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High Temperature Superconductivity

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ABSTRACT:
High-temperature superconductivity (HTS) represents one of the most significant breakthroughs in condensed matter physics, revolutionizing our understanding of superconducting materials. Unlike conventional superconductors, which operate at temperatures close to absolute zero, high-temperature superconductors (HTSs) exhibit superconducting properties at temperatures well above the boiling point of liquid nitrogen. This paper provides an overview of the development, fundamental principles, and key materials associated with HTS. We delve into the discovery of copper-oxide (cuprate) superconductors in the late 1980s, which marked a pivotal moment in the field, followed by the subsequent identification of iron-based superconductors. The paper also discusses the theoretical models, such as the BCS theory and its extensions, which attempt to explain the mechanisms behind HTS. Additionally, the challenges associated with the practical application of HTS, including material synthesis, critical temperature limitations, and the high costs of cooling, are examined. Current research directions and technological advancements aimed at overcoming these challenges and expanding the applications of HTS in fields such as power transmission, magnetic levitation, and quantum computing are also highlighted. By synthesizing the historical context, theoretical underpinnings, and ongoing research efforts, this paper aims to provide a comprehensive understanding of high-temperature superconductivity and its potential impact on future technological innovations.

Introduction

Ever since Kamerlingh Onnes discovered that mercury becomes superconducting at temperatures less than 4 K, scientists have been searching for superconducting materials with higher transition temperatures. Until 1986 a compound of niobium and germanium (Nb_3Ge) had the highest known transition temperature, 23 K, less than a 20-degree increase in 75 years. Most researchers expected that the next increase in transition temperature would be found in a similar metallic alloy and that the rise would be only one or two degrees. In 1986, however, the Swiss physicist Karl Alex Müller and his West German associate, Johannes Georg Bednorz, discovered, after a three-year search among metal oxides, a material that had an unprecedentedly high transition temperature of about 30 K. They were awarded the Nobel Prize for Physics in 1987, and their discovery immediately stimulated groups of investigators in China, Japan, and the United States to produce superconducting oxides with even higher transition temperatures.

These high-temperature superconductors are ceramics. They contain lanthanum, yttrium, or another of the rare-earth elements or bismuth or thallium; usually barium or strontium (both alkaline-earth elements); copper; and oxygen. Other atomic species can sometimes be introduced by chemical substitution while retaining the high-T_c properties. The Table lists the member of each major family of high-T_c materials with the highest observed superconducting transition temperature. The value 134 K is the highest known T_c value. Within each family of high-T_c materials, only the subscripts (i.e., stoichiometry) vary from one compound to another. Samples in the families containing bismuth or thallium always exhibit a great deal of atomic disorder, with atoms in the “wrong” crystallographic sites and with impurity phases. It is possible that such disorder is required to make these compounds thermodynamically stable.

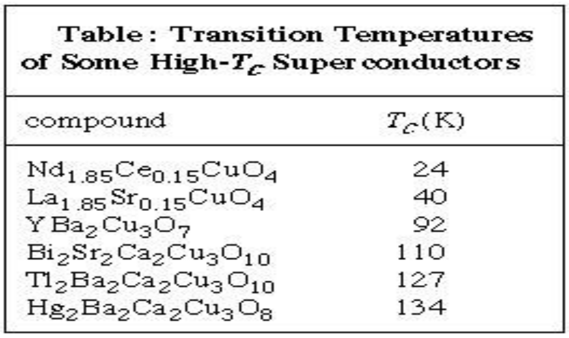

Table: Transition Temperatures of Some High-T_c Superconductors

compound	T_c(K)
$Nd_{1.85}Ce_{0.15}CuO_4$	24
$La_{1.85}Sr_{0.15}CuO_4$	40
$YBa_2Cu_3O_7$	92
$Bi_2Sr_2Ca_2Cu_3O_{10}$	110
$Tl_2Ba_2Ca_2Cu_3O_{10}$	127
$Hg_2Ba_2Ca_2Cu_3O_8$	134

