A Review of the Fundamental Principles and Research Progress in Superconductors

Yunxin Song *

Shenzhen College of International Education, Shenzhen, China

* Corresponding Author Email: psmadeline1004@outlook.com

Abstract. Since the discovery of superconductors in 1911, their zero-resistance conductivity and perfect diamagnetism have significantly advanced science and technology. This paper reviews the key principles and parameters of superconductors, focusing on three critical values: critical temperature (Tc), critical magnetic field (Hc), and critical current density (Jc). Superconductors are categorized as low-temperature (LTS) or high-temperature (HTS) based on Tc, and as type I or type II based on magnetic flux penetration. Type I superconductors, such as aluminum, completely expel external magnetic fields, while type II superconductors, such as YBCO, allow partial flux penetration, enabling flux pinning and stable levitation. The Meissner effect is fundamental to superconductivity, with type I superconductors exhibiting only the perfect Meissner state and the normal state, whereas type II superconductors also feature a mixed state. Additionally, this paper discusses BCS theory, which explains Cooper pair formation in conventional superconductors but fails to fully describe high-temperature superconductors due to their strong coupling nature. Recent advancements, such as textured YBCO tapes with aligned grains, have significantly improved superconducting performance. Future breakthroughs will require exploring new mechanisms beyond existing theories to advance next-generation superconducting technologies.

Keywords: Superconductors, Meissner effect, BCS theory, superconductivity.

1. Introduction

The most well-known characteristic of superconductors is the abrupt loss of all electrical resistance when the material is cooled to a temperature below a certain temperature. In 1911, Heike Kamerlingh Onnes liquefied helium gas successfully and found that the liquefaction point of helium gas was 4.25k. Then he chose the metal Hg which is a metal that can be easily purified, to make an experiment about the change of resistivity of the Hg metal when the temperature was low and he detected an unexpected setback. When the temperature decreases, the resistivity of the metal decreases and the resistivity of Hg suddenly falls to nearly 0 which is smaller than $10^{-5}\Omega$ when the temperature is below 4.2k. So, for Hg, the superconducting transition occurs when the temperature is below 4.2k which means the metal Hg transitions from the normal phase to the superconducting phase when it is cooled below 4.2k. Since then, research on superconductivity has begun. The superconducting state, with its unique property of zero electrical resistance, not only challenges the boundaries of classical physics but also gives rise to interdisciplinary breakthroughs ranging from microscopic quantum theory to macroscopic engineering applications. Superconductivity has applications in many areas. The accelerators at CERN, DESY, Brookhaven, and Fermilab are made up of kilometers of superconducting bending and focusing magnets. Besides, the highly homogenous, persistent-mode superconducting magnets used in the development of magnetic resonance imaging (MRI), a medical technology that currently generates over $3 billion in revenue annually [1]. So far, superconductivity research has expanded from fundamental science to cutting-edge technological fields such as quantum computing, high-field magnets, and lossless power transmission. At the same time, the emergence of new systems like iron-based superconductors and topological superconductors continuously enriches the theoretical landscape.

2. Three critical values for superconductors

In the realm of superconductivity research, three fundamental parameters universally govern the operational boundaries and practical applicability of superconducting materials: critical temperature T_C, critical field H_C, and critical current density J_C. These intrinsic parameters are not only mutually interdependent but also collectively dictate the material's performance in technological implementations.

2.1. Critical temperature

There's an abrupt loss of all resistance when the material has been cooling under its critical temperature. Different superconductors have different critical temperatures. There are some low-temperature superconductors whose critical temperatures are generally below 30k such as Nb-Ti alloy (T_C =9k) and Nb_3Sn (T_C =18k). There are also some high-temperature superconductors whose critical temperatures are generally over 30k such as $YBa_2Cu_3O_x$ (YBCO) and $Hg_2Ba_2Ca_2Cu_3O_x$ [1]. The resistivity of YBCO is apparent at 93k and the resistivity drops suddenly at 92k. A state characterized by zero resistance is reached at 80k. These results unequivocally confirm that superconductivity is present in the Y-Ba-Cu-O system, with a transition range between 80k and 93k which is above the boiling point of liquid nitrogen (77k) [2]. So, people can cool the nitrogen rather than helium cooling, cause cooling with helium is often prohibitively costly. For the Hg-Ba-Ca-Cu-O (HBCCO) system, the resistance of $Hg_2Ba_2Ca_2Cu_3O_x$ R(T) experiences a rapid decline, showing a peak in the differential dR/dT at a temperature of 132.5k, and ultimately reaches zero at 95k [3].

