Chapter One

Introduction

1.1 Prelude

Most materials people use are insulators, like plastic, or conductors, like an aluminum pot or a copper cable. Insulators show very high resistance to electricity. Conductors like copper show some resistance. Another class of materials shows no resistance at all when cooled to very low temperatures, cooler than the coolest deep freezer. Called superconductors, they were discovered in 1911. Today, they are revolutionizing the electric grid, cell phone technology and medical diagnosis. Scientists are working to make them perform at room temperature.

1.2 Research Problem

A comprehensive study; that represents superconducting materials in details, Form construction, classifications of types, properties, factors that affect superconductivity applications.

1.3 Literature Review

The first study have been done by many studies in superconductivity

Jose atel 2016.

The first paper present

Hydrogen-rich compounds have been extensively studied both theoretically and experimentally in the quest for novel high-temperature superconductors. Reports on sulfur hydride attaining metallicity under pressure and exhibiting superconductivity at temperatures as high as 200 K has spurred an intense search for room-temperature superconductors in hydride materials. Recently, compressed phosphine was reported to metallize at pressures above 45 GPa, reaching a superconducting transition temperature (T_C) of 100 K at 200 GPa. However, neither the exact composition nor the crystal structures of the superconducting phase have been conclusively determined. In this work, the phase diagram of PH_n (n=1, 2, 3, 4, 5, 6) was extensively explored by means of *ab initio* crystal structure predictions using the minima hopping method (MHM). The results do not support the existence of thermodynamically stable PH_n compounds, which exhibit a tendency for elemental decomposition at high pressure even when vibrational contributions to the free energies are taken into account. Although the lowest energy phases of PH1, 2, 3 displays TC's comparable to experiments, it remains uncertain if the measured values of TC can be fully attributed to a phase-pure compound of PH_n.

*** High Temperature Superconductivity: Materials, Mechanism and Applications**

M.A. Malik, atel 2014

The second paper present:

The immense potential of high temperature superconductivity for
Technological use has kept the subject alive ever since its discovery. Though the mechanism of high temperature superconductivity still remains elusive, a lot of progress has been made resulting in a major reduction in the number of pro-posed mechanisms under consideration. At present, electron phonon interaction or spin fluctuations are considered to be central to the mechanism of super-conductivity. While the transition temperature has not been improved over the last few years and room temperature superconductivity may not be achieved in near future, many technological applications are in use and being constantly improved. New materials with a better promise are also being discovered. This
paper attempts to look back at the progress made so far on all fronts and elucidate the challenges of understanding the mechanism and achieving room temperature superconductivity.

***The Physics and Applications of Superconducting Meta materials**

Steven M, etal 2016

The third paper present

Our objective is to give a basic introduction to the emerging field of superconducting meta materials. The discussion will focus on the RF, microwave, and low-THz frequency range, because only there can the unique properties superconductors be utilized Superconductors have a number of electromagnetic properties not shared by normal metals, and these properties can be exploited to make nearly ideal and novel meta material structures. In section I. we begin with a brief overview of the properties of superconductors that are of relevance to this discussion. In section II we consider some of the shortcomings of normal metal based meta materials, and discuss how superconducting versions can have dramatically superior properties. This section also covers some of the limitations and disadvantages of superconducting meta materials. Section III reviews theoretical and experimental results on a number of unique meta materials, and discusses their properties. Section IV reviews novel applications of superconducting meta materials, while section

V includes a summary and speculates about future directions for these meta materials.

***Space Applications of High-Temperature Superconductors**

Vernon O. Heinen,atel 2016

The forth paper present

The application of superconducting technology in space has been limited by the requirement of cooling to near liquid helium temperatures. The only means of attaining these temperatures has been with cryogenic fluids which severely limits mission lifetime. The development of materials with superconducting transition temperatures (T_c) above 77 K has made superconducting technology more attractive and feasible for employment in aerospace systems. In this paper, potential application of high-temperature superconducting technology in cry coolers' and remote sensing; communications and power systems will be discussed.

1.4 Objectives of the Study

*This research study all phenomena related to superconductivity and the important of superconductivity in life generally.

*****Definition of superconductivity.

*Structure.

* The classifications types.

*Factors affect superconductivity.

* Applications.

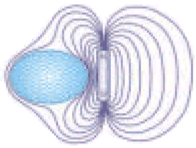
1.5Presentation of The Thesis

This research consist of five chapters the first deals with the introduction of the research, the second about introduction of superconductivity and the classifications, theories, the third talks about the physical properties of superconductivity,and the forth is application of superconductivity, and finally is conclusion and recommendation.

Chapter Two
Superconductors

2.1 Introduction

Superconductors, materials that have no resistance to the flow of electricity, are one of the last great frontiers of scientific discovery. Not only have the limits of superconductivity not yet been reached, but the theories that explain superconductor behavior seem to be constantly under review [1, 2]. In 1911 superconductivity was first observed in mercury by Dutch physicist Heike Kamerlingh Onnes of Leiden University. When he cooled it to the temperature of liquid helium, 4 degrees Kelvin (-452F, -269°C), its resistance suddenly disappeared. The Kelvin scale represents an "absolute" scale of temperature. Thus, it was necessary for Onnes to come within 4 degrees of the coldest temperature that is theoretically attainable to witness the phenomenon of superconductivity. Later, in 1913, he won a Nobel Prize in physics for his research in this area. The next great milestone in understanding how matter behaves at extreme cold temperatures occurred in 1933. German researchers Walther Meissner and Robert Ochsenfeld discovered that a superconducting material will repel a magnetic field (below graphic). A magnet moving by a conductor induces currents in the conductor. This is the principle on which the electric generator operates. But, in a superconductor the induced currents exactly mirror the field that would have otherwise penetrated the superconducting material - causing the magnet to be repulsed [3, 4]. This phenomenon is known as strong diamagnetism and is today often referred to as the "Meissner effect". The Meissner effect is so strong that a magnet can actually be levitated over a superconductive material.



Fig(2.1):Meissner effect

In subsequent decades other superconducting metals, alloys and compounds were discovered. In 1941 niobium-nitride was found to superconduct at 16 K. In 1953 vanadium-silicon displayed superconductive properties at 17.5 K. And, in 1962 scientists at Westinghouse developed the first commercial superconducting wire, an alloy of niobium and titanium (NbTi). High-energy, particle-accelerator electromagnets made of copper-clad niobium-titanium were then developed in the 1960s at the Rutherford-Appleton Laboratory in the UK, and were first employed in a superconducting accelerator at the Fermi lab Tevatron in the US in 1987.

The first widely-accepted theoretical understanding of superconductivity was advanced in 1957 by American physicists John Bardeen, Leon Cooper, and John Schrieffer. Their *Theories of Superconductivity* became known as the BCS theory - derived from the first letter of each man's last name - and won them a Nobel prize in 1972[5,6]. The mathematically-complex BCS theory explained superconductivity at temperatures close to absolute zero for elements and simple alloys. However, at higher temperatures and with different superconductor systems, the BCS theory has subsequently become inadequate to fully explain how superconductivity is occurring. Another significant theoretical advancement came in 1962 when Brian D. Josephson, a graduate student at Cambridge University, predicted that electrical current would flow between two superconducting materials - even when they are separated by a non-superconductor or insulator. His prediction was later confirmed and won him a share of the 1973 Nobel Prize in Physics. This tunneling phenomenon is today known as the "Josephson effect" and has been applied to electronic devices such as the SQUID, an instrument capabable of detecting even the weakest magnetic fields. (Below SQUID graphic courtesy Quantum Design.)

Fig(2.2): SQUID device

The 1980's were a decade of unrivaled discovery in the field of superconductivity. In 1964 Bill Little of Stanford University had suggested the possibility of organic (carbon-based) superconductors. The first of these theoretical superconductors was successfully synthesized in 1980 by Danish researcher Klaus Bechgaard of the University of Copenhagen and three French team members. $(TMTSF)_2PF_6$ had to be cooled to an incredibly cold 1.2K transition temperature (known as T_c) and subjected to high pressure to superconductor. But, its mere existence proved the possibility of "designer" molecules - molecules fashioned to perform in a predictable way. Then, in 1986, a truly breakthrough discovery was made in the field of superconductivity [7, 8]. Alex Müller and Georg Bednorz, researchers at the IBM Research Laboratory in Rüschlikon, Switzerland, created a brittle ceramic compound that superconducted at the highest temperature then known: 30 K. What made this discovery so remarkable was that ceramics are normally insulators. They don't conduct electricity well at all. So, researchers had not considered them as possible high-temperature superconductor candidates. The lanthanum, barium, copper and oxygen compound that Müller and Bednorz synthesized, behaved in a not-as-yet-understood way. (Original article printed in Zeitschrift für Physik Condensed Matter, April 1986.) The discovery of this first of the superconducting copper-oxides (cuprates) won the 2 men a Nobel Prize the following year. It was later found that tiny amounts of this material were actually superconducting at 58

