Research Progress on Novel High-Temperature Superconducting Materials (Postprint)

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Abstract

Since its discovery in 2011, 104 years have elapsed for superconductivity. During this period, the objects of study in superconductivity research have evolved from simple metals to alloys, and then to complex compounds, with the superconducting transition temperature gradually increasing and currently reaching 164 K (high-pressure measurement). In the course of investigating novel high-temperature superconducting materials, the understanding of superconducting physics has also been continually evolving. The Bardeen-Cooper-Schrieffer theory, which has achieved tremendous success in the field of superconductivity, appears to be no longer applicable to some new unconventional superconductors, thus the understanding of unconventional superconducting mechanisms is also on the verge of major breakthroughs. This paper will briefly introduce three classes of high-temperature superconductors discovered to date: copper oxide superconductors, iron-based superconductors, and magnesium diboride superconductors. Drawing upon some experiences from current research, prospects for discovering new superconductors will be presented.

Full Text

Preamble

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Development of Research on New High Temperature Superconductors

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ABSTRACT

Since the discovery of superconductivity in 1911, 104 years have elapsed. During this period, superconducting materials have evolved from simple metals to alloys and then to complex compounds, with the superconducting transition temperature gradually increasing to a proven maximum of 164 K (under high pressure). The investigation of novel high-temperature superconductors has continuously updated our understanding of superconducting physics. The Bardeen-Cooper-Schrieffer (BCS) theory, which achieved tremendous success in conventional superconductors, appears inapplicable to some new unconventional superconductors, suggesting that understanding unconventional superconducting mechanisms faces a major breakthrough. This review briefly introduces three classes of high-temperature superconductors discovered to date: copper oxide superconductors, iron-based superconductors, and magnesium diboride superconductors. Based on accumulated research experience, we propose perspectives on how to search for new superconductors.

KEY WORDS superconductors, superconductivity, Cooper pairs, exploration of new superconductors

Since its discovery in 1911, superconductivity has continuously attracted widespread scientific attention due to its unique charm. This fascination stems not only from its demonstration of quantum mechanics in condensed matter but also from its potential applications. Achieving room-temperature superconductivity remains our ultimate goal. Superconductivity is a phenomenon that occurs when electron systems undergo quantum condensation in condensed matter, exhibiting many exotic properties such as zero resistance at finite temperatures and perfect diamagnetism. Based on these remarkable properties, numerous irreplaceable applications can be developed. Superconductivity holds promise for applications in energy, healthcare, transportation, national defense, and large-scale scientific projects, making it a priority for developed nations worldwide. Currently, the United States, Japan, and the European Union represent the major powers investing heavily in superconducting materials, physics, and technology to secure advantages in future large-scale applications.

The operating environment for superconductors is below their critical temperature. Air contains abundant nitrogen resources, enabling the production of the most economical cryogen—liquid nitrogen—with a boiling point of 77.3 K (approximately -196°C). Therefore, discovering superconductors with critical temperatures above 77.3 K is crucial. High-temperature superconductors are generally defined as those with critical temperatures exceeding 40 K, as the conventional electron-phonon mechanism imposes an upper limit of about 40 K —the so-called McMillan limit. Consequently, the discovery of superconductors breaking the 40 K barrier is extremely significant. Currently, superconducting series exceeding 40 K include copper oxide superconductors and iron-based superconductors, while magnesium diboride superconductors have critical temperatures around 40 K. This article briefly introduces the current status of these three classes of high-temperature superconductors and offers perspectives on future superconducting material development, along with ideas for obtaining novel high-temperature superconductors.

1. Efforts to Pursue High-Temperature Superconducting Materials

Before the end of 1986, extensive work in superconducting material exploration led to the discovery of numerous new superconductors, ranging from single-element to multi-element alloys, oxides, and organic materials—hundreds of materials in total exhibiting superconducting properties. Interested readers may consult reference books on superconducting materials [1]. Prior to 1930, research focused primarily on single-element superconductors. From the 1930s to 1950s, many alloy superconductors, nitrides, and carbides were discovered, where nitrogen and carbon atoms provided strong bonding and suitable phonon modes for electron-phonon coupling to form superconductivity. From the 1950s to 1970s, numerous A15-type superconductors (with β-W structure) were synthesized, such as Nb_3Sn, $Nb_3(Al_{0\cdot75}Ge_{0\cdot25})$, and V_3Si, with Nb_3Ge reaching temperatures up to 23.2 K. These discoveries directly drove the development of large-scale superconducting applications. For instance, NbTi alloy superconducting wires were used to fabricate superconducting magnets producing several Tesla magnetic fields at liquid helium temperatures, enabling the mass production of MRI magnets and superconducting tokamak magnets for nuclear fusion research. Using Nb_3Sn superconducting materials, next-generation superconducting magnets were developed that could generate magnetic fields up to 18 Tesla at liquid helium temperatures, meeting requirements for high-field MRI and scientific experiments.

During the 1970s and 1980s, considerable interest emerged in a large class of layered compound superconductors (compounds of S, Se, Te). These superconductors exhibited strong two-dimensional characteristics, often with coexisting and competing superconductivity and charge-density-wave (CDW) order. Typical materials included 2H-$NbSe_2$, 2H-$TaSe_2$, and 2H-TaS_2. Many issues in this system remain unexplained, such as the formation mechanism of charge density wave order and its competition with superconductivity. Similar systems include spin-density-wave superconductors like $CeRu_2$ and $LnNi_2B_2C$, where Ln represents Y and rare earth elements such as Lu, Er, Ho, and Sm. In the mid-to-late 1970s, researchers noted a large class of superconductors with electron effective masses more than 100 times that of free electrons in the normal state, termed heavy fermion superconductors. These materials included $CeCu_2Si_2$ and UPt_3—compounds of f-orbital electron elements and heavy-element metals. Due to the heavy effective mass of Cooper pairs in heavy fermion systems, superconducting temperatures might not be high according to Bose condensation principles. However, these systems are rich in novel physical properties, with pairing possibly mediated by antiferromagnetic fluctuations and wavefunctions possessing d-wave and p-wave symmetry. Recent important advances have emerged in phase diagram and electronic ground state studies of heavy fermion systems, such as quantum critical phase transitions (QCP), representing a significant direction in current condensed matter physics research.

