Exploring Superconductivity: From Historical Milestones to Future Frontiers

Wenqi Wu *

Ulink College of Shanghai, Shanghai, China

* Corresponding Author Email: wenqi.wu@ulink.cn

Abstract. Superconductivity has been a highly popular topic at the forefront of science since scientists firstly discovered this phenomenon. An enormous number of papers have been devoted to superconductivity during the past 100 years. New discoveries and research are constantly changing, driving people's thinking about the essence of this phenomenon. Superconductivity has great prospects in many areas, it has many possible uses, including transporting, zero wasting electricity transmission, and quantum computer. This paper introduces histories of how scientists found superconductivity, definitions scientists made on superconductivity, mechanism that provides for this phenomenon, and some recent study on superconductivity. By introducing these findings and theorems, understanding of superconductivity will be simpler and clearer, making it more likely to trigger thinking and innovation on the unsolved problem in this region. Finally, a few predictions are made concerning the future usages and study of this topic. This work paves the way to unravel the microscopic mechanism of superconductivity.

Keywords: Superconductivity; Meissner effect; Bardeen-Cooper-Schrieffer theorem.

1. Introduction

Superconductivity is a kind of physical property found in some certain materials where their resistance becomes zero and magnetic fields are expelled from the materials. In 1908, when the Dutch physicist Heike Kamerlingh first condensed helium gas in the laboratory, the condition of discovering superconductivity was satisfied. Till this day, the exploration of superconductivity has been going through over a century. It undergoes some astonishing crests and valleys. After Onnes condensed helium, he and his students began to do experiments under extremely low temperatures. At that time, scientists were guessing what would happen to resistance if the temperature of a substance becomes zero. James Dewar predicted it would decrease to zero. While Lord Kelvin said that the resistance would reach a minimum and then rebound. His reason was that: as the temperature approached 0K, electrons in the substance's structure would stop moving. So Onnes carried out such an experiment and as a result, he found the superconductivity [1].

After that, scientists put into great effort and resources exploring it. During the years, they discovered hundreds of materials that could show superconductivity in low temperatures. They even built theorems, trying to explain this new phenomenon which they had never imagined before. Any development in the region of superconductivity improved people's ideas and insight of this miraculous finding. Up to now, five Nobel prizes in physics were awarded to physicists who had made outstanding contributions related to superconductivity. Superconductor has huge potential in its applications. From long-distance electricity transmission without heat loss to transportation with almost no resistance, superconductors can even do many things that people could not achieve or never imagined. A perfect superconductor that can be used at room conditions has not been found yet and it is a dream to many scientists. There is still a lot of area unsolved in superconductivity and it is waiting for future scientists to explore.

This paper describes the history of discovery of superconductivity, its definition, characteristic and phenomena, some recent research on superconductivity, and its possible future applications.

2. Basic Theory of Superconductivity

2.1. Discovery of Superconductivity

On 10 July 1908, the Dutch physicist Heike Kamerlingh Onnes condensed helium gas for the first time in human history. As a result, he started an entirely new chapter of scientists studying the physics under low temperature. Because of that age, scientists were guessing how the resistivity of metals would differ if the temperature became infinitely close to absolute zero (-273.15K) at that time. In order to find the truth, Kamerlingh Onnes used mercury to carry out an experiment. It is because mercury was the purest metal that can be found at that time. Surprisingly, when temperature was below 4.2K, the resistance of mercury suddenly became 0. Kamerlingh Onnes named this state as 'superconductivity' [2].

Physically, 4.2K was called the critical temperature. After this finding, Kamerlingh Onnes went on doing experiments. First, he noticed that the resistance of mercury alloy disappeared in the same way as pure mercury. Then, what's even better is later, lead and tin were also found to be superconductors but with higher critical temperatures (6K and 4K). All those reduced the difficulties of superconductivity experiments. In 1914, he then made a lead coil and placed it under its critical temperature, wanting to produce magnetic fields as high as 10T. To his disappointment, after he passed current through the coil under critical temperature, when the magnetic field reached a certain value, the coil lost all the features of superconductivity. The experiment turned out that superconductivity requires not only a critical temperature, but also a critical magnetic field strength and a critical current passing through it (current density) [3].

