International Research Journal on Advanced Engineering and Management
https://goldncloudpublications.com
https://doi.org/10.47392/IRJAEM.2025.0341
e ISSN: 2584-2854
Volume: 03
Issue:05 May 2025
Page No: 2159-2163

The Evolution of Superconductivity: Theoretical Foundations and Material Progress

Sangi Bhanu Prasad[1], Kandela Ruchitha[2], Mohammed Faizaan[3], M.A. Zakim[4], Mohammed Hannan Mustafa[5], Syed Abdul Haseeb[6]
[1]Assistant Professor, Dept. of Physics, Lords Institute of Engg. and Tech., Hyderabad, Telangana, India.
[2]Assistant Professor, Dept. of Physics, Methodist College of Engg. and Tech., Hyderabad, Telangana, India.
[3,4,5,6] UG Scholar, Dept. of IT, Lords Institute of Engg. and Tech., Hyderabad, Telangana, India.
Emails: *bhanuprasads@lords.ac.in[1], ruchithakandela125@gmail.com[2], mohammadfaizaan009@gmail.com[3], zakimmohd1@gmail.com[4], hannanmohammed318@gmail.com[5], haseebsyed8910@gmail.com[6]*

Abstract

Superconductivity is a quantum mechanical phenomenon observed in certain materials at temperatures below a critical threshold (Tc), characterized by the complete absence of electrical resistance and the expulsion of magnetic fields—a property known as the Meissner effect. This state arises when electrons form Cooper pairs, enabling them to move through the lattice without scattering, as described by the Bardeen–Cooper–Schrieffer (BCS) theory. Since its discovery in 1911, superconductivity has become indispensable across various scientific and technological domains. The advent of high-temperature superconductors (HTS) in the 1980s, which operate at temperatures achievable with liquid nitrogen, has expanded practical applications. These include magnetic resonance imaging (MRI), particle accelerators, maglev trains, and advanced power transmission systems. Recent research into cuprate superconductors has unveiled a quantum critical point that may elucidate the mechanisms behind high-temperature superconductivity. This paper provides an accessible overview of the theoretical foundations of superconductivity and explores its diverse applications, highlighting its transformative impact on modern technology.

Keywords: *Cooper pairs, BCS theory, Meissner effect, Critical Temperature (Tc), High-Temperature superconductors (HTS), Cuprates, Quantum Critical point, Electron pairing, zero electrical resistance, magnetic field expulsion, quantum mechanics.*

1. Introduction

Superconductivity is a quantum mechanical phenomenon where a material exhibits zero electrical resistance and the expulsion of magnetic fields (the Meissner effect) when cooled below a characteristic critical temperature (T_x). First observed by Heike Kamerlingh Onnes in 1911, this discovery has since evolved through significant theoretical and material advancements. Superconductivity, discovered by Heike Kamerlingh Onnes in 1911, occurs when materials are cooled below a certain critical temperature and exhibit two defining properties: zero electrical resistance and the Meissner effect, where magnetic fields are expelled from the material. These properties allow for extremely efficient current flow and have implications in a range of fields including energy transmission, medical imaging, and quantum computing. The quantum mechanical explanation involves the formation of Cooper pairs—paired electrons with opposite spins and momenta—which move through a crystal lattice without resistance. The discovery of high-temperature superconductors (HTS) in 1986 by Bednorz and Müller opened new avenues, as these materials can operate at liquid nitrogen temperatures, significantly reducing cooling costs and enhancing applicability.

2. Literature Survey

- Meissner and Ochsenfeld (1933): Discovered that superconductors expel magnetic fields, introducing the Meissner effect, a fundamental property.
- London Equations (1935): Offered the first theoretical framework to explain electromagnetic behavior in superconductors.
- Bardeen, Cooper, Schrieffer (1957):

International Research Journal on Advanced Engineering and Management
https://goldncloudpublications.com
https://doi.org/10.47392/IRJAEM.2025.0341
e ISSN: 2584-2854
Volume: 03
Issue:05 May 2025
Page No: 2159-2163

Proposed the BCS theory, the first microscopic theory explaining superconductivity through the formation of Cooper pairs mediated by phonons.

- Reference: Bardeen J., Cooper L. N., Schrieffer J. R., "Theory of Superconductivity", Physical Review, 1957.
- Ginzburg–Landau Theory
- Developed as a phenomenological model that introduces a complex order parameter to describe the superconducting state.
- Reference: Ginzburg, V. L., Landau, L. D., "On the Theory of Superconductivity", ZhETF, 1950.
- Unconventional Superconductivity: High-Tc materials challenge BCS theory, leading to models involving spin fluctuations, charge density waves, and multiband interactions.
- Topological Superconductivity: Theoretical interest in exotic superconducting states with potential for quantum computing applications.

