When Superconductivity Became Clear (to Some)

Associated Press

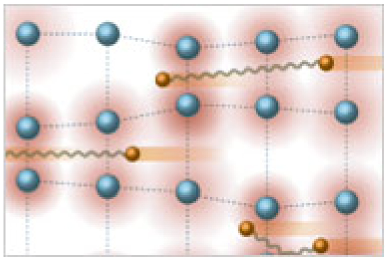
Leon N. Cooper, John Bardeen and J. Robert Schrieffer in 1972.

By KENNETH CHANG
Published: January 8, 2008

CHAMPAIGN, Ill. — Superconductivity, the flow of electricity without resistance, was once as confounding to physicists as it is to everyone else.

Skip to next paragraph

Multimedia


Graphic

Low-Temperature Superconductivity

Related

Times Topics: Superconductors

Times Topics: John Bardeen

For almost 50 years, the heavyweights of physics brooded over the puzzle. Then, 50 years ago last month, the answer appeared in the journal Physical Review. It was titled, simply, “Theory of Superconductivity.”

“It’s certainly one of the greatest achievements in physics in the second half of the 20th century,” said Malcolm R. Beasley, a professor of applied physics at Stanford.

Superconductivity was discovered in 1911 by a Dutch physicist, Heike Kamerlingh Onnes. He observed that when mercury was cooled to below minus-452 degrees Fahrenheit, about 7 degrees above absolute zero, electrical resistance suddenly disappeared, and mercury was a superconductor.

For physicists, that was astounding, almost like happening upon a real-world perpetual motion machine. Indeed, an electrical current running around a ring of mercury at 7 degrees above absolute zero would, in principle, run forever.

If the phenomenon defied intuition, it also defied explanation.

After wrapping up special and general relativity, Albert Einstein tried, and failed, to devise a theory of superconductivity. Werner Heisenberg, the physicist who came up with the Heisenberg uncertainty principle, struggled with the problem, as did other pioneers of quantum mechanics like Niels Bohr and Wolfgang Pauli. Felix Bloch, another thwarted theorist, jokingly concluded: Every theory of superconductivity can be disproved.

This long list of failure was unknown to Leon N. Cooper. In 1955 he had just received his Ph.D. and was working in a different area of theoretical physics at the Institute for Advanced Study in Princeton when he met John Bardeen, a physicist who had already won fame for the invention of the transistor.

Bardeen, who had left his transistor research at Bell Labs for the University of Illinois, wanted to recruit Dr. Cooper for his latest grand research endeavor: solving superconductivity.

“I talked to John for a while,” Dr. Cooper recalled at a conference in October, “and he said, ‘You know, it’s a very interesting problem.’ I said, ‘I don’t know much about it.’ He said, ‘I’ll teach you.’

“He omitted to mention,” Dr. Cooper said, “that practically every famous physicist of the 20th century had worked on the problem and failed.”

Bardeen himself had already made two unsuccessful assaults. Dr. Cooper said the omission was fortunate, because “I might have hesitated.”

Dr. Cooper arrived at the University of Illinois in September 1955. In less than two years, he, Bardeen and J. Robert Schrieffer, a graduate student, solved the intractable puzzle. Their answer is now known as B.C.S. theory after the initials of their last names.

Bardeen died in 1991, but Dr. Cooper and Dr. Schrieffer returned to the University of Illinois in October to commemorate the publication of their superconductivity paper.

Their Herculean achievement was honored with the 1972 Nobel Prize in physics, and it deeply influenced theorists who were putting together theories explaining the to and fro of fundamental particles. The theory has also been applied in subjects as far flung as the dynamics of neutron stars.

B.C.S. theory, however, never achieved recognition in popular culture like relativity and quantum mechanics. That may be understandable given the theory’s complexities, applying quantum mechanics to the collective behavior of millions and millions of electrons. “They were very, very difficult calculations,” Dr. Cooper recalled. “They were superdifficult.”

Even for physicists, the 1957 paper was a difficult one to read.

On the first day of the October conference, Vinay Ambegaokar of Cornell held up a small notebook from 1958. The notebook, Dr. Ambegaokar said, “shows I read it, but I did not understand it.” He said that he continued to prefer approaches “with less constant intellectual effort.” (Soviet physicists had come up with a so-called phenomenological theory — equations that described the behavior of superconductors but did not explain what created that behavior.)

Electrical resistance arises because the electrons that carry current bounce off the nuclei of the atoms, like balls in a diminutive pinball machine. The nuclei recoil and vibrate, sapping energy from the electrons.

In a superconductor, electrons seem more like ghosts than particles, passing the nuclei as if they were not there.