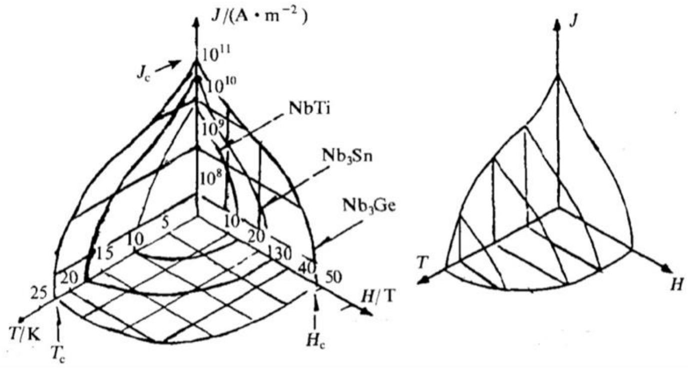

Fig. 1 T-H-J critical surface for materials turning into superconductivity state [3].

According to the graph shown in Fig. 1, J_c stands for current density, T stands for temperature, and H stands for magnetic field strength. Only the material within the shaded region, that is satisfying three conditions at the same time can it be a superconductor. From then on, pioneers in this region started a journey on exploring more useful superconductors and scientific theorems to explain behind this phenomenon.

2.2. The Phenomena of Superconductivity

Superconductivity features many properties, such as zero resistance and Meissner effect. The main feature of superconductivity that scientists firstly identified is zero resistance. According to this assumption, scientists designed an experiment to prove this. They placed a metal coil in a magnetic field and changed the temperature to make it a superconductor. After that, they removed the magnetic field. At this time, there will be an induced current in the coil, which satisfies the following equation $\mathrm{L}\frac{dI}{dt} = -\mathrm{IR}$. This will yield $\mathrm{I(t)} = \mathrm{I(0)}e^{-\frac{\mathrm{Rt}}{\mathrm{L}}}$, or equivalently,

$$\mathrm{R} = \ln\left(\frac{\mathrm{I(0)}}{\mathrm{I(t)}}\right) \cdot \frac{\mathrm{L}}{\mathrm{t}}. \quad (1)$$

Thus, if a resistance exists, it will be in an exponential decay. The smaller the resistance is, the slower the decrease of the current is. In one experiment carried in Great Britain, the current in the coil persisted for more than 2.5 years. So, there is enough evidence to prove that there is zero resistance in superconductors.

Perfect diamagnetism is another feature of superconductors which were found later than zero resistance by scientists. It is now used as one way of testing whether a material is a superconductor. The phrase "perfect diamagnetism" has two terms: perfect and diamagnetism.

In terms of diamagnetism, for general materials their diamagnetism is from the electrons' orbital effect. Their diamagnetism can be explained by Langevin theorem. Because electrons are charged, when an electron is moving in the orbit around the nucleus, according to Ampere's law:

$$\oint \vec{B}\, d\vec{l} = \mu_0 I_{encl}\,. \tag{2}$$

This will induce a magnetic field. Owing to electrons are always in pairs in a non-metal, and their moving directions are opposite (one clockwise and one anticlockwise), as a result, there is no resultant magnetic field. However, when there is an external magnetic field applied to the system, according to Lenz's law, both of electrons in the orbit will induce a magnetic field that opposes the change. So, the substance as a whole shows a diamagnetism [4].

In terms of perfect, it means that superconductors expel the magnetic fields inside itself completely. A perfect diamagnetism has another famous name, which is called the Meissner effect. The Meissner effect was found by Meissner in 1933, he found that when materials were below the critical temperature and became a superconductor, it would expel the magnetic fields inside itself. This is because when applying an external magnetic field to a superconductor, its surface will induce a current. The current will then induce a magnetic field opposite to the applied one. So, the superconductor becomes diamagnetic. Due to zero resistance, the induced current can be huge so that the induced magnetic field can offset the applied magnetic field perfectly. This let the magnetic field inside the conductor to be zero, and as a result, perfect diamagnetism forms [5]. This is an important feature people found on superconductors after zero resistance. After that, The Meissner effect is often used to test whether a material has superconductivity. To observe the Meissner effect, the most obvious way is the magnetic levitation phenomenon. The superconductor will float above the magnet. It is because when a magnet gets close to the superconductor. It will induce a current on the surface of superconductor. Then because of Lenz's law, the superconductor will induce a magnetic field opposing to the magnet downside. Human beings are trying to utilize this phenomenon on maglev trains.