Also in the mid-1970s, organic conductors were discovered. These materials frequently exhibited various phase transitions due to low-dimensional characteristics, causing structural instabilities and numerous exotic phenomena in electrical transport measurements. In 1980, French scientist Denis Jerome discovered the first organic superconductor in the $(TMTSF)_2X$ family. In 1987, Urayama et al. found superconductivity with Tc = 11 K in $(BEDT\text{-}TTF)_2Cu(SCN)_2$. Recent discoveries reveal that organic superconductors share many properties with high-temperature oxide superconductors, such as spin fluctuations playing important roles. Research on organic superconductors presents many opportunities for breakthroughs in both materials and superconducting science.

The discovery of copper oxide superconductors in 1986 and iron-based superconductors with transition temperatures reaching 55 K in 2008 opened new chapters in high-temperature superconducting materials and unconventional superconducting mechanism research. [Figure 1: see original paper] displays the discovery timeline and superconducting transition temperatures of typical superconductors, while Table 1 categorizes superconductors and lists the highest transition temperature for each family.

In the 75 years following the discovery of superconductivity—until 1986—the superconducting transition temperature had only been raised to about 23.2 K, primarily in single-element metals and multi-element alloys. Some superconductors were also discovered in oxide materials, such as oxygen-deficient $SrTiO_3$ (Tc = 0.2-0.4 K) and Ba_1 K BiO_3 (Tc 30 K), Li_1 Ti_2 O_4 (Tc 12 K). These materials generally exhibited low superfluid density, and the superconducting physics might still involve phonons as the pairing medium.

In October 1986, scientists K. A. Müller and J. G. Bednorz at IBM’ s Zurich research laboratory discovered possible superconducting signatures below 30 K in the oxide ceramic material LaBaCuO [2], later confirmed by other groups. Müller and Bednorz received the 1988 Nobel Prize in Physics for this discovery. Subsequently, in the worldwide race for high-temperature superconductors, scientists prepared nearly a hundred superconductors across multiple series. Chinese scientists (Zhao Zhongxian, Chen Liquan, et al.) [3] and American scientists (Chu Ching-wu, Wu Maokun, et al.) [4] independently discovered $YBa_2Cu_3O_7\ \delta$ superconductors operating above liquid nitrogen temperature (77.3 K). Currently, the transition temperature of $HgBa_2Ca_2Cu_3O_9\ \delta$ copper oxide superconductors has reached over 130 K at ambient pressure and 164 K under high pressure. Copper oxide superconductors have begun to show promise in certain applications.

Based on different chemical compositions and structures, copper oxide superconductors are classified into several families: lanthanum-based superconductors (typical formula $La_2\ \ Sr\ CuO_4$ or $La_2\ \ Ba\ CuO_4$, 简称 214 structure); yttrium barium copper oxide superconductors (yttrium-based, typical formula $YBa_2Cu_3O_7$ or $YBa_2Cu_4O_8$, 简称 123 or 124 structure, with 247 structure also reported); bismuth-based superconductors ($Bi_2Sr_2CuO_6$ or Bi-2201, $Bi_2Sr_2CaCu_2O_8$ or Bi-2212, $Bi_2Sr_2Ca_2Cu_3O_{10}$ or Bi-2223); thallium-based superconductors ($Tl_2Ba_2CuO_6$ or Tl-2201, $Tl_2Ba_2CaCu_2O_8$ or Tl-2212, $Tl_2Ba_2Ca_2Cu_3O_{10}$ or Tl-2223); and mercury-based superconductors $HgBa_2Ca\ \ _1Cu\ O_2\ \ \ _1\ \delta$ (n=1-3) structures. [Figure 2: see original paper] shows the atomic structures of several typical copper oxide superconductors, revealing that all share CuO_2 planes as their main structural feature, with Cu^{2+} and O^{2-} alternating to form a square lattice. Superconductivity is fundamentally believed to originate from these CuO_2 planes, which can be single-layer (as in $La_2\ \ Sr\ CuO_4$), double-layer adjacent (as in $YBa_2Cu_3O_7$), or triple-layer adjacent (as in $HgBa_2Ca_2Cu_3O_9\ \delta$). [Figure 3: see original paper] displays the structures of Hg-based superconductors with the formula $HgBa_2Ca\ \ _1Cu\ O_2\ \ \ _1\ \delta$ (n=1-3), showing compounds with progressively increasing numbers of CuO_2 layers per unit cell. Researchers have found that superconducting transition temperature increases with layer number up to a certain point before decreasing. One possible explanation is that multi-layer CuO_2 materials have higher superfluid electron density. If the superconducting transition temperature is determined by superfluid density—i.e., phase stiffness—this picture appears quite reasonable. Detailed structures and properties of these materials are available in other references [5] and will not be elaborated here.