K, due to a small amount of lead having been added as a calibration standard - making the discovery even more noteworthy. Müller and Bednorz discovery triggered a flurry of activity in the field of superconductivity. Researchers around the world began "cooking" up ceramics of every imaginable combination in a quest for higher and higher Tc's. In January of 1987 a research team at the University of Alabama-Huntsville substituted yttrium for lanthanum in the Müller and Bednorz molecule and achieved an incredible 92 K T_c. For the first time a material (today referred to as YBCO) had been found that would superconduct at temperatures warmer than liquid Nitrogen - a commonly available coolant. Additional milestones have since been achieved using exotic - and often toxic - elements in the base perovskite ceramic [9, 10]. For more than 20 years the mercury copper-oxides held the record for highest transition temperature at 138 K. However, recently the thallium copper-oxides have moved into the lead. When incorporated into a 3212 structure, thallium, barium, tellurium, copper and oxygen will produce a T_c near 147K with purity comparable to the mercuric cuprates. The first company to capitalize on high-temperature superconductors was Illinois Superconductor (today known as ISCO International), formed in 1989. This amalgam of government, private-industry and academic interests introduced a depth sensor for medical equipment that was able to operate at liquid nitrogen temperatures (~ 77K). In recent years, many discoveries regarding the novel nature of superconductivity have been made [11, 12]. In 1997 researchers found that at a temperature very near absolute zero an alloy of gold and indium was both a superconductor and a natural magnet. Conventional wisdom held that a material with such properties *could not exist!* Since then, over a half-dozen such compounds have been found. Recent years have also seen the discovery of the first high-temperature superconductor that does not contain any copper (2000), and the first all-metal perovskite superconductor (2001).Also in 2001 a material that had been sitting on laboratory shelves for decades was found to be an extraordinary new superconductor. Japanese researchers measured the transition temperature of magnesium diboride at 39 Kelvin - far above the highest T_c of any of the elemental or binary alloy superconductors. While 39 K is still well below the Tc's of the "warm" ceramic superconductors, subsequent refinements in the way MgB_2 is fabricated have paved the way for its use in industrial applications. Laboratory testing has found MgB_2 will outperform NbTi and Nb_3Sn wires in high magnetic field applications like MRI. Though a theory to explain high-temperature superconductivity still eludes modern science, clues occasionally appear that contribute to our understanding of the exotic nature of this phenomenon. In 2005, for example, Superconductors ORG discovered that increasing the weight ratios of alternating planes within the layered perovskites can often increase T_c significantly. Further increases in transition temperatures were then noticed when high dielectric constant alloys were used. This has led to the discovery of more than 130 new high-temperature superconductors, including a candidate for a new world record. The most recent "family" of superconductors to be discovered is the "pnictides". These iron-based superconductors were first observed by a group of Japanese researchers in 2006[13, 14, and 15]. Like the high-T_c copper-oxides, the exact mechanism that facilitates superconductivity in them is a mystery. However, with Tc's over 50K, a great deal of excitement has resulted from their discovery.

2.2 Superconductors

Superconductivity is a phenomenon of exactly zero electrical resistance and expulsion of magnetic flux fields occurring in certain materials, called **superconductors**, when cooled below a characteristic critical temperature. It was discovered by Dutch physicist Heike Kamerlingh Onnes on April 8, 1911, in Leiden. Like ferromagnetism and atomic spectral lines, superconductivity is a quantum mechanical phenomenon. It is characterized by the Meissner effect, the complete ejection of magnetic field lines from the interior of the superconductor as it transitions into the superconducting state. The occurrence of the Meissner effect indicates that superconductivity cannot be understood simply as the idealization of *perfect conductivity* in classical physics. The electrical resistance of a metallic conductor decreases gradually as temperature is lowered. In ordinary conductors, such as copper or silver, this decrease is limited by impurities and other defects. Even near absolute zero, a real sample of a normal conductor shows some resistance. In a superconductor; the resistance drops abruptly to zero when the material is cooled below its critical temperature. An electric current flowing through a loop of superconducting wire can persist indefinitely with no power source. In 1986, it was discovered that some cuprate-perovskite ceramic materials have a critical temperature above 90 K (−183 °C). Such a high transition temperature is theoretically impossible for a conventional superconductor, leading the materials to be termed high-temperature superconductors. The cheaply-available coolant liquid nitrogen boils at 77 K, and thus superconducting at higher temperatures than this facilitates many experiments and applications that are less practical at lower temperatures.

2.3 Classification of Superconductors

There are many criteria by which superconductors are classified. The most common are:

2.3.1 Response to A Magnetic Field

A superconductor can be Type I, meaning it has a single critical field, above which all superconductivity is lost and below which the magnetic field is completely expelled from the superconductor; or Type II, meaning it has two critical fields, between which it allows partial penetration of the magnetic field through isolated points. These points are called vortices. Furthermore, in multicomponent superconductors it is possible to have combination of the two behaviours. In that case the superconductor is of Type-1.

2.3.2 By Theory of Operation

It is conventional if it can be explained by the BCS theory or its derivatives, or unconventional, otherwise.

2.3.3 By Critical Temperature

A superconductor is generally considered high-temperature if it reaches a superconducting state when cooled using liquid nitrogen – that is, at only $T_c > 77$ K) – or low-temperature if more aggressive cooling techniques are required to reach its critical temperature.

2.3.4 By Material

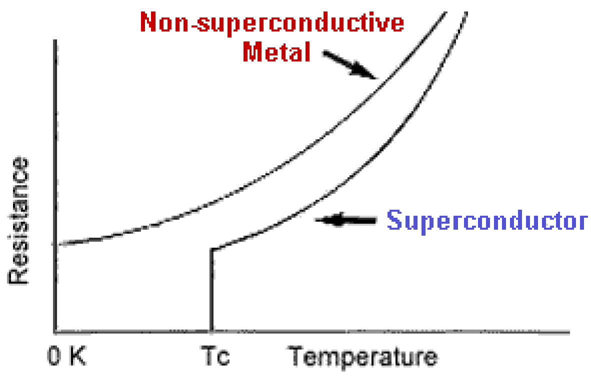
Superconductor material classes include chemical elements (e.g. mercury or lead), alloys (such as niobium-titanium, germanium-niobium, and niobium nitride), ceramics (YBCO and magnesium diboride), superconducting pnictides (like fluorine-doped LaOFeAs) or organic superconductors (fullerenes and carbon nanotubes; though perhaps these examples should be included among the chemical elements, as they are composed entirely of carbon).

2.4Types I and II Superconductors

There are thirty pure metals which exhibit zero resistivity at low temperatures and have the property of excluding magnetic fields from the interior of the superconductor (Meissner effect). They are called Type II superconductors. The superconductivity exists only below their critical temperatures and below a critical magnetic field strength. Type I superconductors are well described by the BCS theory. Starting in 1930 with lead-bismuth alloys, a number of alloys were found which exhibited superconductivity; they are called Type II superconductors. They were found to have much higher critical fields and therefore could carry much higher current densities while remaining in the superconducting state. The variations on barium-copper-oxide ceramics which achieved the superconducting state at much higher temperatures are often just referred to as high temperature superconductors and form a class of their own.

2.4.1Type I Superconductors and a Periodic Chart Comparison

The Type I category of superconductors is mainly comprised of metals and metalloids that show *some* conductivity at room temperature. They require incredible cold to slow down molecular vibrations sufficiently to facilitate unimpeded electron flow in accordance with what is known as BCS theory. BCS theory suggests that electrons team up in "Cooper pairs" in order to help each other overcome molecular obstacles - much like race cars on a track drafting each other in order to go faster. Scientists call this process phonon-mediated coupling because of the sound packets generated by the flexing of the crystal lattice[16,17].Type I superconductors - characterized as the "soft" superconductors - were discovered first and require the coldest temperatures to become superconductive. They exhibit a very sharp transition to a superconducting state (see below graph) and "perfect" diamagnetism - the ability to repel a magnetic field completely. Below is a list of known type I superconductors along with the critical temperature, Surprisingly, copper, silver and gold, three of the best metallic conductors, do not rank among the superconductive elements[18].



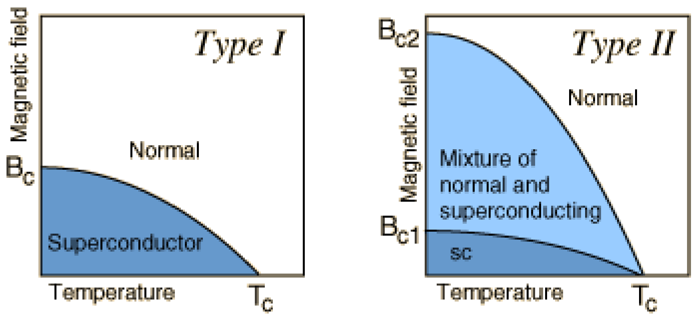
Fig(2.3):comparison between superconductor and non-superconductive.

Table (2.1):this table show the critical temperature of type I elements:

Mat	T_c
Rh	0
W	0.015
Ir	0.1
Lu	0.1
Ga	1.083
In	3.408
Pb	7.193

2.4.1.1Critical Magnetic Field

The superconducting state cannot exist in the presence of a magnetic field greater than a critical value, even at absolute zero. This critical magnetic field is strongly correlated with the critical temperature for the superconductor, which is in turn correlated with the bandgap. Type II superconductors show two critical magnetic field values, one at the onset of a mixed superconducting and normal state and one where superconductivity ceases.



