High-temperature superconductivity

High-temperature superconductors (abbreviated **high-T_c** or **HTS**) are materials that have a superconducting transition temperature (T_c) above 30 K (−243.2 °C). From 1960 to 1980, 30 K was thought to be the highest theoretically possible T_c. The first high-T_c superconductor[1] was discovered in 1986 by IBM researchers Karl Müller and Johannes Bednorz, for which they were awarded the Nobel Prize in Physics in 1987.

Until Fe-based superconductors were discovered in 2008,[2] [3] the term **high-temperature superconductor** was used interchangeably with **cuprate superconductor** for compounds such as bismuth strontium calcium copper oxide (BSCCO) and yttrium barium copper oxide (YBCO).

"High-temperature" has two common definitions in the context of superconductivity:

1. Above the temperature of 30 K that had historically been taken as the upper limit allowed by BCS theory. This is also above the 1973 record of 23 K that had lasted until copper-oxide materials were discovered in 1986.
2. Having a transition temperature that is a larger fraction of the Fermi temperature than for conventional superconductors such as elemental mercury or lead. This definition encompasses a wider variety of unconventional superconductors and is used in the context of theoretical models.

The label high-Tc may be reserved by some authors for those with critical temperature greater than the boiling point of liquid nitrogen (77 K or −196 °C). However, a number of materials - including the original discovery and recently discovered pnictide superconductors - had critical temperatures below 77K but are commonly referred to in publication as being in the high-Tc class.[4] [5]

Technological applications benefit from both the higher critical temperature being above the boiling point of liquid nitrogen and also the higher critical magnetic field (and critical current density) at which superconductivity is destroyed. In magnet applications the high critical magnetic field may be more valuable than the high T_c itself. Some cuprates have an upper critical field around 100 teslas. However, cuprate materials are brittle ceramics which are expensive to manufacture and not easily turned into wires or other useful shapes.

Two decades of intense experimental and theoretical research, with over 100,000 published papers on the subject,[6] have discovered many common features in the properties of high-temperature superconductors,[7] but as of 2009, there is no widely accepted theory to explain their properties. Cuprate superconductors (and other unconventional superconductors) differ in many important ways from conventional superconductors, such as elemental mercury or lead, which are adequately explained by the BCS theory. There also has been much debate as to high-temperature superconductivity coexisting with magnetic ordering in YBCO,[8] iron-based superconductors, several ruthenocuprates and other exotic superconductors, and the search continues for other families of materials. HTS are Type-II superconductors, which allow magnetic fields to penetrate their interior in quantized units of flux, meaning that much higher magnetic fields are required to suppress superconductivity. The layered structure also gives a directional dependence to the magnetic field response.

History and progress

- April 1986 - The term *high-temperature superconductor* was first used to designate the new family of cuprate-perovskite ceramic materials discovered by Johannes Georg Bednorz and Karl Alexander Müller,[1] for which they won the Nobel Prize in Physics the following year. Their discovery of the first high-temperature superconductor, LaBaCuO, with a transition temperature of 30 K, generated great excitement.
- LSCO ($La_{2-x}Sr_xCuO_4$) discovered the same year.
- January 1987 - YBCO was discovered to have a T_c of 90 K.[9]
- 1988 - BSCCO discovered with T_c up to 108 K,[10] and TBCCO (T=thallium) discovered to have T_c of 127 K.[11]
- As of 2009, the highest-temperature superconductor (at ambient pressure) is mercury barium calcium copper oxide ($HgBa_2Ca_2Cu_3O_x$), at 135 K and is held by a cuprate-perovskite material,[12] which possibly reaches 164 K

under high pressure.[13]

- Recently, iron-based superconductors with critical temperatures as high as 56 K have been discovered.[14] [15] These are often also referred to as high-temperature superconductors.

