Superconductivity: Theory and Applications

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Abstract

Superconductivity is a phenomenon in the solid-state physics that occurs under a certain critical temperature (often referred to as Tc) in some materials. A superconducting material is characterized by its infinitely high electrical conductivity and the absence of any magnetic field in the interior. From many areas of research, this so-called superconductivity has become indispensable. This paper takes a simple approach to explain the theory behind Superconductivity and its applications.

Keywords: Superconductivity, Type-I and Type-II, Cooper pairs, Meisnner's effect.

Introduction

Superconductors are materials whose electrical resistance drops below the transition temperature to zero. The superconductivity in 1911 from Heike Kamerlingh Onnes discovered. It is a macroscopic quantum state. Many metals, but also other materials are superconducting below their critical temperature T_c. For most materials, this temperature is very low; to achieve superconductivity, the material must generally be cooled with liquefied helium whose boiling point is -269 °C. Only in the case of high-temperature superconductors is sufficient to be cooled down with liquefied nitrogen whose boiling point is - 196 °C.

In the superconducting state, the interior of the material remains free of electric and magnetic fields. An electric field would be degraded immediately by the non-resistant movable charge carriers. Magnetic fields are displaced by the construction of appropriate shielding currents on the surface, which compensate with their own magnetic field, the inner magnetic field. A not too strong magnetic field penetrates only about 100 nm into the material; this thin layer carries the shielding and line currents. This "Meissner-Oxfield effect" can, for example, levitate a superconducting sample in the magnetic field.

The current flow through the superconductor lowers the transition temperature. The transition temperature also decreases when an external magnetic field is applied. If the magnetic field exceeds a critical value, different effects are observed depending on the material. Breaks the superconductivity suddenly, it is called a superconductor of the first kind or the Type I. On the other hand, superconductors of the second kind (Type II) have two critical field strengths; from the lower one, the field begins to penetrate; in the higher one, the superconductivity collapses. In the area in between, the magnetic field increasingly penetrates the conductor in the form of microscopically fine tubes. The magnetic flux in these flow tubes is quantized. Type II superconductors are attractive for technical applications due to their high current carrying capacity. Technical applications of superconductivity are the generation of strong magnetic fields - for particle accelerators, nuclear fusion reactors, magnetic resonance imaging levitation- as well as measuring and energy technology.

In September 1986, the K. Alexander Muller and J. Georg Bednorz had reported that the ceramic substance lanthanum barium copper oxide of 35 Kelvin (even at the relatively high temperature -238 °C) loses any electrical resistance; for this discovery they were awarded the Nobel Prize in Physics the next year.[1] Although this transition temperature is still quite low, it is still more than ten degrees higher than the best conventional superconductors which comprise about three dozen elements and several thousand alloys and compounds that have metallic conductivity. Soon thereafter, critical temperatures above 90 K were reported. If it were indeed possible to find a superconducting material at ordinary ambient temperatures (around 300 K), this would most likely profoundly change modern technology.

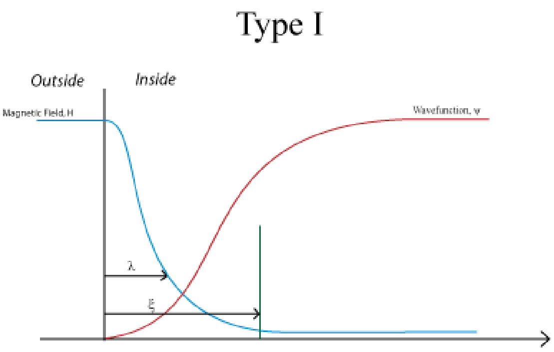

Figure 1.a: The current flow through the superconductor lowers the transition temperature. The transition temperature also decreases when an external magnetic field is applied. If the magnetic field exceeds a critical value, different effects are observed depending on the material. Breaks the superconductivity suddenly, it is called a superconductor Type I.

Now, onto a new mechanism: the magnetic effect of spin fluctuations in the atoms of the conducting medium. Although this transition temperature is still quite low, it is still more than ten degrees higher than the best conventional superconductors which comprise about three dozen elements and several thousand alloys and compounds that have metallic conductivity. Soon thereafter, critical temperatures above 90 K were reported. If it were indeed possible to find a superconducting material at ordinary ambient temperatures (around 300 K), this would most likely profoundly change modern technology.