Fig(2.4):show type I and type II

It is the nature of superconductors to exclude magnetic fields (Meissner effect) so long as the applied field does not exceed their critical magnetic field. This critical magnetic field is tabulated for 0K and decreases from that magnitude with increasing temperature, reaching zero at the critical temperature for superconductivity. The critical magnetic field at any temperature below the critical temperature is given by the relationship

$$B_c \approx B_c(0)\left[1-\left(\frac{T}{T_c}\right)^2\right] \qquad (2.1)$$

At T=0

Where

$B_c \equiv critical\ magnetic\ field$

$T \equiv temperture$

$T_C \equiv critical\ temperture$

2.4.2TypeIISuperconductors

Except for the elements vanadium, technetium and niobium, the Type II category of superconductors is comprised of metallic compounds and alloys. The recently-discovered superconducting "perovskites" (metal-oxide ceramics that normally have a ratio of 2 metal atoms to every 3 oxygen atoms) belong to this Type II group. They achieve higher Tc's than Type I superconductors by a mechanism that is still not completely understood. Conventional wisdom holds that it relates to the planar layering within the crystalline structure. Although, other recent research suggests the holes of hypocharged oxygen in the charge reservoirs are responsible. (Holes are positively-charged vacancies within the lattice.) The superconducting cuprates (copper-oxides) have achieved astonishingly high Tc's when you consider that by 1985 known Tc's had only reached 23 Kelvin. To date, the highest Tc attained at ambient pressure for a material that will form stoichiometrically (by direct mixing) has been 147 Kelvin. And the highest Tc overall is 202 Celsius for a material which does not form stoichiometrically. It is almost certain that other, more-synergistic compounds still await discovery among the high-temperature superconductors. The first superconducting Type II compound, an alloy of lead and bismuth, was fabricated in 1930 by W. de Haas and J. Voogd. But, was not recognized as such until later, after the Meissner effect had been discovered. This new category of superconductors was identified by L.V.

Shubnikov at the Kharkov Institute of Science and Technology in the Ukraine in 1936 when he found two distinct critical magnetic fields (known as H_{c1} and H_{c2}) in $PbTl_2$. The first of the oxide superconductors was created in 1973 by DuPont researcher Art Sleight when $Ba(Pb,Bi)O_3$ was found to have a Tc of 13K. The superconducting oxocuprates followed in 1986. Type II superconductors - also known as the "hard" superconductors - differ from Type I in that their transition from a normal to a superconducting state is gradual across a region of "mixed state" behavior. Since a Type II will allow *some* penetration by an external magnetic field into its surface, this creates some rather novel mesoscopic phenomena like superconducting "stripes" and "flux-lattice vortices". While there are far too many to list in totality, some of the more interesting TypeII superconductors are listed below [19,20,21].

Table (2.2): the critical temperture and critical field of type II compounds

Material	Transition Temp (K)	Critical Field
NbTI	10	15
PbMoS	14.4	6.0
Nb3 Sn	18.3	24.5
Nb3Al	18.7	32.4

2.5 High-Temperature Superconductivity

Until 1986, physicists had believed that BCS theory forbade superconductivity at temperatures above about 30 K[22,23,24]. In that year, Bednorz and Müller discovered superconductivity in a lanthanum-based cuprates perovskite material, which had a transition temperature of 35 K (Nobel Prize in Physics, 1987). It was soon found that replacing the lanthanum with yttrium (i.e., making YBCO) raised the critical temperature to 92 K[25,26,27,28].

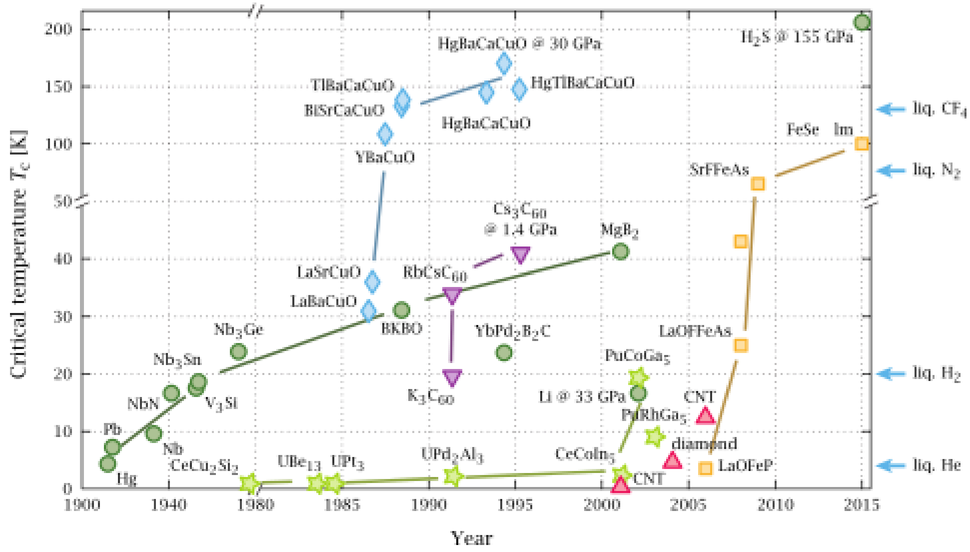


Fig (2.5) Timeline of superconducting materials

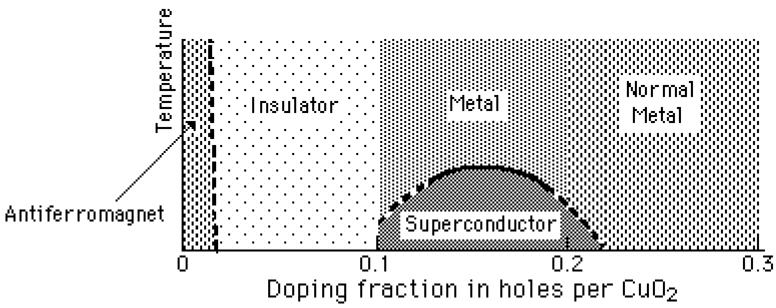
This temperature jump is particularly significant, since it allows liquid nitrogen as a refrigerant, replacing liquid helium. This can be important commercially because liquid nitrogen can be produced relatively cheaply, even on-site. Also, the higher temperatures help avoid some of the problems that arise at liquid helium temperatures, such as the formation of plugs of frozen air that can block cryogenic lines and cause unanticipated and potentially hazardous pressure buildup[29].

Many other cuprates superconductors have since been discovered, and the theory of superconductivity in these materials is one of the major outstanding challenges of theoretical condensed matter physics. There are currently two main hypotheses – the resonating-valence-bond theory, and spin fluctuation which has the most support in the research community. The second hypothesis proposed that electron pairing in high-temperature superconductors is mediated by short-range spin waves known as paramagnons.

Since about 1993, the highest-temperature superconductor has been a ceramic material consisting of mercury, barium, calcium, copper and oxygen ($HgBa_2Ca_2Cu_3O_{8+\delta}$) with T_c = 133–138 K. The latter experiment (138 K) still awaits experimental confirmation; however.In February 2008, an iron-based family of high-temperature superconductors was discovered. Hideo Hosono, of the Tokyo Institute of Technology, and colleagues found lanthanum oxygen fluorine iron arsenide ($LaO_{1-x}F_xFeAs$), an oxypnictide that superconducts below 26 K. Replacing the lanthanum in $LaO_{1-x}F_xFeAs$ with samarium leads to superconductors that work at 55 K. In May 2014, hydrogen sulfide (H2S) was predicted to be a high-temperature superconductor with a transition temperature of 80 K at 160 giga pascals of pressure[30]. In 2015, H2S has been observed to exhibit superconductivity at below 203 K but at extremely high pressures — around 150 giga pascals.

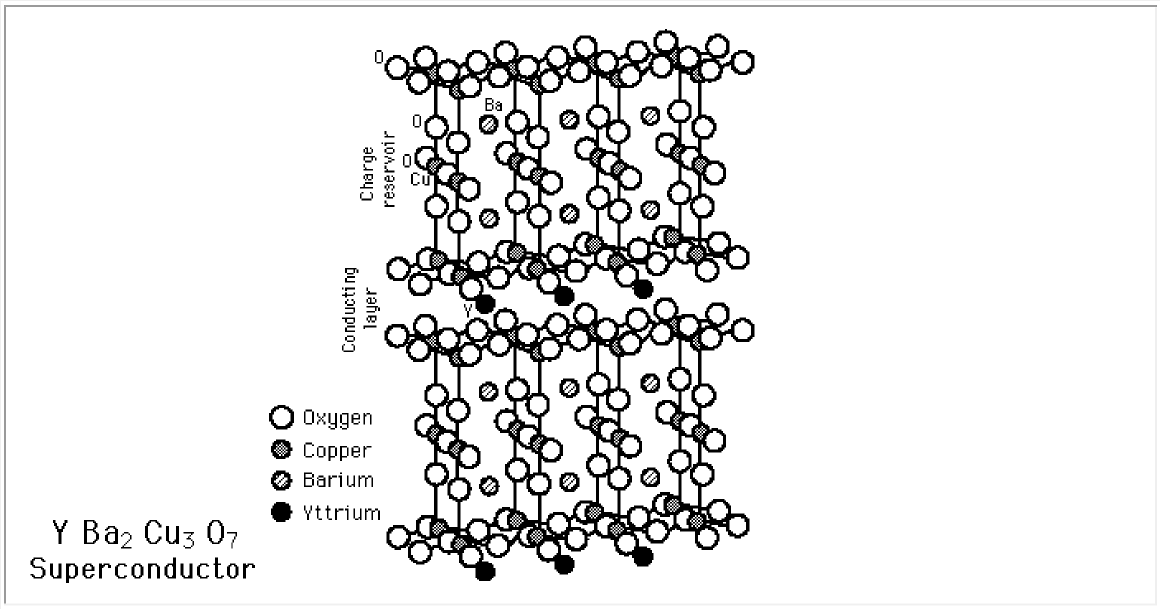
2.6 Cuprates Superconductor Phases

Illustrative of the complexity of the high-temperature superconductor materials is this phase diagram which applies to the cuprate materials. At very low doping, they show the long range order of an antiferromagnet [31].