After more than twenty years of intensive research the origin of high-temperature superconductivity is still not clear, but it seems that instead of *electron-phonon* attraction mechanisms, as in conventional superconductivity, one is dealing with genuine *electronic* mechanisms (e.g. by antiferromagnetic correlations), and instead of s-wave pairing, d-waves are substantial.

One goal of all this research is room-temperature superconductivity.[16] However following numerous announcements of room-temperature superconductivity that were discredited on examination, most condensed matter physicists now treat with extreme skepticism any claims of this nature.

Examples

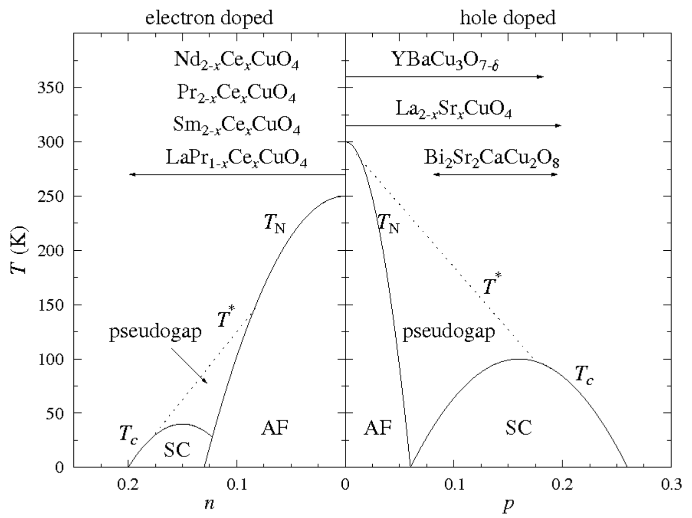
Examples of high-T_c cuprate superconductors include $La_{1.85}Ba_{0.15}CuO_4$, and YBCO (Yttrium-Barium-Copper-Oxide), which is famous as the first material to achieve superconductivity above the boiling point of liquid nitrogen.

Transition temperatures of well-known superconductors (Boiling point of liquid nitrogen for comparison)

Transition temperature (in kelvins)	Material	Class
133	$HgBa_2Ca_2Cu_3O_x$	Copper-oxide superconductors
110	$Bi_2Sr_2Ca_2Cu_3O_{10}$(BSCCO)	
90	$YBa_2Cu_3O_7$ (YBCO)	
77	Boiling point of liquid nitrogen	
55	SmFeAs(O,F)	Iron-based superconductors
41	CeFeAs(O,F)	
26	LaFeAs(O,F)	
20	Boiling point of liquid hydrogen	
18	Nb_3Sn	Metallic low-temperature superconductors
10	NbTi	
9.2	Nb	
4.2	Hg (mercury)	

Cuprates

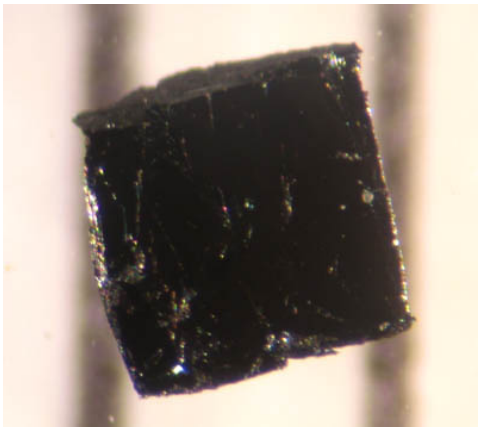
Cuprate superconductors are generally considered to be quasi-two-dimensional materials with their superconducting properties determined by electrons moving within weakly coupled copper-oxide (CuO_2) layers. Neighbouring layers containing ions such as lanthanum, barium, strontium, or other atoms act to stabilize the structure and dope electrons or holes onto the copper-oxide layers. The undoped 'parent' or 'mother' compounds are Mott insulators with long-range antiferromagnetic order at low enough temperature. Single band models are generally considered to be sufficient to describe the electronic properties.