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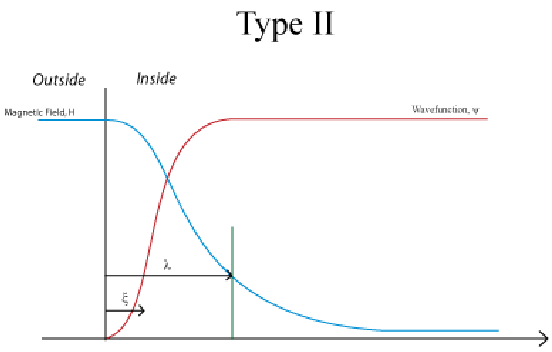

Figure 1.b: Type II Superconductors have two critical field strengths; from the lower one, the field begins to penetrate; in the higher one, the superconductivity collapses. In the area in between, the magnetic field increasingly penetrates the conductor in the form of microscopically fine tubes

Cooper pairs as carriers

The magnetism which could solve the puzzle is in sharp contrast to anything known about the mechanism of conventional cryogenic superconductivity. In materials which have this effect at a few degrees or degrees fraction above the absolute zero (and sometimes even under high pressure), form the electron Cooper pairs. Unlike single electrons, Cooper pairs do not collide with their peers and are not scattered at the impurities in the conducting medium; therefore, they encounter no resistance in their movement. [2]Thus, in a superconductor current flows without electrical voltage and remains in a closed circuit if desired. It is noteworthy that electrons in metals can even combine in pairs, even though they would have to repel themselves as carriers of equal (negative) charge. In the 1950s, Leon N. Cooper found an explanation together with John Bardeen and J. Robert Schrieffer.[3]

The BCS theory, states that electrons in conventional superconductors overcome their mutual repulsion in two ways: The movement of the other electrons shields a portion of the negative charge that seeks to drive the pair apart. Above all, there are mediators who help overcome the mutual repulsion of the electrons, namely the ions that make up the metal lattice. An electron that travels past these ions may shift their position slightly. Such temporary distortions of the lattice called phonons in solid state and quantum physics create small regions of positive charge, which in turn attract other electrons.

But in the opinion of most researchers, the traditional model cannot explain the superconductivity of copper oxide ceramics. Indeed, in a high transition temperature BCS superconductor, electrons and phonons would interact strongly, distorting the structure of the material such that it would no longer be superconducting, and probably not even conductive any more. Moreover, in the BCS model, the electrons must always be much more energetic than the phonons: they move much faster, so that the first electron has passed the displaced ion long before the second arrives; and over this distance their mutual repulsion has less effect. However, in the cuprates, electrons and phonons move approximately equally fast: this means that paired electrons do not stay at a sufficient distance to satisfy the theory.

So far electrons as charge carriers of the current, but, these are so-called holes in most cuprates: positively charged regions that result from the absence of an electron. They are generated by doping the material with foreign atoms, which bind electrons to themselves. In the following, we therefore call the components of a Cooper pair no longer electrons or holes, but simply charge carriers.

Because of the difficulty of explaining high transition temperatures using the phonon model, many other pair mediators have been proposed, including excitons, plasmons (the carriers generate a joint movement of the charge cloud) and polarons (the charge carriers cause large local shifts of the ions and other charge carriers on the way). Other models treat each charge as two separate particles that can jump back and forth between the layers of the conductor.

Now the new connections are complicated. They consist of several layers, which isolate the conductive copper oxide layer. So far, no experiment is known that clearly differentiates between the different model concepts. However, in the meantime, the symmetry of the superconducting state is a very important property that can guide the search for the true mechanism of pair formation. By symmetry, what is meant is the shape of the wave function which mathematically describes the superconducting state and, among other things, indicates how the two charge carriers of a Cooper move relative to one another. This results in the likelihood of finding a partner in one place in the other's reference system.

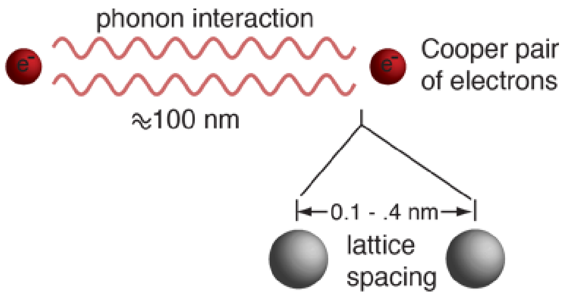

Figure 2: In superconductors, electron pairs couple over 100s nanometres. This is three orders of magnitude larger than the lattice space. These coupled electrons adapt the characteristics of a boson and go into the ground state

From the symmetry one could infer the mechanism of pair formation, because some mating models produce a characteristic symmetry. Until a few years ago, theoreticians were split into two, the one favoured models, mostly modifications of the BCS theory with phonon mediation - in which states with s-wave symmetry came out; the others preferred more exotic mechanisms that produced states with d-wave symmetry.