Fig(2.6)

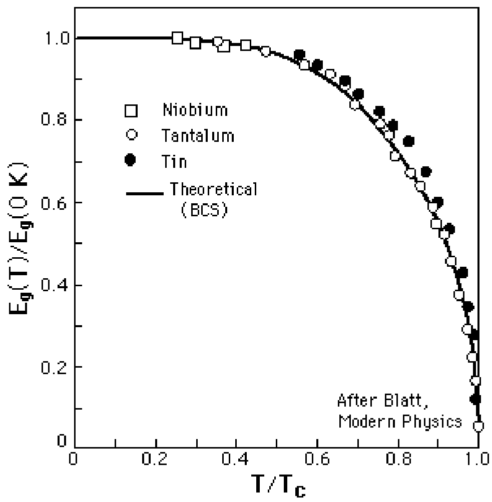
Doping breaks up the antiferromagnetic order and they become insulators. Only with doping fraction between about 0.1 and 0.2 do they become superconductors.



fig(2.7) The high temperature superconductors are ceramic materials with layers of copper-oxide spaced by layers containing barium and other atoms. The yttrium compound is somewhat unique in that it has a regular crystal structure while the lanthanum version is classified as a solid solution. The yttrium compound is often called the 1-2-3 superconductor because of the ratios of its constituents.

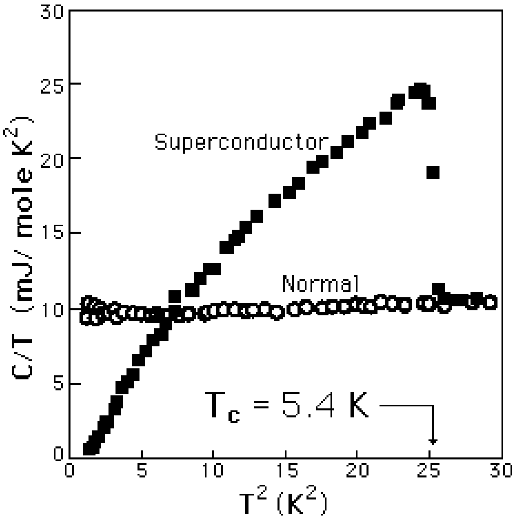
After Jorgensen, Physics Today 32,33, (1991)

2.7 Energy Gap in Superconductors as a Function of Temperature



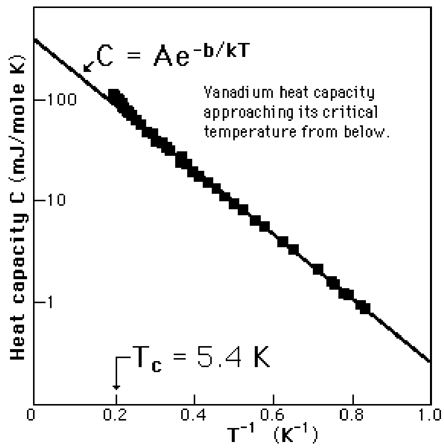
Fig(2.8) The effective energy gap in superconductors can be measured in microwave absorption experiments. The data at left offer general confirmation of the BCS theory of superconductivity

2. 8 Vanadium Heat Capacity



Fig(2.9) The heat capacity of superconducting vanadium is very different from that of vanadium which is kept in the normal state by imposing a magnetic field on the sample. The exponential increase in heat capacity near the critical temperature suggests an energy band gap for the superconducting material. This evidence for a band gap is one of the pieces of experimental evidence which supports the BCS theory of superconductivity.

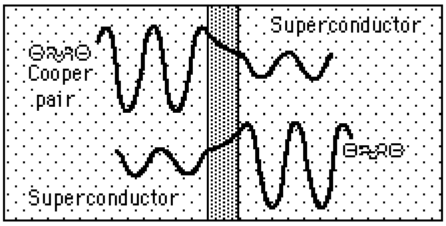
2. 9 Exponential Heat Capacity



Fig(2.10) As it is warmed toward its critical temperature, the heat capacity of vanadium increases 100-fold in just 4 K. This exponential increase suggests an energy gap which must be bridged by thermal energy. This energy gap evidence was part of the experimental motivation for the BCS theory of superconductivity.

2.10 Josephson Junction

Two superconductors separated by a thin insulating layer can experience tunneling of Cooper pairs of electrons through the junction. The Cooper pairs on each side of the junction can be represented by a wave function similar to a free particle wave function. In the DC Josephson effect, a current proportional to the phase difference of the wave functions can flow in the junction in the absence of a voltage. In the AC Josephson effect, a Josephson junction will oscillate with a characteristic frequency which is proportional to the voltage across the junction. Since frequencies can be measured with great accuracy, a Josephson junction device has become the standard measure of voltage[34,35].



Fig(2.11):josephen junction

The wave function which describes a Cooper pair of electrons in a superconductor is an exponential like the free particle wave function. In fact, all the Cooper pairs in a superconductor can be described by a single wave function in the absence of a current because all the pairs have the same phase - they are said to be "phase coherent" (Clarke). If two superconductors are separated by a thin insulating layer, then quantum mechanical tunneling can occur for the Cooper pairs without breaking up the pairs. Clarke envisions this condition as the wave functions for Cooper pairs on each side of the junction penetrating into the insulating region and "locking together" in phase. Under these conditions, a current will flow through the junction in the absence of an applied voltage (the DC Josephson effect).

2.11 Josephson Voltage Standard

When a DC voltage is applied to a Josephson junction, an oscillation of frequency

$$f_{Josephson} = \frac{2e\ \Delta V}{h} \qquad (2.2)$$

Where

f ≡frequancy.

e≡charge of electron.

v≡voltage.

h≡plank constant.

occurs at the junction. Since this relationship of voltage to frequency involves only fundamental constants and since frequency can be measured with extreme accuracy, the Josephson junction has become the standard voltage measurement.

Josephson junction standards can yield voltages with accuracies of one part in 10^10. NIST has produced a chip with 19000 series junctions to measure voltages on the order of 10 volts with this accuracy.

2.12The Standard Volt

The standard volt is now defined in terms of a Josephson junction oscillator. The oscillation frequency of a Josephson junction is given by

$$f_{Josephson} = \frac{2e\ \Delta V}{h} \qquad (2.3)$$

so the relationship between frequency and voltage across the junction depends only upon the fundamental constants e and h. For one microvolt applied to the junction the frequency is

$$f_{Josephson} = 483.6\ \text{MHz}$$

The standard volt is now defined as the voltage required producing a frequency of 483,597.9 GHz.

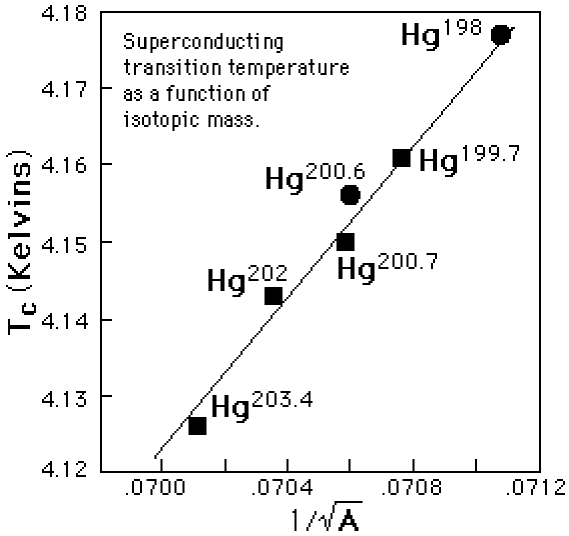
2.13 Cooper Pairs

The transition of a metal from the normal to the superconducting state has the nature of a condensation of the electrons into a state which leaves a band gap above them. This kind of condensation is seen with super fluid helium, but helium is made up of bosons -- multiple electrons can't collect into a single state because of the Pauli exclusion principle[36]. Froehlich was first to suggest that the electrons act as pairs coupled by lattice vibrations in the material. This coupling is viewed as an exchange of phonons, phonons being the quanta of lattice vibration energy. Experimental corroboration of an interaction with the lattice was provided by the isotope effect on the superconducting transition temperature. The boson-like behavior of such electron pairs was further investigated by Cooper and they are called "Cooper pairs". The condensation of Cooper pairs is the foundation of the BCS theory of superconductivity.