Simplified doping dependent phase diagram of cuprate superconductors for both electron (n) and hole (p) doping. The phases shown are the antiferromagnetic (AF) phase close to zero doping, the superconducting phase around optimal doping, and the pseudogap phase. Doping ranges possible for some common compounds are also shown. After.[17]

The cuprate superconductors adopt a perovskite structure. The copper-oxide planes are checkerboard lattices with squares of O^{2-} ions with a Cu^{2+} ion at the centre of each square. The unit cell is rotated by 45° from these squares. Chemical formulae of superconducting materials generally contain fractional numbers to describe the doping required for superconductivity. There are several families of cuprate superconductors and they can be categorized by the elements they contain and the number of adjacent copper-oxide layers in each superconducting block. For example, YBCO and BSCCO can alternatively be referred to as Y123 and Bi2201/Bi2212/Bi2223 depending on the number of layers in each superconducting block (n). The superconducting transition temperature has been found to peak at an optimal doping value (p =0.16) and an optimal number of layers in each superconducting block, typically n = 3.

Possible mechanisms for superconductivity in the cuprates are still the subject of considerable debate and further research. Certain aspects common to all materials have been identified.[7] Similarities between the antiferromagnetic low-temperature state of the undoped materials and the superconducting state that emerges upon doping, primarily the $d_{x^2-y^2}$ orbital state of the Cu^{2+} ions, suggest that electron-electron interactions are more significant than electron-phonon interactions in cuprates – making the superconductivity unconventional. Recent work on the Fermi surface has shown that nesting occurs at four points in the antiferromagnetic Brillouin zone where spin waves exist and that the superconducting energy gap is larger at these points. The weak isotope effects observed for most cuprates contrast with conventional superconductors that are well described by BCS theory.



A small sample of the high-temperature superconductor BSCCO-2223.

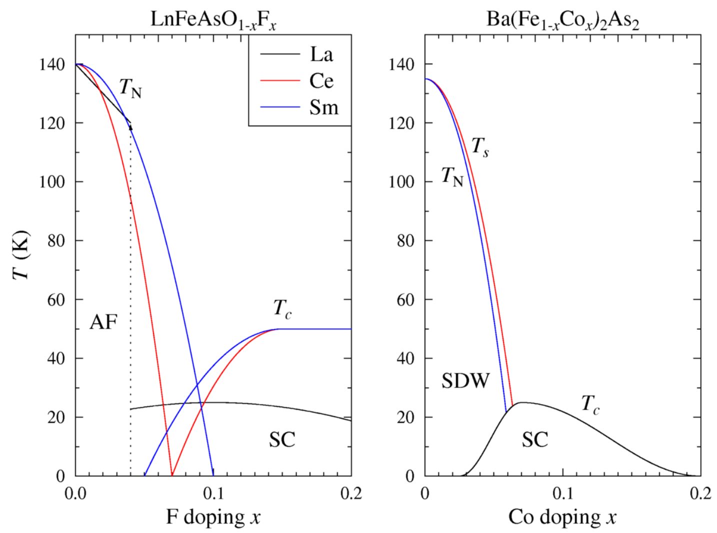
Similarities and differences in the properties of hole-doped and electron doped cuprates:

- Presence of a pseudogap phase up to at least optimal doping.

- Different trends in the Uemura plot relating transition temperature to the superfluid density. The inverse square of the London penetration depth appears to be proportional to the critical temperature for a large number of underdoped cuprate superconductors, but the constant of proportionality is different for hole- and electron-doped cuprates. The linear trend implies that the physics of these materials is strongly two-dimensional.
- Universal hourglass-shaped feature in the spin excitations of cuprates measured using inelastic neutron diffraction.
- Nernst effect evident in both the superconducting and pseudogap phases.

