A Physical Picture of Superconductivity

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Abstract

A universal mechanism of superconductivity applicable to “low temperature” and “high temperature” superconductors is proposed in this paper. With this model of mechanism experimental facts of superconductors can be qualitatively explained. A function is introduced to describe the average separation distance between vibrating lattice atoms, which is crucial for the transition from normal to superconductive state. However, the most attractive and exciting conclusion that can be derived from this physical picture, is that given atoms of other element be successfully sandwiched between ferromagnetic atoms one by one, a superconductor constructed this way is most likely to have a very high transition temperature.

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Since H. Kamerlingh Onnes found superconductivity in 1911, this unique phenomenon of conductors has perplexed man for nearly a century, while his understanding about this mysterious property has improved markedly. In 1957, J. Bardeen, L. N. Cooper and J. R. Schrieffer proposed BCS theory, which provided a deeper understanding of the microscopic mechanism of superconductivity. However, after Bednorz and Müller suggested that high $T_c$ superconductors possibly exist in cuprates in 1986, the recorder of transition temperature of superconductors changed constantly and rose drastically. During this period of time, a wealth of high $T_c$ superconductivity theories sprung up. Yet, the mechanism of superconductivity remains unsettled, and there is not yet a decisive theory concerning the mechanism of high $T_c$ superconductivity, though different theories place emphasis on different aspects and view them from different points. Some authors postulated that the mechanism responsible for high $T_c$ superconductors may not be pairing. In addition, it is believed that there should be no difference between mechanisms of “low temperature” and “high temperature” superconductivity. In this paper we propose a universal mechanism of superconductivity that can be applied to “low temperature” and “high temperature” superconductors by presenting a physical picture of conduction electrons and lattice atoms. We view superconductivity as a consequence of “vibration harmony” between conduction electrons and the vibrating lattice atoms.

It is well-known that the temperature of a material is related largely to the thermal vibration kinetic energy of its lattice atoms. When its temperature decreases, the lattice atoms of the material vibrate less violently. This means that the temperature of the material is the main factor that affects the
vibration amplitude of lattice atoms. As a result, it is widely accepted that the root cause of superconductivity lies in the interaction between conduction electrons and lattice atoms of the material, whose vibration is depicted by energy quanta called phonons. Inasmuch as superconductor forms when the temperature of the material is sufficiently low, it is reasonable to infer that the vibration amplitude of the lattice atoms decreases as the material’s temperature decreases, and consequently the time average separation distance between lattice atoms becomes shorter; when the vibration amplitude is sufficiently small, electrons can transport resistlessly among lattice atoms and a superconductor thus forms.

Before we proceed to present the physical picture of superconductivity, it is instructive to examine the structure of an atom, which is well known as “solar system”\(^7\). That is, the nucleus centers while electrons move around it, from inner to outer shell, ending up with Fermi level. The conduction electrons are those move in the outermost shell.

Let’s now take a closer view into a conductor. Fig.1 shows the difference of lattice atoms array between the normal and superconductive state. When the temperature of a material is high, its lattice atoms vibrate so vigorously that some of them are very near while some others quite far, as is illustrated in Fig.1a. When the temperature of the material is sufficiently low, however, the lattice atoms vibrate very slightly and array in a better order, thus the conduction electrons can transfer between atoms without being scattered and macroscopic resistance exists no longer.
How this transition is realized? For simplicity, we plot only one atom chain, as shown in Fig.2. Suppose an electron moving clockwise around atom A, when arriving at the border of atom B, on account of the tendency to maintain its original momentum and that the instantaneous separation distance $d_{AB}(t)$ between atom A and B is sufficiently small, the electron can thus go into the orbital of atom B with certain probability, moving anti-clockwise around atom B. Put alternatively, the electron has two choices, i.e., it either moves around atom A in the original direction, or transfers to its nearest neighboring atom B and moves around it in the opposite direction. Similarly, when the electron arrives at the edge of atom C, it can go into the orbital of atom C and moves again clockwise around it, and anti-clockwise around atom D · · · The electron thus transfers from atom A to D smoothly, without being reflected or scattered and consequently losing its energy, which means non-resistivity macroscopically.

It should be emphasized that it is the small average separation distance $d_{AB}(t)$ between lattice atoms that allows conduction electrons to move in
such a path of semi-circles with arrows from one atom to another shown in Fig. 2. In other words, the electrons will naturally move in this interesting path among lattice atoms and superconductive state forms, as long as the vibrating lattice atoms are so close to each other that it matches (is harmonic to) the energy and momentum of free electrons in the bulk material. It should also be noted that a conductor will exhibit superconductivity as long as there are in the bulk material such continuous passageways shown in Fig. 2, no matter how zigzag they are and how few there are, even only one atom chain.

