Experiments debunk 'pseudogap' role in superconductivity, pave way to practical superconductors

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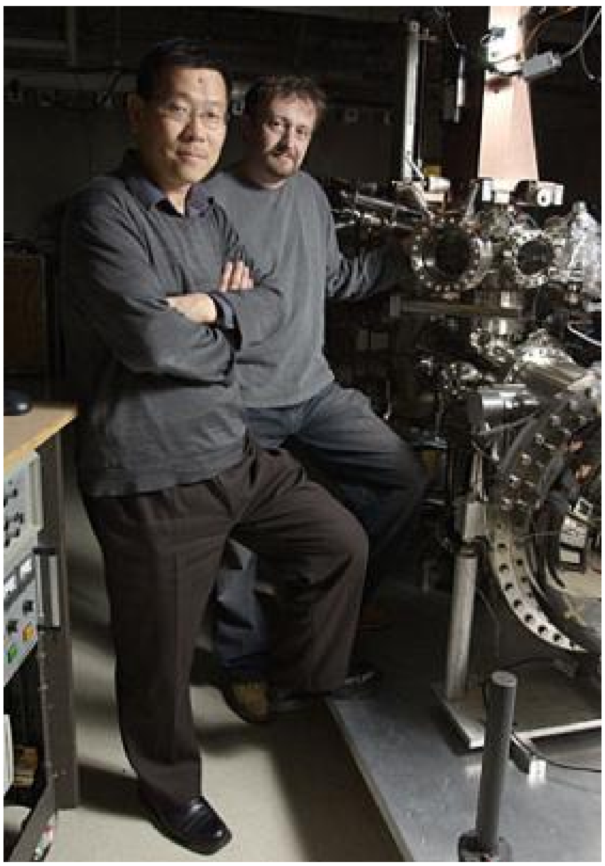

Stanford physicists Zhi-Xun Shen (left) and Norman Mannella used the Advanced Light Source at Berkeley Lab to cast new doubts on any direct link between the phenomena known as pseudogaps and high-temperature superconductivity. Photo: L.A. Cicero

A phenomenon of solid-state physics known as "pseudogaps," suspected by some scientists of playing a key role in the mystery of high-temperature superconductors, has now been found to occur in materials of a completely different nature. This discovery casts new doubts on any direct link between pseudogaps and high-temperature superconductivity.

Working at the Advanced Light Source (ALS) of the Lawrence Berkeley National Laboratory, multi-institutional collaborators led by researchers with Berkeley Lab and Stanford University have identified pseudogaps in manganites, manganese oxide materials that, below a certain critical temperature, become ferromagnetic and display colossal magnetoresistance (CMR). The pseudogaps found in these manganites are the same as those found in the high-temperature (high-TC) superconducting copper oxide materials (cuprates), even though ferromagnetism is the antithesis of superconductivity.

"Based on our new findings, theorists will probably have to re-examine whether the pseudogap phase in the cuprates constitutes a unique hallmark of high-TC superconductivity or if it is a more general phenomenon characteristic of transition metal oxides," said Norman Mannella, a physicist with a joint appointment at Berkeley Lab and Stanford University who has been at the center of several important manganite studies. "In the future, similar experiments will have to be conducted on other transition metal oxides to elucidate this important issue."

Said Zhi-Xun Shen, a global leader in the study of high-TC superconductivity and a Stanford professor in the departments of Physics and Applied Physics and at the Stanford Synchrotron Radiation Laboratory: "I think our findings will add fire to the debate over one of the great scientific mysteries of our time: What is behind the phenomenon of high-TC superconductivity? Are many of the anomalous properties we see in the cuprates manifestations of high-TC superconductivity and CMR? What is the underlying physics ingredient that gives rise to these two competing sibling states? These are important questions that future experiments will try to answer."

The collaboration published its results in the Nov. 25 edition of the journal Nature, in a paper titled "Nodal Quasiparticle in Pseudogapped Colossal Magnetoresistive Manganites." Co-authoring the paper with Mannella and Shen were Wanli Yang and Xingjiang Zhou, both with joint appointments at Berkeley Lab and Stanford; Hong Zheng and John Mitchell, both of Argonne National Laboratory; Jan Zaanen of Leiden University in the Netherlands; Thomas Devereaux of Canada's University of Waterloo; Naoto Nagaosa of Japan's University of Tokyo; and Zahid Hussain of Berkeley Lab.

Superconductivity is a state in which a material loses all electrical resistance: Once established, an electrical current will flow forever. Since the 1950s, superconductivity in certain metals, chilled to a critical transition temperature of around 18 degrees Kelvin (18 K), has been a staple of scientific research, but too costly for widespread use. In 1986, a class of cuprates was discovered with superconducting transition temperatures above the 77 K boiling point of liquid nitrogen.

