboratory). "It is also a great demonstration of how NSLS-II can be used to study quantum phases of materials and their spectacular, unexpected properties."

"This result emphasizes the vital importance of the role of nanoscale domains in high-temperature superconductivity. Without the domain pinning effects that have been observed, the CDW might carry current and further disrupt the superconductivity," added co-author Ian Robinson, a physicist at Brookhaven as well as at University College London. "Imaging these subtle 'phase' domain structures is still in its infancy and this work highlights the need to develop better imaging techniques so that structural details can be seen directly."

More information: X. M. Chen et al. Charge density wave memory in a cuprate superconductor, *Nature Communications* (2019). DOI: 10.1038/s41467-019-09433-1

Provided by Brookhaven National Laboratory