2.2. Critical field

The critical field is the minimum magnitude of the magnetic field needed to eliminate superconductivity below Tc. Different superconductors have different values of critical field. Certain high-Tc compounds possess anisotropic layered structures, hence there is considerable anisotropy in the upper critical field. $H_{C2}^{\parallel}$ is H_C when the direction of the magnetic field is parallel to the main crystal structure. $H_{C2}^{\perp}$ is H_C when the direction of the magnetic field is perpendicular to the main crystal structure. The magnetic anisotropy parameter follows that

$$\eta = \frac{H_{C2}^{\parallel}(T)}{H_{C2}^{\perp}(T)} \tag{1}$$

When the magnetic anisotropy parameter is to quantify the degree of magnetic field directional anisotropy of materials. To be specific, η of Nb-Ti and Nb3Sn are 1, which means these compounds are isotropic. η of MgB_2, YBCO and Bi-2223 are respectively 2-3, 5-7, and 50-200, which means MgB_2 is weak anisotropic, YBCO is moderate anisotropic and Bi-2223 is strongly anisotropic [1]. Different types of superconductors have different kinds of critical fields. For type-I superconductors, there's only one critical field H_C. When the magnetic field strength exceeds H_C, the superconducting state disappears completely. For type-II superconductors, there are a first critical magnetic field, second critical magnetic field, and irreversibility field. Figure 1 shows the phase diagram of superconductors.

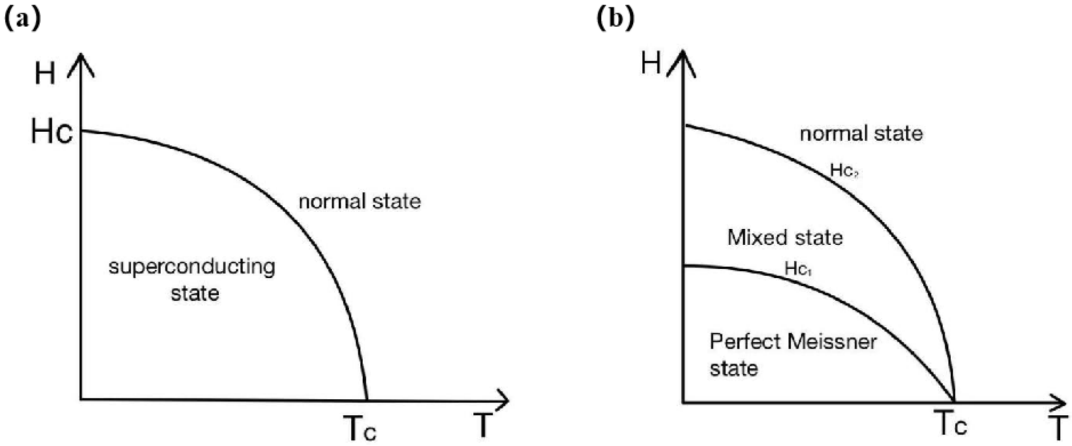

Figure 1. (a) Phase diagram of type-I superconductor (b) Phase diagram of type-II superconductor

Between $H^*(T)$ and $H_{c1}(T)$, magnetic flux starts to partially enter the superconductor as quantized flux vortices, so it is in a mixed state., which means flux lines are in a quantized form(each vortex carries a quantum of magnetic flux). Between $H_{c2}(T)$ and $H^*(T)$, although a superconducting state exists, current-carrying capability vanishes. And there's a complete disappearance of the superconducting state when the field strength exceeds $H_{c2}(T)$.

2.3. Critical current density

Since electric currents generate magnetic fields, when the current passing through a superconductor reaches a certain level, it can cause the superconductor reaches a certain level, it can cause the superconductor to lose its superconducting properties, which means there is a critical current density for superconductors. In practical application, the cross-sectional area of superconductors remains constant; therefore, for ease of reference, the critical current is generally utilized to indicate the critical current density in engineering scenarios [4]. Deformation-textured coated conductors generally have a higher J_C ,c because applying plastic deformation such as rolling or stretching to the material would align the grains or crystals within the material. Besides, coated conductor refers to a type of high-temperature superconducting (HTS) wire or tape engineered for practical power applications. It consists of multiple functional layers deposited on a flexible metallic substrate (e.g., stainless steel or nickel alloy). To be specific, the rolling-assisted biaxially textured substrate is based on Ni, with buffer layers arranged from bottom to top as CeO_2 or Y_2O_3, YSZ, and CeO_2, while the high-temperature superconductor functional layer is YBCO. The bottom CeO_2 or Y_2O_3 is used to improve the growth and texture of the subsequent layer, YSZ is used to improve the growth of YBCO, CeO_2 is used to improve the texture of YBCO, and YBCO is used to carry high critical currents [1].

