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Recent Developments in Superconductor Theory and Materials – A Review

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ABSTRACT
A normal conductor shows some resistance even near absolute zero but in a superconductor, when the material cooled below its critical temperature, the resistance suddenly drops to zero.The rapid expansion of the field of superconductivity in the past decade has been due to three factors; First, the microscopic theory provides a basis for interpretation of experimental data and prediction of new effects. Second, new superconducting materials have been discovered, some of which remain superconducting to very high magnetic fields. And third, applications are beginning to appear. These include superconducting instruments and voltage standards.This paper reveals the recent developments in the superconductor theory and materials.

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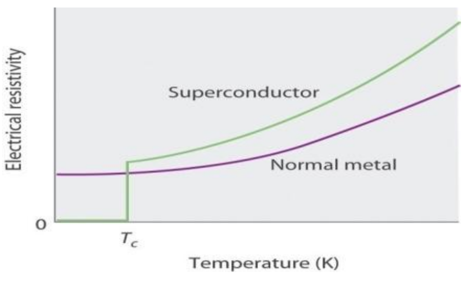
I. INTRODUCTION

The sector of superconductivity has emerged as one of themostthrilling fields of solidstate physics and solidstate chemistry over the past decade. The phenomenon changed into first located in 1911 by KamerlinghOnnes in Leiden at the same time aslooking atthe electric resistance of mercury at very low temperatures close to4.2 k , the melting point of helium. It changed intodiscovered that the electrical resistance of mercury reducedconstantly from its melting point (233 k) to 4.2 kafter which, insidesome hundredths of a degree, dropped unexpectedly to about a millionth of its originalvalueon the melting point as shown Fig1.Similar results were obtained by using various other metals such as Pb, Sn and In.

However, due to the requirement of very low temperature, it wasno longerpossibleto manufacture such devices. it's farbothdifficult and costly to achieve the liquid helium temperature and keep it for a long time. accordinglysoon after the invention of superconductivity, plenty ofresearchworkchanged into undertaken to expand a superconducting material having as excessiveessential temperature as possible. some ofsubstanceswhich includevarious metals, alloys, intermetallic and interstitial compounds, and ceramics have beenemployed for this cause. exceptthese types of efforts, the mostessential temperature (Tc) of simplest 23 kbecomeachieved in Nb3Ge, an intermetallic compound of niobium and germanium within the12 months 1977. therefore the scientists had nearly given up the hopeof manufacturing superconducting gadgets for which it turned intoessential to have a superconductor with the transition temperature identical to or higher than 77k, the liquid nitrogen temperature, if no longer the room temperature

Fig 1 Electrical resistivity versus temperature



In 1986, Bednorz and Muller reported their discovery on the La-Ba-Cu-O system of ceramic superconductors which shown T_c equal to 34 K. Thus, contrary to the previous findings, a new class of ceramic superconductors was discovered which showed critical temperature considerably greater than that of the metallic superconductors. They named these material as high -T_c ceramic superconductors . They were awarded the Noble Prize in 1988 for such an important discovery which created an unprecedented world-wide interest in the field of oxide ceramic superconductors. In 1987, a ceramic superconductor of the composition $YBa_2Cu_3O_7$ was discovered which showed T_c equal to 90 K. In 1988, the value of T_c further shot up to about 125 K for thallium cuprates.

II. LITERATURE SURVEY

2.1 Metallic superconductors

Superconductivity was discovered in 1911 by Heike KamerlinghOnnes shortly after his discovery of helium liquefaction in metal mercury. This then novel effect existed only at 4.2Kelvin. At 39K, magnesium diboride has the highest transition temperature among metallic superconductors at atmospheric pressure. This limits the use of metallic superconductivity in a few applications, because the cooling requires liquid helium, making it very difficult and expensive.. The properties of metallic superconductors are explained by the BCS theory.In 2015, hydrogen sulphide H_2S was reported to be a metallic conductor under high pressure(100-300 GPa) with a transition temperature of -70 °C (203 K), setting a record.

2.2High temperature superconductors

Until 1986 a compound of niobium and germanium (Nb_3Ge) had the higest known transition temperature 23K, 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 Muller and his associate Gerg Bednorz discovered, a material that had an unprecedentedly high transition temperature of about 30 K.

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
YH_6	224
YH_9	243

Table1 Transition temperatures of some High–T_c superconductors.

2.2.1Ferrous high-temperature superconductors

Iron based superconductors are a type of high temperature superconductor in that they have a transition temperature (T_c) much higher than a few degrees kelvin above absolute zero. 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.

2.2.2Theory behind the high temperature superconductors

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.

III. RECENT WORK IN SUPERCONDUCTIVITY

3.1 Scientists have synthesized a new high temperature superconductor, Yttrium hydride (YH_6).

An international team led by Artem R. Oganov a professor at Skoltech and MISIS, and Dr. Ivan Troyan from the institute of crystallography of RAS performed theoretical and experimental research on a new high temperature superconductor, yttrium hydride (YH_6). Their findings were published in the journal Advanced Materials.