Initially, these "high-TC superconductors" created enormous excitement over one day spurring the possibility of room-temperature superconductors. However, whereas superconductivity in superchilled metals is well understood, the mechanism behind high-TC superconductivity is still unexplained, and the mystery has severely hampered further development of high-TC materials.

"Complex phenomena in solids is going to be a major theme of physics in the 21st century," Shen said. "High-TC cuprates, with their rich phases and extremely high superconducting transition temperatures, are the most dramatic examples of complex phenomena in solids and thus the most challenging and important problem of the field over the last two decades."

Of pseudogaps and ARPES

Among the possible explanations for high-TC superconductivity, one that has gained traction in recent years involves pseudogaps. Electrons move through a metal conductor at an escalating distribution of velocities and energies that peaks at what is called the "Fermi level." When the metal is superchilled to become a superconductor, an energy gap opens up near the Fermi level, in which electrons are "forbidden." In the high-TC cuprates, however, a partial energy gap, one in which some electrons can reside, will open up well above the superconducting transition temperature. This partial energy gap became known as a pseudogap.

Experiments in recent years by Shen and others have shown that the spectrum of electron energy states in high-TC cuprate pseudogaps can be characterized by a d-wave symmetry similar to that found in the electron energy spectrum of the superconducting state of these materials. The spectrum is shaped like a cloverleaf, small in the nodal direction, which runs diagonal to the copper-oxide chemical bonds, and large in the antinodal direction, which runs parallel to the bonds. This structural similarity between the pseudogap and the superconductivity state, including the dichotomy between the nodal and antinodal directions, led scientists to speculate on a close relationship between pseudogaps and superconductivity in high-TC cuprates.

Shen's revelations about pseudogaps in high-TC cuprates were obtained through a technique called ARPES, for angle-resolved photoemission spectroscopy. In this technique, X-rays are flashed on a sample, causing electrons to be emitted through the photoelectric effect. Measuring the kinetic energy of emitted electrons and the angles at which they are ejected identifies their velocity and scattering rates. This in turn yields a detailed picture of the electron energy spectrum.

In the experiments reported in this new Nature paper, Mannella, Shen and their co-authors used the ARPES technique to study the CMR effect in a two-layer manganite compound consisting of a mixture of lanthanum, strontium, manganese and oxygen, called LSMO. Under the CMR effect, the application of a magnetic field will cause the electrical resistance in LSMO to drop by as much as 1,000 percent. This is in stark contrast to what happens when a high-TC cuprate is exposed to a magnetic field. The cuprate's superconductivity will repel the magnetic field until the field exceeds some critical value, at which point the magnetic field will destroy the superconductivity.

It was therefore quite a surprise when the authors observed that in response to the photoemission X-rays, the LSMO manganites displayed the same pseudogap spectrum, with the same nodal and antinodal dichotomy, as has been found in the high-TC superconducting cuprates.

"Our findings therefore cast doubt on the assumption that the pseudogap state in the copper oxides and the nodal-antinodal dichotomy are hallmarks of the superconductivity state," the authors state in their Nature paper.

Said co-author Zaanen of Leiden University, "There is no reason now to believe that any existing theory gets even close to explaining where the superconductivity in high-TC cuprates is coming from. High-TC superconductivity remains an enigma and belongs on the same list as the origin of life, the cosmological constant and the beginning of the Big Bang."

Polarons elucidated

Even as the ARPES experiments by Mannella, Shen and their colleagues cast new doubts on the role of pseudogaps in high-TC superconductivity, they provide new support for the role of polarons in CMR. A polaron is a "quasiparticle," formed when an electron gets trapped in an energy distortion in the atomic lattice of a crystal, much like a golf ball gets trapped in a divot. When a vibration moving through the lattice, called a phonon, interacts with the trapped electron, the properties of both become bundled up into a single physical entity, the polaron. Earlier research at the ALS by Mannella and Charles Fadley, a scientist with appointments at Berkeley Lab and the University of California-Davis, had linked the formation of polarons in LMSO to the CMR effect. This latest research further substantiates the earlier findings and indicates that polaron formation is crucial to CMR.

"What might be even more interesting is the emerging picture that polarons are present not only in CMR materials but also in high-TC cuprates," Mannella said. "This indicates that polaron formation is a general characteristic of all transition metal oxides. It also hints that something related to polaron physics is going on in high-TC superconductivity as well."

These latest ARPES experiments were conducted at ALS Beamline 10.0.1, which utilizes a state-of-the-art undulator magnetic insertion device to generate beams of X-rays with properties similar to that of a laser. The coherent and tunable X-rays from Beamline 10.0.1 are 100 million times brighter than those from the best X-ray tubes and provide an exceptionally high degree of angular resolution for ARPES-based experiments.

Source: Stanford University (by Lynn Yarris)