3. Meissner effect

One important feature of superconductors is the Meissner effect. There are 3 states: Perfect Meissner State, mixed state, and normal state. Perfect Meissner state is defined as a thermodynamic state (which is, thus, reversible) where the magnetic induction B within the volume V of a substantial superconducting material (the sample) situated in a static magnetic field H0 becomes zero. Besides, the magnetic field strength B follows:

$$B = H + 4\pi M \quad (2)$$

because B should be 0, hence $M = \frac{-1}{4\pi} H$ and $\chi = M/H = -1/4\pi$. So, it can alternatively be defined as the superconducting state characterized by a spatially uniform magnetic susceptibility χ=-1/4 π persisting throughout the entire bulk specimen. A material is rigorously classified as a bulk superconductor when its principal dimensions in all three spatial axes exceed the so-called penetration depth λ which is a fundamental length scale in superconductivity that quantifies the exponential decay of an external magnetic field within a superconducting material [5]. The concept of penetration depth originates from the London equations. The field penetration follows:

$$B(x) = B_0 \cdot e^{-x/\lambda} \tag{3}$$

Where x is how deep it is from the surface, and the penetration depth λ follows:

$$\lambda = \sqrt{\frac{m}{\mu_0 n_s e^2}} \tag{4}$$

3.1. Type-I superconductors

For type-I superconductors, when $H < H_c$ and H_c is the thermodynamic critical field, put a uniform spherical sample of superconducting material in a steady magnetic field H at a temperature T above the critical temperature (T_c), the material exists in its normal state which is shown in Fig.3(a). However, as we reduce the temperature and reach the critical point, the material transitions into the superconducting state. Experimental verification of the magnetic field surrounding the sphere indicates that the field lines exhibit deformation, as illustrated in Fig.3(b). Inside the material itself, there is essentially no magnetic field, except possibly in a very narrow surface layer that is around a hundred atoms thick. So, the material is in Perfect Meissner State. When a coil is placed around the sphere, the induced electromotive force (emf) in the coil demonstrates that a superconducting state is being formed, and the magnetic flux through the coil significantly decreases from its original value to zero [6]. This observation aligns with the fact that the interior of the material exhibits no magnetic field. Materials such as aluminum (Al) and lead (Pb) demonstrate these behaviors in low-temperature, weak-magnetic-field environments. Type-I superconducting cavities made of lead (Pb) or tin (Sn) can shield external magnetic field interference when the external field is below the critical field H_c. This can be used in particle physics experiments, such as providing a magnetic field-free environment for low-energy electron beams to reduce trajectory deflection caused by Lorentz force. The Meissner effect of Type-I superconductors still holds unique value in precision magnetic shielding, low-temperature microwave devices, and fundamental physics research, but its low critical magnetic field limits large-scale engineering applications.

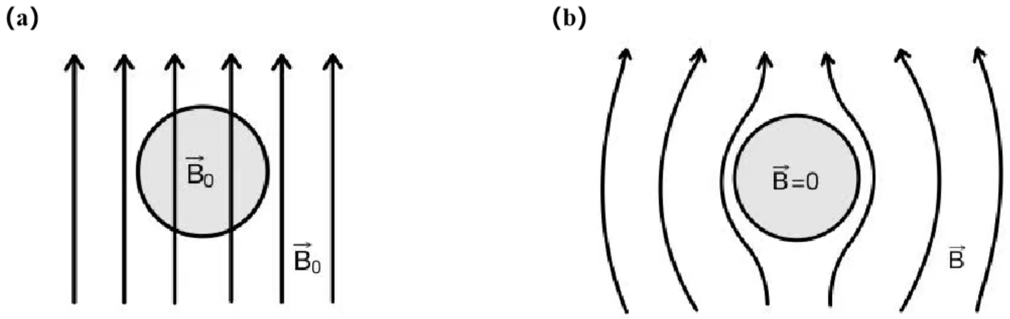

Figure 2. (a) Superconducting material in an external magnetic field $\vec{B_0}$ when $T > T_C$. (b) The temperature is lower than T_C