Structures and properties

The compounds have crystal structures containing planes of Cu and O atoms, and some also have chains of Cu and O atoms. The roles played by these planes and chains have come under intense investigation. Varying the oxygen content or the heat treatment of the materials dramatically changes their transition temperatures, critical magnetic fields, and other properties. Single crystals of the high-temperature superconductors are very anisotropic—i.e., their properties associated with a direction, such as the critical fields or the critical current density, are highly dependent on the angle between that direction and the rows of atoms in the crystal.

If the number of superconducting electrons per unit volume is locally disturbed by an applied force (typically electric or magnetic), this disturbance propagates for a certain distance in the material; the distance is called the superconducting coherence length (or Ginzburg-Landau coherence length), ξ. If a material has a superconducting region and a normal region, many of the superconducting properties disappear gradually—over a distance ξ—upon traveling from the former to the latter region. In the pure (i.e., undoped) classic superconductors ξ is on the order of a few thousand angstroms, but in the high-T_c superconductors it is on the order of 1 to 10 angstroms. The small size of ξ affects the thermodynamic and electromagnetic properties of the high-T_c superconductors. For example, it is responsible for the cusp shape of the specific heat curve near T_c that was mentioned above. It is also responsible for the ability of the high-T_c superconductors to remain superconducting in extraordinarily large fields—on the order of 1,000,000 gauss (100 teslas)—at low temperatures.

The high-T_c superconductors are type II superconductors. They exhibit zero resistance, strong diamagnetism, the Meissner effect, magnetic flux quantization, the Josephson effects, an electromagnetic penetration depth, an energy gap for the superconducting electrons, and the characteristic temperature dependencies of the specific heat and the thermal conductivity that are described above. Therefore, it is clear that the conduction electrons in these materials form the Cooper pairs used to explain superconductivity in the BCS theory. Thus, the central conclusions of the BCS theory are demonstrated. Indeed, that theory guided Bednorz and Müller in their search for high-temperature superconductors. It is not known, however, why the transition temperatures of these oxides are so high. It was generally believed that the members of a Cooper pair are bound together because of interactions between the electrons and the lattice vibrations (phonons), but it is unlikely that these interactions are strong enough to explain transition temperatures as high as 90 K. Most experts believe that interactions among the electrons generate high-temperature superconductivity. The details of this interaction are difficult to treat theoretically because the motions of the electrons are strongly correlated with each other and because magnetic phenomena play an important part in determining the microscopic properties of these materials. These strong correlations and magnetic properties may be responsible for unusual temperature dependencies of the electric resistivity ρ and Hall coefficient R_H in the normal state (i.e., above T_c). (For a discussion of the Hall effect, *see* magnetism: Magnetic forces.) It is observed that at temperatures above T_c the electric resistivity, although higher for superconductors than for typical metals in the normal state, is roughly proportional to the temperature T, an unusually weak temperature dependence. Measurements of R_H show it to be significantly temperature-dependent in the normal state (sometimes proportional to $1/T$) rather than being roughly independent of T, which is the case for ordinary materials.

Applications

Films of the new materials can carry currents in the superconducting state that are large enough to be of importance in making many devices. Possible applications of the high-temperature superconductors in thin-film or bulk form include the construction of computer parts (logic devices, memory elements, switches, and interconnects), oscillators, amplifiers, particle accelerators, highly sensitive devices for measuring magnetic fields, voltages or currents, magnets for medical magnetic-imaging devices, magnetic energy-storage systems, levitated passenger trains for high-speed travel, motors, generators, transformers, and transmission lines. The principal advantages of these superconducting devices would be their low power dissipation, high operating speed, and extreme sensitivity.