2.14 Isotope Effect, Mercury

If electrical conduction in mercury were purely electronic, there should be no dependence upon the nuclear masses. This dependence of the critical temperature for superconductivity upon isotopic mass was the first direct evidence for interaction between the electrons and the lattice. This supported the BCS theory of lattice coupling of electron pairs.

It is quite remarkable that an electrical phenomenon like the transition to zero resistivity should involve a purely mechanical property of the lattice. Since a change in the critical temperature involves a change in the energy environment associated with the superconducting transition, this suggests that part of the energy is being used to move the atoms of the lattice since the energy depends upon the mass of the lattice [37]. This indicates that lattice vibrations are a part of the superconducting process. This was an important clue in the process of developing the BCS theory because it suggested lattice coupling, and in the quantum treatment suggested that phonons were involved.



Fig(2.12):show isotope effect, Merecury

2.15 Meissner Effect

When a superconductor is placed in a weak external magnetic field **H**, and cooled below its transition temperature, the magnetic field is ejected. The Meissner effect does not cause the field to be completely ejected but instead the field penetrates the superconductor but only to a very small distance, characterized by a parameter λ, called the London penetration depth, decaying exponentially to zero within the bulk of the material. The Meissner effect is a defining characteristic of superconductivity. For most superconductors, the London penetration depth is on the order of 100 nm.The Meissner effect is sometimes confused with the kind of diamagnetism one would expect in a perfect electrical conductor: according to Lenz's law, when a *changing* magnetic field is applied to a conductor, it will induce an electric current in the conductor that creates an opposing magnetic field. In a perfect conductor, an arbitrarily large current can be induced, and the resulting magnetic field exactly cancels the applied field[38].The Meissner effect is distinct from this—it is the spontaneous expulsion which occurs during transition to superconductivity. Suppose we have a material in its normal state, containing a constant internal magnetic field. When the material is cooled below the critical temperature, we would observe the abrupt expulsion of the internal magnetic field, which we would not expect based on Lenz's law. The Meissner effect was given a phenomenological explanation by the brothers Fritz and Heinz London, who showed that the electromagnetic free energy in a superconductor is minimized provided[39]

$$\nabla^2 H = \lambda^{-2} H \tag{2.4}$$

where **H** is the magnetic field and λ is the London penetration depth.

This equation, which is known as the London equation, predicts that the magnetic field in a superconductor decays exponentially from whatever value it possesses at the surface.A superconductor with little or no magnetic field within it is said to be in the Meissner state. The Meissner state breaks down when the applied magnetic field is too large. Superconductors can be divided into two classes according to how this breakdown occurs. In Type I superconductors, superconductivity is abruptly destroyed when the strength of the applied field rises above a critical value H_c. Depending on the geometry of the sample, one may obtain an intermediate state consisting of a baroque pattern of regions of normal material carrying a magnetic field mixed with regions of superconducting material containing no field. In Type II superconductors, raising the applied field past a critical value H_{c1} leads to a mixed state (also known as the vortex state) in which an increasing amount of magnetic flux penetrates the material, but there remains no resistance to the flow of electric current as long as the current is not too large. At a second critical field strength H_{c2}, superconductivity is destroyed[40]. The mixed state is actually caused by vortices in the electronic superfluid, sometimes called fluxons because the flux carried by these vortices is quantized. Most pure elemental superconductors, except niobium and carbon nanotubes, are Type I, while almost all impure and compound superconductors are Type II.

2.16 BCS Theory of Superconductivity

The properties of Type I superconductors were modeled successfully by the efforts of John Bardeen, Leon Cooper, and Robert Schrieffer in what is commonly called the BCS theory. A key conceptual element in this theory is the pairing of electrons close to the Fermi level into Cooper pairs through interaction with the crystal lattice. This pairing results from a slight attraction between the electrons related to lattice vibrations; the coupling to the lattice is called a phonon interaction.Pairs of electrons can behave very differently from single electrons which are fermions and must obey the Pauli exclusion principle. The pairs of electrons act more like bosons which can condense into the same energy level. The electron pairs have a slightly lower energy and leave an energy gap above them on the order of.001 eV which inhibits the kind of collision interactions which lead to ordinary resistivity. For temperatures such that the thermal energy is less than the band gap, the material exhibits zero resistivity[41]. Bardeen, Cooper, and Schrieffer received the Nobel Prize in 1972 for the development of the theory of superconductivity.

2.17 London Moment

Conversely, a spinning superconductor generates a magnetic field, precisely aligned with the spin axis. The effect, the London moment, was put to good use in Gravity Probe B. This experiment measured the magnetic fields of four superconducting gyroscopes to determine their spin axes. This was critical to the experiment since it is one of the few ways to accurately determine the spin axis of an otherwise featureless sphere [42].

2.17.1 The London Equations

A simple but useful description of the electrodynamics of superconductivity was put forward by the brothers Fritz and Heinz London in 1935,shortly after the discovery that magnetic field are expelled from superconductors. Their proposed equations are consistent with the Meissner effect and can be used with Maxwell's equation to predict how the magnetic field and surface current vary with distance from the surface of superconductor.

In order to account for the Meissner effect, the London brothers proposed that in the superconductor,equation (2.3)

$$curl\ \frac{\partial J_{pc}}{\partial t} = \frac{-n_{pc}\ e^2}{m}\frac{\partial B}{\partial t}\ (2.5)$$

Where:

(pc mean perfect conductor)

J_{pc} ≡ current density.

n_{pc} ≡number of state.

B ≡magnetic field.

t ≡time.

is replaced by the more restrictive relationship *London equations:*-

$$\boldsymbol{curl\, J_s} = \frac{\boldsymbol{-n_s\ e^2}}{\boldsymbol{m}}\boldsymbol{B}\ (\mathbf{2.6})$$

where

n_s ≡number of state.

$$\frac{\partial J_s}{\partial t} = \frac{n_s e^2}{m} E\ (2.7)$$

Where

E≡electric field.

It is important to note that these equations are not an explanation of superconductivity. They were introduced as restriction on Maxwell's equations so that the behavior of superconductors deduced from the equations was consistent with experimental observations,and in particular with the Meissner effect. Their status is somewhat similar to ohm's law,which is a useful description of the behavior of many normal metals,but which does not provide any explanation for the conduction process at the microscopic level. To demonstrate how the London equations lead to the Meissner effect, we proceed in the same way as for the perfect conductor. First we use Ampère's law, curl B = μ0Js, to substitute for Js in Equation (2.6), and we obtain

Curl (curl B)=- $\frac{\mu 0 n_s e^2}{m} B$ =- $\frac{1}{\lambda^2} B$ (2.8)

Where

μ0 ≡ permeability.

λ ≡ penetration depth.

$$\lambda = \left(\frac{m}{\mu 0 n_s e^2}\right)^{\frac{1}{2}} \quad (2.9)$$

But curl(curl B) = grad(div B) − $\nabla^2 B$ = $-\nabla^2$B, since div B = 0. So

$$\nabla^2 B = \frac{1}{\lambda^2} B \quad (2.10)$$

This equation is similar to :

$$\nabla^2 \left(\frac{\partial B}{\partial t}\right) = \frac{\mu 0 n_s e^2}{m} \frac{\partial B}{\partial t} \quad (2.11)$$

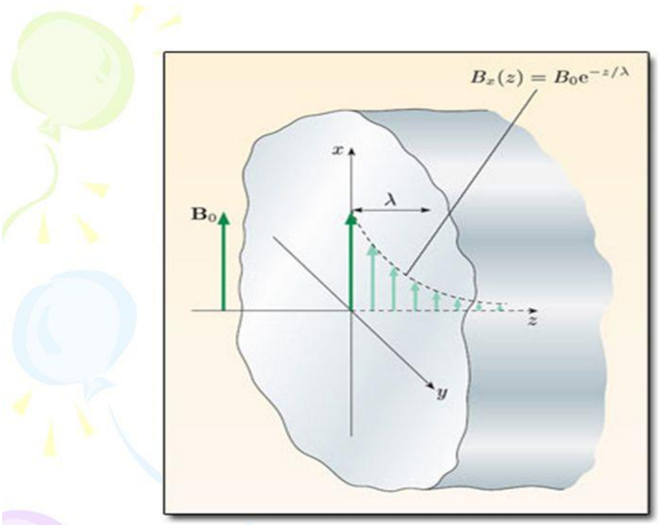
but ∂B/∂t has been replaced by B. The important point to note about this equation is that the only solution that corresponds to a spatially uniform field (for which$\nabla^2 B = 0$) is the field that is identically zero everywhere. If B were not equal to zero, then $\nabla^2 B$ would not be zero, so B would depend on position., If we consider again the simple one-dimensional geometry, then we obtain the solution to Equation (2.10) by simply replacing the partial time derivatives of the fields in the solution for the perfect conductor,yields :

$$\frac{\partial B_x}{\partial t}(z,t) = \frac{\partial B_0}{\partial t}(t)\, e^{-\frac{z}{\lambda}} \quad (2.12)$$

by the fields themselves, that is,

$$B_x(z) = B_0 e^{-\frac{z}{\lambda}} \qquad (2.13)$$

Therefore, the London equations lead to the prediction of an exponential decay of the magnetic field within the superconductor, as shown in figure(2.13)



The penetration of a magnetic field into a superconducting material, showing the penetration depth.