Clues to the nature of superconductivity began to accumulate when Walther Meissner and Robert Ochsenfeld, two German physicists, measured the magnetic field inside a superconductor and discovered, to everyone’s surprise, that it was exactly, precisely zero. Further, any magnetic field that was present in a material would disappear as it was cooled into a superconductor.

This phenomenon, known as the Meissner Effect, was the first sign that superconductors were more than just the perfect conductors envisioned in the early theories.

Then there were signs of a large energy gap between the lowest energy, superconducting state and the next possible, higher-energy configuration. That kept the electrons trapped in the superconducting state.

Finally, experiments showed that the temperature at which an electrical resistance disappeared varied when heavier or lighter versions of an atom were substituted; the weight of atoms play a negligible role in the electrical resistance of ordinary conductors.

Bardeen believed that if he could understand the energy gap, he would understand superconductivity.

In 1955, David Pines — Dr. Schrieffer's predecessor in the Bardeen group — came up with the first breakthrough.

Negatively charged electrons generally repulse each other, but Dr. Pines showed that vibrations in the lattice of nuclei could generate a minuscule attraction.

When an electron passes near a positively charged atomic nucleus, the opposite electric charge slightly pulls the nucleus toward the electron. The electron flits away, leaving behind a positively charged wake, and that, in turn, attracts other electrons.

Dr. Pines's result showed why the weight of the atoms mattered — heavier atoms accelerate more slowly.

The next two key breakthroughs came via mass transit.

In December 1956, Dr. Cooper was on a 17-hour train ride to New York City. He had spent his first months applying his theoretical bag of tricks on the equations. "I did it and I did it and I did it, and I got absolutely nowhere," he said. "I wasn't feeling that clever any more."

On the train, Dr. Cooper discarded his failed calculations. "I just thought and thought, 'I know this is a difficult problem, but it seems so simple,'" he said. Physicists think of electrons in a normal conductor as piling on top of one another in a "Fermi sea," named after Enrico Fermi, who was still formulating the theory at the University of Chicago.

Dr. Cooper realized that it was only the electrons near the top of the Fermi sea that were crucial. "You introduce a small effect," he said, "and somehow you get a superconductor."

As he worked on the problem for the next few months, Dr. Cooper realized that these electrons not only attracted others as Dr. Pines had shown, but also grouped themselves into pairs. It now seemed that superconductivity depended on these pairs, subsequently named Cooper pairs.

Contrary to simple expectations, the two electrons did not revolve closely around each other but were far apart, with many other electrons in between. The multitude of overlapping pairs made the calculations a morass.

A year after Dr. Cooper's trip, Dr. Schrieffer headed to New York for a scientific conference. (At the same time, Bardeen headed to Stockholm to collect his first Nobel Prize, for the transistor.) Dr. Schrieffer had been looking at statistical approaches to solve the tangle of Cooper pairs. On the subway, he wrote down the answer, which turned out to be fairly simple in form.

The Cooper pairs essentially coalesced into one large clump that moved together, and the energy gap prevented the scattering of any one pair. Dr. Schrieffer gives the analogy of a line of ice skaters, arm in arm. "If one skater hits a bump," he said, the skater is "supported by all the other skaters moving along with it."

Back in Illinois, he showed what he had written to Dr. Cooper and then Bardeen. Bardeen was convinced.

Charles P. Slichter, a professor of physics at Illinois then and now and who had conducted many of the experiments teasing out the clues to superconductivity, remembered Bardeen's stopping him in the hallway one day.

"John wasn't a great talker," Dr. Slichter said. "I could see he had something he wanted to say, and we sort of stood there. It seemed like we stood there for five minutes."

Dr. Slichter was tempted to say something, "but I knew I shouldn't, because if I did, I would shut him up. So he spoke to me finally. 'Well, Charlie, I think we've solved superconductivity.'

"And wow, it is the most exciting moment in science I've ever experienced," Dr. Slichter said.

In February 1957, the three submitted a paper, essentially outlining their ideas, to Physical Review. Their longer, more complete paper did not appear in print until December that year.

A new puzzle appeared in 1986 with the discovery of so-called high-temperature superconductors. These superconductors work at higher, though still very low, temperatures.

No theory has emerged as convincing; one session at the Illinois conference was a mass interrogation of the competing theorists.

The theorists agreed that high-temperature superconductors were different, that the attractive force did not come from the vibrations of nuclei. Rather, they said, the attraction somehow arose from the flipping of the atoms’ tiny magnetic poles. Beyond that, they did not agree.

Other types of superconductors, and more theories, could well follow.

As Dr. Beasley of Stanford said in the closing talk of the conference: “We have no idea of the limits of superconductivity in the universe. If 85 percent of the universe is dark matter, I hope 5 percent of it is superconducting.”