EXPLORING THE RECENT ADVANCEMENT OF HIGH TEMPERATURE SUPERCONDUCTORS

V. S. Rawat and *S.V. Sharma

Regional Institute of Education, Ajmer (Rajasthan) India
***Author for Correspondence: e-mail**: svsriea@yahoo.co.in

ABSTRACT

High temperature superconductors have become an astonishing industrial focus due to their extraordinary applications in different fields such as healthcare, energy, computing, and transportation. Conventional superconductors have been found to have limited applicability due to their low transition temperature. The discovery of high temperature superconductors has augmented their potential applications and opened one of the most exciting fields of research to revolutionise science, medical science and technology. Hence, it is very much necessary to understand the mechanisms/theories, challenges and the basic principles accounted for the phenomenon of superconductivity in high temperature superconductors and their numerous functional aspects of applications in everyday settings of life. Present review study attempted to explore plausible choice of mechanisms/theories responsible for occurrence of superconductivity in high temperature superconductors and understanding the challenges of high temperature superconductors. Also attempts have been made to find possible explanation of variation of superconducting properties of high temperature superconductors in terms of Bardeen-Cooper-Schrieffer Theory, Spin Fluctuation Theory, Resonating Valence Bond Theory, Fermi Surface Theory, Charge Density Wave Theory and Electron Phase Connection Theory. It is revealed by the study that despite of innumerable researches, none of the mechanisms/theories provide full fledged explanation of the superconducting phenomenon in high temperature superconductors.

Keywords: *High Temperature Superconductors, Spin Fluctuation, RVB Theory, Fermi Surface Theory, Charge Density Wave Theory and Electron Phase Connection Theory.*

1. INTRODUCTION

Superconductors are amazing materials characterized by zero electrical resistance and expulsion of magnetic fields below a critical transition temperature (T_c) [1, 2]. Superconducting materials have been categorized into two primary types namely, Type I (conventional superconductors) and Type II (high temperature superconductors). It has been reported that Type II superconductors normally exhibit higher critical transition temperatures as compared to Type I superconductors [1-10]. However, both types of superconductors still require cryogenic cooling conditions. Numerous efforts have been made to achieve a milestone for developing room-temperature superconductors [9, 10]. Researches in this field have led to noteworthy progress in understanding and manipulating the properties of the superconductors [1-44]. Advancement in the transition temperature has been essential for enabling superconductivity phenomenon greatly to broaden the practical applications of these materials. Efforts to raise transition temperature have enabled applications of superconducting materials in areas such as energy storage, power transmission, and high-performance magnets [12, 13, 19, 21]. The discovery of high-temperature superconductors (HTS) has marked a turning point in superconducting research [3-44], broadening the potential for applications. Superconducting materials, while still requiring significant low cooling temperature, offer higher operational temperatures, bringing them closer to practical, large-scale uses. However, further advancements are necessary to overcome such limitations and high maintenance costs associated with the cryogenic environments for significant low cooling. Bednorz and Müller discovered superconductivity in lanthanum barium copper oxide (LBCO) which had a transition temperature (T_c) of 35 K [3]. Superconductivity has been discovered in the YBaCuO system with a T_c onset of 93 K [4]. Many more families of compounds have since been discovered, with even higher T_c values [3-44]. Superconductivity has been discovered in the system BiSrCaCuO, with the Tc onset of 120 K [5, 6]. Onset transition temperature of ∼125 K has been reported in The TlBaCaCuO system [7]. Schilling et al, [8] have reported the T_c equal to 135 K in the HgBaCaCuO system at ambient pressure and ∼160 K under high pressure. Recently, the material with the transition temperature as high as approximately 250 K has been reported in highly pressurized lanthanum decahydride at 200 GPa [9, 10]. Neil Ashcroft has predicted in his theoretical research work that solid metallic hydrogen at extremely high pressure (~500 GPa) should become superconducting at approximately room temperature [11]. A room-temperature superconductor is defined as a material which is capable of displaying superconductivity a room temperature i.e. operating temperature encounters in everyday settings of life. Present study attempted to explore recent advancement of high temperature superconductors in terms of a variety of applications of superconductors and mechanisms/theories responsible for occurrence of superconductivity in high temperature superconductors. Also the study attempted to review different explanations of variation of superconducting properties of high temperature superconductors in terms of Bardeen-Cooper-Schrieffer (BCS) Theory, Spin Fluctuation (SF) Theory, Resonating Valence Bond (RVB) Theory, Fermi Surface (FS) Theory, Charge Density Wave (CDW) Theory and Electron Phase Connection (EPC) including understanding the challenges of high temperature superconductors.