The dominant theory with d-wave symmetry is the spin-wave model, which was developed mainly by Douglas J. Scalapino of the University of California at Santa Barbara and David Pines of the University of Illinois (headquartered in Urbana). Thus, a moving charge tilts the spin orientation (and thus the magnetic momentum) of the atoms in the superconducting medium. The charge carrier creates a magnetic disturbance in its wake - a spin wave (rather short-term spin fluctuations). The wake of this However, there is one way to make the different signs visible. One uses a well-known property of ring-shaped superconductors: they can trap magnetic fields in the space they contain, in the form of discrete field-line bundles, so-called flux quanta.

One can imagine a single quantum of flux as a tube. Its magnetic flux strength (magnetic field times the area enclosed by the tube) is a fundamental constant (h / 2e, where h stands for Planck's constant and e is the charge of an electron).

Rings of conventional superconductors with s-symmetric wave functions always include integer multiples of this flux quantum. On the other hand, rings of superconductors with a d-symmetric state can also quantify the

magnetic flux in other ways: Depending on the energy and the magnetic flux of the system, they sometimes capture half-integer multiples of the flux quantum. As it turns out, the presence or absence of half-integer flux quanta decides whether and how the leaves of the wave function change signs. stern wave attracts a second girder, and the two form a Cooper pair.

It was initially hoped that the symmetry of the superconducting state would clearly indicate the correct theory. But for some years now, we know that different mechanisms can produce the same symmetry. Although it is not possible to conclude without doubt that the symmetry is based on the underlying mechanism, it is nevertheless possible to improve the theoretical models. For example, clear evidence that the superconducting state is not d-wave symmetric would preclude spin waves as a pairing mechanism.

d-wave symmetry

A demonstrable effect of the d-wave symmetry is that the Cooper pairs in some directions - relative to the atomic lattice are less strongly bound together; accordingly, individual unpaired charge carriers should be traveling in certain directions. One has already tried to track them down - for example, by examining how well magnetic fields penetrate the superconductor or how much heat is needed to raise the temperature of the material. All in all, the results speak for the occurrence of unpaired carriers at low temperatures, but most physicists were not convinced of this; because the experiments yielded more indirect statements, which are compatible with other states of symmetry (such as modified s-waves).

Instead of researching free bearers, other physicists measured how the strength of Cooper pair bonding varies with angle. They investigated how charge carriers are excited by high-frequency light to exit the material, how transmitted light changes its frequency, and how electrons overcome thin insulating layers between other materials and cuprates due to the quantum mechanical tunnelling effect.

Although it was found that the strength of the pair bond is dependent on angle, but the striking evidence for d-waves was not yet provided. For d- symmetric states, the wave function changes its sign: of the four leaves, two are positive and the others are negative. Because the experiments did not detect the sign change, they did not provide clear evidence for d- wave symmetry.

However, there is one way to make the different signs visible. One uses a well-known property of ring-shaped superconductors: they can trap magnetic fields in the space they contain, in the form of discrete field-line bundles, so-called flux quanta.One can imagine a single quantum of flux as a tube. Its magnetic flux strength (magnetic field times the area enclosed by the tube) is a fundamental constant (h / 2e, where h stands for Planck's constant and e is the charge of an electron).Rings of conventional superconductors with s-symmetric wavefunctions always include integer multiples of this flux quantum. On the other hand, rings of superconductors with a d-symmetric state can

also quantify the magnetic flux in other ways: Depending on the energy and the magnetic flux of the system, they sometimes capture half-integer multiples of the flux quantum. As it turns out, the presence or absence of half-integer flux quanta decides whether and how the leaves of the wave function change signs.Semi-quantum flux quanta have been recently demonstrated, although some physicists had predicted their existence as early as the late 1970s. Dieter Wohlleben found first indications of magnetization experiments in 1993.[5] Later, Dave Wollman and Dale Van Harlingen from the University of Illinois reported more reliable evidence; They measured the current and voltage in superconducting rings, which consisted of a yttrium-barium-copper oxide single crystal and a thin lead layer.

Recently, a research group at IBM received the first direct observations and images of such half flux quanta.[6] They used special cuprate rings with transversal thin layers of insulating material. These barriers - called Josephson junctions - are so narrow that Cooper pairs can tunnel through them. The British physicist Brian Josephson had predicted this effect named after him in 1962 and in 1973 received the Nobel Prize.[7]

The Josephson effect only occurs when there is a phase difference between the Cooper pairs on either side of the barrier. (The phase of a wave function describes, graphically, which part of its cycle the wave is going through.) With d-wave superconductors, rings with Josephson junctions can now be constructed, which inevitably change the phase of the Cooper pair rotating in them. This phase change corresponds to a sign change of the wave function.

