Al-imad Journal of Humanities and Applied Sciences (AJHAS)
مجلة العماد للعلوم الإنسانية والتطبيقية

ISSN: 0000-0000
Volume 1 – Issue 1 – 2025
Pages 16-20

High-Temperature Superconductors: Recent Advances in Mechanisms and Persistent Challenges

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الموصلات الفائقة عالية الحرارة: آليات مستجدة وتحديات قائمة

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Received: 27-04-2025; Accepted: 08-07-2025; Published: 22-07-2025

Abstract:
This review synthesizes cutting-edge developments in high-temperature superconductivity (HTS), focusing on unresolved pairing mechanisms and technological hurdles. Since the discovery of cuprates (1986), iron-based superconductors (2008), and record-breaking hydrides ($T_c \approx 288$ K at 267 GPa), HTS research has expanded dramatically. Despite progress, a unified theory for unconventional pairing in cuprates and iron-based systems remains elusive. We analyze competing mechanisms—spin/orbital fluctuations, phonon-mediated interactions, and intertwined orders—highlighting the pseudogap phase enigma in cuprates. Recent breakthroughs include room-temperature hydrides, nickelate superconductors, and interface-engineered systems. However, persistent challenges include material heterogeneity, vortex pinning limitations, grain boundary issues in practical conductors, and the quest for ambient-pressure room-temperature superconductivity. Bridging fundamental theory with materials engineering is crucial for transformative applications.

Keywords: High-temperature superconductivity, Unconventional-pairing mechanisms, Cuprate superconductors, Iron-based superconductors, Room-temperature hydrides.

الملخص
تُلخص هذه المراجعة أحدث التطورات في مجال الموصلية الفائقة عالية الحرارة *(HTS)*، مع التركيز على آليات الاقتران غير المُحَلّة والعقبات التكنولوجية. منذ اكتشاف الكوبريتات (1986)، والموصلات الفائقة القائمة على الحديد (2008)، والهيدريدات التي حطمت الأرقام القياسية (درجة حرارة ≈ 288 كلفن عند 267 جيجاباسكال)، شهدت أبحاث الموصلية الفائقة عالية الحرارة توسعًا هائلاً. وعلى الرغم من التقدم المُحرز، لا يزال التوصل إلى نظرية موحدة للاقتران غير التقليدي في الكوبريتات والأنظمة القائمة على الحديد أمرًا بعيد المنال. نُحلل الآليات المُتنافسة - تقلبات الدوران/المدار، والتفاعلات بوساطة الفونونات، والترتيبات المتشابكة - مُسلّطين الضوء على لغز طور الفجوة الزائفة في الكوبريتات. تشمل الاكتشافات الحديثة الهيدريدات في درجة حرارة الغرفة، والموصلات الفائقة النيكلاتية، والأنظمة المُصممة هندسيًا للواجهات. ومع ذلك، تشمل التحديات المستمرة تباين المواد، وقيود تثبيت الدوامات، ومشاكل حدود الحبيبات في الموصلات العملية، والسعي لتحقيق موصلية فائقة عند الضغط المحيط ودرجة حرارة الغرفة. يُعدّ الربط بين النظرية الأساسية وهندسة المواد أمرًا بالغ الأهمية للتطبيقات التحويلية.

الكلمات المفتاحية: موصلية فائقة عالية الحرارة، آليات اقتران غير تقليدية، موصلات فائقة كوبريتية، موصلات فائقة قائمة على الحديد، هيدريدات بدرجة حرارة الغرفة.

Introduction

Superconductivity, the quantum state of matter characterized by zero electrical resistance and the expulsion of magnetic fields (Meissner effect), was revolutionized by the discovery of "high-temperature" superconductivity (HTS) in copper-oxide ceramics (cuprates) by Bednorz and Müller in 1986 (Bednorz & Müller, 1986). This discovery shattered the previously perceived T_c ceiling (~23 K) predicted by conventional Bardeen-Cooper-Schrieffer (BCS) theory (Bardeen et al., 1957), which explained superconductivity via electron-phonon coupling forming Cooper pairs. The subsequent discovery of iron-based superconductors (FeSC) in 2008 (Kamihara et al., 2008) and, more dramatically, hydrogen-rich superconductors at megabar pressures exhibiting T_c near room temperature (Drozdov et al., 2015; Somayazulu et al., 2019) further expanded the HTS landscape. Despite these monumental advances, a unified microscopic theory explaining the pairing mechanism in the most prominent ambient-pressure HTS families (cuprates, FeSC) remains elusive, constituting one of the grand challenges in condensed matter physics. This review synthesizes recent progress in understanding the mechanisms underpinning HTS in various material classes and critically examines the persistent scientific and technological challenges hindering their widespread application.

Material Landscape of High-Temperature Superconductors

Cuprates: Layered perovskite structures (e.g., La2-xBaxCuO4 ، YBa2Cu3O7-δ ، Bi2Sr2Can-1CunO2n+4) with superconducting CuO_2 planes. Hole or electron doping of the antiferromagnetic Mott insulating parent state induces superconductivity, with maximum Tc ~ 135 K at ambient pressure (Schilling et al., 1993).