2. SIGNIFICANCE OF HIGH TEMPERATURE SUPERCONDUCTORS

Despite being a physical phenomenon, superconductivity has a wide range of potential to utilize it in energy transfer as well as magnet-based technology [12, 13]. Its unique characteristics-perfect diamagnetism and zero electrical resistance allow for magnetic levitation applications like maglev trains as well as effective, lossless energy transfer [12, 13, 19, 21]. However, wider use is restricted by the need for low working temperatures, underscoring the significance of high-temperature superconducting materials research for extensive functional applications. Superconductors' zero-resistance characteristic enables energy-efficient transmission, promoting energy conservation and environmental sustainability [12-21]. Additionally, applications in particle accelerators, quantum computing, and magnetic resonance imaging (MRI) technologies depend on the large current capacity and steady magnetic fields of superconductors [12].

3. MECHANIMS/THEORIES

It is well known to us that a theoretical understanding of superconductivity phenomenon for low transition temperature superconductors (conventional superconductors) has been presented on the basis of BCS theory. Following mechanism/theories have been discussed as a framework for understanding the superconducting phenomenon in high temperature superconductors [18-21]:

3.1 Bardeen-Cooper-Schrieffer Theory (BCS Theory)

The BCS theory was proposed by three physicists, namely Bardeen, Cooper, and Schrieffer, in the year 1957. Their theory was one of the most successful theories in the domain of the conventional superconductor. According to their theory, whenever electrons entering upon a material during the interaction with phonons to form Copper pairs, allowing for movement without energy loss in the superconducting state and transient increasing the cation density due to movement of electrons. The Pauli Exclusion Principle is governed by the electrons, as fermions which prohibits identical quantum behavior for two electrons. Though, Cooper pairs, consisting of electrons not only opposite spins but also momentum, characteristics such as bosons, enabling them to gain the least energy state and trend to least the system's energy. The stability of Cooper pairs is temperature-sensitive, high temperature scan disrupt them, limiting conventional superconductors to extremely low temperatures [22, 23]. Temperature sensitivity is responsible for the stability of Copper pairs, at the elevate temperature can interrupt them, minimizing the traditional superconductors to extremely lower values of temperature. Although the BCS principle works well for typical superconductors, it has trouble with high-temperature superconductors, particularly in the cuprates. At temperatures over their critical point, cuprates demonstrate the pseudo gap phenomena, which cannot be explained by BCS theory, and exhibit d-wave symmetry, which is in contradiction to the s-wave symmetry predicted by BCS. Additionally, the applicability of BCS theory is challenged by the strong electron-electron interactions and doping-dependent characteristics of cuprate superconductors [22, 23]. These drawbacks imply that in order to provide a thorough explanation of high-temperature superconductors, new theories/mechanisms to existing ones are required. Nevertheless, its merits, the inadequacies of BCS theory in explaining the properties of high-temperature superconductors such as the pseudo gap and the d-wave symmetry in cuprates highlights the need for more comprehensive theoretical frameworks/mechanisms [13,18-25].

3.2 Spin Fluctuation (SF) Theory

Antiferromagnetic interactions in copper-oxygen planes are the focus of spin fluctuation (SF) theory, which postulates that electron spin fluctuations are the source of superconducting pairing. Its importance is confirmed by the fact that it was developed to explain superconductivity in cuprates under strong electron-electron interactions and antiferromagnetic correlations. It suggests d-wave or odd-parity p-wave pairing, which is consistent with experimental results in cuprates [24-26]. The mechanism of cuprate superconductors differs significantly from that of conventional superconductors. Strong electron interaction is essential to cuprates. In cuprates close to the antiferromagnetic phase transition, electron spins vary greatly, in contrast to normal electron repulsion that prevents pairing. These variations provide an effective attraction that permits the production of Cooper pairs, deviating from the phonon-mediated mechanism proposed by BCS theory. The intricate interaction of these variables in cuprate superconductivity is depicted in the figure, which shows the relationship between frequency fluctuations, momentum diffusion, and transition temperature. Lower transition temperatures are seen with decreasing momentum diffusion or frequency fluctuations [27]. Though several elements of the microscopic mechanics of cuprate superconductors are still unclear, SF or SCR theory offers significant insights. It is anticipated that continued theoretical and experimental researches will deepen our understanding about new superconducting materials, their uses and technologies [13, 18, 26].