With sufficient cooling, this automatic sign change spontaneously generates just enough current to include exactly half a magnetic flux quantum. If an external magnetic field is applied during cooling, then flux values of 3/2, 5/2, 7/2 and so on times the flux quantum are threaded through such a ring.

On a specially prepared substrate, they grown thin-film rings of the Yttrium-Barium-Copper Oxide (YBCO) superconductor, specifically so that one of the rings consisted of three sections, with the crystal lattice of each section 30 degrees from that of the adjacent one was rotated and thus each interface between the sections a Josephson contact formed.

If the Cooper pairs are in a state with d-wave symmetry, their wave function must change sign after completely passing through the ring.

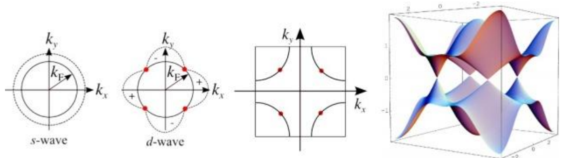

Figure 4: In the Cooper pairs of conventional superconductors, the wave functions are as symmetrical as possible: they have spherical or s-wave symmetry. That is, the probability of a paired charge carrier relative to the other falls equally exponentially of the wave function, with one of the two particles in the centre, the probabilities of finding the partner in all directions of space. In a graphical representation appear as concentric spheres. The next, slightly lower degree of symmetry is the d-state. In the diagram, it resembles four-leaved clover, with each leaf representing an area in which one partner of the Cooper pair is likely to be relative to the other. Moreover, in d-symmetry, the partners are not so close together that the mutual repulsion would interfere with their coupling.

If, on the other hand, the material was in the s-wave state, the boundary layers would have no effect; a complete cycle would take place without a sign change. After fabricating these tiny tricrystal rings -each measuring only about 50 microns (one-thousandth of a millimeter) in diameter. They then cooled them down to their critical temperature. Due to the material's geometry, their conduction state was unstable, and therefore a weak supercurrent developed by itself.

The magnetic fields trapped in the rings were imaged with a SQUID scanning microscope. SQUIDs (for superconducting quantum interference detectors) are the most sensitive magnetic field sensors currently available. By carefully calibrating the gauges with several different methods, we were able to be sure that in the tricrystal ring was actually exactly half a flux quantum. As a control, the rings were used with an even number of Josephson junctions, which in fact did not contain any flux quanta (because the sign undergoes an even number of changes and thus returns to its original state at the end).

In addition, they slightly varied the experimental conditions to show that the results were indeed based on the symmetry of the Cooper pair wave function and not on other physical effects. So, it was proved that small changes in the ring geometry turned on and off the spontaneously formed half flux quantum. Furthermore, with a weak external magnetic field, they were able to make the other rings confine integer flux quanta, demonstrating that indeed all the rings were functioning. Experiments with thin films without rings or with disks instead of rings also showed the half- integer flux quantum effect, proving that the result is determined by the internal symmetry of the superconductor and not by the geometry of the sample.

The study of symmetry can help to limit the variety of possible pair mechanisms. Above all, it is important to repeat the experiments with other cuprate superconductors. For example, when doped with electron donors, neodymium-copper-copper oxide appears to have s-wave symmetry. If confirmed, it would be a blow to the spin wave model, as most researchers would prefer a unified mechanism for all high-temperature superconductors. In addition, it would mean that the new substances are even more complicated than previously thought. By systematically examining the symmetry at different composite cuprates, one could discard inaccurate theories.

Superconductivity at the room temperature?

The vision of a novel electrical technology has not been affected by all this. Almost all the mechanisms under discussion do not exclude a superconductor at room temperature. According to rough estimates with the spin wave model, superconductivity could well be more than 20 °C - theoretically even several hundred degrees, though this seems unrealistic. Such prospects are a big step forward from the predictions of traditional BCS theory that the critical temperature can be at most -233 °C.

Certainly, scientists are not yet ready to conclusively determine the mechanism of Cooper pair formation. But with the capture and counting of magnetic flux quanta in tiny rings, they have a promising method of discovering their secret from the enigmatic new substances. If this succeeds, further high-temperature superconductors should be specifically developed, and their applications should be found.

Classification of Superconductors

Of the large number of different superconductors, which have been classified into 32 different classes, [8] in Particular the first discovered metallic superconductors and the technically significant A15 phases and the ceramic high-temperature superconductors are significant.