3.2. Type-II superconductors

For the type-II superconductor, when $H < H_{c1}$ the material is in a Perfect Meissner state, the magnetic flux pass-through is completely expelled from the material, and the field inside the material is zero. When $H_{c1} < H < H_{c2}$ the material turns into a mixed state, magnetic flux partially penetrates the material [7]. If we place a superconducting block under this condition such as YBCO on a permanent magnet and cool it with liquid nitrogen, this superconducting block will achieve levitation. That's because when it is in the superconducting state, superconducting current will be continuously induced on the surface of the YBCO block, and the magnetic field induced by the superconducting current is opposite to the external magnetic field of the permanent magnet, which will expel the magnetic field from the YBCO block and generate a repulsive force. This repulsive force can cancel out the weight of the superconductor, causing it to levitate. Besides, the magnetic flux partially penetrates the superconductor as quantized flux vortices, but these magnetic flux lines can be pinned by defects or lattice inhomogeneities within the material, which prevent magnetic flux lines from moving in the material. Then, the magnetic field of the permanent magnet interacts with the pinned magnetic flux lines, creating a "locking" effect. Even when the superconductor experiences slight disturbances, the pinning force pulls it back to its original position, enabling stable self-stabilized levitation. This principle is applied in superconducting maglev trains such as Japan's JR-Maglev which utilizes strong magnetic fields generated by superconducting magnets to achieve both levitation and propulsion of the train, reaching speeds of up to 600 km/h, frictionless bearings for energy transmission systems which reduce energy loss and improve efficiency in wind turbines or flywheel energy storage systems.

4. BCS theory

For a long time, the phenomenon of low-temperature superconductivity has remained perplexing and challenging to comprehend. It is actually a macroscopic quantum phenomenon, and a proper microscopic explanation can only be derived from quantum mechanics. The BCS theory (Bardeen-Cooper-Schrieffer theory) is the microscopic theory that explains the superconductivity of conventional superconductors. This theory bears the names of its creators, John Robert Schrieffer, Leon Cooper, and John Bardeen. The BCS theory is based on the nearly free electron model and is established under the premise of weak electron-phonon interactions (weak coupling) [8].

4.1. Explanation

When the conductor is in the normal state, apply voltage to the conductor and the electrons start to move in a directed manner. The electrons collide with photons which are generated by the vibration of the crystal lattice, so the direction of electron movement is deflected and electrons transfer energy to the lattice. This phenomenon is called photon scattering and that is why there is resistance in the conductor. At low temperatures, the lattice is almost not vibrating, but when an electron moves through a crystal lattice, it attracts a nearby positively charged atom core, causing a local lattice distortion (the atom core vibrates). This distortion propagates as a photon which is a quantized energy packet of lattice waves (atom cores in a crystal oscillate around their equilibrium positions) and is a quasiparticle. And it creates a transient region of positive charge. This positive area attracts a second electron, effectively mediating an attractive interaction which is a phonon-mediated attraction between the two electrons. This attraction overcame the original coulomb repulsion. So, electrons are exchanging phonons, forming a cooper pair. The BCS theory asserts that Cooper pairing is strictly restricted to electrons with equal and opposite momenta (k and -k) and opposite spins, which are spin singlet (total spin S=0), while pairings under alternative momentum configurations are deemed negligible [9]. Under this condition, the energy of the pair is minimized, which stabilizes the pair. So, the charge carrier of the superconductor is the Cooper pair which means the vibration of the lattice is already contained in the Cooper pair. Hence, the Cooper pairs flow without scattering and that's why the conductor in a superconducting state has zero electrical resistance. BCS theory indicates the electronic-phonon coupling and the formation mechanism of Cooper pairs and provides key theoretical support for the practical application of superconducting technology.

4.2. Applications

For MRI, BCS theory predicts the critical temperature (T_c) and critical field (H_c) of the low-temperature superconductors (LTS), guiding the better design of superconducting magnets in Magnetic Resonance Imaging (MRI). For example, the 1.5 T MRI magnet uses NbTi wire(T_c≈9k) to achieve zero-resistance operation under liquid helium cooling which ensures the uniformity and stability of the magnetic field. For particle accelerators, the accelerator of CERN: LHC uses the NbTi superconducting magnet based on BCS theory. This magnet generates a strong magnetic field of 8.3T at 1.9K to confine high-energy particle beams. For superconductor cables, BCS theory guided the improvement in current carrying capacity of the low-temperature superconductors (LTS) such as MgB_2 The LIPA project in the United States utilized liquid hydrogen-cooled MgB_2 cables, achieving $J_c \geq 10^5$ A/cm² at 20 K and reducing power transmission losses by 90%.