3. Theoretical Framework Analysis

This study adopts a comprehensive and integrative methodology to analyze the evolution of superconductivity, encompassing both theoretical developments and material progress. The methodology consists of three main components: (1) literature review, (2) comparative analysis, and (3) synthesis of empirical data and theoretical models.

The theoretical understanding of superconductivity has undergone significant evolution since its discovery in 1911. This section analyzes the key theoretical models that have shaped our comprehension of the phenomenon, focusing on their conceptual foundations, mathematical formulations, and explanatory power. The framework is divided chronologically and conceptually, highlighting how each theory contributed to explaining superconducting behavior and guiding experimental research.

4. Early Classical Theories

4.1. Perfect Conductivity Hypothesis

In the immediate aftermath of the discovery of superconductivity by Heike Kamerlingh Onnes, early attempts to understand the phenomenon focused on the idea of perfect conductivity—zero electrical resistance. These models, however, failed to explain the Meissner effect, discovered in 1933, where superconductors expel magnetic fields.

4.2. London Equations (1935)

Fritz and Heinz London formulated the first phenomenological model that successfully explained the Meissner effect. The London equations describe how magnetic fields decay exponentially inside superconductors and introduced the concept of a characteristic length scale, the London penetration depth. While lacking a microscopic basis, this model laid the groundwork for future developments. Macroscopic Theory: Ginzburg–Landau Theory (1950) The Ginzburg–Landau (GL) theory, developed by Vitaly Ginzburg and Lev Landau, introduced a complex order parameter to describe the superconducting state. It extended the Landau theory of phase transitions and described superconductivity as a second-order phase transition. GL theory introduces two critical parameters:

- Coherence length (ξ)
- Penetration depth (λ)

The ratio $\kappa = \lambda/\xi$ distinguishes Type I and Type II superconductors. Though still phenomenological, GL theory bridges the gap between classical and quantum descriptions and is particularly useful in analyzing spatial variations in superconductors.

4.3. Microscopic Theory: BCS Theory (1957)

The BCS theory, developed by John Bardeen, Leon Cooper, and Robert Schrieffer, represents the first successful microscopic explanation of superconductivity. The core ideas include:

- **Cooper pairing:** Electrons form bound pairs due to lattice-mediated attractive interactions.
- **Energy gap:** A gap opens in the electronic density of states at the Fermi level.
- **Condensation into a ground state:** All Cooper pairs condense into a single macroscopic quantum state.The BCS theory accurately predicts key experimental observations such as the energy gap, specific heat behavior, and isotope effect in conventional low-temperature superconductors. However, it fails to explain high-temperature superconductivity.

International Research Journal on Advanced Engineering and Management
https://goldncloudpublications.com
https://doi.org/10.47392/IRJAEM.2025.0341
e ISSN: 2584-2854
Volume: 03
Issue:05 May 2025
Page No: 2159-2163

4.4. Extensions and Quantum Field Theories

Several extensions of BCS theory incorporate strong-coupling effects, anisotropy, and multiband superconductivity. The Eliashberg theory refines BCS by incorporating retardation effects and complex electron-phonon interactions. Furthermore, quantum field theoretical approaches, including the use of Green's functions and path integral formalism, have been instrumental in studying fluctuation effects, vortices, and topological superconductivity.

4.5. Unconventional Superconductivity

The discovery of high-temperature superconductors (HTS) in cuprates (1986) and iron-based superconductors (2008) challenged the universality of the BCS framework. These materials exhibit: Non-phonon pairing mechanisms (e.g., spin fluctuations) d-wave or other exotic order parameter symmetries Strong electron correlations Various models such as the resonating valence bond (RVB) theory, Hubbard models, and spin fluctuation theories have been proposed to describe these systems, though a unifying microscopic theory remains elusive.

4.6. Modern and Emerging Theoretical Models

Recent discoveries, such as superconductivity in hydrogen-rich compounds under high pressure and twisted bilayer graphene, have reignited interest in:
Topological superconductivity Multi-gap and multi-band superconductors Flat-band superconductivity Machine-learning-assisted theoretical predictions These developments require hybrid theoretical approaches that combine traditional solid-state physics, quantum field theory, and computational methods.

