A proposed superconductivity theory receives exclusive experimental confirmation

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Superconductivity - a quantum phenomenon in which metals below a certain temperature develop flow of current with no loss or resistance - is one of the most exciting problems in physics, which has resulted in investments worldwide of enormous brain power and resources since its discovery a little over a century ago. Many prominent theorists, Nobel laureates among them, have proposed theories for new classes of superconducting materials discovered several decades later, followed by teams of experimentalists working furiously to provide solid evidence for these theories. More than 100,000 research papers have been published on the new materials.

One such theory began with a proposal in 1989 by Chandra Varma while at Bell Laboratories, NJ, and now a distinguished professor of physics and astronomy at the University of California, Riverside. At UC Riverside, he further developed the theory and proposed experiments to confirm or refute it. That theory has now been experimentally proven to be a consistent theory by physicists in China and Korea.

The experimental results, published in *Science Advances* today (March 4), now allow for a clear discrimination of theories of high-temperature superconductivity, favoring one and ruling others out. The research paper is titled "Quantitative determination of pairing interactions for high-temperature superconductivity in cuprates."

"At the core of most models for the high-temperature superconductivity in cuprates lies the idea of the electron-electron pairing," said Lev P.

Gor'kov, a theoretical physicist at Florida State University who is renowned for making the most important formal advance in the superconductivity field in 1958, while at the Soviet Academy of Sciences. "The paper by Prof. Chandra Varma and his colleagues from China and Korea is the daring and successful attempt to extract the relevant electron-electron interactions directly from experiment. Their elegant approach opens new prospects also for studying the superconductivity mechanisms in other systems with strongly correlated electrons."

A boon to technology

Superconductors are used in magnetic-imaging devices in hospitals. They are used, too, for special electrical switches. The electromagnets used in the Large Hadron Collider at CERN use superconducting wire. Large-scale use of superconductivity, however, is not feasible presently because of cost. If superconductors could be made cheaply and at ordinary temperatures, they would find wide use in power transmission, energy storage and magnetic levitation.

First discovered in the element mercury in 1911, superconductivity is said to occur when electrical resistance in a solid vanishes when that solid is cooled below a characteristic temperature, called the transition temperature, which varies from material to material. Transition temperatures tend to be close to 0 K or -273 C. At even slightly higher temperatures, the materials tend to lose their superconducting properties; indeed, at room temperature most superconductors are very poor conductors. In 1987, some high-temperature superconductors, called cuprates, were discovered by physicists Georg Bednorz and Alexander Müller, so named because they all contain copper and oxygen. These new materials have properties which have raised profound new questions. Why these high-temperature superconductors perform as they do has remained unknown.

A brief history lesson

The superconductivity problem was considered solved by a theory proposed in 1957: the BCS theory of superconductivity. This comprehensive theory, developed by physicists John Bardeen, Leon Cooper and John Schrieffer (the first letter of their last names gave the theory its name), explained the behavior of superconducting materials as resulting from electrons forming pairs, with each pair being strongly correlated with other pairs, allowing them all to function coherently as a single entity. Concepts in the BCS theory and its elaborations have influenced all branches of physics, ranging from elementary particle physics to cosmology.

"But in the cuprates, some of the founding concepts of the physics of interacting particles, such as the quasi-particle concept, were found to be invalid," Varma said. "The physical properties of superconductors above the superconducting transition temperature were more remarkable than the superconductivity itself. Subsequently, almost all the leading theoretical physicists in the world proposed different directions of ideas and calculations to explain these properties as well as superconductivity. But very few predictions stemming from these ideas were verified, and specific experiments were not in accord with them."

A quasi-particle is a packet of energy and momentum that can, in some respects, be regarded as a particle. It is a physical concept, which allows detailed calculation of properties of matter.

In 1989, while at Bell Laboratories, Varma and some collaborators proposed that the breakdown of the quasi-particle concept occurs due to a simple form of quantum-critical fluctuations - fluctuations which are quantum in nature and occur when symmetry of matter breaks down, such as at the phase transition critical point near absolute zero of temperature.

In physics, symmetry is said to occur when some change in orientation or movement by any amount leaves the physical situation unchanged (empty space, for example, has symmetry because it is everywhere the same). Relativity, quantum theory, crystallography and spectroscopy involve notions of symmetry.

"It was at this time that we introduced the concept of marginal Fermi-liquids or marginal quasi-particles through which various properties of superconductivity were explained," Varma said. "We also provided some definitive predictions, which could only be tested in 2000 by a new technique called Angle Resolved Photoemissions or ARPES."

Varma explained that in 1989 there was also no evidence that the same quantum-critical fluctuations promoted the superconductivity transition.

"There was no theory for the cause of such quantum-critical fluctuations or for the symmetry which must change near absolute zero to realize them," he said.

In 1997, Varma proposed transitions to a new class of symmetries, in which the direction of time was picked by the direction of currents. These currents, he suggested, begin to spontaneously flow in each microscopic cell of the cuprates. Since 2004, a group of French scientists at Saclay has been reporting evidence of such symmetries in every high-temperature superconducting compound it could investigate with neutron scattering. Several other kinds of experiments by other research groups are in accord also.

Varma cautioned that some unresolved issues persist. His group is proposing experiments to address them.

In 2003, the year Varma moved to UC Riverside, he formulated a theory for how quantum fluctuations coupled to electrons give rise to the

observed symmetry in superconductivity.

"This was a completely new kind of coupling," he said. "It had very remarkable and unusual predictions for experiments designed to decipher such a coupling."

ARPES to the rescue

In 2010, Varma became aware of high-quality laser-based ARPES in a laboratory at the Institute of Physics in the Chinese Academy of Sciences, Beijing, China. A collaboration with physicist Xingjiang Zhou at the institute ensued, with numerical analysis of the data being done by Han-Yong Choi, a physicist at SungKyunKwan University, Korea, who, in the past, worked with Varma at UCR.

Zhou's team made several improvements in the ARPES technique, which ensured that the quality of data was high and reproducible enough to have full confidence.

"The data obtained and the analysis we describe in our paper are conclusive on the most important issues relevant to superconductivity," Varma said. "Our conclusions - namely, that the quantum fluctuations promoting superconductivity are the same as those that lead to the marginal Fermi-liquid and they are consistently of the form predicted, being stretched exponentially in time in a scale-invariant way relative to stretching in space - also have no theoretical approximations. They are as precise as the quality of the data allows. They also unambiguously address the question of symmetry of superconductivity. Further, they rule out many of the alternative ideas that have been proposed on this problem in the last thirty years since the original discovery. Our observations of the breakdown of time-reversal symmetry and of the fluctuations that follow complete major aspects of our understanding of these problems."