2.2 Brief Introduction to the Mechanism of Copper Oxide Superconductors

The superconducting mechanism of copper oxide superconductors represents one of the most important topics facing condensed matter physicists. In these materials, strong electron-electron interactions lead to normal-state electronic behavior that cannot be understood using Fermi liquid-based quasiparticle pictures or band theory knowledge. Although the superconducting state still arises from Cooper pair condensation, numerous experiments suggest that the primary pairing mechanism may not be electron-phonon coupling. Isotope effect measurements on oxygen revealed that the coefficient α in the isotope effect formula

TcMˆα = C (where C is a constant) is nearly zero near the optimal doping point with the highest superconducting transition temperature, while reaching or exceeding 1 in underdoped regions with lower transition temperatures [7]. In contrast, Bardeen-Cooper-Schrieffer (BCS) theory predicts α 0.5 in the weak coupling limit.

Simple tight-binding electronic band structure calculations suggest that the common CuO_2 planes in copper oxides consist of Cu^{2+} and O^{2-} ions. Since Cu^{2+} has nine electrons in its outermost 3d orbital, unoccupied states exist. Band calculations indicate that the parent material should be a conductor with half-filled bands. However, experiments reveal that the parent material is a Mott insulator with long-range antiferromagnetic characteristics. The Hubbard model can approximately describe both the insulating nature of the parent material (e.g., La_2CuO_4) and the insulating and conducting behavior of the doped superconductor' s normal state. As shown in [Figure 4: see original paper], the undoped parent is a Mott insulator with long-range antiferromagnetism. With hole or electron doping, the system gradually becomes conductive, and superconductivity emerges at low temperatures. On the hole-doping side, superconductivity appears beneath an inverted parabola in the region 0.05 < p < 0.28, with the superconducting transition temperature describable by the empirical formula:

T_c^{max} = 1 - 82.6(p - 0.16)^2

where T_c^{max} represents the critical temperature at the optimal doping point p = 0.16. The pairing symmetry in the hole-doped region has been well-established as d-wave. Below a certain temperature T*, a pseudogap appears in the electronic energy spectrum at the Fermi surface, with its onset temperature varying depending on the measured property but sharing similar symmetry with the superconducting gap. At another lower temperature T_v, strong Nernst signals are observed, possibly corresponding to pre-formed mobile carriers. On the electron-doped side, the antiferromagnetic region persists over a wider doping range, with superconductivity emerging only around 0.10 electrons per Cu ion. Whether the pairing symmetry is d-wave and whether a pseudogap exists in the normal state on the electron-doped side remain unresolved.

Since high-temperature superconductivity arises from doping a Mott insulator, the system simultaneously exhibits numerous competing phases, including stripe phases, electronic crystal phases, charge density waves (CDW), spin density waves (SDW), and antiferromagnetic order (AF). A significant difference between high-temperature and conventional superconductors is that in the former, the Fermi surface evolves continuously with temperature, and the density of states near ($\pm\pi$, 0) or (0, $\pm\pi$) in momentum space is gradually suppressed, creating the so-called pseudogap [8]. Neutron scattering measurements reveal new electronic ordered phases in the pseudogap region, such as stripe phases [9]. Theoretical models suggest that this suppression of electronic density of states near the Fermi surface results from pre-formed electron pairs that condense when temperature drops below T_c [10-12]. While this pre-pairing picture is intuitive, direct experimental evidence remains lacking.

The prevailing view on high-temperature superconducting mechanisms posits that electron pairing occurs under a background of magnetic fluctuations, followed by superconducting condensation. Representative theoretical models include Anderson' s Resonating Valence Bond (RVB) model [12] and the antiferromagnetic spin fluctuation-mediated pairing model [6]. The RVB model proposes that in spin-1/2 systems, neighboring opposite spins form spin singlets, with the ground state being a quantum superposition of these singlets—a so-called quantum fluctuating liquid (spin liquid). These neighboring antiparallel spin pairs experience quantum fluctuations, introducing constraints beyond pure paramagnetic states. The wavefunction describing these antiparallel spin pairs resembles the spin part of superconducting pair wavefunctions [12]. When charge carriers move, the phase of these RVB spin-singlet pairs gradually correlates. Below T__c, itinerant electrons establish phase coherence. Anderson provided a comprehensive interpretation of this model [12], though experimental verification remains challenging. Some experimental evidence now suggests the pseudogap region contains spin-singlet pairing [13], while strong Nernst signals [10] and entropy changes related to superconductivity [11] support this pre-pairing picture.

Direct verification of the RVB model is difficult because measuring the quantum fluctuations in the RVB ground state would reveal new elementary excitations: spinons (chargeless but spin-1/2) and holons (single electron charge but spinless). Experimental physicists are currently striving to detect these two novel quasiparticles.

Another pairing mechanism based on exchange mediation is the so-called antiferromagnetic exchange model [6]. In this picture, two initial electrons with momenta k and -k scatter to k' and -k' states by exchanging one or multiple bosons, such as antiferromagnetic fluctuations. This exchange scattering pairing mode represents the essence of BCS theory, still borrowing the electron-phonon coupling picture. However, since antiferromagnetic fluctuations originate from electron-electron interactions, the pairing interaction potential V__k is positive, whereas in the original BCS phonon exchange picture, V__k is negative. According to Eliashberg theory, the superconducting gap at momentum point k on the Fermi surface can be described by:

$\Delta(\mathrm{k}) = -\ k' \quad V\{\mathrm{kk'}\}\ [\Delta(\mathrm{k'})\ /\ 2\mathrm{E}(\mathrm{k'})]$

This pairing picture is illustrated in [Figure 5: see original paper], where the square frame shows the Brillouin zone of copper oxide superconductors. The black solid line and shaded region depict the Fermi surface and d-wave gap magnitude within the local density approximation, respectively. Hollow arrows represent the two pre-scattering electrons with opposite spin and momentum, while solid arrows show the post-scattering pair, with curved dashed lines indicating the scattering process. Diagonal lines represent nodes where the gap is zero. The initial state momentum (k__x, k__y) transitions to the final state (k__x' , k__y') by exchanging antiferromagnetic spin fluctuations. This physical picture naturally yields a d__{x^2-y^2} pairing order parameter: Δ__s cos k__x - cos k__y.