2.3. BCS theorem

Since the characteristic of superconductivity was found, there had always been a lack in a theorem to explain what superconductivity is, and why it forms. In 1957, John Bardeen, Leon Cooper and John Schrieffer (BCS) stated their new theorem to explain the reason behind superconductivity and it is commonly accepted today [6]. They won the Nobel Prize in Physics 1972 because of this theorem, see Fig. 2.

They explained why electron can move freely and there is no resistance in the superconductors. Their assumption thought that in a structure of metal, the outer shell electrons of an atom is free to move. So, the structure of metal is like positive ions soaked in the sea of delocalized electrons. When adding a potential difference on sides of a metal. It is easy for it to accept electrons on the one side and remove electrons on the other. Thus, flow of charge forms a current in metal. But flow of electrons is not perfect in a metal. The nucleus in the metal is oscillating in the structure and they block electrons' way. So, electrons will collide with the nucleus lattice and let the lattice vibrate more violently. The increase in vibration is the reason of an increase in heat. That's way resistance causes heat loss. Although such vibration can be reduced by lowering the resistor's temperature, it cannot create a perfect flow of electrons of not colliding with nucleus lattice at all.

They introduced a new model, the Cooper pairs [7], to explain the mechanism for superconductivity. When an electron is moving in a crystal lattice, according to coulomb's law

$$F = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 q_2}{r^2}, \tag{3}$$

it will attract the metal nucleus among them, causing a crystal deformation. Then because nucleus is attracted to the deforming place, so this place will be relatively more positive. Thus, an electron which comes after that will be attracted to the deforming area. The two electrons during this process are called Cooper pairs. Through this model, electrons will not collide with crystal lattice so they will go through the superconductor with no energy loss.

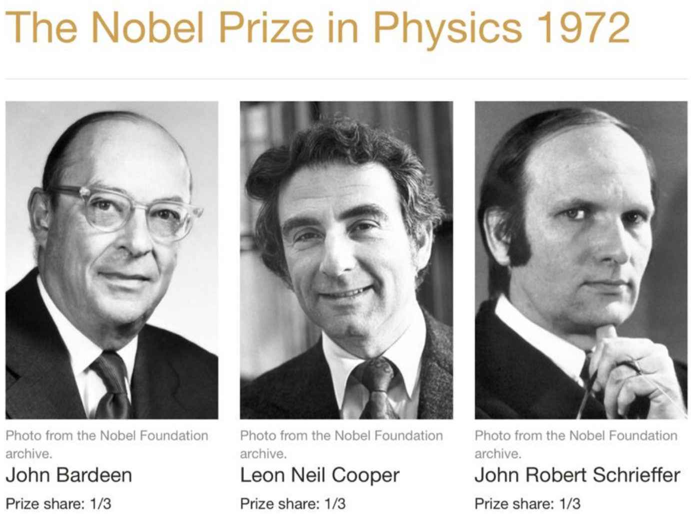

Fig. 2 John Bardeen, Leon Neil Cooper, and John Robert Schrieffer on the website of Nobel Prize holders.

3. Applications

Discovery on superconductivity has never stopped during the past 100 years. In contrast, continuous efforts and resources have been invested in the research, resulting in more or less progress in this field.

3.1. High-Temperature Superconductors

In previous BCS theorem, scientists stated that the formation of Cooper pairs has a close connection to vibration of lattice. As the temperature increases, the lattice vibrates more vigorously. As a result, cooper pairs will be broken. The temperature is around 39K according to experiments. So, scientists at that time predicted that superconductors cannot be formed above 39K [8]. This highest temperature predicted is called McMillan limit. Below were some feats in superconductivity history that were found that don't obey the BCS theorem.

The first class is the Copper-based superconductors. In 1986, two Swiss scientists Bednorz and Muller claimed that they found a new possible high Tc superconductivity in the Ba-La-Cu-O system [9]. Later, it was found to be true. What was more important was that Tc of new superconductor was around 93K and it was even higher than the temperature of liquid nitrogen. In the following few decades, dozens of types of copper oxide high-temperature superconductors were found by different countries, the highest Tc had already reached 134K. Disappointingly, copper oxide ceramic material is easy to layer. It is very weak, making it hard to be shaped to wires. Besides, its electric conductivity is different through different directions. So, in real life, it is nearly impossible to make all the crystal powder in a wire be in the same direction.

