High-temperature superconductivity: A driving force for the revolution in quantum many-body theory

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Abstract

High-temperature superconductivity, a fundamental topic in condensed matter physics, presents one of the critical scientific challenges of this century. The potential for breakthroughs in this field not only promises to reveal numerous novel quantum phenomena and deepen our understanding of quantum many-body physics but also to significantly drive advancements in experimental techniques, theories, and methodologies in probing correlated quantum systems. More importantly, as a non-perturbative quantum system, high-temperature superconductivity offers an ideal platform and a crucial driving force for systematically establishing non-perturbative quantum field theory. Currently, research on high-temperature superconductivity stands at a critical turning point. Achieving significant breakthroughs requires the development of cutting-edge detection technologies built upon novel concepts, the establishment of innovative theoretical frameworks and methodologies, and insightful elucidation of the physical pictures revealed by experimental findings. Such extensive exploration is vital for unveiling fundamental relationships and identifying the governing principles. By integrating these efforts, we can gain profound insights into the mechanisms of high-temperature superconductivity and significantly expand the horizons of quantum many-body theory.

Keywords: high-temperature superconductivity, quantum many-body theory, non-perturbative quantum field theory, strongly correlated systems

PACS: 74.20.−z, 71.10.−w, 71.27.+a **DOI:** 10.7498/aps.74.20250313

CSTR: 32037.14.aps.74.20250313

1 Introduction

The mechanism of high-temperature superconductivity, or more broadly, the problem of high-temperature superconductivity, is a central and unresolved question in condensed matter physics, and one of the grand scientific challenges of this century. Solving this problem would not only reveal the microscopic origin of high-T_c superconductivity but also greatly enhance our ability to predict, control, and optimize superconducting materials, thereby accelerating the discovery of new compounds and expanding the technological applications of high-temperature superconductivity.

However, the significance of high-temperature

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superconductivity research extends well beyond condensed matter physics. A breakthrough in this field would have a profound impact on a wide range of disciplines, including nuclear physics, particle physics, quantum chemistry, and quantum computing. High-T_c superconductors provide an exceptional experimental platform for developing non-perturbative quantum field theories, serving as a driving force in advancing a unified framework that captures the physics of strongly correlated systems and reveals new principles of quantum many-body phenomena. To better understand this, let us briefly revisit the century-long evolution of quantum theory.

Quantum theory, since its inception in the early 20th century, has profoundly reshaped modern civilization. It revealed the laws of the microscopic world and became a driving force behind technological progress. Its development can be roughly divided into three stages: The first stage (1900 to the 1920s) established the fundamental principles of quantum mechanics, laying the foundation of the theory. The second stage (1927 to the 1970s) witnessed the rise of perturbative quantum field theory, which extended quantum mechanics to many-body systems and became central to modern quantum science. The third stage (beginning from the 1950s) focuses on developing non-perturbative quantum field theory to address strongly correlated quantum many-body problems. This task is far more challenging and remains an open question under active investigation.

While numerous physical problems have emerged at each stage of quantum theory's development, certain key challenges have played a vital and irreplaceable role in advancing the field. These problems have served as critical testing grounds for uncovering new physical principles and developing new theoretical frameworks. They share two essential features: the phenomena they reveal lie beyond the explanatory power of existing theories, and their resolution often gives rise to entirely new theoretical paradigms.

For example, during the first stage, two key physical problems played a decisive role in the birth of quantum mechanics. The first was blackbody radiation, which led Planck to introduce the concept of quantum, marking the inception of quantum theory. The second was the hydrogen atom spectrum, a problem that carried significant weight in the development of quantum mechanics. Its study provided crucial experimental support for establishing the mathematical framework of quantum mechanics. In the second stage, characterized by the development of perturbative quantum field theory, research in quantum electrodynamics (QED) assumed a more prominent role than other topics. The pursuit of QED not only laid the theoretical foundation for perturbative quantum field theory but also provided a critical platform for its refinement and experimental verification, becoming one of the most significant achievements of this period.

In the third stage, research initially centered on the strong interaction within nuclei. Its non-perturbative nature placed it beyond the reach of perturbative quantum field theory, and experimental progress was hindered by the need for large-scale particle accelerators. As efforts stalled, the discovery of high-temperature superconductors in the mid-1980s offered new hope [1]. Like strong interactions, high-Tc superconductivity involves strong correlations that defy perturbative methods, but its experimental accessibility and lower entry barrier enabled rapid theoretical and experimental advances.

Moreover, research on high-temperature superconductivity has uncovered a range of novel and potentially universal physical phenomena, offering a coherent framework for exploring the underlying principles of strongly correlated quantum many-body systems. Many of these phenomena lie beyond the explanatory power of existing quantum theory, presenting new challenges to quantum field theory. As such, high-temperature superconductors are not only materials of great application potential but also serve as a vital experimental platform for advancing quantum many-body theory.