Metallic superconductors

Superconductivity was discovered in 1911 by Heike Kamerlingh Onnes shortly after his discovery of helium liquefaction in metal mercury. This then novel effect existed only at 4.2 Kelvin. At 39 K, magnesium diboride has the highest transition temperature among metallic superconductors at atmospheric pressure.[9] This limits the use of metallic superconductivity in a few applications, because the cooling requires liquid helium, making it very difficult and expensive. However, metallic superconductors have been found to be of great importance to them. The properties of metallic superconductors are explained by the BCS theory.

In 2015, hydrogen sulphide $H2S$ was reported to be a metallic conductor under high pressure (100-300 GPa) with a transition temperature of -70 °C (203 K)[10], setting a record.

High temperature superconductors

As high-temperature superconductor HTSC, solid or non-solid materials are referred to, the superconductivity - unlike conventional superconductors - does not come from the electron-phonon interaction. Most of the time, it occurs in not metallic, but ceramic materials. Although it seems certain that pair formation (known as "Cooper pairs") of the electrons is responsible for the superconductivity, predominantly d-wave pairing occurs instead of the conventional singlet pairing, which suggests unconventional electronic mating mechanisms. The cause has been unexplained for more than 25 years.

The name comes from the fact that high-temperature superconductors usually have significantly higher transition temperatures T_c than conventional superconductors. The temperatures are up to 203 K , which is about 180 K higher than the temperature range of conventional superconductors and already in the range of naturally occurring temperatures on the earth's surface. [10]

Ferrous high-temperature superconductors

A novel, unexpected class of high-temperature superconductors[11,12] was discovered in Japan in 2008: compounds of iron, lanthanum, phosphorus and oxygen can be superconducting. According to Pnictogen Phosphor, these superconductors are called iron pnictides.

The proportion of iron atoms was surprising, because every other superconducting material becomes normally conducting due to sufficiently strong magnetic fields. These strong internal magnetic fields could even be a prerequisite for superconductivity. The guesswork on the physical fundamentals has become even bigger. So far, it is only clear that the current flow is carried by pairs of electrons, as described in the BCS theory . However, the effect that connects these Cooper pairs is unclear. It seems certain that it is not - as with metallic superconductors - an electron- phonon interaction.

By choosing other admixtures such as arsenic, the transition temperature can be increased from originally 4K to at least 56K. 13

Use of High temperature superconductors

High-temperature superconductors are preferably operated at 77 K, if possible, provided that the current density is low enough so that transition temperature is not exceeded. The sufficient cooling with liquid nitrogen is particularly inexpensive. Such applications exist in metrology and in cables. However, due to the extremely inhomogeneous current distribution over the cross section, the low current density is not always achievable.

In applications with - possibly only occasionally - higher current density, the HTSC must be cooled more strongly. If the same performance data as conventional superconductors, such as niobium- titanium, are to be achieved, the temperature must be lowered accordingly.

With SQUIDs, with which even very small magnetic field changes can be measured, cooling with liquid nitrogen has been practiced for some time. However, as the temperature increases, so too does the noise of the signal, which is why, for example, a superconducting material at room temperature would not find widespread use in electronics today. While high-temperature SQUIDs have the higher noise compared to the older helium technology, they are also present and undesirable, but are often accepted because of the cost and handling benefits of nitrogen cooling.

The main disadvantage of high-temperature superconductors is the brittleness of the ceramic material. Nevertheless, it has been possible to produce a flexible conductor material by filling the ceramic material in tubes made of silver, which were then rolled into flexible bands.[1]A so-manufactured, only nitrogen- cooled, 1 km long underground cable for operation with 10 kV in the medium-voltage network has been used since May 2014 in the power supply of the city of Essen as part of a pilot project. It replaces a conventional 110 kV ground line.

Theory behind the high temperature

Currently, the cause of the high transition temperatures is unknown. Due to unusual isotope effects, it can be ruled out, however, that electron pair formation, as in conventional superconductivity, results exclusively from the conventional electron-phonon interaction. However, the BCS theory remains applicable, as this theory leaves the nature of the interaction open and ultimately acts as a kind of "molecular field approximation." Like the theory of critical phenomena in second-order phase transitions, however, significantly different numbers are observed in many quantities than in conventional superconductors in the power laws valid near the critical temperature.

Instead of the electron-phonon interaction, the superconductivity is presumed to be due to antiferromagnetic electron-electron correlations, which, due to the special lattice structure of the ceramic superconductors, lead to an attractive interaction of neighbouring electrons and thus to a pairing like conventional Cooper pairs of the BCS. Lead theory.] However, the isotope effects can be explained even more difficult with these interactions. Alternatively, there is also a generalization of the BCS theory according to Gorkow (GLAG theory) or completely new explanatory approaches such as the bisolitone model.