Experimental evidence supporting magnetic pairing mechanisms includes superconducting gap symmetry similar to the pseudogap—both exhibiting d-wave symmetry [14, 15]. Inelastic neutron scattering experiments measuring the imaginary part of spin susceptibility '' (after phonon background subtraction) show a (π, π) resonance peak at 41 meV [16], a phenomenon occurring prominently in the superconducting state. In contrast, strong kinks observed in electron energy dispersion relations by angle-resolved photoemission spectroscopy indicate very strong electron-phonon coupling [17], leading some to propose phonon-mediated pairing hypotheses. Strong polarization through Jahn-Teller effects in copper oxides could also induce pairing. Thus, the mechanism of copper oxide superconductors remains far from resolved. Continued experimental and theoretical work will eventually clarify the superconducting mechanism and may lead to even higher temperature superconductivity. The normal state of copper oxide superconductors exhibits many novel phenomena, such as the pseudogap, constituting a central problem in condensed matter physics. This anomalous metallic behavior in the normal state arises from electron correlation effects, which are widespread in other transition metal compound systems, gradually forming an entirely new frontier field: correlated electron states.

2.3 Studies on Vortex Dynamics and Mixed-State Physics of High-Temperature Superconductors

After entering the superconducting state, the phase coherence among charge carriers causes superconductors to expel external magnetic fields. When the external field exceeds a certain value (the lower critical field H_{c1}), magnetic flux lines can nucleate inside the superconductor through thermal activation or quantum processes due to large surface shielding currents. Superconducting electron coherence requires that any area enclosed by a superconductor must contain quantized magnetic flux. Based on the sign of interfacial energy between superconducting and normal states (comparing magnetic energy within the penetration depth to condensation energy within the coherence length), superconductors are classified as Type I (positive interfacial energy) or Type II (negative interfacial energy). Since Type II superconductors have negative interfacial energy, the magnetic flux inside becomes quantized in units of the flux quantum Φ_0 = h/2e = 2.07$×10^{-15}$ Vs. Such a line structure surrounded by supercurrent, containing one flux quantum, is called a vortex line or quantum vortex. This state composed of superconducting regions and vortex lines is termed the mixed state. Most superconductors are Type II and exhibit mixed states. In the mixed state, if vortex lines can be effectively pinned, superconductors can carry large supercurrents. Ginzburg and Landau established the Ginzburg-Landau theory from Landau' s theory of second-order phase transitions, successfully describing the behavior of pairing wavefunctions and magnetic fields in superconductors, providing vortex line structures and important parameters for the mixed state, such as the superconducting coherence length , magnetic field penetration depth λ{GL} *(called G-L penetration depth to distinguish it from the London surface penetration depth), and the G-L parameter*

$(=\lambda/\ )$. *When the external field increases further to* $H\{c2\}$, the superconductor becomes completely normal, making H_{c2}(T) the upper critical field. Due to mutual repulsion between vortex lines (stronger at closer distances), they form periodic arrangements (generally triangular lattices) when thermal fluctuations are weak and defects are minimal, resembling atomic crystal lattices. Abrikosov later used G-L theory to calculate the vortex lattice for s-wave superconductors, finding that near H_{c2}(T), the vortex lattice should be a periodic array. These vortex line states are called vortex matter. Fortunately, materials generally contain defects that act as potential wells for vortex lines, pinning them and enabling Type II superconductors to carry large supercurrents even in the mixed state—this is why Type II superconductors can be fabricated into superconducting magnets generating strong magnetic fields.

Since the discovery of high-temperature superconductors in late 1986, vortex dynamics has rapidly developed as an important branch of superconducting physics research. The mixed-state phase diagram, shown in [Figure 6: see original paper], is extremely rich. New physical models have been proposed, and many novel phenomena observed, greatly enriching superconducting physics and laying a solid theoretical foundation for strong-current applications of high-temperature superconductors. The past two decades of vortex dynamics development can be described as "extremely lively." Although the field continues to deepen, its general outline has been established. Vortex dynamics, once merely a chapter in early textbooks to explain G-L theory, has now become an indispensable and substantial branch of superconducting physics.

Compared with conventional superconductors, high-temperature superconductors exhibit intrinsic characteristics that determine their similarities and differences in vortex dynamics. First, the coherence length of high-temperature superconductors is about 1 nm, one to two orders of magnitude smaller than conventional superconductors. Since single pinning center energy scales with ^{n} (n=1-3), the elementary pinning energy in high-temperature superconductors is much lower, requiring collective pinning to be effective. Second, many high-temperature superconductors possess extreme anisotropy, describable by quasi-two-dimensional superconducting planes with interlayer Josephson coupling. Vortex lines can be pictured as vortex pancakes on superconducting planes connected by Josephson vortex strings. This picture suits extremely anisotropic systems like Bi, Tl, or Hg 2212 and 2223 systems, or $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ multilayers. For less anisotropic Bi, Tl, or Hg 1212 and 1223 systems, and $YBa_2Cu_3O_7$, anisotropic three-dimensional continuum models remain appropriate. Due to this anisotropy, the mixed-state phase diagram of high-temperature superconductors exhibits complex and interesting fine structures, including many previously unknown phase boundaries. Third, high operating temperatures enable strong thermal fluctuations that reduce collective pinning potential U_c and greatly enhance thermally activated vortex creep. Fourth, high-temperature superconductors have large _n/ ratios, where high _n values correspond to small damping constants (Bardeen-Stephen constant). Low values significantly reduce the volume for most probable vortex hopping (or tunneling), favoring quantum tunneling processes and resulting in large quantum tunneling rates and fluctuation amplitudes, where _n represents normal-state resistivity. Any two or three of these four fundamental features combine to create new characteristics of high-temperature superconductors.