2 Research background of high-T_c superconductivity

Superconductivity is a macroscopic quantum phenomenon that emerges at low temperatures. Superconductors with a critical transition temperature at or above 40 K are commonly referred to as high-T_c superconductors. Existing high-T_c superconductors can be classified into two categories based on the presence or absence of strong magnetic fluctuations. The first category possesses strong antiferromagnetic fluctuations and includes cuprates [1], iron-based [2], and nickel-based superconductors [3]. The second category lacks such magnetic signatures and includes magnesium diboride [4] and high-pressure hydride superconductors [5].

Superconductors are ideal conductors with zero electrical resistance and exhibit perfect diamagnetism, setting them apart from ordinary conductors. Perfect diamagnetism means that an applied magnetic field is completely expelled from the interior of a superconductor. The absence of resistance eliminates energy loss and heat generation during power transmission, enabling superconductors to carry extremely large critical currents and generate magnetic fields far stronger than those achievable with conventional materials. Additionally, their exceptional sensitivity to even minute changes in magnetic fields makes them ideal for ultra-sensitive magnetic detection, again an advantage unmatched by any other material.

Superconducting technology has a wide range of applications, encompassing cutting-edge fields such as quantum computing, superconducting maglev trains, thermonuclear fusion, large accelerators, high-power transmission, and magnetic resonance imaging for brain and heart diagnosis. It spans multiple fields, including electronics, transportation, energy, mechanical engineering, biomedicine, and large scientific facilities. As a vital pillar of contemporary technological development, superconducting technology has become a key focus of global high-tech competition.

Currently, most superconducting applications rely on conventional metallic superconductors, which have low superconducting transition temperatures. While high-temperature superconducting materials can significantly reduce the cost of maintaining low temperatures and improve system stability, their complex fabrication processes and inadequate mechanical properties result in high costs, limiting their scope of use. To break through this bottleneck, it is essential not only to improve the fabrication techniques but also to deepen our understanding of the physical principles of high-T_c superconductivity and discover more high-performance materials.

Superconducting condensation relies on two fundamental processes: electron pairing and the establishment of global phase coherence [6]. Electron pairing refers to the formation of Cooper pairs, where two electrons bind into a boson-like state via an effective attractive interaction. Once the phases of these Cooper pairs become coherent throughout the system, they condense into a macroscopic superconducting state, exhibiting zero electrical resistance and perfect diamagnetism.

In conventional superconductors, the attractive interaction responsible for electron pairing primarily arises from electron-phonon coupling: an electron distorts the lattice, which in turn mediates an effective attraction with another electron, leading to the formation of Cooper pairs. However, the pairing mechanism in high-temperature superconductors, such as cuprates and iron-based compounds, is a complex puzzle yet to be fully solved. Magnetic fluctuations, strong electronic correlations, and other unknown factors may play essential roles, and determining the origin of electron pairing in these materials remains one of the central challenges in understanding the high-T_c mechanism.

3 Challenges Posed by High-T_c Superconductivity

Over the past four decades, investigations into high-temperature superconductivity have uncovered a range of striking physical phenomena that defy explanation within the existing quantum theory. These challenges have not only hindered the resolution of the high-T_c mechanism but also posed profound difficulties for the quantum many-body theory. Below are some of the most prominent mysteries discovered in high-Tc superconductors:

1. **Linear Resistivity:** In conventional conductors, low-temperature resistivity typically follows a quadratic or quintic dependence on temperature. In sharp contrast, optimally doped high-temperature superconductors exhibit a linear temperature dependence of resistivity, even at low temperatures [7]. The physical origin and underlying mechanism of this anomalous behavior remain unresolved.

2. **Mott-Ioffe-Regel Limit of Resistivity:** Electrical resistance arises from electron scattering, characterized by the mean free path of electrons. Traditional transport theory asserts that this mean free path cannot be shorter than the interatomic spacing, thereby imposing an upper bound on resistivity known as the Mott-Ioffe-Regel (MIR) limit [8]. However, experiments on high-temperature superconductors have revealed that resistivity can significantly exceed this limit [7,8], challenging the traditional transport theory.

3. **Pseudogap effect:** In a superconducting transition, the specific heat shows a sharp peak near the critical temperature T_c, followed by a rapid decline as the temperature decreases. This behavior is attributed to the formation of gapped bound states in the superconducting phase. The pseudogap effect [9–11] describes the appearance of a partial energy gap on the Fermi surface in the normal (non-superconducting) state, leading to a decrease in specific heat even above T_c. This phenomenon results in a loss of low-energy entropy (below approximately 25 meV) [12,13]. Infrared spectroscopy reveals that this loss of entropy is transferred to high-energy states around 1 eV. The strong coupling between high- and low-energy scales is unprecedented, suggesting that some foundational principles of perturbative quantum field theory, such as renormalizability, may need to be reexamined.