Equipment made with the high-temperature superconductors would also be more economical to operate because such materials can be cooled with inexpensive liquid nitrogen (boiling point, 77 K) rather than with costly liquid helium (boiling point, 4.2 K). The ceramics have problems, however, which must be overcome before useful devices can be made from them. These problems include brittleness, instabilities of the materials in some chemical environments, and a tendency for impurities to segregate at surfaces and grain boundaries, where they interfere with the flow of high currents in the superconducting state.

Physics of high temperature superconductors

Several families of cuprate HTS superconductors have been discovered. They all have a layered structure consisting of CuO_2 layers separated by insulating layers (see Fig. 1). Superconductivity occurs in the CuO_2 layers, and the insulating layers serve as charge reservoirs supplying the charge carriers to the CuO_2 layers. [1-2]

Fig. 1: MRI scanner for medical applications (Philips Ingenia 3.0T MR System).

The wires of the superconducting magnet (3 Tesla) consist of the conventional low-temperature superconductor NbTi.

The discovery of cuprate superconductors was not accidental as advertised by many scientists, but born from the idea that a very strong electron-lattice interaction is needed in order to arrive at high values of Tc. One would argue that the BCS theory already addresses this issue, however, limitations in this theory are that the lattice frequency, the number of free carriers and the coupling between carriers and the lattice are all interdependent. This has the consequence that clear limits on Tc are set, thus excluding high temperature superconductivity within the BCS approach. Bednorz and Müller [3], instead, observed that some oxide superconductors showed a rather high value of Tc in spite of an extremely low carrier density. This led them to conclude, that an unconventionally large coupling between the carriers and the lattice had to be present which is beyond the framework considered in BCS theory. As a possible route for achieving such a strong coupling, they assumed that polaron formation could be at work, where specifically the concept of JahnTeller polarons [12] was considered [13–15]. A polaron is a quasi-particle where the carrier and the lattice deformation cloud, as depicted in Fig. 5, form a new entity which can travel through the lattice. In order to achieve superconductivity two of these quasi-particles combine to a bipolaron which in contrast to the conventional Cooper pair is correlated over a few nm only. This limits the number of pairs within a unit volume and overlap between them is unlikely (Fig. 2 (right)).

The formation of this quasi-particle and its bound state is possible only when there is an extremely strong interaction supporting a high superconducting transition temperature. Simultaneously, the density of the carriers can be rather small. The crucial issue of these considerations was the search for a suitable material [4-5]. While Bednorz and Müller first started with the perovskite $SrTiO_3$ they soon found out that it is indeed possible to induce superconductivity in it, however with a disappointingly small transition temperature (<3K) [16]. The next compound was again a perovskite type oxide, a nickelate, where superconductivity could not be verified. Finally, they came along with the cuprates, the high-temperature superconductors. Their starting concept of the bipolaron mechanism of high-temperature

superconductivity was thus realized, remained, however, under strong debate and a variety of novel and exotic theories followed rapidly after this discovery, where no consensus exists until today [6-10]. It has to be emphasized that in spite of the existing controversies in this field, the Nobel laureates initiated a number of experiments to verify their concept, mainly by concentrating on isotope experiments. While in conventional superconductors the isotope effect on Tc is inversely proportional to the square root of the ionic mass and constant, in cuprates it depends on the number of carriers and eventually even vanishes [17, 18]. The latter fact has been advocated to require novel theories, however, also polaron based theories are able to explain it [13–15]. Besides of the isotope effect on Tc a number of novel isotope effects were observed, as e.g. one on the penetration depth and the energy gap.