3.3 Resonating Valence Bond (RVB) Theory

Strong electron interactions in undoped materials produce a Mott insulating state with anti-ferromagnetic characteristics and non-conductivity in the Resonating Valence Bond theory proposed by P W Anderson. The RVB (Resonating Valence Bond) hypothesis offers a fresh viewpoint on high temperature superconductors. Anti-ferromagnetic order is broken by doping; either with electrons or holes, the material becomes superconducting instead of insulating. The conducting state of a material can be altered by doping-induced changes in electron interactions. According to this idea, electron pairs resonate or "jump" in a unique electron pairing mechanism in contrast to the Cooper pairing in BCS theory. Intense electron correlation and anti-ferromagnetic interaction give birth to RVB pairing, which creates a fluid, unconventional superconducting state with distinctive characteristics associated with superconducting phenomena. In contrast to the s-wave pairing found in conventional superconductors. Additionally, it discusses the energy phenomena known as the pseudo gap. Typical electronic states above the superconducting phase transition have been the result of significant electron correlation and non-local pairing, which are consistent with RVB's hypothesis [13, 18, 27].

3.4 Fermi Surface Theory

Fermi surface theory postulates that the reconstruction of electronic states close to the Hermitian surface is the source of superconductivity. Understanding the doping effects in high-temperature superconductors requires an understanding of Fermi surface theory in respect of either promoting or impeding electron pairing by changing the electrical structure and consequently the Fermi surface. A vital factor is the electronic density of states in context to pair production which is aided by a high density close to the Fermi level and hindered by a low density. High temperature superconductors such as YBaCuO have varying characteristics upon doping, which cannot be fully explained by the BCS theory. However, by taking into account the effects of doping on the Fermi surface and electronic structure, Fermi surface theory may be able to explain such variations. High-temperature superconductors usually display d-wave pairing. The idea of building a nest on this pairing is clarified by the Fermi surface. Therefore, studying the Fermi surface is crucial to understanding the processes of high-temperature superconductors. This kind of exploration is necessary to improve our understanding of the complex behaviors and characteristics of high-temperature superconductors [13, 18, 28].

3.5 Charge Density Wave Theory

Superconductivity in high temperature superconductors is associated with charge density waves in the cupro-oxide planes, which are symbolized by stripes theory [29] among other things. The features of some superconductors are explained by the Charge Density Wave (CDW) hypothesis, which postulates that periodic fluctuations in charge density are caused by lattice vibrations in materials. These modulations, which occasionally align with copper links to create patterns like stripes, show how lattice structure and charge distribution interact dynamically, providing insight into the intricate behaviors of superconductors. In certain instances, superconductivity may be inhibited by situations favourable to CDW production, resulting in CDWs developing between electrons rather than Cooper pairs. Nonetheless, superconductivity and CDWs can coexist potentially resulting in new phenomena. The recurring structure of CDWs may even help Cooper in these situations establishment of pairs. Researchers can alter the characteristics of superconductors by adjusting CDWs, highlighting the interaction between CDWs and superconductivity. This hypothesis is unable to explain behaviors of all superconductors [13, 18, 30].

3.6 Electron Phase Connection Theory

The superconducting phase is one of the ordered phases, beginning with the overall interaction of the electronic system. In solid-state physics, considering superconductivity as an ordered phase provides a deep viewpoint. In this context, an ordered state denotes a substance's high antiparticle correlations, which produce unique features, especially with regard to magnetic fields. This order is demonstrated by superconductivity, which allows electricity to flow without resistance due to the coherent behavior of electron pairs, also known as Cooper pairs. Our understanding of superconductivity's basic principles is strengthened by this perspective, which emphasizes how collective and interrelated particle behavior is. Ferromagnetic, antiferromagnetic, superconducting, Charge Density Wave (CDW), and Bose-Einstein Condensate (BEC) phases are among the ordered states known to exist in superconductors. In antiferromagnetism, which is essential to the spin fluctuation model, neighboring electrons have opposing spins, whereas in ferromagnetism, electrons align their spins in the same direction. Comprehension of superconductivity in high temperature requires knowledge of the superconducting phase, which is defined by cohesive electron interactions that create Cooper pairs. Periodic changes in a material's electron density are a key component of the charge density wave theory's CDW phase. At ultra-low temperatures, bosonic particles collectively inhabit the lowest energy state in the Bose-Einstein condensate (BEC) phase. Each of these phases adds to our understanding of the distinct characteristics and behaviors of superconducting and related materials, highlighting the complex nature of order in these materials [13,18, 31].

