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A Review on Theory of Superconductivity, High Transition Temperature and the Applications of Superconductivity

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Abstract

Superconductors are materials that exhibit *zero electrical resistance* and *perfect diamagnetism* below a characteristic transition temperature (Tc). When cooled below Tc, resistance falls abruptly to zero, unlike normal conductors which retain finite resistance even near absolute zero. Many metals exhibit superconductivity at temperatures close to absolute zero, while recent discoveries have identified ceramic materials that remain superconducting at temperatures above 100 K. According to BCS theory, electrons in a superconducting state form bound pairs known as Cooper pairs due to attractive interactions, resulting in a collective quantum state. Materials with Tc above 77 K are classified as high-temperature superconductors. This review presents the basic principles of superconductivity, transition temperature behavior, Meissner effect, BCS theory, Josephson effect, high-Tc materials, and major technological applications in transportation, magnetic levitation, NMR, power transmission, and energy storage.

Keywords: Superconductivity, Transition Temperature, BCS Theory, High-Tc Superconductors, Josephson Effect, Maglev, SMES.

1. Introduction

Superconductivity was discovered by Heike Kamerlingh Onnes in 1911 during his investigation of mercury at cryogenic temperatures. He observed that the electrical resistance of mercury abruptly vanished at 4.2 K. The temperature at which a material loses all electrical resistance is known as the **critical transition temperature (Tc)**.

Since this discovery, extensive research has led to the identification of numerous superconducting materials, including high-Tc ceramic compounds. The development of superconductivity has enabled advanced technologies such as magnetic levitation (Maglev) trains, MRI machines, SQUIDs, and lossless power transmission lines.

2. Basic Characteristics of Superconductors

Superconductors exhibit two fundamental properties when cooled below Tc:

2.1 Zero Electrical Resistivity

$$\rho = 0 \text{for } T < T_c$$

A superconductor demonstrates infinite conductivity below Tc. If the applied current exceeds the **critical current density (Jc)**, superconductivity is destroyed.

2.2 Perfect Diamagnetism (Meissner Effect)

$$B = 0 (B = \text{Magnetic Induction})$$

When placed in an external magnetic field and cooled below Tc, a superconductor expels magnetic flux from its interior. Superconductivity is lost if the applied magnetic field exceeds the **critical magnetic field (Hc).**

3. Transition Temperature

Low-temperature physics deals with behavior of materials near absolute zero (−273.15°C). Many pure metals, alloys, and compounds exhibit zero resistance below their critical temperature.

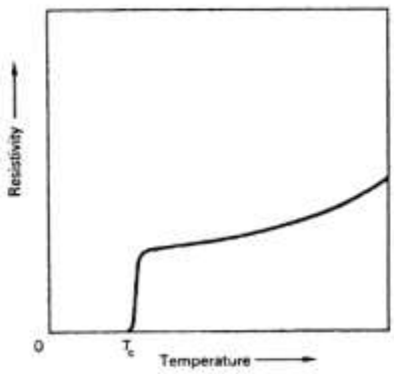

Figure 1: *Ideal resistive behavior of a superconductor showing a sharp drop to zero resistance below Tc.*
The transition temperature may be slightly affected by impurities. While metals like iridium and molybdenum superconduct only in highly pure states, some metals such as copper, sodium, and iron do not superconduct even at the lowest temperatures achieved.
Certain alloys, however, exhibit superconductivity even when their constituent elements do not. Ceramic oxide-based superconductors such as $YBa_2Cu_3O_7$ (YBCO) remain superconducting near 100 K and are economically favorable because they can be cooled using liquid nitrogen.

	Ta–Nb	Pb–Bi	3Nb–Zr	Nb_3Sn	Nb_3Ge
T_c (°K)	6·3	8	11	18	23

	Nb	Pb	Ta	Sn	Zr	Bi	Ge
T_c (°K)	9·3	7·2	4·5	3·7	0·8	not s/c	not s/c

Table 1: *Transition temperatures of selected superconducting elements, compounds, and alloys.*

4. Meissner Effect

Discovered by Walther Meissner and Robert Ochsenfeld in 1933, the Meissner effect states that when a material transitions into the superconducting state, it expels magnetic flux lines from its interior, becoming a perfect diamagnet. When heated above Tc, magnetic flux reenters the material and it returns to its normal state.

5. BCS Theory

The microscopic foundation of superconductivity was established in 1957 by Bardeen, Cooper, and Schrieffer, known as **BCS Theory**. According to this theory Electrons in a normal conductor move independently.