Iron-based superconductors

Iron-based superconductors contain layers of iron and a pnictogen—such as arsenic or phosphorus—or a chalcogen. This is currently the family with the second highest critical temperature, behind the cuprates. Interest in their superconducting properties began in 2006 with the discovery of superconductivity in LaFePO at 4 K[23] and gained much greater attention in 2008 after the analogous material LaFeAs(O,F)[14] was found to superconduct at up to 43 K under pressure.[15]



Simplified doping dependent phase diagrams of iron-based superconductors for both Ln-1111 and Ba-122 materials. The phases shown are the antiferromagnetic/spin density wave (AF/SDW) phase close to zero doping and the superconducting phase around optimal doping. The Ln-1111 phase diagrams for La[18] and Sm[19] [20] were determined using muon spin spectroscopy, the phase diagram for Ce[21] was determined using neutron diffraction. The Ba-122 phase diagram is based on.[22]

Since the original discoveries several families of iron-based superconductors have emerged:

- LnFeAs(O,F) or $LnFeAsO_{1-x}$ with T_c up to 56 K, referred to as 1111 materials.[3] A fluoride variant of these materials was subsequently found with similar T_c values.[24]
- $(Ba,K)Fe_2As_2$ and related materials with pairs of iron-arsenide layers, referred to as 122 compounds. T_c values range up to 38 K.[25] [26] These materials also superconduct when iron is replaced with cobalt
- LiFeAs and NaFeAs with T_c up to around 20 K. These materials superconduct close to stoichiometric composition and are referred to as 111 compounds.[27] [28] [29]
- FeSe with small off-stoichiometry or tellurium doping.[30]

Most undoped iron-based superconductors show a tetragonal-orthorhombic structural phase transition followed at lower temperature by magnetic ordering, similar to the cuprate superconductors.[21] However, they are poor metals rather than Mott insulators and have five bands at the Fermi surface rather than one. The phase diagram emerging as the iron-arsenide layers are doped is remarkably similar, with the superconducting phase close to or overlapping the magnetic phase. Strong evidence that the T_c value varies with the As-Fe-As bond angles has already emerged and shows that the optimal Tc value is obtained with undistorted $FeAs_4$ tetrahedra.[31] The symmetry of the pairing wavefunction is still widely debated, but an extended s-wave scenario is currently favoured.

Other materials sometimes referred to as high-temperature superconductors

Magnesium diboride is occasionally referred to as a high-temperature superconductor because its T_c value of 39 K is above that historically expected for BCS superconductors. However, it is more generally regarded as the highest T_c conventional superconductor, the increased T_c resulting from two separate bands being present at the Fermi energy.

Fulleride superconductors[32] where alkali-metal atoms are intercalated into C_{60} molecules show superconductivity at temperatures of up to 38 K for Cs_3C_{60}.[33]

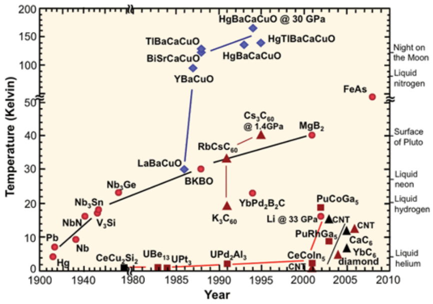
Some organic superconductors and heavy fermion compounds are considered to be high-temperature superconductors because of their high T_c values relative to their Fermi energy, despite the T_c values being lower than for many conventional superconductors. This description may relate better to common aspects of the superconducting mechanism than the superconducting properties.

Theoretical work by Neil Ashcroft predicted that solid metallic hydrogen at extremely high pressure should become superconducting at approximately room-temperature because of its extremely high speed of sound and expected strong coupling between the conduction electrons and the lattice vibrations.[34] This prediction is yet to be experimentally verified.

All known high-T_c superconductors are Type-II superconductors. In contrast to Type-I superconductors, which expel all magnetic fields due to the Meissner Effect, Type-II superconductors allow magnetic fields to penetrate their interior in quantized units of flux, creating "holes" or "tubes" of normal metallic regions in the superconducting bulk. Consequently, high-T_c superconductors can sustain much higher magnetic fields.

