

## HIGH-TEMPERATURE SUPERCONDUCTIVITY AND SUPERDIAMAGNETISM

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**Abstract:** Superconductivity is a remarkable quantum phenomenon characterized by zero electrical resistance and perfect diamagnetism, known as the Meissner effect. Since the discovery of high-temperature superconductivity (HTS) in copper-oxide ceramics (cuprates) in 1986, researchers have struggled to understand the mechanisms behind superconductivity at temperatures far exceeding those predicted by the conventional Bardeen–Cooper–Schrieffer (BCS) theory. This paper explores the fundamental principles of superconductivity, focusing on the phenomena of superdiamagnetism and the mechanisms proposed for high-temperature superconductivity. It also reviews major experimental findings and theoretical models, and discusses the current challenges and future directions of research aimed at achieving room-temperature superconductivity.

**Keywords:** High-temperature superconductors; Meissner effect; superdiamagnetism; Cooper pairs; cuprates; critical temperature; BCS theory; quantum materials.

### Introduction

Superconductivity was first discovered by **Heike Kamerlingh Onnes** in 1911 when mercury was cooled below 4.2 K, resulting in the sudden disappearance of electrical resistance. Since then, superconductivity has become one of the central topics in condensed matter physics. Two fundamental features define a superconductor:

1. **Zero electrical resistance**, enabling lossless current flow.
2. **Perfect diamagnetism**, or **superdiamagnetism**, manifested in the **Meissner effect**, where a superconductor expels magnetic flux lines from its interior.

For most of the 20th century, superconductivity was successfully described by the **Bardeen–Cooper–Schrieffer (BCS) theory** (1957), which attributes the superconducting state to the condensation of electron pairs—**Cooper pairs**—mediated by lattice vibrations, or phonons. However, this model predicted superconductivity only at very low temperatures (below about 30 K).

The discovery of **high-temperature superconductivity** by **Johannes Bednorz and Karl Müller** in 1986 in the La–Ba–Cu–O system, with a critical temperature ( $T_c$ ) above 35 K, challenged all existing theories [1]. Soon after, new materials such as **YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> (YBCO)** with  $T_c \approx 92\text{K}$  were synthesized, marking the birth of a new class of materials known as **cuprates**. These discoveries opened new opportunities for practical applications and triggered intense research into understanding the microscopic origins of HTS.

## 2. Theoretical Foundations of Superconductivity

### 2.1 Conventional Superconductivity: The BCS Framework

The **BCS theory** explains superconductivity as a result of the formation of Cooper pairs—bound states of electrons with opposite spins and momenta. The effective attraction between electrons arises from phonon exchange, leading to an energy gap  $\Delta$  in the electronic density of states.

In conventional superconductors, the pairing has **s-wave symmetry**, meaning the gap is isotropic. The transition temperature  $T_c$  is given approximately by

$$k_B T_c = 1.14 \hbar \omega_D e^{-1/N(0)V}$$

where  $\omega_D$  is the Debye frequency,  $N(0)$  is the density of states at the Fermi level, and  $V$  is the pairing potential.

While successful for metals like lead, tin, and aluminum, the BCS theory cannot account for the much higher  $T_c$  values observed in cuprates and other unconventional superconductors [2].

## 2.2 High-Temperature Superconductivity and Cuprate Materials

High-temperature superconductors differ from conventional ones both structurally and electronically. **Cuprates** possess a layered perovskite structure containing **CuO<sub>2</sub> planes**, where superconductivity originates. The parent compounds are typically **antiferromagnetic Mott insulators**, becoming superconducting only upon doping with charge carriers (holes or electrons).

Key features distinguishing HTS from conventional superconductors include:

- **d-wave pairing symmetry**, with nodes in the superconducting gap [3];
- **strong electronic correlations** between copper d-electrons;
- the presence of a **pseudogap phase**, a partial suppression of the density of states above  $T_c$ ;
- and the coexistence of superconductivity with competing orders such as spin-density or charge-density waves.

The mechanism of pairing in HTS remains one of the great unsolved problems of modern physics. Various models propose that pairing arises not from phonons, but from **spin fluctuations** or **electronic correlations** [4].