All HTSCs with high transition temperatures show characteristic anomalies in the electrical properties and the thermal conductivities already in the normal conducting state: the electrical resistance increases linearly with the temperature even at low temperatures and the Wiedemann-Franz law is also fulfilled in the middle T-range. Normal metals show a potential-dependent temperature behaviour of the resistor, and the WF law is not met in the middle T range. So far there is no theory that can explain these anomalies and the superconductivity together. [14]

Also, it has not yet been shown experimentally or theoretically refuted whether superconductivity is possible at room temperature. Earlier theoretical estimates of a "maximum transition temperature" have been proven wrong after the discovery of high-temperature superconductors.

Recent Work in Superconductivity

Superconductivity achieved in an unlikely material

In a paper[15] published in 2016, Scientists have claimed to have reached superconductivity in a non- superconducting material.

A research team at the University of Houston developed a superconductivity at the point of meeting for two phases of a material. The material they used for this experiment is calcium arsenide (CaFe2As2) which is non-superconducting.

It is suggested that in order to achieve improved transition temperatures, the use of artificial or natural composite interfaces is possible. The researchers induced the high transition temperature for the CaFe2As2 by antiferromagnetic/metallic layer stacking.

Superconductivity being induced or amplified at the interface between two different compounds was first proposed in the 1970s. Previously the experiments achieving superconductivity in a non-superconducting compound could not successfully rule out the effects of chemical doping or stress from the results. In this experiment the reach team worked the at ambient pressure and used non-doped calcium arsenide. Then heated the compound to 350 °C to achieve annealing, the process in which the compound cools slowly after it is heated. When cooled unevenly the process causes two different phases to occur in the calcium iron arsenide. Although these two phases are not superconducting, the scientists detected superconductivity at the point of two phases coexisting.The CaFe2As2 reached superconductivity at 25 K. These results are a positive development to create better, cheaper superconducting material for technological applications.

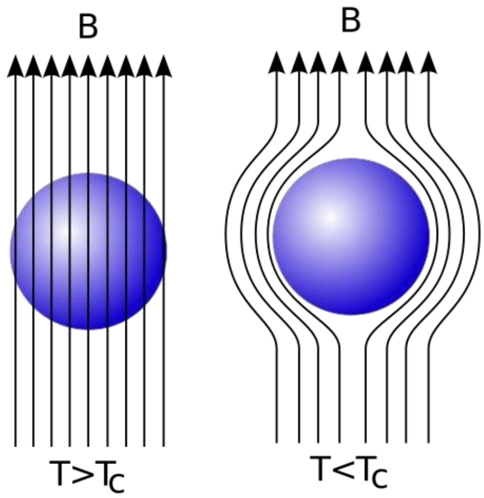

Figure 5: When a superconductor is put under magnetic field, some electric current passes through it to cancel out the field which keeps the magnetic field outside. This is called the Meissner effect.

Superconductors Under Pressure

Researchers at the Max Planck Institute in Dresden, Germany, have developed a measurement technique with which unconventional superconductors can be efficiently and precisely investigated.[16] At the first use of their pressure chamber, they demonstrated that the superconductor becomes strontium-ruthenate at much higher temperatures than normally superconducting when stretched or compressed. This allows new insights into the nature of superconductivity in this material. In addition, the Dresden method will facilitate the exploration of a broad field of superconducting materials.

The reconnaissance vehicle, developed by the research team of Clifford W. Hicks, compressed and stretched a sample of strontium-ruthenate. As a result, the atoms of the material come together, or they move away from each other. This alters the interaction between the electrons in the superconductor, which is crucial for the formation of superconductivity. In all superconductors, two electrons combine with each other to form a pair. These, called Cooper pairs, move through the material in different ways than single electrons, which ultimately leads to the disappearance of electrical resistance. Unconventional superconductors react to pressure differently than conventional ones. There are significant differences between the Cooper pairs of different superconductor types. In conventional superconductors, the Cooper pairs show no magnetism, since the magnetic moments of the two electrons align oppositely. In the case of strontium ruthenate, on the other hand, the magnetic moments of the electrons align in parallel. They are like two compass needles, pointing both in the same direction. As the magnetic moments increase rather than neutralize, the Cooper pairs remain magnetic and the superconductor reacts differently to external magnetic fields than a conventional one.