Fig(2.13)

2.17.2 Penetration Depth

The characteristic length, λ, associated with the decay of the magnetic field at the surface of a superconductor is known as the **penetration depth**, and it depends on the number density n_s of superconducting electrons [43].

We can estimate a value for λ by assuming that all of the free electrons are superconducting. If we set $n_s = 10^{29}\ m^{-3}$, a typical free electron density in a metal, then we find that

$$\lambda = \left(\frac{m}{\mu_0 n_s e^2}\right)^{1/2} = 1.7\times10^{-8}\,\text{m} \simeq 20\ \text{nm}. \qquad \textbf{(2.14)}$$

The small size of λ indicates that the magnetic field is effectively excluded from the interior of macroscopic specimens of superconductors, in agreement with the experimentally observed Meissner effect.

The small scale of the field penetration means that carefully-designed experiments are needed to measure the value of λ. Many experiments have been done with samples that have a large surface to volume ratio to make the penetration effect of the field appreciable. Thin films, thin wires and colloidal particles of superconductors have all been used for this purpose. But it is also possible to use large specimens if the measurement is sensitive to the amount of magnetic flux passing through the superconductor's surface, and not to the ratio of flux excluded by the superconductor to flux through the normal material, which is close to unity.

In a classic experiment performed in the 1950s, Schawlow and Devlin measured the self-inductance of a solenoid within which they inserted a long single-crystal cylinder of superconducting tin, 7.4 mm in diameter. They minimized the space between the coil and the tin cylinder, and since no magnetic flux passed through the bulk of the superconductor, the flux was essentially restricted to a thin cylindrical shell of thickness λ at the surface of the cylinder. The inductance of the solenoid was therefore determined mainly by the magnitude of the penetration depth[44]. To measure the inductance, a capacitor was connected in parallel with the solenoid, and the natural angular frequency, $\omega_n = 1/\sqrt{LC}$, of the LC circuit was measured. The precision of the frequency measurement was about one part in 10^6, which corresponded to a precision of 0.4 nm in the value of the penetration depth. The result that they obtained for the penetration depth of tin for temperatures much lower than the critical temperature was 52 nm.The number density of superconducting electrons depends on temperature, so the penetration depth is temperature dependent. For $T \ll T_c$, all of the free electrons are superconducting, but the number density falls steadily with increasing temperature until it reaches zero at the critical temperature. Since $\lambda \, \alpha n_s^{-1/2}$ according to the London model, the penetration depth increases as the temperature approaches the critical temperature, becoming effectively infinite – corresponding to a uniform field in the material – at and above the critical temperature. Figure (2.15) shows this temperature dependence for tin, which is well represented by the expression

$$\lambda(T) = \frac{\lambda(0)}{\left[1-(T/T_c)^4\right]^{1/2}}, \tag{2.15}$$

where λ(0) is the value of the penetration depth at T = 0 K.

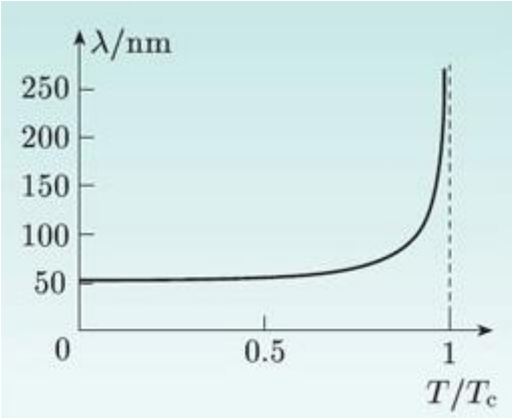


Fig (2.14) The penetration depth λ as a function of temperature for tin.

2.17.3 Characteristic Lengths in Superconductors

Arising in the theoretical and experimental investigations of superconductivity are two characteristic lengths, the London penetration depth and the coherence length.

The London penetration depth refers to the exponentially decaying magnetic field at the surface of a superconductor. It is related to the density of superconducting electrons in the material. The fact of exclusion of magnetic fields from the interior of the superconductor is called the Meissner effect. An independent characteristic length is called the coherence length. It is related to the Fermi velocity for the material and the energy gap associated with the condensation to the superconducting state. It has to do with the fact that the superconducting electron density cannot change quickly-there is a minimum length over which a given change can be made, lest it destroy the superconducting state. For example, a transition from the superconducting state to a normal state will have a transition layer of finite thickness which is related to the coherence length. Experimental studies of various superconductors have led to the following calculated values for these two types of characteristic lengths[44,45]

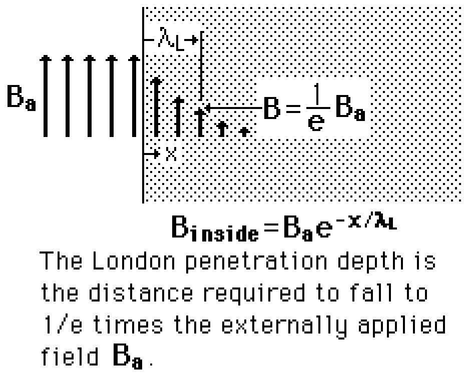
Table(2.3): show calculated values for these two types of characteristic lengths

Material	Coherence length ξ_0(nm)	London penetration depth λ_L(nm)	Ratio λ_L/ξ_0
Sn	230	34	0.16
Al	1600	16	0.010
Pb	83	37	0.45
Cd	760	110	0.14
Nb	38	39	1.02

2.17.4 London Penetration Depth in Superconductors

One of the theoretical approaches to the description of the superconducting state is the London equation. It relates the curl of the current density J to the magnetic field:

$$\vec{\nabla} \times \vec{J} = -\frac{1}{\mu_0 \lambda_L^2}\vec{B} \qquad \textbf{(2.16)}$$



Fig(2.15)

The London equation can be shown to require that the magnetic field exponentially decays to zero inside a superconductor.The nature of the decay, depends upon the superconducting electron density n:

$$\lambda_L = \sqrt{\frac{\varepsilon_0 m c^2}{n e^2}}$$

λ_L = London penetration depth
n = superconducting electron density

(2.17)

2.17.5Coherence Length in Superconductors

One of the characteristic lengths for the description of superconductors is called the coherence length. It is related to the Fermi velocity for the material and the energy gap associated with the condensation to the superconducting state. It has to do with the fact that the superconducting electron density cannot change quickly-there is a minimum length over which a given change can be made, lest it destroy the superconducting state[46]. For example, a transition from the superconducting state to a normal state will have a transition layer of finite thickness which is related to the coherence length.

$$\xi_0 = -\frac{2 \hbar v_F}{\pi E_g}$$

v_F = Fermi velocity
E_g = Superconducting band gap

(2.18)

2.18 Conventional Theories

During the 1950s, theoretical condensed matter physicists arrived at an understanding of "conventional" superconductivity, through a pair of remarkable and important theories: the phenomenological Ginzburg-Landau theory (1950) and the microscopic BCS theory (1957). In 1950, the phenomenological Ginzburg-Landau theory of superconductivity was devised by Landau and Ginzburg[47]. This theory, which combined Landau's theory of second-order phase transitions with a Schrödinger-like wave equation, had great success in explaining the macroscopic properties of superconductors. In particular, Abrikosov showed that Ginzburg-Landau theory predicts the division of superconductors into the two categories now referred to as Type I and Type II. Abrikosov and Ginzburg were awarded the

2003 Nobel Prize for their work (Landau had received the 1962 Nobel Prize for other work, and died in 1968). The four-dimensional extension of the Ginzburg-Landau theory, the Coleman-Weinberg model, is important in quantum field theory and cosmology. Also in 1950, Maxwell and Reynolds *et al.* found that the critical temperature of a superconductor depends on the isotopic mass of the constituent element[48]. This important discovery pointed to the electron-phonon interaction as the microscopic mechanism responsible for superconductivity. The complete microscopic theory of superconductivity was finally proposed in 1957 by Bardeen, Cooper and Schrieffer[49]. This BCS theory explained the superconducting current as a superfluid of Cooper pairs, pairs of electrons interacting through the exchange of phonons. For this work, the authors were awarded the Nobel Prize in 1972.The BCS theory was set on a firmer footing in 1958, when N. N. Bogolyubov showed that the BCS wavefunction, which had originally been derived from a variational argument, could be obtained using a canonical transformation of the electronic Hamiltonian. In 1959, Lev Gor'kov showed that the BCS theory reduced to the Ginzburg-Landau theory close to the critical temperature[50,51]. Generalizations of BCS theory for conventional superconductors form the basis for understanding of the phenomenon of super fluidity, because they fall into the lambda transition universality class. The extent to which such generalizations can be applied to unconventional superconductors is still controversial.

Chapter Three

Properties of Superconductors

3.1 Introduction

Most of the physical properties of superconductors vary from material to material, such as the heat capacity and the critical temperature, critical field, and critical current density at which superconductivity is destroyed.

On the other hand, there is a class of properties that are independent of the underlying material [52]. For instance, all superconductors have exactly zero resistivity to low applied currents when there is no magnetic field present or if the applied field does not exceed a critical value. The existence of these "universal" properties implies that superconductivity is a thermodynamic phase, and thus possesses certain distinguishing properties which are largely independent of microscopic details.