Iron-Based Superconductors (FeSC): Diverse crystal structures (e.g., '1111' like LaFeAsO1-xFx, '122' like BaFe2As2, '11' like FeSe1-xTex) featuring Fe-pnictogen/chalcogen layers. Superconductivity emerges upon doping or isovalent substitution from a metallic, often magnetically ordered parent state. Maximum ambient-pressure Tc~ 55 K (in monolayer FeSe on $SrTiO_3$) (Ge et al., 2015).

Hydride Superconductors: Hydrogen-rich compounds (e.g., H3S ،LaH10 ،YH9 ،C-S-H) synthesized under extreme pressures (>> 100 GPa). Predicted by conventional BCS theory enhanced by high phonon frequencies and strong electron-phonon coupling. Record Tc /s of 203 K in H3S (Drozdov et al., 2015) and ~288 K in C-S-H at 267 GPa (Snider et al., 2020), approaching room temperature.

Nickelates: Recent discovery of superconductivity in infinite-layer nickelates (e.g., Nd 0.8 Sr 0.2 NiO2), structurally analogous to cuprates but with $Ni1^{+}$ instead of $Cu2^{+}$, offering a new comparative platform. Maximum Tc~ 15 K so far (Li et al., 2019).

Other Systems: Includes fullerides, MgB2 (Tc=39 K), and interfacial superconductivity (e.g LaAlO3/SrTiO3 ، FeSe/STO).

Theoretical Frameworks and Recent Mechanistic Insights

The central question revolves around the nature of the attractive interaction binding electrons into Cooper pairs in HTS materials.

Beyond Conventional BCS (Phonons): While phonons mediate pairing in hydrides and MgB2, their role in cuprates and FeSC is debated. Isotope effects are often small or negative, and strong electron correlations dominate. However, recent experiments suggest significant electron-phonon coupling in specific modes or at specific momenta in cuprates and FeSC, potentially cooperating with other mechanisms (Reznik et al., 2006; Johnston et al., 2010).

Spin Fluctuation Mediated Pairing: The proximity of HTS to magnetic instabilities strongly suggests spin fluctuations (SF) as a primary pairing mediator, particularly in cuprates and FeSC. Theories like the spin-fluctuation exchange mechanism often predict d-wave pairing symmetry in cuprates (observed experimentally) and s+-wave symmetry in FeSC (sign-changing order parameter between hole and electron Fermi surfaces) (Scalapino, 2012). Resonant inelastic X-ray scattering (RIXS) and inelastic neutron scattering (INS) provide direct evidence for spin fluctuations correlated with Tc (Le Tacon et al., 2011).

Orbital Fluctuations: In FeSC, orbital ordering and fluctuations are prominent. Theories propose that orbital fluctuations could promote s++-wave pairing (sign-preserving) (Kontani & Onari, 2010). The interplay and relative strength of spin vs. orbital fluctuations remain a key area of investigation, often material-dependent.

Excitonic, Plasmons, and Other Mechanisms: More exotic proposals involving inter-band excitations (excitons), charge fluctuations, or plasmon-mediated pairing have been suggested, though less widely supported by current evidence.

Pseudogap Phase (Cuprates): A defining feature of underdoped cuprates is the pseudogap phase above Tc, where electronic states are gapped but without long-range phase coherence. Its origin (precursor superconductivity, competing orders like charge density waves (CDW) or spin density waves (SDW), or a distinct phase) and its relationship to superconductivity are intensely debated. Recent scanning tunneling microscopy (STM) and X-ray diffraction studies show intertwined CDW and superconducting orders, suggesting a complex interplay (da Silva Neto et al., 2014; Comin & Damascelli, 2016).

Unconventional Pairing Symmetry: Cuprates exhibit dx^2-y^2-wave pairing. FeSC show a variety, including s± and potentially nodal s-wave or d-wave depending on material and doping. Nickelates also show signs of unconventional pairing. Establishing the precise gap structure is crucial for identifying the pairing mechanism.

Role of Correlations: Strong electron-electron correlations are universally acknowledged as crucial in cuprates (Mott physics) and significant in FeSC and nickelates. Dynamical mean-field theory (DMFT) and related approaches are essential tools for modeling these systems (Kotliar et al., 2006). The multi-orbital nature of FeSC adds further complexity.

Recent Breakthroughs and Material Developments

Hydride Room-Temperature Superconductivity: The discovery of superconductivity above 200 K in H3S (Drozdov et al., 2015) and near 288 K in carbonaceous sulfur hydride (C-S-H) under extreme pressures (Snider et al., 2020) marked a watershed moment. These materials are understood within a strong-coupling phonon-mediated BCS framework, albeit requiring immense pressures for metallization and stability. The search for metastable or chemically precompressed hydrides stable at lower pressures is intense (e.g., ternary hydrides like LaBH8).

