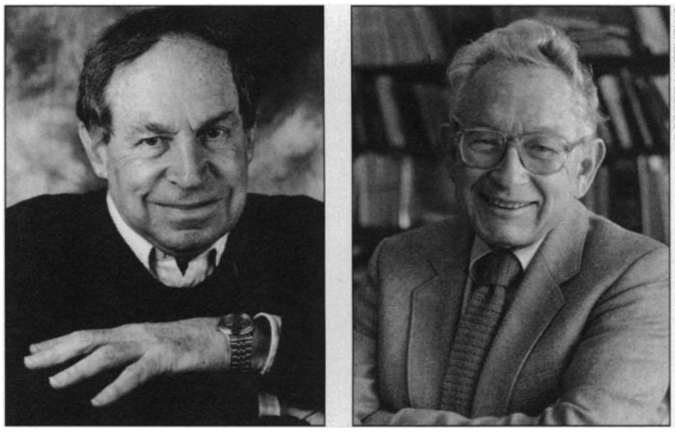
PHYSICS

Theory Meets Experiment in High-T Superconductivity

Since the adventure of high-temperature superconductivity began 7 years ago, experimentalists have been like navigators without a map. They have managed to concoct class after class of high-temperature superconducting materials (HTSCs), but all of that work was done largely by relying on trial, error, and lab-honed intuition rather than theory. Not to say that there were no theories. On the contrary, there have been a plethora of theoretical explanations for how these ceramic materials could carry current without resistance at temperatures tens of degrees higher than had ever been seen before. "In the early days, a theorist always could find data that supported his theory," says Robert Dynes of the University of California, San Diego.



Duel of views. David Pines *(left)* and Philip Anderson differ about the mechanism of electron pairing in high-temperature superconductors.

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The problem was, the theories were mostly too vague or too complex for decisive tests. But a paper on page 337 of this issue signals a change in the field, say Dynes and others. In it, physicists Sudip Chakravarty of the University of California, Los Angeles, Philip Anderson of Princeton University, and coauthors Asle Sudbø and Steven Strong present a theory of high-temperature superconductivity specific and detailed enough to be tested and, perhaps, offer guidance to experimentalists in their search for better materials. Perhaps. But that doesn't mean the search for a theory of high-temperature superconductivity is over.

That's because the theory detailed in the paper is only one of two current leading candidates. Both have been several years in the making and are just now going head to head in experimental tests. In the meantime their advocates are making large—and largely incompatible—claims. Says Anderson, his theory's major architect, "I have been sure that I have been right since 1991," which is when he had the insight that led to the present form of his theory. David Pines of the University of Illinois, Urbana-Champaign, readily matches that bravado, saying that he is "practicing understatement" when he calls the theory that he and his colleagues have developed "a strong contender."

Although they wind up far apart, both theories start with the same premise: that the electrons in a superconductor have to form bound pairs for the material to lose its electrical resistance. Electrons traveling on their own through a normal conductor, such as copper, bounce and scatter around the crystal lattice, impeding the flow of current. But for quantum mechanical reasons, electron pairs can be immune to such scattering.

When it comes to explaining how electrons in HTSCs can maintain such marriages at temperatures that were unthinkably high a decade ago, the two theories quickly diverge. Anderson's explanation adds an unconventional twist to the 35-year-old BCS theory, which successfully accounts for electron pairing in traditional, low-temperature superconductors. In those materials, explains Chakravarty, vibrations in the crystal lattice are thought to act as the matchmakers. As an electron moves through a superconductor's lattice, it creates a traveling distortion, called a phonon, by pulling slightly on the lattice's much heavier nuclei as it flits by. The resulting phonon snares a second electron like an ocean wave scooping up a surfer. The result is resistance-free superconductivity.

That conventional picture was thought to break down, however, at temperatures above about 30 Kelvin, well below the operating temperature of many HTSCs. At those temperatures, conventional wisdom holds that the additional thermal energy ought to bring about a mass divorce of coupled electrons and put an end to the superconductive state. But Anderson, who has been wrestling with this conundrum since HTSCs parachuted onto science's center stage, thinks that in the new materials, electron pairs gain stability from a previously unrecognized quantum mechanical process in which electron pairs "tunnel" between the closely spaced copper-oxide layers in the crystal structures of many of these materials. The tunneling process, suggests Chakravarty, in effect augments the binding energy of the paired electrons, allowing superconductivity to persist at elevated temperatures.

Pines doesn't see it that way. Rather than pinning the basis of high-temperature superconductivity on phonon-induced interactions, Pines opts for a completely different pairing mechanism: magnetic disturbances, or spin fluctuations, in the lattice. The rough idea here is that electrons pair in the wake of a kind of magnetic wave in the lattice, something analogous to but fundamentally different from the mechanical wave of a phonon.

Partly because both theories rest on subtle quantum-mechanical arguments and intensive computer calculations, other theorists are withholding their votes about which is likely to be right, says Dynes. Indeed, neither theory is necessarily on the right track, adds Anthony Leggett, a theorist at the University of Illinois. Says Leggett: "If I had to bet, we probably need some fundamentally new idea" that neither Anderson nor Pines has pursued.

But for the first time, say researchers, it may be possible to resolve such doubts in the laboratory. Both theories make predictions that are within reach of experiments, among them the temperature at which superconductivity should break down in specific classes of materials and the effect of impurities on the superconductors' behavior. Conversely, says Venky Venkatesan at the University of Maryland's Center for Superconductivity Research, experimentalists have become skilled enough "that we can make materials that can test sound theories."

One key test pivots on a subtle physical consequence of the two theories' different electron coupling mechanisms. If Anderson's theory is right, the electron pairs ought to carry a certain kind of angular momentum (akin to the turning momentum of a spinning top), which physicists refer to as having s-wave character. If Pines' theory is right, the pairs ought to carry angular momentum with d-wave character. Leggett, Illinois' Dale Van Harlingen, and their colleagues may already be on their way to adjudicating the issue with sophisticated electron tunneling experiments in HTSCs. At a physics meeting in March, they presented preliminary evidence that hints at d-wave behavior, but Leggett says he still has reservations and that more experiments are needed. To all researchers interviewed by *Science*, though, that kind of contact between HTSC theory and experiment is a welcome novelty.

–Ivan Amato