Due to these features, vortex dynamics and mixed-state phase diagrams in high-temperature superconductors are exceptionally rich. Defects in high-temperature superconductors are small-scale, so vortex pinning occurs via collective pinning modes. In such systems, the activation energy for vortex motion diverges in the small current limit, theoretically predicting the existence of a disordered vortex solid state (vortex glass state) with zero dissipation. References [18, 19] provide detailed discussions on vortex dynamics in high-temperature superconductors.

2.4 Applied Research on Copper Oxide Superconductors

Although copper oxide superconductors can achieve critical temperatures up to 130 K at ambient pressure, they have not yet enabled large-scale strong-current applications due to several inherent drawbacks. First, their extremely strong layered structure leads to large electron effective mass anisotropy ratios m_c/m_{ab}, reaching 50-100 for YBaCuO and up to 10,000 for Bi-2212. This extreme anisotropy creates vortex pancakes in the mixed state with small elastic energy, resulting in strong vortex position fluctuations that make it difficult to support superconducting critical currents at high magnetic fields. Second, the superconducting coherence length is very short, with in-plane coherence lengths of approximately 1-2 nm and c-axis coherence lengths of only 0.2-0.5 nm. These two drawbacks prevent implementation of the industrially common powder-in-tube method for wire fabrication. For Bi-2223 materials, despite extreme anisotropy, powder-in-tube technology combined with pressing and sintering can produce oriented kilometer-length wires with critical currents around 200 A after high-pressure oxygen treatment. However, the sheath material must be silver, making costs difficult to reduce to low values (e.g., typical copper wire costs \$2-5/kA-m, while silver-sheathed materials may target \$50-100/kA-m). Additionally, this material' s greatest disadvantage is that critical current rapidly disappears when the magnetic field increases slightly, as the extremely anisotropy-induced vortex pancakes become highly mobile.

[Figure 7: see original paper] presents the temperature-field phase diagrams for $REBa_2Cu_3O_7\ \delta$ (REBCO, where RE is Y or rare earth elements) and $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) and $Bi_2Sr_2Ca_2Cu_3O_{12}$ (Bi-2223) materials, showing significant differences in behavior. REBCO performs much better in external magnetic fields, maintaining effective supercurrent capacity in strong magnetic fields at liquid nitrogen temperatures. While Bi-2223 wires may have advantages in short-distance cable applications, particularly before YBaCuO second-generation tape technology matures.

Copper oxide superconductor applications manifest in several important areas: (1) YBaCuO second-generation tapes (coated conductors); (2) high-temperature superconducting filters based on YBaCuO or Tl-2212 thin film superconductors; (3) superconducting quantum interference devices based on YBaCuO or other systems; and (4) bulk materials prepared from YBaCuO. These are briefly discussed below.

2.4.1 YBCO Coated Conductors Significant progress has been achieved using highly textured Ni-W substrates coated with buffer layers (such as CeO_2) followed by YBaCuO epitaxial superconducting films prepared via metal organic chemical vapor deposition (MOCVD) or pulsed laser deposition (PLD). These films are collectively termed second-generation high-temperature superconducting tapes or coated conductors, as shown in [Figure 8: see original paper]. The metal substrate is typically highly textured Ni-W tape; buffer layers include CeO_2, MgO, or $SrTiO_3$ oxides; HTS represents the superconducting film layer; and protective silver or copper films are deposited on the surface. American Superconductor Corporation and SuperPower have produced 1500 m lengths with 200 A/cm-w current and 1000 m lengths with 300 A/cm-w current using ion bombardment assisted deposition (IBAD) and MOCVD. Japan' s Fujikura has prepared 1000 m lengths reaching 572 A/cm-w via chemical vapor deposition, while Sumimoto achieved 500 m lengths with 700 A/cm-w using chemical methods. Recently, Korean companies have also made significant progress, producing 1000 m lengths with 420 A/cm-w current.

This technology faces considerable challenges in producing complete kilometer-scale high-critical-current tapes. Main difficulties include: (1) ensuring excellent texture quality for Ni-W substrates, multiple buffer layers, and final YBaCuO films; (2) eliminating any cracks in the superconducting layer—given the short coherence length of Cooper pairs, cracks prevent supercurrent flow, which is unacceptable for applications; and (3) maintaining texture and reducing defects as superconducting layer thickness increases to 1 m, which is difficult while trying to increase total superconducting current per wire. Recent international work using $GdBa_2Cu_3O_7$ systems appears to improve this issue, achieving higher single-wire supercurrents. In China, systematic research is being conducted at the Suzhou Institute for Advanced Study, Shanghai Jiao Tong University, and Shanghai University, with short-sample critical currents reaching internationally advanced levels.