5. Limits

BCS is only proper in explaining the principle of LTS which is a perturbative system (weakly coupled), but for HTS which is a non-perturbative system (strongly coupled), perturbative expansion is not proper for it. Later studies analyzed the phonon characteristics of different materials and formulated the strong coupling theory, enhancing the original BCS framework. Yet, breakthroughs in copper-based and HTS based on iron revealed limitations in the BCS model's description of electron-phonon interactions. The origins of HTS continue to be an active area of research [7]. So far, in addition to the electron-phonon mechanism, various other mechanisms have been proposed, such as the exciton mechanism involving various exchange interactions, the bipolaron model, the resonating valence bond (RVB) mechanism, and the electron-negative P center model, among others. However, the RVB model, represented by Anderson, which emphasizes non-phonon effects, is particularly popular and influential. These theoretical models are able to explain certain experimental phenomena and possess a degree of rationality. However, when applied to explain specific superconductors, they encounter numerous difficulties. Currently, there is no single theory that successfully clarifies the mechanisms of high-temperature superconductivity that have been discovered [8]. Besides, there are also some limits on applications of superconductors. For instance, current copper-oxide superconductors (e.g., Bi-2223) have critical temperatures (T_c) of up to 135 K, while iron-based superconductors $SmFeAsO_{1-x}F_x$ have T_c values around 55 K. However, these critical temperatures are still far below the temperature for room-temperature superconductors (>300 K), which indicates a substantial gap in practical material performance. Although the materials that have critical temperatures above the liquid nitrogen temperature range have been developed, these materials ‘complex lattice structure leads to inadequate flux pinning ability. This inadequate flux pinning ability significantly restricts the materials’ current-carrying capacity in high magnetic field environments. Right now, superconductivity technology is at a critical stage, moving from lab research to industrial use. To overcome the challenges mentioned above, experts in materials science, physics, and electrical engineering must work together.

6. Conclusion

Superconductivity, marked by zero electrical resistance and the Meissner effect (the expulsion of magnetic fields), is a revolutionary phenomenon in physics. This paper highlights three key properties of superconductors: critical temperature (T_c), critical magnetic field (H_c), and critical current density (J_c). The Meissner effect manifests distinctly in Type-I superconductors, which completely expel magnetic fields below H_c, and Type-II superconductors, where partial flux penetration enables stable levitation—used in technologies like maglev trains. The BCS theory explains Cooper pair formation via weak electron-phonon interactions in conventional superconductors but struggles with high-temperature superconductors requiring stronger coupling models. Practical applications, from MRI machines to energy-efficient grids, rely on the Meissner effect and flux pinning. By connecting quantum behaviors like magnetic flux expulsion to real-world innovations, this work paves the way for advanced superconducting materials and technologies.

References

[1] Larbalestier D, Gurevich A, Feldmann D M, et al. High-T c superconducting materials for electric power applications [J]. Nature, 2001, 414 (6861): 368 - 377.

[2] Wu M K, Ashburn J R, Torng C J, et al. Superconductivity at 93 K in a new mixed-phase Y-Ba-Cu-O compound system at ambient pressure [J]. Physical review letters, 1987, 58 (9): 908.

[3] Schilling A, Cantoni M, Guo J D, et al. Superconductivity above 130 k in the hg–ba–ca–cu–o system[J]. Nature, 1993, 363 (6424): 56 - 58.

[4] Yusheng Zhou. Basal Research on Electromagnetic Characteristics of High-Temperature Superconductor Applied in Pulsed Power [D]. Wuhan: Huazhong University of Science & Technology, 2006.

[5] Kozhevnikov V. Meissner effect: History of development and novel aspects [J]. Journal of Superconductivity and Novel Magnetism, 2021, 34 (8): 1979 - 2009.

[6] Young H D, Freedman R A, Sandin T R, et al. University physics [M]. Reading, MA: Addison-Wesley, 1996.

[7] Jifeng Shao. Study of Superconductivity and Structure of Bismuth-Chalcogenide [D]. University of Science and Technology of China, 2016.

[8] Lijing Qi, Yan Zhang, Xiande Wang. Studies on the Superconducting Material [J]. Jilin Institute of Chemical Technology, 2014, 31 (07): 72 - 74. DOI: 10.16039/j.cnki.cn22-1249.2014.07.003.

[9] Qiang Zhang. Superfluidity and pairing phenomena ultra-cold atomic Fermi gases in mixed dimensions with population imbalance [D]. Zhejiang University, 2020.DOI: 10.27461/d.cnki.gzjdx.2020.001784.