5. Recent Work in Superconductivity

Researchers conducted both theoretical and experimental studies on a new high-temperature superconductor, yttrium hydride (YH6). Their findings were published in the journal Advanced Materials. Yttrium hydrides are among the three highest-temperature superconductors known to date. Leading this group is a material with an unknown sulfur-carbon-hydrogen (S-C-H) composition exhibiting superconductivity at 288 K. This is followed by lanthanum hydride (LaH10), which superconducts at temperatures up to 259 K, and finally yttrium hydrides YH6 and YH9, with maximum superconducting temperatures of 224 K and 243 K, respectively. The superconductivity of YH6 was first predicted theoretically by Chinese scientists in 2015. All these hydrides achieve their highest superconducting temperatures only under extremely high pressures: approximately 2.7 million atmospheres for the S-C-H compound, and about 1.4 to 1.7 million atmospheres for LaH10 and YH6. These high pressure requirements remain a significant obstacle for large-scale production. Before 2015, the record for high-temperature superconductivity was 138 K (or 166 K under pressure). The idea of room-temperature superconductivity, once considered unrealistic, has now become a reality. The current challenge is to achieve room-temperature superconductivity at much lower pressures. Historically, the highest-temperature superconductors were first predicted through theoretical models before being synthesized and experimentally confirmed. In the search for new superconducting materials, chemists rely on theoretical predictions to guide practical experiments. Theoretical predictions of critical superconducting temperatures generally have an error margin of 10–15%, with similar accuracy for predictions of critical magnetic fields. However, an unusual discrepancy was observed for YH6: the experimentally measured critical magnetic field is 2 to 2.5 times greater than theoretical predictions. This significant difference has not been seen before and remains unexplained, presenting a new puzzle for scientists.

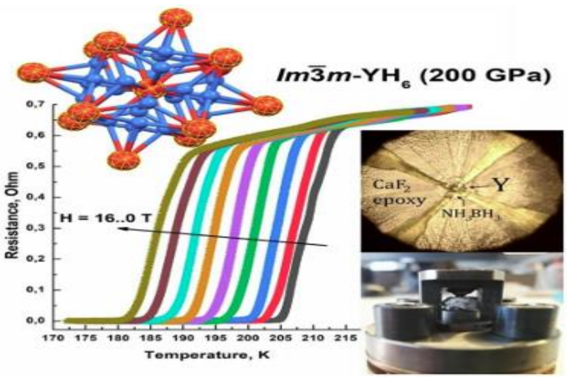

Figure 1 **Newly synthesized high temperature superconductor, Yttrium hydride(YH6)**

International Research Journal on Advanced Engineering and Management
https://goldncloudpublications.com
https://doi.org/10.47392/IRJAEM.2025.0341
e ISSN: 2584-2854
Volume: 03
Issue:05 May 2025
Page No: 2159-2163

In a 2016 study, scientists reported achieving superconductivity in a material that is normally non-superconducting. A research team at the University of Houston demonstrated superconductivity in calcium arsenide ($CaFe_2As_2$) by exploiting the interface between two different phases of the material. The team suggested that enhanced superconducting transition temperatures can be achieved by using artificial or natural composite interfaces. Specifically, they induced high-temperature superconductivity in $CaFe_2As_2$ through the stacking of antiferromagnetic and metallic layers. The concept that superconductivity can be induced or enhanced at the interface between two distinct compounds dates back to proposals from the 1970s. However, earlier experiments that claimed to induce superconductivity in non-superconducting materials often could not definitively exclude the effects of chemical doping or mechanical stress. In this experiment, the researchers worked at ambient pressure using undoped calcium arsenide. They annealed the material by heating it to 350°C and then allowing it to cool slowly. This annealing process caused the material to separate into two distinct phases. While neither of these individual phases exhibited superconductivity, the researchers observed superconductivity precisely at the interface where the two phases coexist. The calcium arsenide reached superconductivity at 25 K. These findings represent a promising step toward developing improved, cost-effective superconducting materials for various technological applications. Figure 1 shows Newly synthesized high temperature superconductor, Yttrium hydride(YH6)Figure 2 shows Overall Superconductivity

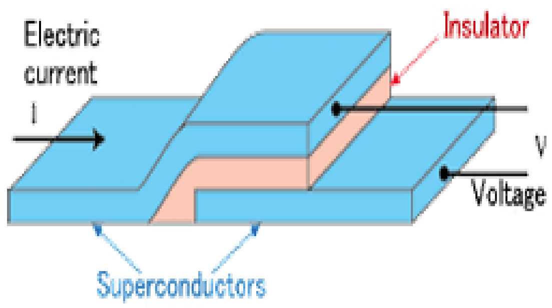

Figure 2 Overall Superconductivity

Superconductivity has numerous applications, ranging from magnetic levitation (Maglev) trains to magnetic resonance imaging (MRI) machines. However, producing superconducting materials remains expensive and technically challenging. Although significant progress has been made and a wide range of research is ongoing in the field of superconductivity, the fundamental reason why superconductivity occurs at unexpectedly high temperatures in some materials remains unknown. If physicists one day unlock this secret, it may become possible to design custom-made materials that exhibit superconductivity at normal ambient temperatures. Such a breakthrough would have profound technological implications, though it is not yet within reach.