4. **Fermi arc:** In conventional conductors, the Fermi surface forms a closed shell that separates occupied and unoccupied electronic states within the Brillouin zone. However, in underdoped cuprate superconductors, the Fermi surface is fragmented, manifesting as disconnected arc-like segments instead of a closed loop [14]. These arc-like structures, known as Fermi arcs, are characteristic of the pseudogap state. Surprisingly, quantum oscillations, which typically require a closed Fermi surface, have been observed in these materials under strong magnetic fields [15]. This unexpected finding poses a fundamental challenge to our understanding of the electronic structure of high-T_c cuprates.

5. **Connection between linear resistivity and T_c:** Experiments have shown that the square root of the linear coefficient of low-temperature linear resistivity varies linearly with the superconducting transition temperature T_c in overdoped cuprate superconductors [16]. This intriguing connection suggests that the interactions responsible for both high-temperature superconductivity and linear resistivity may have a common origin. However, the underlying mechanism remains unclear.

Undoubtedly, the puzzling phenomena observed in high-temperature superconductors extend well beyond the examples discussed above, although these particular examples alone already present striking contradictions with existing quantum theories. These interconnected phenomena not only challenge current theoretical frameworks but also offer a unique opportunity for the development of new quantum paradigms. Resolving these issues could deepen our understanding of the mechanisms underlying high-temperature superconductivity and inspire the creation of new quantum many-body theories, with potentially far-reaching implications for condensed matter physics and related fields.

4 Impact of high-T_c superconductivity on quantum many-body physics

The mechanism of high-temperature superconductivity remains elusive, yet research in this area has substantially advanced quantum many-body physics in three key aspects:

First, it has significantly deepened our understanding of strong correlation effects in quantum systems. Extensive experimental and theoretical investigations have confirmed that high-T_c pairing possesses d-wave symmetry [17], and have uncovered a wide range of novel quantum phenomena. These insights have not only enabled quantitative descriptions of complex correlated effects but have also broadened our understanding of interacting quantum systems, laying a firm foundation for future exploration. Moreover, research on high-temperature superconductivity has catalyzed progress in other frontiers of condensed matter physics, such as heavy fermion physics, colossal magnetoresistance, and quantum spin liquids, acting as a key driver of quantum many-body physics.

Second, it has driven significant innovation in experimental techniques. Research on high-temperature superconductivity has acted as a powerful catalyst, accelerating the rapid development of advanced measurement methods such as angle-resolved photoemission spectroscopy (ARPES), scanning tunneling microscopy (STM), neutron scattering, and resonant inelastic X-ray scattering (RIXS). These techniques have played an indispensable role in probing the complex phenomena associated with high-T_c superconductors. They have also been widely adopted across condensed matter physics and materials science, promoting the development of both physics and its interdisciplinary fields.

Third, it has propelled the development of quantum many-body theory and computational methods. While a comprehensive non-perturbative quantum field theory is still lacking, research on high-T_c superconductivity has substantially deepened our understanding of the quantum many-body landscape, particularly in relation to quantum criticality and quantum entanglement. It has also driven significant progress in computational methods such as quantum Monte Carlo and tensor-network renormalization group methods. These methods, inspired by the challenges posed by high-T_c superconductors, have shown a lasting and far-reaching impact on the broader study of quantum many-body problems.

Despite these achievements, resolving the high-T_c problem and advancing quantum many-body theory require a fundamental theoretical framework that can account for both high-T_c superconductivity and other many-body phenomena. This demands more than the accumulation of experimental data and novel physical phenomena. Instead, it demands deep analysis of the data and phenomena to uncover the underlying principles. Only through this approach can we provide a clearer theoretical picture for experiments, facilitate the discovery of new physical effects, and ultimately unravel the high-T_c mechanism.

5 Uncovering universal principles as the key to breakthroughs

Research into high-T_c superconductivity has uncovered numerous unknown quantum phenomena, broadening our understanding of the complexity and diversity inherent in quantum many-body systems. At the same time, it has exposed the limitations of current approaches. Existing studies focus on explaining isolated phenomena, with insufficient attention to underlying universal behavior. Theoretical studies often stay symptom-oriented without a systematic effort to uncover the deeper connections among seemingly disparate observations. This fragmented approach hampers a comprehensive understanding of the high-T_c mechanism and impedes progress in related fields.

