The Mystery of Cuprate High Temperature Superconductors

Morihiko Nishida

When a current passes through a metal, some portion of the energy will be converted into heat and lost. This is because metal has non-zero electric resistance and Joule heating occurs. If the resistance is zero, we can transport electricity without energy loss. Such materials indeed exist at low temperatures: superconductor.

Superconductivity was first discovered in 1911 by Kamerlingh Onnes. He tried cooling mercury down to the liquid helium temperature 4 K = -269℃ and found that its electric resistance fell to zero. After Onnes's discovery, the zero-resistance was also confirmed in other materials including lead (at 7 K) and niobium nitride (at 16 K), opening a new research field in solid-state physics.

More than 40 years later, the mechanism of superconductivity was theoretically revealed by Bardeen, Cooper, and Schrieffer [1]. The theory was named BCS theory using their initials. According to the BCS theory, an electron with a certain velocity vibrates crystal lattice. The vibration of lattice in turn attracts another electron moving in the opposite direction, giving rise to the effective attractive force between the two electrons. As a result, below the certain critical temperature T_c where the thermal motion of electrons is negligible, electrons favor forming so-called Cooper pairs. One of the striking features of superconductivity is coherence. In non-superconducting metals, electrons move independently with each other and scattered by impurities and lattice vibrations which cause the electrical resistance. On the other hand, Cooper pairs in a superconductor are known to move coherently. Thanks to this coherence, electric resistance is considerably suppressed. As a result, the supercurrent transferred by Cooper pairs flows without resistance. Although the critical temperature T_c depends on materials, BCS theory predicts that it cannot be higher than ~ 30 K.

Since its formulation, the BCS theory has been widely accepted because of its successful explanation of experimental results. However, in 1985, a novel superconductor was discovered by Bednorz and Müller. They found that a copper oxide material, $La_{2-x}Ba_xCuO_4$, exhibits superconductivity with $T_c =$ 30 K [2]. Notably, the parent material of La_2CuO_4 is an insulator and the superconductivity emerges by chemical doping. Because of this unexpected character, the result was not immediately accepted among the physicists. Soon after, the Meissner effect was observed as another fingerprint of superconductivity. At this stage, the superconductivity of the material was undoubtedly recognized. A few months later, a different copper oxide superconductor, $YBa_2Cu_3O_7$, was discovered with an anomalously high T_c of 90 K. These copper oxide superconductors were named high-critical temperature cuprate superconductors and attracted great attention among physicists. The current record of T_c at ambient pressure is as high as 133 K = -140°C [3]. Since BCS theory predicts the maximum T_c to be ~ 30 K, the mechanism of cuprate superconductors is considered different from that of conventional superconductors. Then, why they become superconducting?

After thirty-five years since the first discovery of the cuprate superconductor, much progress has been achieved on the understanding of its mechanisms. Crystal structure study revealed that the cuprate has two-dimensional CuO_2 planes stacked along the other dimension. According to various experimental studies, Cooper pairs seem to form in the CuO_2 planes. Although the mechanism of the Cooper pair formation is still under debate, one of the most plausible scenarios is that the attractive interaction between electrons is mediated by the spin fluctuation [4]. Cooper pairs can tunnel between the CuO_2 layers in a quantum mechanical way, acquiring three-dimensional coherence, and exhibit bulk superconductivity [5].

Despite the profound progress on the understanding of cuprate superconductors, there remains a lot to be clarified. The interplay between the superconducting phase and other electronic phases is one of them. Some cuprate superconductors are known to exhibit spin- or charge-ordered phases above T_c, where spin or charge aligns in specific patterns on the CuO_2 plane. It has become a hot issue to clarify whether these phases are competing with superconductivity or not. Generally, the magnetically-ordered phase is considered to substantially affect the superconductivity since the Cooper pair of cuprate is likely mediated by the spin-fluctuation. If the magnetically-ordered phase competes with the superconductivity and hence suppresses T_c, we might be able to increase T_c by selectively destroying the magnetic order. In my opinion, this can be achieved with a recent laser technique. If the CuO_2 plane is distorted by the strong laser irradiation, spins are expected to be randomized or to align in a different pattern. Usually, such an intense laser needed to alter the crystal structure would also destroy the Cooper pairs, but thanks to recent advances on the laser technology, it may be possible to selectively distort crystal structure without destroying Cooper pairs, for example by tuning the wavelength and pulse duration of the laser pulses.

Revealing the mechanism of cuprate superconductors has a significant meaning in the scientific point of view. Superconductors are often understood as a symmetry broken system, analogous to spontaneous symmetry breaking in the context of particle physics. Recently the Higgs oscillation of the superconducting order parameter was observed [6, 7], which is a direct analogy from the Higgs Boson of particle physics. Observation of Higgs Boson needs huge amounts of time and energy, but Higgs mode in superconductors is relatively easy to access. Thus, superconductors can be utilized to further explore novel phenomena in a symmetry broken system which is difficult to test in high energy experiments.

Besides, as I mentioned in the introduction part, superconductors can transfer electricity without energy loss. The superconductor is now utilized as a lead wire in MRI, in which a huge amount of current flows, to avoid energy loss and consequent Joule heating. In the future, it may be applied to the transmission line. Since a few percent of electricity is lost during the transmission in power lines, superconductors seem to have the potential to solve the energy problem. The biggest problem is that we need low-temperature conditions to realize superconductivity. To solve this problem, the cuprate high-temperature superconductor is a strong candidate, and we need to understand the superconductivity in cuprate to achieve superconductivity at even higher temperatures.

References:

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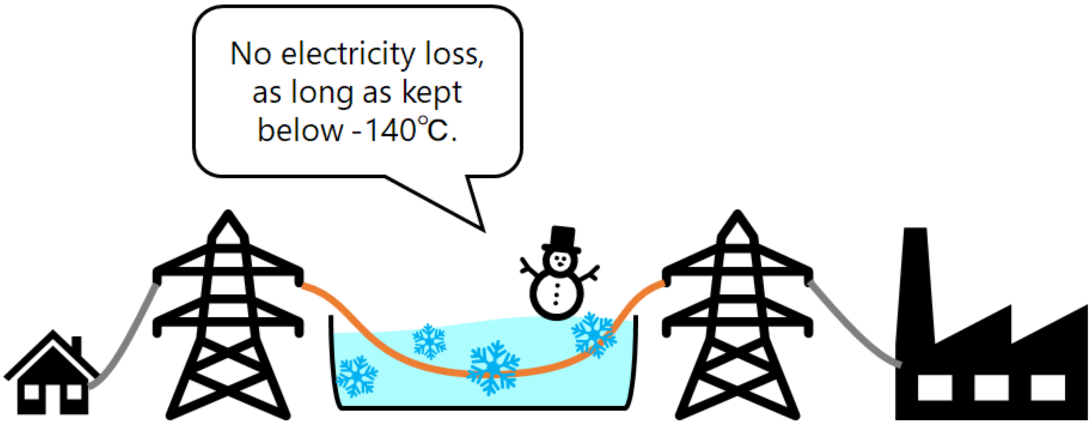
No electricity loss,
as long as kept
below -140℃.