Development of technological applications

Since the discovery of superconductiviy in 1911 by Heike Kammerlingh Onnes and Gilles Holst [1] tremendous advances have been made both in understanding the nature of superconductivity and the materials which show it. A second revolution in the field of superconductivity happened in 1986 with the finding of the cuprate hightemperature superconductors [3] with transition temperatures well above the boiling point of liquid nitrogen (77 K or −196°C). In the cover story of Time Magazine (11 May 1987) the importance of this discovery was stated as a “starting breakthrough that could change our world” with euphoric predictions of all kinds of technical applications [19, 20]. In fact, it was already obvious from the very beginning in 1911 that superconductivity bares a great potential for a variety of unique technologies, including superconducting magnets, transmission power cables, electrical motors and generators, energy storage devices, maglev trains, and various kinds of superconducting sensors, to give only a few examples [2, 19–24]. Figure 2 shows a schematic overview of the broad spectrum of already existing applications using high-temperature superconductors (HTSs).

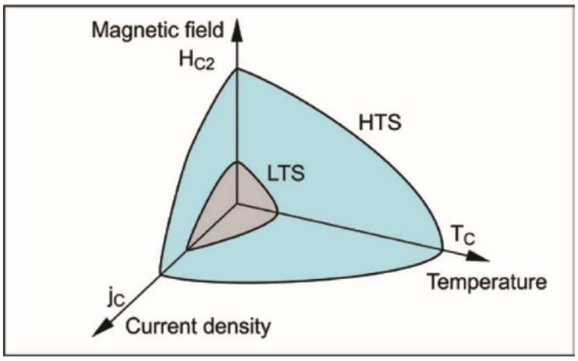

Fig. 2: Schematic diagram of the critical parameters (critical temperature Tc , critical current density jc , and upper critical magnetic field 2c H) of a superconductor (LTS, low-temperature superconductor; HTS, high-temperature superconductor).

After the discovery of superconductivity it took quite some time to find superconducting materials which are suitable for power applications. Such a material must have a rather high Tc and carry a high electrical current (high critical current density j c) in a high magnetic field (high critical magnetic field Hc) (see Table 1). In 1954 the intermetallic compound Nb3 Sn was found to be such a material, followed by other A15 compounds and NbTi (up to now still the most used material for technical applications) [2, 21, 22]. Using these materials it was possible to build superconducting magnets which produce the high magnetic fields needed e.g. in magnetic resonance imaging (MRI) scanners for medical diagnostics (see Fig. 3).

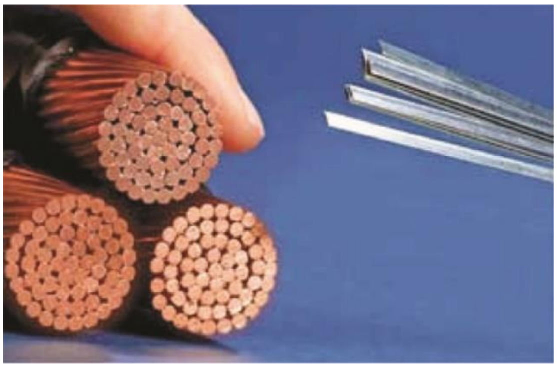

Fig. 3: Superconducting cable made of a HTS material (right) is able to carry 150 times the electrical current of traditional copper wire of the same size (left). (Courtesy of American Superconductor Corp.).

Table 1: Crucial parameters of a superconducting material relevant for technical applications.

High criticall temperature Tc (>77 K)
High critical current density j_c
High critical magnetic field H_c
Good and stable mechanical properties
Simple and low-cost production

The discovery of the cuprate HTSs [3] opened a new era of applications. It became in principle possible to operate superconducting devices at much higher working temperatures than conventional ones, i.e. above the boiling point of liquid nitrogen (77K or −196°C) which is much cheaper and much easier to obtain and to handle than liquid helium (4 K or −269°C). However, the high transition temperature Tc is not the only crucial parameter for superconducting wires useful for electrical power engineering [11-15]. The wires must carry a high current density (high citical curent density jc) and withstand a high magnetic field (high critical magnetic field Hc). Cuprate HTSs are so-called type II superconductors which are characterized by two critical magnetic fields: the lower critical magnetic field 1 Hc and the upper critical magnetic field 2 c H . For technical applications 2 Hc is relevant. This is illustrated in Fig. 12 where the critical parameters Tc , jc , and 2 Hc of a low-temperature superconductor (LTS) are compared to those of a cuprate HTS. Note that in the ideal case all parameters of a HTS are higher than those of a LTS which makes the former so interesting for technical applications. However, there are some other drawbacks for the application of cuprate HTSs as discussed below.