4. CHALLANGES IN HIGH TEMERTAURE SUPERCONDUCTORS

Since the discovery of superconductivity, several mechanisms/theoretical models have been proposed to explain superconducting properties of high temperature superconductors. Researchers have highlighted that understanding the formation of pseudo gaps, figuring out the microscopic causes and making precise transition temperature predictions are concerns and issues which are need to be investigated meticulously [20-22, 24-27, 31- 44]. These open questions emphasize the breadth and complexity of the study of high-temperature superconductors and the necessity for more focused researches. Our grasp of these extraordinary superconducting materials is being advanced by ongoing research that attempts to answer these open questions. An electron gap on the Fermi surface that appears above the transition temperature and indicates a shift in the electron state prior to the onset of superconductivity is known as the pseudo gap, and it is a prominent feature of high-temperature superconductors. According to Navindar's research, the pseudo gap phase vanishes at specific critical doping concentrations, which correspond to cuprate superconductor peak transition temperatures [32]. One of the main unanswered questions about high-temperature superconductors is their full-fledged mechanism/theory. Although Cooper pairs are essential for these materials' electron interactions, the precise mechanism of their formation is up for discussion. In contrast to conventional superconductors, which are dominated by electron-phonon interactions, there is no agreement on the creation of Cooper pairs in high-temperature superconductors. Although theories such as self-selected fluctuation and strong electron correlation have been proposed, none offer a comprehensive description of every superconductor property and phenomenon. Furthermore, different Understanding these materials is made more difficult by the anticipated distinct processes that result from the architectures seen in several high-temperature superconductors. Another major challenge is predicting the superconductor's transition temperature. Accurate temperature prediction is hampered by the incompleteness of the numerous theoretical models for high-temperature superconductors. Fermi surface theory, for instance, helps evaluate spatial relationships for Cooper pair production, but other relevant parameters must be taken into account for a thorough prediction of transition temperatures. This calls for combining many analytical models, a difficult undertaking as a result of these ideas' contradictions. The difficulty in taking into consideration the many factors that affect transition temperature highlights the need for more cohesive and thorough theories in the study of superconductivity [13, 18, 38].

5. APPLICATION OF HIGH TEMERTAURE SUPERCONDUCTORS

The exploitation of high temperature superconducting materials is made more feasible particularly in the context of applications that are technical and industrial in nature. Some of the most important applications [12, 13, 19-21, 39, 40, 42-44] are discussed below:

5.1. Magnets
Compared to conventional electromagnets, high temperature superconductors require less cooling and improve energy efficiency, current capacity, and magnetic field strength, revolutionizing magnet technology. Particle accelerators, magnetic resonance imaging (MRI) scanners, and Maglev trains are some of the applications that can benefit from the capacity of superconductors to sustain high magnetic fields without the need for constant energy input [12, 19-21].

5.2. Electrical equipment
Because of enhanced stability and capacity to transport energy, high temperature superconducting wires exhibit a high level of value in power systems, microwave filters and analog-to-digital converters. High temperature superconducting cables provide a safer, space-efficient option for energy transfer. Filters and converters of high temperature superconducting materials with lower energy losses and better accuracy are especially beneficial for sectors demanding little interference and high signal fidelity [12, 19-21].

5.3. Quantum mechanics
Superconductors play a significant role in quantum computers and communication. They allow improved data encryption and provide marvelous processing capacity through qubits. In particular, superconductors promote precise quantum data transmission and storage due to their function in high-precision detectors and quantum repeaters [17-21, 41].

5.4. Motor development
HTS motors are developing as efficient alternatives to conventional motors, notably in synchronous motor designs. The zero-resistance function decreases heat production, boosting motor efficiency. However, in order to sustain low temperatures, these motors need dependable cooling [12,13, 19].