Ongoing research

The question of how superconductivity arises in high-temperature superconductors is one of the major unsolved problems of theoretical condensed matter physics as of 2010. The mechanism that causes the electrons in these crystals to form pairs is not known.[7] Despite intensive research and many promising leads, an explanation has so far eluded scientists. One reason for this is that the materials in question are generally very complex, multi-layered crystals (for example, BSCCO), making theoretical modelling difficult.



Superconductor timeline

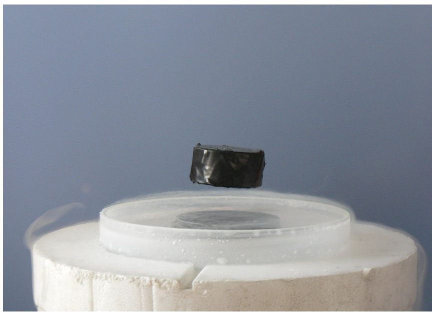
Improving the quality and variety of samples also gives rise to considerable research, both with the aim of improved characterisation of the physical properties of existing compounds, and synthesizing new materials, often with the hope of increasing T_c. Technological research focusses on making HTS materials in sufficient quantities to make their use economically viable and optimizing their properties in relation to applications.

A cable containing Gadolinium has been demonstrated to carry 2800 A at 76 K. The cable has an outside diameter of 7.5mm and a bend radius of 12.5 cm.[35]

Possible mechanism

There have been two representative theories for HTS. Firstly, it has been suggested that the HTS emerges from antiferromagnetic spin fluctuations in a doped system.[36] According to this theory, the pairing wave function of the cuprate HTS should have a $d_{x^2-y^2}$ symmetry. Thus, determining whether the pairing wave function has *d*-wave symmetry is essential to test the spin fluctuation mechanism. That is, if the HTS order parameter (pairing wave function) does not have *d*-wave symmetry, then a pairing mechanism related to spin fluctuations can be ruled out. (Similar arguments can be made for iron-based superconductors but the different material properties allow a different pairing symmetry.) Secondly, there was the **interlayer coupling model**, according to which a layered structure consisting of BCS-type (*s*-wave symmetry) superconductors can enhance the superconductivity by itself.[37] By introducing an additional tunnelling interaction between each layer, this model successfully explained the anisotropic symmetry of the order parameter as well as the emergence of the HTS. Thus, in order to solve this unsettled problem, there have been numerous experiments such as photoemission spectroscopy, NMR, specific heat measurements, etc. But, unfortunately, the results were ambiguous, some reports supported the d symmetry for the HTS whereas others supported the s symmetry. This muddy situation possibly originated from the indirect nature of the experimental evidence, as well as experimental issues such as sample quality, impurity scattering, twinning, etc.

Junction experiment supporting the d symmetry



The Meissner effect or a magnet levitating above a superconductor (cooled by liquid nitrogen)

There was a clever experimental design to overcome the muddy situation. An experiment based on flux quantization of a three-grain ring of $YBa_2Cu_3O_7$ (YBCO) was proposed to test the symmetry of the order parameter in the HTS. The symmetry of the order parameter could best be probed at the junction interface as the Cooper pairs tunnel across a Josephson junction or weak link.[38] It was expected that a half-integer flux, that is, a spontaneous magnetization could only occur for a junction of d symmetry superconductors. But, even if the junction experiment is the strongest method to determine the symmetry of the HTS order parameter, the results have been ambiguous. J. R. Kirtley and C. C. Tsuei thought that the ambiguous results came from the defects inside the HTS, so that they designed an experiment where both clean limit (no defects) and dirty limit (maximal defects) were considered simultaneously.[39] In the experiment, the spontaneous magnetization was clearly observed in YBCO, which supported the d symmetry of the order parameter in YBCO. But, since YBCO is orthorhombic, it might inherently have an admixture of s symmetry. So, by tuning their technique further, they found that there was an admixture of s symmetry in YBCO within about 3%.[40] Also, they found that there was a pure $d_{x^2-y^2}$ order parameter symmetry in the tetragonal $Tl_2Ba_2CuO_6$.[41]