Besides the cuprate HTSs other superconducting materials were discovered after 1986 which are also suitable for applications, such as magnesium diboride MgB2 with Tc = 39 K (−234°C) [9] and a series of iron-based compounds called pnictides with a Tc up to 56 K (−221°C) [10].

In the following we will focus on applications using cuprate HTSs. Their essential novelty is clearly the high superconducting transition temperature Tc compared to those of LTSs. This implies a drastic reduction of cooling costs, a major factor for large scale technologies. The main criteria a superconducting material should fulfill for applications are summarized in Table 3. One essential hurdle to handle with was to produce useful HTS materials in the form of long robust and flexible cables for high power engineering as well as stable high-quality thin films for low power electronics and sensor devices. HTSs are very complex materials consisting of several elements with multiple phases. They are very brittle ceramics which makes it difficult to optimize all the crucial material aspects. Furthermore, cuprate HTSs are layered superconductors with a short coherence length ξ. The supercurrents predominantly flow in the copper-oxygen planes. Consequently, the critical parameters j c and Hc as well as the coherence length ξ are highly anisotropic. To achieve a sufficiently high current density for high power application, the grains in the wires have to be well aligned over distances as long as several 100 m. This is a difficult material science problem, but nowadays such HTS cables are available and are tested in real electric power grids (see Figs. 4).

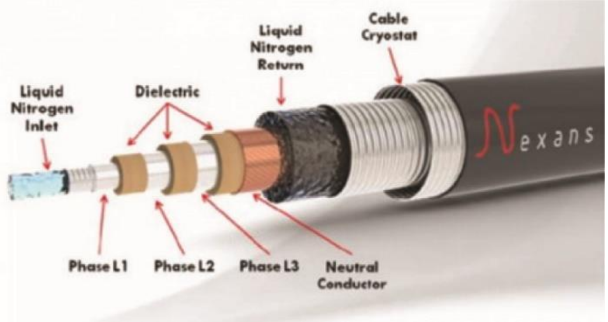

Fig. 4: HTS power transmission cable developed by Nexans SuperConductors GmbH. The concentric arrangement of three phases L1, L2, and L3 allows a very compact cable design. The conducting parts of the cable (L1, L2, L3) consists of a HTS material. The cable is cooled by liquid nirogen.

Since 1986 tremendous progress has been made to fabricate useful HTS materials for various kinds of applications. A schematic overview of HTS applications is shown in Fig. 10 and detailed descriptions of HTS applications are given in Refs. [19, 20, 22–24]. Here we only present a small selection of some unique applications of cuprate HTSs.

Certainly the greatest commercial potential for HTS materials is in electric power applications which require long and flexible high-quality HTS wires and cables with

the desired physical properties. Examples of such power applications include high-power transmission cables, high-field superconducting magnets, motors and generators, synchronous condensers, transformators, and faultcurrent limiters [19, 20, 22–24]. Such wires and cables are developed by several companies around the world and are available on the market. Figure 14 shows an example of a HTS power transmission cable consisting of three cores for the three phases of electric power