6. ISSUES OF HIGH TEMPERATURE SUPERCONDUCTORS
High temperature superconductors encounter hurdles in theoretical comprehension and practical implementation. Issues include the requirement for cryo cooling, material brittleness and maintenance needs which obstruct their usage for commercial applications. Inadequacies in existing mechanisms/theories further obstruct the understanding of superconductivity in high temperature superconductors. Future researchers are required to pay their synergetic efforts to build superconducting devices capable of working under normal situation, thereby cutting prices and broadening their uses. Improved manufacturing processes might make high temperature superconducting technology accessible for bigger applications to completely transform a variety of industries, including computers, transportation, healthcare, energy, communications, quantum computing, and sensing technologies [12, 17-21].

7. CONCLUSION
Since inception of superconductors, the journey began with conventional superconductors, evolved to cuprate high temperature superconductors, and then to non-copper oxide superconductors. With each new superconducting material discovered, understanding of superconductivity has been deepened. Superconductivity has the potential to transform fully from a merely scientific curiosity to technical significance into a variety of industries, including computers, transportation, healthcare, and energy. Conventional superconductors, described by the BCS theory, have built a firm foundation for applications needing minimum resistance and large magnetic fields. However, the discovery of high temperature superconductors has increased the possible uses of this technology and challenged established theoretical frameworks. Today, superconductors are important for emerging industries like quantum computing and improved medical imaging, while the practical implementation of superconducting power systems promises to transform our energy infrastructure with a few limitations. High-temperature superconductors need costly cooling systems and are brittle, limiting their wide range of applications. Theoretical approaches, including BCS theory, electron-phonon interactions, and magnetic causes, give partial explanations but are unsatisfactory in addressing the entire spectrum of observed phenomenon of superconductivity and associated properties, especially in unconventional superconducting materials. However, as the field of superconductivity expands, new phenomenon such as pseudo gaps has been observed, challenging conventional theoretical frameworks. It is, therefore, necessary to put further concentrated efforts and carry out multidisciplinary collaborative researches for

further building sound understanding the high temperature superconductors and applying their full potential in science, medical science and technology for betterment of life leading to the better real world.

ACKNOWLEDGEMENTS

This study is dedicated to indelible memory of two giant scholars Late Professor B.N. Mishra, University of Allahabad, Allahabad and Late Professor R.J. Singh, Aligarh Muslim University, Aligarh for their expertise, proper guidance and unflagging support which acted as stimuli for me (SVS) to conduct research in the field of high temperature superconductivity. I (SVS) feel indebted to both of them for the opportunity to work in their unforgettable company for several years.