2.4.2 Superconducting Electronic Devices Superconducting electronic materials are playing increasingly important roles and receiving high international attention due to their indispensable applications in national defense, healthcare, environmental monitoring, radio astronomy, quantum information, and other cutting-edge fields. Superconducting SQUID devices offer advantages in submarine detection, superconducting filters in communications, and superconducting hot-electron devices in single-photon and THz signal detection. The U.S. has vigorously developed superconducting all-digital RF systems for defense projects, fully exploiting superconducting electronics' ultra-high-speed, low-loss performance. Recent high-sensitivity superconducting detection system projects organized by Europe, America, and Japan have accelerated development and application toward even higher sensitivity. Rapid advances in refrigeration technology continue to accelerate superconducting electronic material and device development. In China, Peking University and Nanjing University have conducted distinctive research on high-temperature superconducting SQUID applications, with some metrics reaching internationally advanced levels.

2.4.3 High-Temperature Superconducting Filter Applications High-temperature superconducting filters exhibit high out-of-band rejection, extremely low in-band insertion loss, and steep band edges, achieving nearly ideal filter performance. Consequently, superconducting filter systems offer unparalleled advantages in filter performance and frequency resource utilization efficiency compared to other filters. Current mobile communications face issues including frequency resource scarcity, low anti-RF interference capability, small base station coverage, and poor call quality—problems that high-temperature superconducting technology can effectively address. Therefore, as mobile communications develop, demand for superconducting filters will become increasingly urgent. Application of high-temperature superconducting filter systems in mobile communication base stations will not only become a breakthrough for practical superconducting technology industrialization but also significantly impact daily life and hold important social significance. Additionally, superconducting filters have absolute advantages in defense communications filtering, such as missile guidance and satellite return communications. Thus, development of special superconducting filters is needed, including narrowband filters, high-power filters, and frequency-tunable filters. Tsinghua University, the Institute of Physics of the Chinese Academy of Sciences, and Chengdu University of Electronic Science and Technology have made excellent progress in high-temperature superconducting filters.

2.4.4 Bi-2212 Wires/Tapes Bi-2212 tapes/wires show promise for high-field applications. At 4.2 K and extremely high fields up to 45 T, they can still carry engineering current densities of practical significance. Due to Bi-2212' s advantages in high-field and ultra-high-field magnet fabrication, Europe, America, and Japan attach great importance to this material and have achieved remarkable progress, completing trials of 30 T all-superconducting magnets. Bi-2212 has clear application prospects in high-field magnet systems, high-resolution NMR spectrometer magnets, and energy storage and accelerator magnets requiring high magnetic fields. In China, the Northwest Institute for Nonferrous Metal Research and Western Superconducting Technologies are conducting research in this area.

2.4.5 YBCO Bulk Materials Yttrium (gadolinium, samarium) barium copper oxide bulk materials have special application prospects because they can trap high magnetic fields, such as in magnetic levitation, flywheel energy storage, and wastewater treatment. Therefore, this direction continues to attract attention from important international research institutions. Current best performance achieves trapped magnetic fields of 25 T at 4.2 K and 17 T at 25 K, with diameters reaching about 20 cm. New fabrication methods have been developed, such as using thin films as seeds to prepare high-quality large single-domain Y(Gd,Sm)BaCuO materials with improved magnetic levitation forces. In China, good results have been achieved in YBCO bulk melt-textured materials, with ongoing research at the General Research Institute for Nonferrous Metals, Shaanxi Normal University, and Shanghai Jiao Tong University, where some metrics have reached internationally advanced levels.

3. Iron-Based Superconductor Materials and Physics Research

The breakthrough in iron-based superconductor research occurred in late February 2008, when Professor Hosono’ s group at Tokyo Institute of Technology discovered that doping the parent material LaFeAsO with F elements could achieve superconductivity at 26 K [21], opening a new chapter in high-temperature superconductivity research.

3.1 Structural Types and Basic Characteristics of Iron-Based Superconductors

The research history of iron arsenide parent materials ROFeAs (where R represents rare earth elements La, Pr, Ce, Nd, Sm, etc.) dates back to 1974 when Jeitschko at DuPont searched for new functional materials. Subsequently, a German research group synthesized a series of new materials with the same ZrCuSiAs structure, named quaternary phosphorus oxides LnOMPn (Ln = La, Ce, Pr, Nd, Sm, Eu, Gd; M = Mn, Fe, Co, Ni; Pn = P, As). This system has space group P4/nmm with layered tetragonal structure, alternating along the c-direction as $-(LnO)_2-(MP)_2-(LnO)_2-$, with two formula units per cell. For parent materials, interlayer charges are balanced, such as $(LnO)^{+1}$ and $(MP)^{-1}$. Since some quaternary phosphorus oxides LnOMPn (1111 structure) are superconducting at low temperatures, this system constitutes another layered superconductor family beyond copper oxides. [Figure 9: see original paper] shows the structures of LaFeAsO (1111) and $BaFe_2As_2$ (122). In the 1111 phase, doping F at O sites induces superconductivity. Doping K at Ba sites or substituting other transition metal ions (Co, Ni, Ir, Rh, Pt) at Fe sites also produces superconductivity.

Following Hosono’ s discovery of 26 K superconductivity in $LaFeAsO_1$ F (x = 0.05-0.12), a new wave of high-temperature superconductor searches emerged. Within a single year, scientists discovered over seven typical structures: 11 (FeSe), 111 (LiFeAs, NaFeAs), 122 ((Ba, Sr, Ca)Fe_2As_2), 1111 (REFeAsO, RE = rare earth), 32522 ($Sr_3Sc_2O_5Fe_2As_2$), 42622 ($Sr_4V_2O_6Fe_2As_2$), and 43822

($Ca_4Mg_3O_8Fe_2As_2$). Specific structures and superconducting transition temperatures are discussed in later sections. In this global competition, Chinese scientists, drawing on years of accumulated expertise, immediately recognized the system' s importance and rapidly produced a large body of important work, discovering and synthesizing key superconducting systems. They first measured superconductivity above 40 K under ambient pressure via chemical doping [22], quickly raising it to 55 K [23], and through collaboration confirmed the parent material' s antiferromagnetic properties [25], establishing the unconventional nature of iron-based superconductors and causing great international impact. [Figure 10: see original paper] shows the main structures and corresponding superconducting transition temperatures of current iron-based superconductors.