In 2014 the world's longest HTS cable was integrated to the power grid of Essen (Germany) and put into real operation. The system consists of a one-kilometer 10 kV (2300 A) HTS cable (Fig. 14), including a joint and a faultcurrent limiter, cooled by liquid nitrogen, and connecting two substations in the city center of Essen [25]. It was designed to replace a high-voltage cable (110 kV) with a medium-voltage (10 kV) cable, thus saving space in substations by eliminating the need for transformers and other bulky equipment. The particularly efficient and spacesaving technology transports five times more electricity than conventional cables with almost no losses. The field test of this novel power grid system may be pathfinding for planning future energy supply systems of cities. This new system also contains a fault-current limiter based on HTS technology which must be able to withstand fault currents. The simplest form of it makes use of the fact that above a certain critical current, a superconductor becomes a normal resistive conductor, and consequently the high current through the system can be switched to low. Various types of fault-current limiters were developed by several companies and are available on the market. Another rather advanced field of applications are rotating electromechanical machines such as motors, generators, and synchronous condensers. All these machines contain copper coils which partly can be replaced by coils made of HTS material, especially the rotor coils. HTS rotating machinery has several advantages compared to conventional designs. The losses can be reduced by a factor of two including the cooling of the HTS system. The higher magnetic fields produced by HTS rotor coils allow a very compact design of a motor concerning weight and size. For instance, American Superconductor has designed a 36.5 MW HTS ship propulsion engine that has only 20% of the weight and volume of a conventional one.

HTSs are also promising materials to realize efficient energy storage devices. There are in principle two types of such devices [20, 24]: (i) A superconducting magnetic energy storage (SMES) device consists basically of a superconducting coil in which electric energy is stored in the form of a frictionless flowing electric supercurrent in the coil. The use of a HTS material for the coil allows a compact and efficient construction of the device. (ii) In a flywheel energy storage (FES) device a rotor (flywheel) is accelerated to a high speed and the energy in the system is conserved as rotational energy. When energy is extracted (added) from the system, the rotational speed of the flywheel is reduced (increased) according to the law of conservation of energy. The flywheels spinning at high speeds (20 000 to over 50 000 rpm) are suspended by frictionless magnetic bearings based on HTS technology.

An interesting application of HTS technology is employed in superconducting magnetic levitation (SCMaglev) trains developed by the Central Japan Railway Company (JR Central) and the company's Railway Technical Research Institute. The SCMaglev railway system is based on the principle of magnetic repulsion between the track and the cars. The coils on the car that produce the magnetic field are made of HTS material. In 2015 a SCMaglev train reached a speed of 603 km/h on a 42.8 km magnetic-levitation test track in Japan. This is the world record for manned passenger trains. Commercial SCMaglev service is scheduled for 2027 between Tokyo and Nagoya being 286 km apart. The SCMaglev train would run at a top speed of 500 km/h and connect the two cities in 40 min, less than half the present travel time in a Shinkansen.

There are a number of applications which do not require HTS materials in long wire forms, high power levels or high magnetic fields. These are mainly related to the field of electronic devices and often call for small thin HTS films.

Due to the increasing demand for wireless communication, the largest commercial use of HTS electronic devices is as filters in cell phone base stations where the low microwave resistivity and noise of HTS thin films operating at 77 K (liquid nitrogen) enables a broader signal range than conventional metallic filters. HTS materials are also used for high-Q resonant cavities in high-energy particle accelerators.

Another important application of HTS electronics is the SQUID (Superconducting QUantum Interference Device) which makes use of the Josephson effect (tunneling of Cooper pairs through a narrow barrier between two superconductors, called a Josephson junction). SQUIDs are very effective sensors to detect tiny magnetic fields and play an important role in various commercial applications such as in basic research, technical material testing and characterization, and medical diagnostics. As an example, SQUIDS can detect with good spatial resolution the magnetic fields generated by human heart currents or currents in the brain.

Predictions for the future are always uncertain, but it may be stated that superconductivity very likely will continue to provide unexpected discoveries and surprises, ranging from new types of superconducting materials to novel kinds of technologies. However, unless there is no other way to solve a technological problem, devices based on superconductors are always in strong competition with technological solutions which are more practical and cheaper.