The difference expresses itself by a characteristic reaction to external influences. Theoretical physicists expected that the unconventional superconductor should react more strongly to external this, researchers developed a pressure cell. They have designed the system so that they can be precisely controlled with little experimental effort in the cooling unit, which provides the necessary temperatures for superconductivity just above absolute zero (-273 °C).The sample holder contains three piezocrystals, which increase their length when an electrical voltage is applied. Two of them are connected to the sample via a U-shaped bracket, so that the bow comes under tension as the piezocrystals get longer. A third piezocrystal is directly coupled to the sample so that it experiences pressure when the voltage is applied. The device allowed the researchers to precisely stretch and compress the superconducting crystal. Since crystals can have different physical properties along different directions, it is also important that pressure can be applied to the pressure chamber in certain crystal directions. Even under low tension or pressure, the transition temperature rises by 40%.

The surprising result of the experiments: The transition temperature increased even with very small strains and compressions of a few thousandths of the initial length by more than 4%, namely from about 1.3 K to about 1.9 K. The sharp increase in the transition temperature took, contrary to expectations, a parabolic course. On the other hand, researchers observed a much weaker change in the critical temperature along another crystal direction. At Zug, she climbed slightly in this crystal direction, and when pressed, she decreased.

The results give theoretical physicists now boundary conditions for the explanation of the exotic superconductivity of strontium ruthenate in the hand. On their basis, they can discard or favour certain models.

Nearly isotropic superconductivity in $(Ba,K)Fe_2As_2$

A group of iron- and arsenic-containing superconductors discovered last year sheds new light on the still enigmatic high-temperature conduction of the cuprates. These so-called pnictides, which include

$SmFeAsO_{1-x}F_x$ and $Ba_{1-x}K_xFe_2As_2$ belonging to superconductivity up to temperatures of 56 K. Although this is well below the transition temperatures of the cuprates, which reach up to 150 K. But it also clearly exceeds the corresponding values for the metallic low- temperature conductors. These new "high-temperature conductors" are so interesting because, in addition to many similarities with the cuprates, they also show striking differences. Although the pnictides have a layered structure like the cuprates, their superconductivity does not seem to run along crystal planes but in three dimensions.

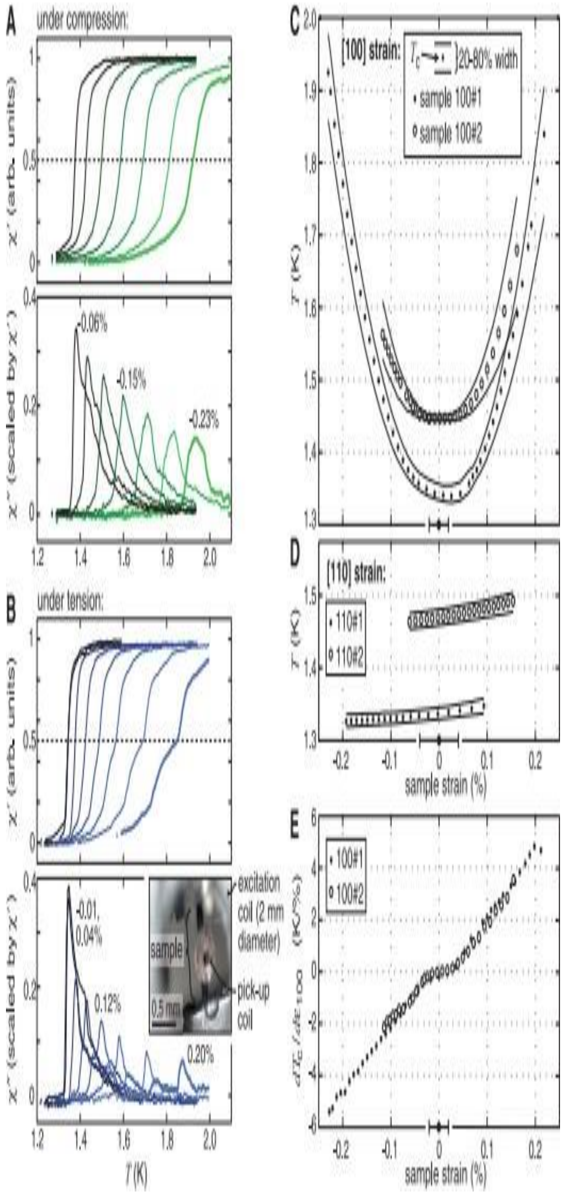

Figure 7: “Superconductivity of Sr2RuO4 under strain. (A and B) In-phase (c′) and out-of-phase(c″) parts of the ac susceptibility, measured at 369 Hz on the ⟨100⟩-oriented sample shown in the inset of (B). Approximate strains for some curves are indicated. arb. units, arbitrary units. (C)Tc versus⟨100⟩-oriented strain e100 of two samples of Sr2RuO4, one with a zero-strain Tc of 1.35 K [for which the raw data are shown in (A) and (B)] and the other with 1.45 K. e > 0 indicates tension. Tc is taken as the 50% point of c′, and the black lines are the 20 and 80% points, giving a measure of the transition width. The error bar on the horizontal axis indicates the error in locating e =0(29). (D) Tc versus ⟨110⟩ strain e110 for two further samples cut from the same crystals as in (C). The temperature scale is the same as in (C), highlighting the large difference in response between the two directions.(E) dTc/de for the data in (C).” [17]