3.2 Mechanism of Iron-Based Superconductors

Iron-based superconductors represent a core issue in current condensed matter physics research. The key to superconductivity lies in the FeAs planes. Simple band calculations indicate that six electrons from Fe 3d orbitals participate in conduction, creating multi-band and multi-Fermi-surface situations. Early neutron diffraction experiments on LaFeAsO determined the magnetic structure [24], showing that the parent material' s antiferromagnetic wave vector connects hole and electron pockets. Therefore, Mazin [25] and Kuroki [26] proposed that electrons pair by exchanging antiferromagnetic fluctuations between hole and electron pockets. For the same reasons discussed previously, the gap signs at the pre- and post-scattering momentum points must be opposite, leading to the so-called S± pairing scenario: gaps on hole and electron Fermi surfaces are nearly isotropic but have opposite signs. Early angle-resolved photoemission spectroscopy [27] found relatively isotropic gaps on both Fermi surfaces. Under this framework, phase-sensitive tests feasible in real space for copper oxides become difficult because Fermi velocities are nearly isotropic on each Fermi surface. Only quasi-particle quantum interference experiments [28] and neutron scattering [29] provided indirect evidence. Recent studies introducing non-magnetic impurities and examining impurity states around them have found experimental evidence for S± pairing [30].

Alternative physical pictures for iron-based superconductor mechanisms include local spin exchange pairing, built on the assumption that iron-based superconductors, like copper oxides, possess strong electron correlation characteristics [31]. In this picture, electrons pair through local antiferromagnetic interactions, with the gap function phenomenologically written as Δ_s   cos k_x + cos k_y. Additionally, proposals suggest pairing arises from strong orbital fluctuations (primarily d_{xz} and d_{yz}), yielding an S++ gap form [32]. Recent experiments doping non-magnetic or weakly magnetic Cu impurities into NaFeAs superconductors successfully observed quasi-particle density of states from pair-breaking inside the gap, providing strong support for the S± pairing picture [25]. Research on iron-based superconductor pairing mechanisms is deepening, though complete understanding will require more time. References [33-38] detail progress in iron-based superconducting materials and physics.

Recently, a Tsinghua University group used molecular beam epitaxy to prepare single-layer FeSe films on $SrTiO_3$ substrates. Low-temperature scanning tunneling spectroscopy measurements revealed a 20 meV gap feature, corresponding to a temperature above 77 K if it is a superconducting gap [39]. Subsequent angle-resolved photoemission spectroscopy confirmed this gap’ s existence and its disappearance around 65 K [40, 41]. Transport and inductive magnetic measurements on these FeSe films [42] showed resistance onset at approximately 54.5 K and zero resistance at 23.5 K. Angle-resolved photoemission further revealed the absence of hole-like Fermi surfaces near the Brillouin zone center Γ point in single-layer FeSe films, making them difficult to explain using Mazin’ s earlier S± model. This work on single-layer FeSe films [39] has stimulated many efforts to detect higher superconducting transition temperatures and provides new sample systems and perspectives for solving iron-based superconducting mechanisms. Chinese scientists have now reached the world forefront in iron-based superconducting mechanism research.

3.3 Mixed-State Properties and Application Prospects of Iron-Based Superconductors

Iron-based superconductors exhibit very high magnetic field-to-temperature ratios, with dH_{c2}/dT reaching -10 T/K. Direct measurements reveal that the low-temperature upper critical field of 1111 systems can approach 100 T, while 122 and 11 systems can exceed 50 T at low temperatures. [Figure 11: see original paper] compares upper critical fields among iron-based superconductors and other high-temperature (YBaCuO) and practical superconductors [45], showing that $Ba_{0\cdot6}K_{0\cdot4}Fe_2As_2$ has exceptionally high upper critical fields at low temperatures, surpassing other systems. Thus, iron-based superconductors show excellent prospects for strong-field magnet applications. Recent results demonstrate that in $FeSe_{0\cdot5}Te_{0\cdot5}$ superconducting thin films, despite a superconducting transition temperature of only ~18 K, supercurrent density [43] can reach 10^5 A/cm^2 at 4.2 K and 30 T—an excellent metric already meeting some application requirements using mature pulsed laser deposition technology. Using powder-in-tube and rolling techniques, the Institute of Electrical Engineering of the Chinese Academy of Sciences has produced Sr_1 K Fe_2As_2 wires achieving critical currents of 10^5 A/cm^2 at 4.2 K, reaching internationally leading levels [44]. As shown in [Figure 11: see original paper], iron-based superconductors possess very high upper critical fields, reaching the order of 100 T at liquid helium temperatures [45].

4. MgB_2 Superconductor Research

4.1 Background and Basic Structure of MgB_2 Superconductors

Magnesium diboride superconductors were accidentally discovered by Japanese scientists in 2001 [46]. The structure consists of triangular Mg lattices interleaved with honeycomb hexagonal boron planes (see [Figure 12: see original paper]). Its superconducting transition temperature reaches 40 K. As a very simple binary intermetallic compound, it was an overlooked discovery in superconductor exploration. With relatively long coherence length, weak layered characteristics, and simple binary composition, kilometer-length wires can be easily fabricated using powder-in-tube rolling and in-situ reaction techniques, and high-quality films can be prepared by vapor deposition, showing certain application potential.