Qualitative explanation of the spin-fluctuation mechanism

While, despite all these years, the mechanism of high-T_c superconductivity is still highly controversial, this being due to mostly the lack of exact theoretical computations on such strongly interacting electron systems, most rigorous theoretical calculations, including phenomenological and diagrammatic approaches, converge on magnetic fluctuations as the pairing mechanism for these systems. The qualitative explanation is as follows. (Note that, in the following argument, one can replace “electron” with “hole” and vice versa depending on the actual material.)

In a normal conductor, a hole is created whenever an electron is moved. This causes a resistivity because charge neutrality must be conserved and as electrons move under an electric field, they drag holes behind them through defects and thermal oscillations in the system. In contrast, in a superconductor, one gets an unlimited supply of electrons without creating holes behind. This is through the creation of so-called Cooper pairs in a superconductor. Cooper pairs are pairs of electrons. In a normal conductor, creation of an electron leads to creation of a hole, which conserves the number of particles. But in a superconductor, it's possible to create a Cooper pair without creating holes and therefore not to conserve the number of particles, hence leading to the unlimited supply of electrons.

In a conventional superconductor, Cooper pairs are created as follows. When an electron moves through the system, it creates a depression in the atomic lattice through lattice vibrations known as phonons. If the depression of the lattice is strong enough, another electron can fall into the depression created by the first electron—the so-called water-bed effect—and a Cooper pair is formed. When this effect becomes strong enough, Cooper pairs win over the creation of holes behind the electrons, and the normal conductor turns into a superconductor through an unlimited supply of electrons by the creation of Cooper pairs.

In a high-T_c superconductor, the mechanism is extremely similar to a conventional superconductor. Except, in this case, phonons virtually play no role and their role is replaced by spin-density waves. As all conventional superconductors are strong phonon systems, all high-T_c superconductors are strong spin-density wave systems, within close vicinity of a magnetic transition to, for example, an antiferromagnet. When an electron moves in a high-T_c superconductor, its spin creates a spin-density wave around it. This spin-density wave in turn causes a nearby electron to fall into the spin depression created by the first electron (water-bed effect again). Hence, again, a Cooper pair is formed. Eventually, when the system temperature is lowered, more spin density waves and Cooper pairs are created and superconductivity begins when an unlimited supply of Cooper pairs, denoted as a phase transition, happens. Note that in high-T_c systems, as these systems are magnetic systems due to the Coulomb interaction, there is a strong Coulomb repulsion between electrons. This Coulomb repulsion prevents pairing of the Cooper pairs on the same lattice site. The pairing of the electrons occur at near-neighbor lattice sites as a result. This is the so-called *d*-wave pairing, where the pairing state has a node (zero) at the origin.

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External links

- High temperature superconductivity research at Cornell University (http://people.ccmr.cornell.edu/~jcdavis/)
- Superconductor Science and Technology (http://iop.org/EJ/journal/SUST)
- American Superconductor and Consolidaded Edison laying first superconductor grid in New York (http://www.newscientist.com/article/dn11907-superconducting-power-line-to-shore-up-new-york-grid.html)
- Video of a magnet floating on a HTSC (http://youtube.com/watch?v=c3asSdngzLs)
- High-Temperature Superconductor Technologies (http://suptech.com/tech_faq.htm)
- High-Temperature Superconductivity in Cuprates (http://www.springer.com/materials/book/978-1-4020-0810-8) (2002) Book
- Summary of 3 types of cuprate SC - with structure diagrams (http://hoffman.physics.harvard.edu/research/SCmaterials.php)
- New LaOFeAs HTS (http://www.sciam.com/article.cfm?id=iron-exposed-as-high-temp-superconductor) SciAm
- University of Manchester Investigation of High Temperature Superconductivity (http://www.cactusconnects.co.uk/High_Temperature_Superconductivity.htm)

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