Conclusion

Superconductivity is a phenomenon where electrical current flows through a material without resistance or energy loss, enabled by the formation of so-called Cooper pairs. In this state, electrons move through the material without encountering any barriers. Engineers have harnessed this remarkable effect in a variety of applications. However, traditional superconductivity only occurs at extremely low temperatures, which necessitates complex and costly cooling systems. This made the discovery of high-temperature superconductors particularly surprising. These materials exhibit superconductivity at relatively higher temperatures—still cold, but significantly warmer than those required for conventional superconductors. As a result, they reduce the need for intense cooling, making practical applications more feasible. Superconductivity has many promising applications, such as magnetic levitation (Maglev) trains, MRI machines, and resonance technologies. Yet, the production of superconducting materials remains expensive and technically challenging. Despite extensive innovation and research in the field, the precise mechanism behind high-temperature superconductivity is still not fully understood. If scientists can one day uncover this mystery, it may become possible to design custom materials that exhibit superconductivity at room temperature. Such a breakthrough would revolutionize technology across many sectors—but for now, it remains a vision of the future.

References

[1]. Bardeen, J., Cooper, L. N., & Schrieffer, J. R. (1957). Theory of Superconductivity. Physical Review, 108(5), 1175–1204. https://doi.org/10.1103/PhysRev.108.1175

[2]. Ginzburg, V. L., & Landau, L. D. (1950). On the Theory of Superconductivity. Zh. Eksp. Teor. Fiz., 20, 1064–1082.

[3]. London, F., & London, H. (1935). The Electromagnetic Equations of the Supraconductor. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 149(866), 71–88.

[4]. Kamerlingh Onnes, H. (1911). The Superconductivity of Mercury. Leiden Communications, 120b, 122b, 124c.

[5]. Bednorz, J. G., & Müller, K. A. (1986). Possible High Tc Superconductivity in the Ba−La−Cu−O System. Zeitschrift für Physik B Condensed Matter, 64, 189–193. https://doi.org/10.1007/BF01303701

[6]. Scalapino, D. J. (2012). A Common Thread: The Pairing Interaction for Unconventional Superconductors. Reviews of Modern Physics, 84(4), 1383–1417. https:// doi.org/ 10.1103/RevModPhys.84.1383

[7]. Lee, P. A., Nagaosa, N., & Wen, X.-G. (2006). Doping a Mott Insulator: Physics of High-Temperature Superconductivity. Reviews of Modern Physics, 78, 17–85. https://doi.org/10.1103/RevModPhys.78.17

[8]. Hosono, H., & Kuroki, K. (2015). Iron-Based Superconductors: Current Status of Materials and Pairing Mechanism. Physica C: Superconductivity and its Applications, 514, 399–422. https:// doi.org/ 10.1016/ j.physc.2015.02.003

[9]. Drozdov, A. P., Eremets, M. I., Troyan, I. A., Ksenofontov, V., & Shylin, S. I. (2015). Conventional Superconductivity at 203 Kelvin at High Pressures in the Sulfur Hydride System. Nature, 525, 73–76. https://doi.org/10.1038/nature14964

[10]. Cao, Y., Fatemi, V., Demir, A., Fang, S., Tomarken, S. L., Luo, J. Y., ... & Jarillo-Herrero, P. (2018). Unconventional Superconductivity in Magic-Angle Graphene Superlattices. Nature, 556, 43–50. https://doi.org/10.1038/nature26160

[11]. Poole, C. P., Farach, H. A., Creswick, R. J., & Prozorov, R. (2014). Superconductivity (3rd ed.). Academic Press.

[12]. Tinkham, M. (2004). Introduction to Superconductivity (2nd ed.). Dover Publications.

[13]. Deutscher, G. (2005). Andreev–Saint-James Reflections: A Probe of the Pairing State in High-Tc Superconductors. Reviews of Modern Physics, 77, 109–135. https:// doi.org/10.1103/RevModPhys.77.109