Fig (3.1) Electric cables for accelerators at CERN. Both the massive and slim cables are rated for 12,500 A. Top: conventional cables for LEP; bottom: superconductor-based cables for the LHC

3.2 Zero Electrical DC Resistance

The most obvious characteristic of a superconductor is the complete disappearance of its electrical resistance below a temperature that is known as its critical temperature. Experiments have been carried out to attempt to detect whether there is any small residual resistance in the superconducting state. A sensitive test is to start a current flowing round a superconducting ring and observe whether the current decays. The current flowing in the superconducting loop clearly cannot be measured by inserting an ammeter into the loop, since this would introduce a resistance and the current would rapidly decay.

Fig (3.2) Cross section of a preform superconductor rod from abandoned Texas Superconducting Super Collider (SSC).

The simplest method to measure the electrical resistance of a sample of some material is to place it in an electrical circuit in series with a current source I and measure the resulting voltage V across the sample. The resistance of the sample is given by Ohm's law as R = V / I. If the voltage is zero, this means that the resistance is zero[53].Superconductors are also able to maintain a current with no applied voltage whatsoever, a property exploited in superconducting electromagnets such as those found in MRI machines. Experiments have demonstrated that currents in superconducting coils can persist for years without any measurable degradation. Experimental evidence points to a current lifetime of at least 100,000 years. Theoretical estimates for the lifetime of a persistent current can exceed the estimated lifetime of the universe, depending on the wire geometry and the temperature [54].In a normal conductor, an electric current may be visualized as a fluid of electrons moving across a heavy ionic lattice. The electrons are constantly colliding with the ions in the lattice, and during each collision some of the energy carried by the current is absorbed by the lattice and converted into heat, which is essentially the vibrational kinetic energy of the lattice ions. As a result, the energy carried by the current is constantly being dissipated. This is the phenomenon of electrical resistance and Joule heating[55].The situation is different in a superconductor. In a conventional superconductor, the electronic fluid cannot be resolved into individual electrons. Instead, it consists of bound pairs of electrons known as Cooper pairs. This pairing is caused by an attractive force between electrons from the exchange of phonons. Due to quantum mechanics, the energy spectrum of this Cooper pair fluid possesses an energy gap, meaning there is a minimum amount of energy ΔE that must be supplied in order to excite the fluid. Therefore, if ΔE is larger than the thermal energy of the lattice, given by kT, where k is Boltzmann's constant and T is the temperature, the fluid will not be scattered by the lattice. The Cooper pair fluid is thus a super fluid, meaning it can flow without energy dissipation[56].In a class of superconductors known as type II superconductors, including all known high-temperature superconductors, an extremely low but nonzero resistivity appears at temperatures not too far below the nominal superconducting transition when an electric current is applied in conjunction with a strong magnetic field, which may be caused by the electric current. This is due to the motion of magnetic vortices in the electronic super fluid, which dissipates some of the energy carried by the current. If the current is sufficiently small, the vortices are stationary, and the resistivity vanishes. The resistance due to this effect is tiny compared with that of non-superconducting materials, but must be taken into account in sensitive experiments. However, as the temperature decreases far enough below the nominal superconducting transition, these vortices can become frozen into a disordered but stationary phase known as a "vortex glass". Below this vortex glass transition temperature, the resistance of the material becomes truly zero. Suggest a method of monitoring the current that does not involve interfering with the superconducting loop. The magnitude of the magnetic field is directly proportional to the current circulating in the loop, and the field can be measured without drawing energy from the circuit. Experiments of this type have been carried out over periods of years, and the magnetic field – and hence the superconducting current – has always remained constant within the precision of the measuring equipment. Such a **persistent current** is characteristic of the superconducting state. From the lack of any decay of the current it has been deduced that the resistivity ρ of a superconductor is less than 10^{-26} Ω m. This is about 18 orders of magnitude smaller than the resistivity of copper at room temperature ($\simeq 10^{-8}$ Ω m).Resistivity is the reciprocal of conductivity, that is, $\rho = \sigma^{-1}$. We prefer to describe a superconductor by $\rho = 0$, rather than by $\sigma = \infty$.

3.3 Superconducting Phase Transition

In superconducting materials, the characteristics of superconductivity appear when the temperature T is lowered below a critical temperature T_c. The value of this critical temperature varies from material to material. Conventional superconductors usually have critical temperatures ranging from around 20 K to less than 1 K. Solid mercury, for example, has a critical temperature of 4.2 K. As of 2009, the highest critical temperature found for a conventional superconductor is 39 K for magnesium diboride (MgB_2),[57] although this material displays enough exotic properties that there is some doubt about classifying it as a "conventional" superconductor[55]. Cuprates superconductors can have much higher critical temperatures: $YBa_2Cu_3O_7$, one of the first cuprates superconductors to be discovered, has a critical temperature of 92 K, and mercury-based cuprates have been found with critical temperatures in excess of 130 K. The explanation for these high critical temperatures remains unknown. Electron pairing due to phonon exchanges explains superconductivity in conventional superconductors, but it does not explain superconductivity in the newer superconductors that have a very high critical temperature[58].Similarly, at a fixed temperature below the critical temperature, superconducting materials cease to superconduct when an external magnetic field is applied which is greater than the critical magnetic field. This is because the Gibbs free energy of the superconducting phase increases quadratic ally with the magnetic field while the free energy of the normal phase is roughly independent of the magnetic field. If the material superconducts in the absence of a field, then the superconducting phase free energy is lower than that of the normal phase and so for some finite value of the magnetic field (proportional to the square root of the difference of the free energies at zero magnetic field) the two free energies will be equal and a phase transition to the normal phase will occur. More generally, a higher temperature and a stronger magnetic field lead to a smaller fraction of the electrons in the superconducting band and consequently a longer London penetration depth of external magnetic fields and currents. The penetration depth becomes infinite at the phase transition [59,60].The onset of superconductivity is accompanied by abrupt changes in various physical properties, which is the hallmark of a phase transition. For example, the electronic heat capacity is proportional to the temperature in the normal (non-superconducting) regime. At the superconducting transition, it suffers a discontinuous jump and thereafter ceases to be linear. At low temperatures, it varies instead as $e^{-\alpha/T}$ for some constant, α. This exponential behavior is one of the pieces of evidence for the existence of the energy gap. The order of the superconducting phase transition was long a matter of debate. Experiments indicate that the transition is second-order, meaning there is no latent heat. However, in the presence of an external magnetic field there is latent heat, because the superconducting phase has lower entropy below the critical temperature than the normal phase. It has been experimentally demonstrated that, as a consequence, when the magnetic field is increased beyond the critical field, the resulting phase transition leads to a decrease in the temperature of the superconducting material [61].Calculations in the 1970s suggested that it may actually be weakly first-order due to the effect of long-range fluctuations in the electromagnetic field. In the 1980s it was shown theoretically with the help of a disorder field theory, in which the vortex lines of the superconductor play a major role, that the transition is of second order within the type II regime and of first order (i.e., latent heat) within the type I regime, and that the two regions are separated by a critical point. The results were strongly supported by Monte Carlo computer simulations.

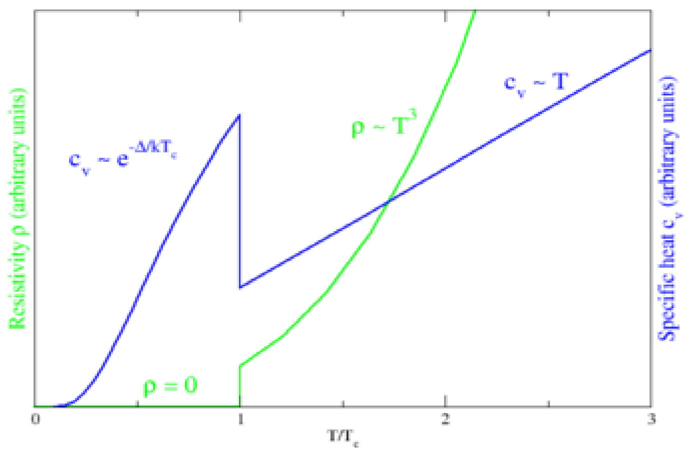


Fig (3.3) Behavior of heat capacity (c_v, blue) and resistivity (ρ, green) at the superconducting phase transition

3.4Persistent Currents Lead To Constant Magnetic Flux

An important consequence of the persistent currents that flow in materials with zero resistance is that the magnetic flux that passes through a continuous loop of such a material remains constant [62]. To see how this comes about, consider a ring of metal, enclosing a fixed area *A*, as shown in Figure (3.4.a). An initial magnetic field $\mathbf{B}_0$ is applied perpendicular to the plane of the ring when the temperature is above the critical temperature of the material from which the ring is made. The magnetic flux Φ through the ring is B_0A, and if the ring is cooled below its critical temperature while in this applied field, then the flux passing through it is unchanged. If we now change the applied field, then a current will be induced in the ring, and according to Lenz's law the direction of this current will be such that the magnetic flux it generates compensates for the flux change due to the change in the applied field. From Faraday's law, the induced emf in the ring is $-d\Phi/dt = -A d(B - B_0)/dt$, and this generates an induced current I given by[63]

$$L\frac{dI}{dt} = -A\frac{dB}{dt}, \qquad (3.1)$$

where L is the self-inductance of the ring.