The second is the Iron-based superconductors. In 2008, a Japanese scientist declared that he found a new superconductor with Tc of 26K material occasionally. That is iron-based superconductors. This finding is surprising because iron that has a large magnetic moment was considered to prevent superconductivity from forming because the spin of electrons is resistive to the formation of cooper pairs [10]. In the newly found iron-based superconductor, although Tc is not so high, it even didn’t follow the same function as copper oxide ceramic material. It is the second kind of material scientists found that was above McMillan limit. letting scientists see new hope of the presence of room temperature superconductor. A few months later, iron-based superconductors’ Tc peaked at 57.3K. After that, no further increase was shown.

In addition, there are also recent study on superconductors. In 2023, a Korean team claimed that they found, for the first time in the world, a room-temperature superconductor with critical temperature greater than 400 K, they said that it was proved with critical current, critical temperature, critical magnetic field, zero resistivity and Meissner effect [11], but the truth are waited to be determined. According to their study, they heat a mixture of lead oxide and lead sulfate to produce pyrite. Heat the copper and phosphorus mixture again to produce cuprous phosphide. Finally, they were ground, mixed, and heated to obtain this superconducting material [12]. After that, many teams and colleges did duplicated experiments to test the truth. In the end, they draw the conclusion that LK99 isn’t a real superconductor. The reason they gave is because of the impurity of copper sulfite in the crystal. Korean team proved zero resistance because they observed that LK99’s resistance showed a dramatic decrease when temperature reached 104.5°C. While one chemist stated the unusual pattern in LK99 in 104.5°C is because it is the temperature of copper sulfite to change its phase. So, the sudden change in resistance has great connection to copper sulfite. And it is the main reason why LK99 showed a similar phenomenon as Meissner effect. Up to now, scientific circles thought that LK99 is not a real superconductor, it is just a coincidence [13].

3.2. Applications of Superconductivity in Daily Life

In people’s daily life, there has always been a great application field and potential economic effect of materials with superconductivity. It has always been a researching target and to scientists. Especially those with high critical temperatures.

For the major application, that might be the super-conducting generators. Because of zero heat loss, so when inputting current in superconductors, they can generate great magnetic field. Besides, there is no need of coolant, and the generators can work in high efficiency.

Besides generators, transferring of electricity in long distance is another usage of superconductors. When using superconductors to transfer electricity, there will be no energy loss along the way because of zero resistance. Enormous energy which is wasted now could be saved in the future. This can make great contribution to solving the pollution and energy depletion issue.

Moreover, when using superconductors to the transporting system, like the maglev trains, there will be very small resistance of force (only air resistance). Less or no work will be done against friction. In this way, energy will be saved. And transporting tools can be at higher efficiency and velocity [14].

Finally, superconductivity can help researchers in other fields a lot by providing conditions which cannot be achieved now. For example, the large magnetic field that superconductors provide is helpful to experiments using circular collider. For example, the CERN Future Circular Collider (FCC) is now concerning the realization of using Nb3Sn, a material shows superconductivity, to make magnets. It is now the best candidate material for the construction of high-field superconducting dipole magnets [15].

4. Conclusion

Superconductivity is a promising and important research direction for many field including physics and material science. This paper gives a basic knowledge and concept of superconductivity. It shows how people found superconductivity thought predictions and experiments. Furthermore, the paper describes attempts of people from different eras in history trying to explain this amazing phenomenon and their efforts in finding new high temperature superconductors. During this process, there were both successes and failures. There were outdated theorems which were proven to be incorrect, and also speculations that were not proven yet. No matter what the result is, these ideas and research results are worthy of respect and learning from. If room temperature superconductors are found one day in the future, with the help of them, people can do a lot of things which are impossible nowadays. From transporting to no-heat-loss electricity transmission, they can certainly improve people's lives. In conclusion, this paper is helpful for people to get a general knowledge of current status and progress of superconductivity research, and to have a concept about the bottleneck and possible future development of this technology.

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