- In a superconductor, electrons form *Cooper pairs* through lattice-mediated attractive interactions.
- Cooper pairs condense into a quantum coherent ground state resistant to scattering.
- This leads to zero resistance and the Meissner effect.

BCS theory earned the authors the **1972 Nobel Prize in Physics.**

6. Josephson Effect

Predicted by Brian Josephson in 1962, the Josephson effect occurs when two superconductors are separated by a thin insulating barrier.

- Cooper pairs tunnel through the insulator.
- A supercurrent flows even without applied voltage.
- This junction forms the basis of ultra-sensitive devices like SQUIDs.

7. High-Tc Superconductors

High-temperature superconductors are defined as materials with **Tc > 77 K**, the boiling point of liquid nitrogen.

The first high-Tc ceramic superconductor was discovered by Bednorz and Müller in 1986, with Tc = 35.1 K, earning the **1987 Nobel Prize**.

Common high-Tc classes include:

- Copper oxide ceramics (e.g., YBCO)
- Bismuth-strontium-calcium-copper oxides (BSCCO)
- Iron-based pnictides
- Magnesium diboride (MgB_2), Tc = 39 K

Although ceramics are brittle and difficult to fabricate into wires, they remain central to HTS applications.

8. Applications of Superconductivity

8.1 Magnetic Levitation (Maglev) Trains

Superconducting magnets enable frictionless transportation by levitating the train above the track.
Examples:

- **Shanghai Maglev (China)** – operational since 2004, 30 km line.
- **Changsha Maglev (China)** – opened in 2016, 18.5 km.
- **Japan's L0 Series Maglev** – aims for speeds up to 600 km/h.

Fig 2: Magnetic Levitating Train

8.2 Power Transmission and Generation

Superconducting cables:

- Eliminate resistive losses.
- Have higher power carrying capacity.
- Reduce environmental impact.

HTS cables and fault-current limiters are increasingly deployed in modern smart grids.

Superconducting generators and motors are highly efficient, compact, and used in naval propulsion and industrial applications.

8.3 Power Storage (SMES)

Superconducting Magnetic Energy Storage (SMES):

- Stores energy in magnetic fields generated by superconducting coils.
- Provides extremely fast charge/discharge.
- Enhances grid reliability and stabilizes fluctuating renewable energy.

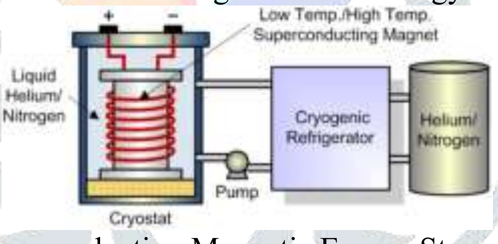

Fig 3: Superconducting Magnetic Energy Storage

8.4 Nuclear Magnetic Resonance (NMR)

Superconducting magnets are essential for generating strong and stable magnetic fields in:

- NMR spectroscopy
- MRI scanners
- Fast Field-Cycling NMR systems

NMR depends heavily on superconductors to improve sensitivity and resolution.

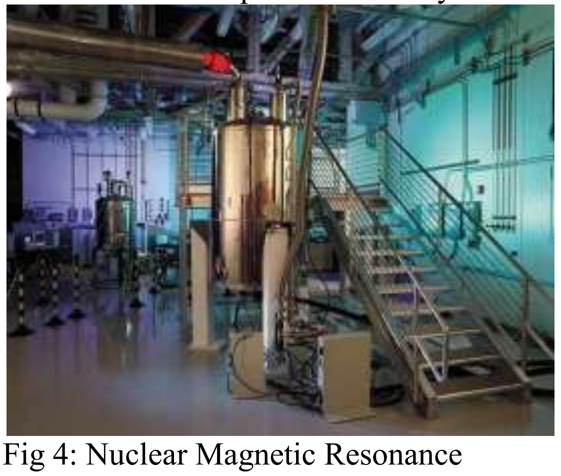

Fig 4: Nuclear Magnetic Resonance

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9. Conclusion

This review highlights the fundamental concepts of superconductivity, its transition temperature behavior, and recent advancements, particularly in high-Tc ceramic superconductors. Materials such as $YBa_2Cu_3O_7$ operate above the boiling point of liquid nitrogen, making them suitable for practical applications. Ceramic superconductors, despite their brittleness, remain the most promising candidates for developing efficient power systems, magnetic levitation technologies, and advanced scientific instruments. Continued research in ceramic metal oxides aims to further enhance Tc and broaden real-world applications.

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