As we have arrived at the conclusion that the average separation distance between atoms is crucial for a conductor to transit from a normal to a superconductive state, now we have to consider a crucial problem: how to describe this average distance? We introduce a functional $S$ to do this as follows.

$$S = \frac{\sum_{<i,j>} \frac{1}{t} \int_0^t d_{ij}^2(t) dt}{\sum_{<i,j>}}$$ (1)

where $d_{ij}(t)$ is the instantaneous separation distance between nucleus $i$ and $j$ at time $t$, and the sum extends over all nearest-neighbor pairs of nuclei. The integral in Eq. (1) represents the time average of $d_{ij}(t)$. The function $d_{ij}(t)$ is related to the kinetic energy and interaction potentials of the nuclei, while their kinetic energy is related largely to the bulk temperature of the material. This means that the functional $S$ is a function of the temperature of the material and the potential between lattice atoms. Thus one can write

$$S = S(E_k(T), v) = S(T, v)$$ (2)
where $E_k(T)$ is the average kinetic energy of lattice atoms in a bulk material, $T$ is the temperature of the bulk material and $v$ is the average potential between lattice atoms.

With this physical picture of superconductivity we can now proceed to explain the experimental facts of superconductors. We exemplify only a few basic ones, while others can also be interpreted without difficulty.

**Non-resistivity.** As aforementioned, due to the sufficiently small average separation distance between lattice atoms, conduction electrons can transmit from atom to atom without being scattered and thus no macroscopic resistance raised.

**Meissner effect.** According to Ampere’s molecular current theory of magnetism, a bulk material’s magnetic field is formed by its atomic currents, i.e., all valence electrons moving around their nuclei in the same direction. However, in this model of superconductivity, the number of electrons moving clockwise equals that of anticlockwise. Consequently, the macroscopic average magnetic field in a bulk superconductor is zero. It should be reiterated that it is the small separation distance between nuclei and appropriate momentum or energy of conduction electrons that makes the conduction electrons move in such a semi-circle trajectory with arrows shown in Fig.2. Any sufficient increase in energy and momentum of an electron or in the average separation distance between lattice atoms will destroy this subtle transferring pattern. Therefore, when the applied external magnetic field is strong enough, the interaction between the electrons and the magnetic field will break this harmony between conduction electrons and lattice atoms, and consequently the material loses superconductivity and becomes again
normal state.

Frequency dependent electromagnetic behavior. As the superelectron absorbs enough energy from the electromagnetic field, the pattern of electronic movement is also undermined. The analysis is similar to that of Meissner effect.

An interesting and exciting conclusion can be drawn from this physical picture of superconductivity that electrons move around nuclei in reverse direction to each other one by one. Taking into account that valence electrons in a ferromagnetic substance move in approximately the same direction, we can deduce that given another kind of atoms be successfully sandwiched between ferromagnetic atoms one by one, i.e., replace all the anticlockwise atoms in Fig.2, with all their electrons moving exactly in reverse direction to their neighboring ferromagnetic atoms, a superconductor constructed this way, is expected most likely to have a very high transition temperature.

In conclusion, we have proposed a novel mechanism of superconductivity applicable to “low temperature” and “high temperature” superconductors. Anderson suggested in 1987 that the new high $T_c$ materials may arise from purely repulsive interactions, which was motivated by the fact that the superconductivity seems to originate from doping an otherwise insulating state. However, this can be interpreted by the present model as that the doped atoms act as bridges across the intrinsic atoms, shortening the average separation distance $S$ defined by Eq.(1), and thus increases transition temperature of the doped material.
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7see, for example, J. L. Mayo, Superconductivity: the threshold of a new technology, TAB Book Inc.(1988), p.18-20.

8This may be considered to conflict with standard electron gas model which is characterized by Bloch wavefunction. However, it is noted that Bloch's wavefunction is obtained in the approximations that the lattice atoms are perfectly periodic and at rest, which is not the realistic situation. The assumption $V(x) = V(x + na)$, upon which Bloch wavefunction is obtained, will not hold in a real, even perfect crystal at finite temperature, especially at high temperature. We argue that an electron in
any bulk material must move around some certain nucleus with certain probabilities, maybe this one at this time, that one at that time, but it “rotates” around nuclei.

9 One major factor affecting the potential between lattice atoms is external pressure, which has been studied extensively. For detail, see, for example, J. S. Schilling and S. Klotz, in Physical Properties of High Temperature Superconductors III, edited by Donal M. Ginsberg (World Scientific, 1992), p.59-157.

10 In a pure ferromagnetic metal, e.g., iron, its conduction electrons have a strong tendency to rotate around their nuclei at the same direction. With the present model of superconductivity, it is not difficult to understand why ferromagnetic elements have no superconductive transition temperatures.
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