Throughout the history of physics, the establishment of new physical theories has often followed a path from empirical observation to mathematical formulation. The process begins with identifying universal patterns through careful analysis of experimental data, followed by the formulation of quantitative physical laws. Major breakthroughs in classical and quantum mechanics have confirmed this paradigm. In the quest to develop non-perturbative quantum theories, discovering universal patterns or principles remains crucial. For instance, in the study of high-T_c superconductivity, recognizing these universal properties is key to future breakthroughs.

What is the key factor determining the superconducting transition temperature, and is there a common underlying principle governing it? This has been a central question in high-T_c superconductivity studies over the past four decades.

It is widely accepted that the strength of the pairing interaction primarily dictates the superconducting transition temperature: stronger interactions generally result in higher transition temperatures. While this picture appears simple, identifying the underlying physical mechanisms is far from trivial. In known high-T_c superconductors, antiferromagnetic fluctuations provide the primary pairing mechanism in cuprate and iron-based superconductors. In contrast, electron-phonon interactions dominate in MgB_2 and hydrogen-rich superconductors under high pressure. Additionally, factors such as quasi-two-dimensional electronic structures and orbital fluctuations also have a great influence on the superconducting properties. These differences reflect fundamental variations among distinct superconducting families.

Is there a common principle underlying the electron pairing interactions in high-T_c superconductors? Current research provides an affirmative answer. Detailed analyses of electronic structures across various high-temperature superconductors have revealed a universal pattern: the metallization of bands formed by electrons engaged in strong chemical bonds, particularly σ-bonds, plays a central role in enabling high-T_c superconductivity [18]. This common factor has been confirmed by theoretical calculations and experimental studies in cuprates [18], magnesium diboride [19], and hydrogen-rich superconductors [20]. Although the multi-orbital nature of iron ions introduces additional complexity in iron-based superconductors, the metallization of σ-bond electrons remains a valid inference. Such metallization inevitably weakens crystal structure, reducing its mechanical stability and facilitating chemical doping. These predictions align well with observed features in cuprate and iron-based superconductors, supporting the universality of this underlying principle.

The reason why the metallization of σ-bonding electrons favors high-temperature superconductivity is due to the intrinsic nature of the σ-bond, which represents a strongly bound electron pair within a molecule. In crystals, σ-bonding electrons hybridize to form energy bands and serve as the primary interaction stabilizing the crystal structure. Metallization of these electrons implies the breaking of these strong covalent bonds, allowing the σ-electrons to become mobile and contribute to electrical transport. However, this process inevitably compromises the structural stability of the crystal, making the metallization of σ-bonding electrons particularly challenging. This fundamental constraint is one of the key reasons why high-temperature superconductors are so difficult to find.

Metallizing σ-bonding bands while maintaining the structural integrity of the crystal is crucial for enabling high-T_c superconducting pairing. This mechanism is well exemplified in MgB_2, where metallization of σ-bonding bands changes this graphite-like material into a high-T_c superconductor. Although the binding strength of σ-bonding electrons diminishes upon metallization, it can still be significantly stronger than other pairing interactions, making it a dominant force in facilitating high-temperature superconductivity. This phenomenon implies that the metallization of σ-bonds, or more generally, of electrons in strong chemical bonds, may represent a universal pathway to high-T_c superconductivity. This insight not only enhances our understanding of the underlying mechanisms but also lays a theoretical foundation for discovering new high-temperature superconductors. Nevertheless, quantitatively formulating this principle and establishing a precise correlation with the superconducting transition temperature remains a challenge.

6 Summary

High-temperature superconductivity is a fertile ground for the emergence of novel quantum phenomena, concepts, methods, and technologies. The unconventional behaviors observed in cuprates and iron-based superconductors remain inadequately explained within existing quantum many-body theories, presenting both a fundamental challenge and a valuable platform for theoretical investigation. Beyond advancing nonperturbative quantum field theory, this research offers unique opportunities to uncover new quantum states and emergent effects.

To resolve the mechanism of high-temperature superconductivity, it is crucial to identify and systematically describe the underlying physics. This process relies not only on in-depth analysis of experimental data but also on the development of robust theoretical methods for tackling quantum many-body problems. It is also vital to innovate experimental techniques, particularly those capable of directly probing microscopic interactions with energy and momentum resolution [13]. Such techniques are essential for unambiguously identifying the pairing interaction, thereby addressing the longstanding challenge of uncovering the origin of high-T_c superconductivity.

Research on high-temperature superconductivity highlights fundamental challenges while also offering opportunities for significant breakthroughs in both quantum theory and innovative experimental techniques. By closely integrating theoretical and experimental finding, there is hope that the mysteries surrounding high-temperature superconductivity will eventually be unraveled, leading to new advancements in quantum many-body theory.

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