The behavior of metallic low-temperature superconductors such as aluminum or lead can be explained by the BCS theory of Bardeen, Cooper and Schrieffer. Accordingly, the conduction electrons close together with the aid of vibrations of the crystal lattice to form Cooper pairs which form a supra-fluid condensate at a sufficiently low temperature. The high temperatures at which pnictides and cuprates become superconducting can not be explained in this way. In the case of the cuprates, which are normally antiferromagnetic non-conductors, superconductivity becomes possible only after doping with substances which withdraw electrons from the copper oxide planes in the cuprate crystal. Thanks to the resulting holes, the previously stuck in a "traffic jam" electrons in the copper oxide planes can move freely.

The superconductivity of the cuprates is therefore essentially a two-dimensional matter and thus strongly anisotropic. If a superconducting cuprate is exposed to a homogeneous magnetic field, the superconductivity is destroyed at a certain critical magnetic field strength, which depends on the orientation of the magnetic field relative to the crystal. If the field lines are parallel to the crystal planes, the magnetic field can hardly affect the electrons moving in the planes. The field can therefore only slightly affect the superconductivity and the critical field strength at which the superconductivity breaks down is relatively large. By contrast, if the field lines are perpendicular to the crystal planes, this has a strong influence on the electron movement and the critical field strength is much smaller.

It had therefore been assumed that the crystal planes are also crucial in the high-temperature superconductivity of the pnictides. The superconducting properties of the pnictides should therefore also show a strong directional dependence.

Initial experiments, in which material properties of the pnictides were measured in weak magnetic fields, seemed to confirm this. However, researchers from China and the US now have the directional dependence of the critical field strength of monocrystalline Ba 1 -x K x Fe 2 As 2 determined directly and observed no appreciable anisotropy. The pnictide samples were exposed to field were either perpendicular or parallel to the Eisenarsenidebenen. In both cases, the temperature-dependent critical field strength showed the same behavior. The crystal planes therefore did not seem to play a decisive role in this "three-dimensional" high-temperature superconductivity.

strengths of up to 150 Tesla. The field lines The fact that the superconducting pnictides seem to be more complicated than previously thought is also true for angle-resolved measurements of the photoemission spectra of Ba 1-x K x Fe 2 As 2close, which one carried out at the Leibniz Institute for Solid State and Materials Research in Dresden.

The energies of the electrons which were knocked out of the sample by monochromatic UV radiation were measured. From the measured data Sergey Borisenko and his colleagues reconstructed the Fermi surfaces of the studied pnictide, ie the surface in the momentum space of the electrons, up to which all electron states were filled up. This revealed conspicuous structures in the form of wheels with spokes, which had not been found in previous theoretical calculations. These structures appeared in both the superconducting and normal conducting states. They suggest that the Fermi area of Ba 1-x K x Fe 2 As 2despite the two-dimensional layer structure of the material, has a complicated spatial structure. The high-temperature superconductivity does not have to be two- dimensional.

Conclusion

What Superconductivity does is directing electricity without losing energy by unusual physical phenomenon, the formation of so-called Cooper pairs. In this state, electrons flow through the material without encountering obstacles. In many applications, engineers have taken advantage of this effect.

Unfortunately, superconductivity occurs only at extremely low temperatures. To use the materials, therefore, extensive cooling systems are necessary. All the more astonished were scientists when they came across high-temperature superconductors a few years ago: with these substances, the effect already occurs at higher temperatures. Even if cooling is still necessary, it may be lower than with conventional superconductors.

Superconductivity has a lot of applications from Maglev (Magnetic levitation) Trains to Magnetic Resonance machines. But the production of a superconducting compound is still expensive and complex. There are many developments and a broad spectrum of research going on in the area of Superconductivity, however, it is still unknown why superconductivity begins at an unexpectedly high temperature. If physicists should someday come up with the secret, could possibly produce tailor-made materials in which superconductivity occurs even at normal ambient temperatures the consequences for the technology would be so profound but they are not yet in sight.

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