## 2.3 Superdiamagnetism and the Meissner Effect

One of the defining signatures of superconductivity is **superdiamagnetism**, the complete expulsion of magnetic fields from the interior of a superconductor upon entering the superconducting state. This effect was first observed by **Walther Meissner and Robert Ochsenfeld** in 1933 [5].

The magnetic field **B** inside a superconductor obeys the **London equation**:

$$\nabla^2 \mathbf{B} = -\frac{\mathbf{B}}{\lambda_L^2}$$

where  $\lambda_L$  is the **London penetration depth**—the characteristic distance over which magnetic fields decay inside the material.

Superdiamagnetism reflects the rigidity of the superconducting wave function's phase. Any magnetic flux attempting to penetrate the superconductor induces screening currents that exactly cancel the field inside. In type-II superconductors (such as cuprates), magnetic flux can enter as quantized vortices beyond the lower critical field  $H_{c1}$ , while remaining excluded below it [6].

## 3. Mechanisms Proposed for High-Temperature Superconductivity

### 3.1 Spin Fluctuation Models

In cuprates, where strong electron-electron repulsion dominates, phonon-mediated pairing seems insufficient. Instead, **spin fluctuation theories** propose that electrons couple via dynamic spin excitations arising from antiferromagnetic correlations [7]. These fluctuations can mediate an effective attraction between electrons with opposite momenta and spins, leading to d-wave pairing symmetry.

### 3.2 Hubbard and t-J Models

The **Hubbard model** and its simplified form, the **t-J model**, are theoretical frameworks describing strongly correlated electrons in narrow energy bands. The Hamiltonian for the Hubbard model is:

$$H = -t \sum_{\langle i,j \rangle, \sigma} (c_{i\sigma}^\dagger c_{j\sigma}) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

where  $t$  is the hopping parameter, and  $U$  represents the on-site Coulomb repulsion. In the strong-coupling limit ( $U \gg t$ ), superconductivity may arise from correlated motion of doped holes in the antiferromagnetic background [8].

### 3.3 Quantum Criticality and the Pseudogap

Experimental evidence suggests that many HTS materials are located near a **quantum critical point**, where a competing order (such as magnetism or charge order) disappears at zero temperature [9]. Quantum fluctuations at this point can enhance pairing. Additionally, the **pseudogap** observed above  $T_c$  may represent preformed Cooper pairs lacking long-range phase coherence, or a competing order that suppresses superconductivity.

## 4. Experimental Observations and Technological Applications

### 4.1 Evidence of Superdiamagnetism

The Meissner effect in HTS is readily observed using magnetic susceptibility and magnetization measurements. The transition into the superconducting state results in a sharp drop in magnetic susceptibility, indicating the onset of perfect diamagnetism. This behavior provides direct evidence of macroscopic quantum coherence in HTS materials.

### 4.2 Critical Currents and Magnetic Levitation

One of the most striking demonstrations of superdiamagnetism is **magnetic levitation**, where a superconducting sample repels a magnet due to flux expulsion and flux pinning. HTS materials such as YBCO can levitate permanent magnets stably above liquid nitrogen baths, showcasing practical applications in **Maglev trains**, **frictionless bearings**, and **energy storage systems** [10].

### 4.3 Applications and Challenges

HTS materials are already used in:

- **Superconducting magnetic energy storage (SMES)** systems;
- **Fault current limiters** in power grids;
- **MRI and NMR devices** with stronger, more stable magnetic fields;
- **SQUID sensors** for detecting extremely weak magnetic signals.

However, challenges remain, such as fabricating materials with uniform grain boundaries, enhancing flux pinning, and improving mechanical stability.

## Conclusion

High-temperature superconductivity and superdiamagnetism illustrate the profound interplay between quantum mechanics and collective electron behavior. While the Meissner effect and zero resistance define all superconductors, the mechanisms underlying HTS remain elusive. The complexity of cuprate materials—marked by strong correlations, low dimensionality, and competing quantum orders—continues to defy a unified theory.

Nevertheless, advances in materials synthesis, spectroscopy, and computational modeling are gradually unraveling the mysteries of HTS. The ultimate goal remains the discovery of a **room-**

**temperature superconductor**, which would revolutionize energy technology, transportation, and quantum computing.

**Literature Review**

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