4.2 Superconducting Mechanism of MgB_2

Band calculations reveal that p-orbital electrons from boron atoms participate in conduction. The p-orbitals form bonding and antibonding bands—the so-called σ and π bands—creating complex Fermi surfaces including strongly two-dimensional barrel-shaped σ-band Fermi surfaces and three-dimensional flat π-band Fermi surfaces, as shown in [Figure 13: see original paper]. Further theoretical calculations indicate that σ-band electrons strongly couple with in-plane breathing modes of boron atoms, creating extremely strong electron-phonon interactions that lead to pairing, while π-band electrons may become paired through proximity effects. Experimentally, two gaps of approximately 7 meV and 2 meV have been measured, corresponding to gap values on σ and π bands, respectively [47]. Although band calculations are mature, they generally cannot predict superconducting temperatures. However, based on the electron-phonon interaction picture, superconducting gaps in MgB_2 have been well-calculated, encouraging computational physicists to predict new superconductors through electronic structure calculations based on electron-phonon coupling.

4.3 Application Prospects for MgB_2 Superconductors

High J_c and stable long-length wires/tapes are fundamental for MgB_2 superconducting magnet applications. The powder-in-tube (PIT) technique is one of the main methods for preparing MgB_2 wires/tapes. Hyper Tech (USA), Columbus Superconductor (Italy), Hitachi (Japan), and China' s Northwest Institute for Nonferrous Metal Research have all developed multi-filament MgB_2 long wire/tape fabrication technologies. Columbus produced 1800 m long, 14-filament Cu-based MgB_2 tapes using ex-situ PIT technology, achieving critical current density J_c of 10^5 A/cm^2 at 20 K and 1.2 T. The Northwest Institute for Nonferrous Metal Research has also fabricated kilometer-scale multi-filament MgB_2 wires with J_c reaching 5$×10^{4}$ A/cm^2 (20 K, 2 T), basically meeting requirements for next-generation MRI magnets. They are currently developing open 0.6 T medical MRI systems using their own MgB_2 wires. Within 3-5 years, commercial open medical MRI systems based on MgB_2 superconducting wires should become operational.

MgB_2 superconducting thin films are fundamental for physical research and novel superconducting device development. Collaborations between Pennsylvania State University and Peking University developed hybrid physical-chemical vapor deposition technology using organic magnesium [$(MeCp)_2Mg$] and BH_6 precursors to successfully prepare high-quality MgB_2 superconducting films on SiC substrates, greatly enhancing the upper critical field H_{c2} to over 60 T. Progress has also been achieved in developing novel superconducting quantum interference devices based on MgB_2 films and preparing superconducting layers for resonator cavities in high-energy accelerators.

5. Outlook on Exploring New High-Temperature Superconducting Materials and Studying Unconventional Superconducting Mechanisms

The above description shows that MgB_2 belongs to conventional electron-phonon coupling superconductors, while copper oxides and iron-based superconductors likely involve other mechanisms. To date, no completely successful theory explains copper oxide and iron-based high-temperature superconductivity. However, research on unconventional superconducting mechanisms is flourishing, presenting many novel physical phenomena. As shown in [Figure 14: see original paper], they share a common electronic state characteristic: the superconducting state neighbors an antiferromagnetic phase, with superconductivity emerging gradually as the antiferromagnetic phase is suppressed. Moreover, researchers have found that these materials' normal states, where superconductivity disappears, deviate from or even contradict band calculation results, exhibiting non-Fermi liquid behavior. Consequently, their low-temperature ground states may exhibit quantum phase transitions. These effects are attributed to correlated electron characteristics, forming a frontier field in condensed matter research. Therefore, moderate electron correlation seems necessary for discovering novel high-temperature superconductors.

In the quest for high-temperature superconductors, no established rules exist, but some experiences may provide guidance: (1) materials with moderate correlation characteristics, particularly transition metal compounds dominated by 3d and 4d electrons; (2) high-symmetry structures, such as tetragonal phases; (3) antiferromagnetic characteristics combined with moderate electron itinerancy; and (4) layered structures with strong two-dimensional planes, strong magnetic fluctuations, and possible density of states singularities.

As described above, unconventional superconducting mechanisms are not yet fully understood, so these empirical rules may be partially or completely wrong. The charm of exploring novel high-temperature superconductors may lie in the fact that no existing theory can predict or explain high-temperature superconductivity. The search is extremely challenging. China has made some investments and accumulated experience in novel superconducting materials and applied superconductivity basic research, such as the Ministry of Science and Technology' s targeted 973 project "High-Temperature Superconducting Materials and Physics Research" and the National Natural Science Foundation' s major project "Unconventional Superconducting Materials and Mechanism Research." Most active research groups nationwide are working within these projects. Some trends in exploring novel superconducting materials have emerged, though exploration efforts still lag behind Japan and Europe. In unconventional superconducting mechanism research, combined with recently launched national major instrument projects and Thousand Talents programs, China has established relatively complete spectroscopic measurement capabilities, including angle-resolved photoemission spectroscopy, inelastic neutron scattering, low-temperature high-field scanning tunneling spectroscopy, nuclear magnetic resonance, and various transport measurements. We believe that with persistent effort, open-minded innovation, and continued national support, China will achieve major original breakthroughs in discovering more practical novel superconductors and resolving unconventional superconducting mechanisms.

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Note: Figure translations are in progress. See original paper for figures.