REFERENCES

[1] Onnes H Kamerlingh (1911) Akad, Van Wetenschappen (Amsterdam) 14, 112, 616.
[2] Meissner W and Ochsenfeld R (1933) "Ein neuer Effekt bei Eintritt der Supraleitfähigkeit", Naturwissenschaften, 21 (44):787788(doi:10.1007/BF01504252. S2CID 37842752).
[3] Bednorz J G and Muller KA (1986) Z. Phys. 189, 94.
[4] Wu M K et al (1987) Phys. Rev. Lett. 90, 908.
[5] H. Maeda, et al (1988) Jpn. J. Appl. Phys. Lett. 27, L209.
[6] R.G. Buckley et al (1988) Physica C 156, (4) 629-634.
[7] Sheng and Hermann (1988) Nature, 332, 55-58.
[8] Schelling, et al, (1993) Nature 303, 50.
[9] Somayazulu M et at "Evidence for Superconductivity above 260 K in Lanthanum Super hydride at Megabar Pressures" (2019) Phys. Rev. Lett. 122 (2):027001 (doi:10.1103/PhysRevLett.122.027001)
[10] Drozdov et al (2019) Nature 569, 528-531.
[11] Ashcroft N W (1968) "Metallic Hydrogen: A High-Temperature Superconductor?" Physical Review Letters. 21 (26) 1748–1749 (doi:10.1103/PhysRevLett.21.1748).
[12] Sharma R G, Superconductivity: Basics and Applications to Magnets, Springer Series in Material Science (2015)14, 1-427.
[13] Sharma S V (2015) High Temperature Oxide Superconductors, Laxmi Prakashan, First Edition (ISBN: 878-818524-88-8).
[14] Sharma S V (1993) J. Material Science Letters 12, 137-141.
[15] Sharma S V (1995) Ind. J. Cryogenics 20, 21-28.
[16] Sharma S V (2012) Bulletin of Pure & Applied Sciences (Physics), 31D-1, 51-58.
[17] Sheng Z Z and Herman A M (1988) Phys. Rev. Lett. 60, 937.
[18] Heqi Wu, Proceedings of the 4th International Conference on Materials Chemistry and Environmental Engineering, 153-171, DOI: 10.54254/2755-2721/63/20241015
[19] Sharma S V (2024) International Journal of Advance Research and Innovative Ideas in Education 10 (5) 1882-1886 e-ISSN: 2395-4396.
[20] Sharma S V (2024) International Journal of Science and Research 13(10), 531-533.
[21] Singh V S and Sharma S V (2024) International Journal of Science and Research 13(10), 1758-1760.
[22] Bardeen J et al (1957), Theory of superconductivity, 108 American Physical Society 1175
[23] Dzhumanov S and Ulan S (2023) The validity of the BCS-like theory of Fermi-liquid superconductivity in over doped cuprates, International Journal of Modern Physics B. 38. 10.1142/S0217979224501406.
[24] Keimer B et al (2015), Nature 518, 179.
[25] Singh N (2021), Leading theories of the cuprate superconductivity: A Critique, 580 Physica C: Superconductivity and its Applications 1353782
[26] Moriya T and Ueda k (2000), Spin fluctuations and high temperature superconductivity, 49 Advances in Physics 555-606
[27] Kivelson S. A. et al (1987). Topology of the resonating valence-bond state: Solitons and high-Tc superconductivity. Physical Review B, 35(16), 8865-8868
[28] Orenstein J and Millis A J 2000, Advances in the Physics of High-Temperature Superconductivity, 288 Science 468-474
[29] Zaanen J (1988), Proceedings ACS conference, Crete, Greece, arXiv:cond-mat/9811078 https://doi.org/10.48550/arXiv.cond-mat/9811078
[30] D. J. Scalapino et al, 1986 Scalapino D.J., et al (1986), d-wave pairing near a spin density-wave instability, 34 Physics Review B 8190-8192.

[31] O'Mahony S M et al, J. C. S. (2022) On the electron pairing mechanism of copper-oxide high temperature superconductivity. Proceedings of the National Academy of Sciences, 119 (37) (https://doi.org/10.1073/pnas.2207449119)
[32] Gardew D. (2024), High-Temperature Superconductors. 10.5772/intechopen.1006616
[33] Lynton E.A. and McLean W.L.. (1967). Type II Superconductors. Advances in Electronics and Electron Physics. 23. 10.1016/S0065-2539(08)60059-1
[34] Kaplan Ilya. (2020) The Pauli Exclusion Principle and the Problems of Its Experimental Verification. Symmetry, 12. 320. 10.3390/sym12020320
[35] G. R. Stewart (1984) Heavy Fermi-on Systems, 56 American Physical Society 755-787
[36] Bardeen J, et al, Phys. Rev. (1957) 106, 162
[37] Keimer S. A. et al (2015), from quantum matter to high-temperature superconductivity in copper oxides, 518 Nature 179-186
[38] Yao C and Ma Y (2021), Superconducting materials: Challenges and opportunities for large-scale applications in Science, 24(6), 102541 (https://doi.org/10.1016/j.isci.2021.102541)
[39] Coombs T A et al. (2024), High-temperature superconductors and their large-scale applications. Nature Reviews Electrical Engineering (https://doi.org/10.1038/s44287-024-00112-y)
[40] Kruaehong T, et al (2019) Journal of Materials Science and Applied Energy 8 (3) 460-468
[41] Davide C, Nature. (2017) 541 (7635): 9-10 (doi:10.1038/541009a)
[42] Wu H. (2024), Recent development in High Temperature Superconductor: Principle, materials, and applications (https://doi.org/10.54254/2755-2721/63/20241015)
[43] Troyan I A et al (2024) Progress, Problems and Prospects of Room-Temperature Superconductivity arxiv.org: 2406.11344 (cond-mat.supr-con)
[44] Taiichiro O (1999) Introduction to Superconductivity, Chapter 1: Historical Evolution on the Understanding of Superconductivity, TEION KOGAKU (Journal of Cryogenics and Superconductivity Society of Japan). 34. 134-143. 10.2221/jcsj.34.134