Nickelate Superconductors: The discovery of superconductivity in infinite-layer nickelates (RNiO2, R=Nd, Pr) (Li et al., 2019) provides a long-awaited analog to cuprates. While similarities exist (d9 configuration, layered structure, doping dependence), key differences emerge (prominent rare-earth 5d states near EF, distinct magnetic behavior, lower Tc), challenging direct cuprate parallels and offering new insights into the role of 3d orbitals and correlations (Hwang et al., 2022).

Interface Engineering: Enhanced Tc in monolayer FeSe on SrTiO3 (STO) (Ge et al., 2015) highlights the role of interfacial phonons and charge transfer. Engineering such interfaces provides a pathway to tune electronic structure and pairing interactions.

Advances in Characterization: Techniques like high-field STM/STS, quantum oscillation measurements under high pressure, momentum-resolved electron energy loss spectroscopy (M-EELS), advanced RIXS, and muon spin rotation (μSR) are providing unprecedented microscopic details on electronic structure, gap symmetry, magnetic excitations, and competing orders.

Persistent Scientific Challenges

Unified Pairing Mechanism: A single, universally accepted microscopic theory explaining pairing in cuprates and FeSC remains absent. Disentangling the contributions of spin, orbital, charge, and lattice degrees of freedom and their interplay is immensely complex.

Pseudogap Enigma: The origin and fundamental nature of the pseudogap phase in cuprates, its relationship to superconductivity, and whether it exists in other HTS families are unresolved.

Material Complexity and Heterogeneity: Intrinsic spatial inhomogeneity (chemical, structural, electronic) in cuprates and FeSC complicates the interpretation of experiments and theoretical modeling. Understanding the role of dopants, defects, and disorder is critical.

Role of Phonons in Correlated Systems: Quantifying the contribution of phonons to pairing and their interaction with electronic correlations in cuprates and FeSC is challenging but essential for a complete picture.

Predictive Theory: The ability to reliably predict new HTS materials with higher Tc (especially at ambient pressure) based on fundamental principles is still limited.

Technological and Application Challenges

Ambient Pressure Room-Temperature Superconductivity (AP-RTSC): The holy grail. Hydrides require impractical megabar pressures. No ambient-pressure material approaches room temperature Tc. Discovering or designing such a material remains the ultimate challenge.

Material Synthesis and Processing: Fabricating practical conductors (wires, tapes, films) from brittle, anisotropic cuprates (REBCO) and FeSC is difficult and costly. Achieving high critical current density (Jc) requires effective pinning of magnetic vortices. Hydride synthesis requires complex diamond anvil cells or advanced high-pressure techniques unsuitable for applications.

Vortex Physics and Pinning: At finite temperatures and magnetic fields, vortices penetrate type-II superconductors. Movement of vortices dissipates energy (finite resistance). Effective pinning centers are needed to immobilize vortices and maintain high Jc in applied fields, especially for high-field magnets and power applications.

Grain Boundaries: High-angle grain boundaries in cuprates act as weak links, drastically reducing Jc in polycrystalline materials. Biaxially textured templates or epitaxial films are required, increasing cost. FeSC generally have better grain boundary properties but are still challenging.

Mechanical Properties and Stability: Many HTS materials are brittle ceramics, posing challenges for winding into coils and long-term mechanical stability. Hydrides synthesized under pressure are inherently unstable upon decompression.

Cost: The complex synthesis and processing required for cuprate and FeSC wires/tapes make them significantly more expensive than conventional Nb-based superconductors or copper, hindering widespread adoption despite superior performance.

Cryogenics: While HTS reduce cooling requirements compared to LTS, widespread application still benefits from or requires cryogenic systems (liquid nitrogen for cuprates, ~77K). True room-temperature operation would revolutionize technology.

Conclusion and Future Perspectives

High-temperature superconductivity continues to be one of the most vibrant and challenging frontiers in physics and materials science. While the dream of ambient-pressure room-temperature superconductivity remains unrealized, the discovery of hydrides with near-room-Tc under pressure validates the potential for phonon-mediated mechanisms at high Tc. The enduring mysteries of pairing in cuprates and iron-based superconductors drive fundamental research, revealing the rich physics of strongly correlated electron systems, intertwined orders, and unconventional superconductivity. The emergence of nickelates provides a new comparative platform. Significant progress has been made in understanding the complex phase diagrams, the nature of competing orders like the pseudogap and CDW, and the role of various excitations via advanced experimental probes and sophisticated theoretical models. However, a unified microscopic theory is still lacking. On the technological front, while applications of cuprate and FeSC wires/tapes in niche high-field magnets and power devices are growing, formidable challenges related to material synthesis, vortex pinning, grain boundaries, mechanical properties, and cost persist, especially for widespread grid-scale applications. Future research must continue to bridge fundamental understanding with materials engineering, exploring novel synthesis routes, advanced characterization under operando conditions, defect engineering for pinning, and theoretical predictions guiding the search for new materials – particularly metastable hydrides or entirely new classes stable at ambient conditions. The pursuit of high-temperature superconductivity not only holds transformative technological promise but also deepens our understanding of quantum matter.

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