Yttrium hydrides rank among the three highest-temperature superconductor known to date. The leader among the three is a material with an unknown S-C-H composition and superconductivity at 288 K, which is followed by lanthanum hydride, LaH_{10}, superconducting at temperatures up to 259 K and finally. Yttrium hydrides, YH_6 and YH_9 with maximum superconductivity temperatures of 224 K and 243 K, respectively. The superconductivity of $YH_6$was predicted by Chinese Scientist in 2015. All of these hydrides reach their maximum superconductivity temperatures at very high pressures 2.7 million atmospheres for S-C-H and about 1.4-1.7 million atmospheres for LaH_{10} and YH_6. The high pressure requirements remains a major roadblock for quantity production.

Until 2015, 138K (or 166k under pressure) was the record of high-temperature superconductivity. Room-temperature superconductivity, which would have been laughable just five years ago, has become a reality. Right now, the whole point is to attain room temperatures superconductivity at lower pressures .

The highest temperature superconductors were first predicted in theory and then created and investigated experimentally. When studying new materials, Chemists start by making theoretical predictions and then testing new material in practice.

Prediction of critical superconductivity temperatures, in theory has an error of 10 – 15% and similar results are observed in critical magnetic field predictions. However, the results observed in theory and experiment are quite different for YH_6. The critical magnetic field observed in the experiment is 2 to 2.5 times greater as compared to theoretical predictions. such a discrepancy is observed for the first time by the scientists which are yet to be explained.

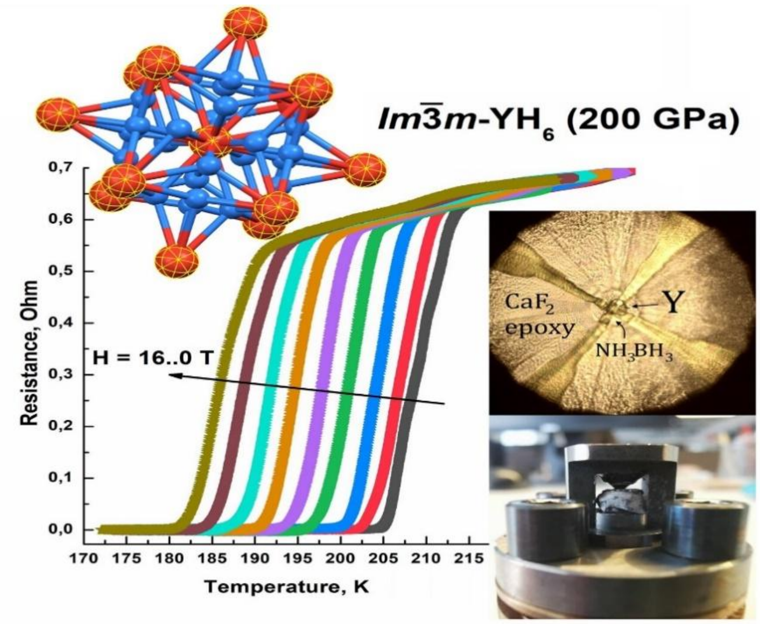


Fig 2:Newly synthesized high temperature superconductor,Yttrium hydride(YH_6)

3.2 Superconductivity achieved in Calcium arsenide ($CaFe_2As_2$)

In a paper 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($CaFe_2As_2$) 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 $CaFe_2As_2$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 research 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 phase co-existing. The $CaFe_2As_2$ reached superconductivity at 25K. These results are a positive development to create better, cheaper superconducting material for technological applications.

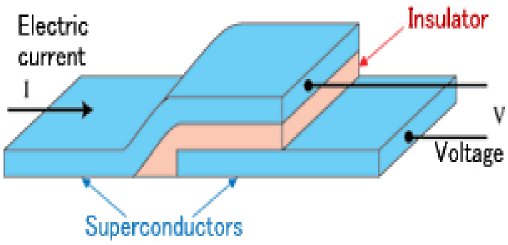


Figure 3 :A thin layer of insulator is placed between two superconductors and the current reaches a certain volume where the electrons are able to pass through the insulator as if itis non-existant which can be used to switch from on to off or other way around at very high speeds. This phenomenon is called the Josephson effect.

3.3Superconductors 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. 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 pressure than conventional superconductors. To test 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℃). The sample holder contains three peizocrystals, 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.

3.4Nearly isotropic superconductivity in (Ba,K)Fe_2As_2

A group of iron and arsenic-containing superconductors discovered new light on the still enigmatic high-temperature conduction of the cuprates. These so-called pnictides, which include $SmFeAsO_{1-x}Fx$ and $Ba_{1-x}K_xFe_2As_2$ belonging to superconductivity upto temperatures of 56K. 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.

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 cannot 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 inthe 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 superconductivityis 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 thefield 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 $Ba_{1-x}K_xFe_2As_2$determined directly and observed no appreciable anisotropy. The pnictide samples were exposed to field strengths of up to 150 Tesla. The field lines 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.

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 $Ba_{1-x}K_xFe_2As_2$close, 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, i.e the surface in the momentum space of the electrons, up to which all electronic 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 $Ba_{1-x}K_xFe_2As_2$ despite the two-dimensional layer structure of the material, has a complicated spatial structure. The high temperature superconductivity does not have to be two-dimensional.

IV. RESULTS

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.

V. CONCLUSION

Many experiments on high-Tc superconductors leads to the simultaneous existence of electron-phonon and electron-electron interactions. Progress in understanding superconducting in iron-based materials has advanced tremendously over the past years due to both theoretical and experimental efforts. HTSC are used in large scale integration technology and it is predictable that in future used in high speed computer and telecommunication.

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