Futures scope

High-temperature superconductivity (HTS) has dramatically transformed the field of condensed matter physics and has significant implications for various technological applications. Discovered in the late 1980s, this phenomenon is characterized by the ability of certain materials to exhibit superconducting properties—zero electrical resistance and the expulsion of magnetic fields—at temperatures significantly higher than those of conventional superconductors. This breakthrough has opened up new avenues for research and technology, reshaping our understanding of superconducting materials and their potential uses.

The journey towards high-temperature superconductivity began with the discovery of copper-oxide (cuprate) superconductors. The first cuprate superconductor, $YBa_2Cu_3O_{7-x}$, was identified in 1987 by Johannes Georg Bednorz and Karl Alexander Müller, who were awarded the Nobel Prize for their pioneering work. This material exhibited superconductivity at temperatures around 92 Kelvin, far exceeding the capabilities of previously known superconductors, which required cooling to temperatures close to absolute zero. The cuprates are characterized by their layered crystal structures and the presence of copper-oxygen planes, which play a crucial role in their superconducting behavior. This discovery sparked a surge of research into other cuprate materials and led to the identification of several other high-temperature superconductors, including compounds with even higher critical temperatures.

Following the cuprates, a new class of high-temperature superconductors was discovered: the iron-based superconductors. These materials, which include compounds such as $LaFeAsO_{1-x}F_x$, were found to exhibit superconductivity at temperatures as high as 55 Kelvin. The discovery of iron-based superconductors in 2008 provided new insights into the mechanisms of high-temperature superconductivity and expanded the range of materials that could potentially be used in practical applications. These superconductors also have a layered structure, similar to the cuprates, but differ in their electronic properties, which has led to new theoretical and experimental investigations into their superconducting mechanisms.

The theoretical understanding of high-temperature superconductivity has evolved significantly over the years. Traditional superconductors were explained by the Bardeen-Cooper-Schrieffer (BCS) theory, which describes superconductivity as a result of electron pairs (Cooper pairs) forming a condensate that flows without resistance. However, the BCS theory struggled to account for the high-temperature superconductors, which exhibit superconductivity at temperatures far beyond the range predicted by the theory. As a result, several alternative models and theories have been proposed, including the Hubbard model and the resonating valence bond (RVB) theory. These models attempt to explain the complex interplay of electrons in the cuprates and iron-based superconductors, though a complete and universally accepted theory remains elusive.

One of the major challenges in high-temperature superconductivity is achieving practical and cost-effective applications. Despite their impressive properties, HTS materials are often difficult to synthesize and require precise conditions to maintain their superconducting state. The high costs associated with cooling these materials to their superconducting temperatures, typically using liquid nitrogen or helium, have limited their widespread adoption. Researchers are actively working to develop new materials with higher

critical temperatures and to improve the synthesis and processing techniques to make HTS more accessible for practical applications.

The potential applications of high-temperature superconductors are vast and transformative. In the field of power transmission, HTS materials could revolutionize the efficiency of electrical grids by reducing energy losses associated with conventional copper cables. Superconducting power cables and magnetic bearings have the potential to significantly enhance the performance of power systems and reduce operational costs. Additionally, HTS materials are being explored for their use in magnetic levitation (maglev) transportation systems, which could offer frictionless, high-speed travel with reduced energy consumption. The unique properties of HTS also make them ideal candidates for applications in quantum computing, where superconducting qubits could provide the foundation for powerful and efficient quantum processors.

In conclusion, high-temperature superconductivity represents a profound advancement in materials science and condensed matter physics. The discovery of HTS materials, such as the cuprates and iron-based superconductors, has expanded our understanding of superconducting phenomena and opened new avenues for technological innovation. Despite the challenges associated with material synthesis and practical application, the potential benefits of HTS in areas such as power transmission, transportation, and quantum computing are immense. Ongoing research and development efforts aim to overcome these challenges and unlock the full potential of high-temperature superconductors, making them a key area of interest for future technological advancements.

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