A≡ conistant.

I≡ induced current.

Note that there is no ohmic term, IR, on the left-hand side of this equation, because we are assuming that $R = 0$. Integrating this equation, we obtain

$$LI + BA = \text{constant}. \qquad (3.2)$$

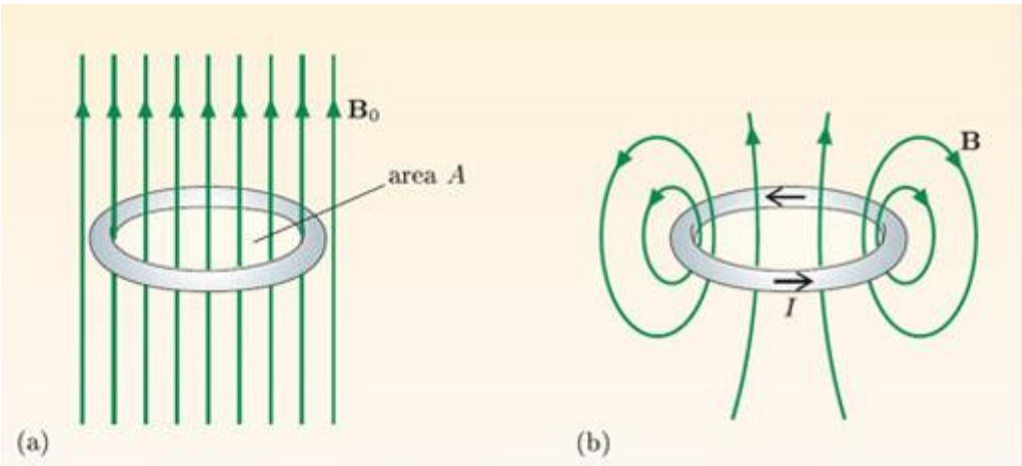


Figure (3.4..a) A ring cooled below its critical temperature in an applied field B_0. (3.4.b) When the applied field is removed, a superconducting current maintains the flux through the ring at the same value.

But LI is the amount of flux passing through the ring generated by the current I flowing in the ring – this is just the definition of self-inductance L – so $(LI + BA)$ is the total magnetic flux through the ring. The total flux threading a circuit with zero resistance must therefore remain constant – it cannot change. If the applied magnetic field is changed, an induced current is set up that creates a flux to compensate exactly for the change in the flux from the applied magnetic field. Because the circuit has no resistance, the induced current can flow indefinitely, and the original amount of flux through the ring can be maintained indefinitely. This is true even if the external field is removed altogether; the flux through the ring is maintained by a persistent induced current, as in Figure (3.4.a). However, note that constant flux through the ring does not mean that the magnetic field is unchanged. In Figure (3.4.a) there is a uniform field within the ring, whereas in Figure (3.4.b) the field is produced by a current flowing in the ring and will be much larger close to the ring than at its centre[64].An important application of the constant flux through a superconducting circuit is shown in Figure (3.5). A superconducting solenoid, used to produce large magnetic fields, is connected to a power supply that can be adjusted to provide the appropriate current to generate the required field. For some applications it is important for the field to remain constant to a higher precision than the stability of the power supply would allow. A stable field is achieved by including a superconducting switch in parallel with the solenoid. This is not a mechanical switch, but a length of superconducting wire that is heated to above its critical temperature to 'open' the switch, and cooled below the critical temperature to 'close' it. With the switch open, the current from the power supply is set to give the required field strength. The switch is then closed to produce a completely superconducting circuit that includes the solenoid, the switch and the leads connecting them. The flux through this circuit must remain constant in time, so the field inside the solenoid will also remain constant in time. An added bonus is that the power supply can now be disconnected, which means that no energy is being dissipated while maintaining the field.

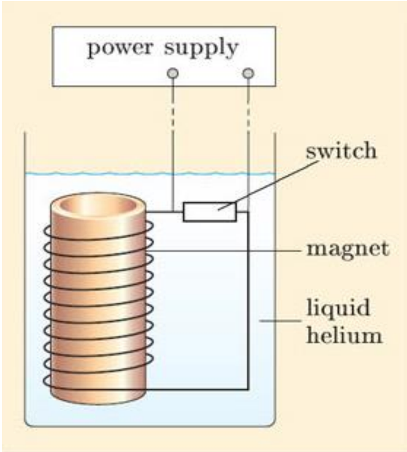


Figure (3.5) A superconducting solenoid with a superconducting switch that allows it to operate in a persistent current mode.

Superconducting coils with persistent currents can be used in high-speed magnetically-levitated trains. In the system used on the Yamanashi Maglev Test Line in Japan (Figure 3.6.a), superconducting coils mounted on the sides of the train induce currents in coils mounted in the walls of a guideway, and the attractive and repulsive forces between the superconducting magnets and the track-mounted coils both levitate the train and provide lateral guidance. The train is propelled forwards by attractive and repulsive forces between the superconducting magnets and propulsion coils located on the walls of the guideway that are energised by a three-phase alternating current that creates a shifting magnetic field along the guideway. In 2003, a train reached the record-breaking speed of 581 km h^{-1} onthistrack.

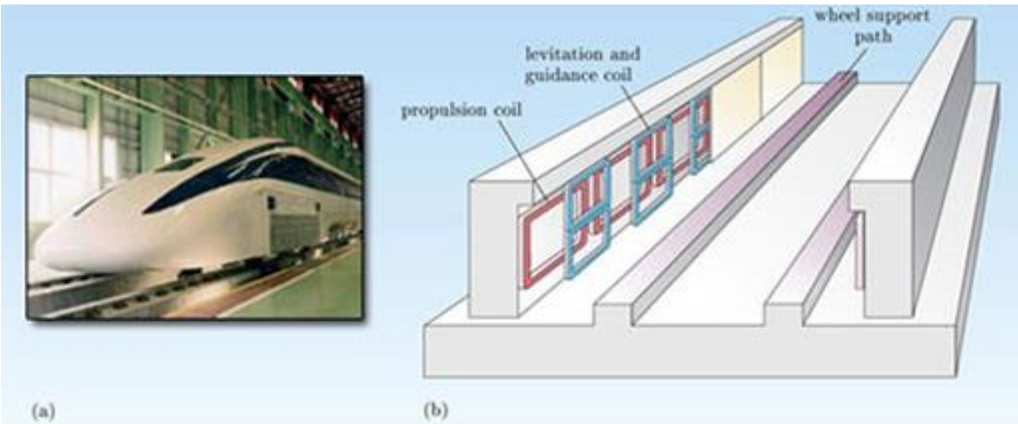


Figure (3.6.a) A train that uses superconducting coils for magnetic levitation. (3.6.b) The guideway for the train, showing the coils used for levitation, guidance and propulsion.

A second application is the use of a superconducting tube to screen sensitive components from magnetic fields, as shown in Figure (3.7). The tube is cooled below its critical temperature in a very small magnetic field. If a magnetic field is subsequently applied in the region of the tube, screening currents will be induced that generate fields which cancel out the applied field within the tube. However, note that effective screening requires a long tube, because only this geometry will generate a uniform magnetic field in the middle of the tube.

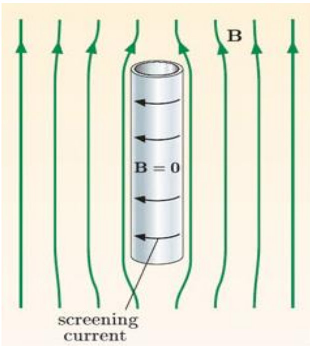


Figure (3.7) A long superconducting tube screens the region inside from externally applied magnetic fields.

3.5 The Meissner Effect

It is already discussed in chapter two, but here, the effect is being represented form another point of view. The second defining characteristic of a superconducting material is much less obvious than its zero electrical resistance. It was over 20 years after the discovery of superconductivity that Meissner and Ochsenfeld published a paper describing this second characteristic. They discovered that when a magnetic field is applied to a sample of tin, say, in the superconducting state, the applied field is excluded, so that $B = 0$ throughout its interior. This property of the superconducting state is known as the **Meissner effect** [65].The exclusion of the magnetic field from a superconductor takes place regardless of whether the sample becomes superconducting before or after the external magnetic field is applied. In the steady state, the external magnetic field is cancelled in the interior of the superconductor by opposing magnetic fields produced by a steady screening current that flows on the surface of the superconductor. It is important to recognize that the exclusion of the magnetic field from inside a superconductor cannot be predicted by applying Maxwell's equations to a material that has zero electrical resistance. We shall refer to a material that has zero resistance but does not exhibit the Meissner effect as a **perfect conductor**, and we shall show that a superconductor has additional properties besides those that can be predicted from its zero resistance.

Consider first the behaviour of a perfect conductor. We showed in the previous subsection that the flux enclosed by a continuous path through zero resistance material – a perfect conductor – remains constant, and this must be true for *any* path within the material, whatever its size or orientation. This means that the magnetic field throughout the material must remain constant, that is, $\partial \mathbf{B}/\partial t = \mathbf{0}$. The consequences of this are shown in Figure (3.8) parts (a) and (b).

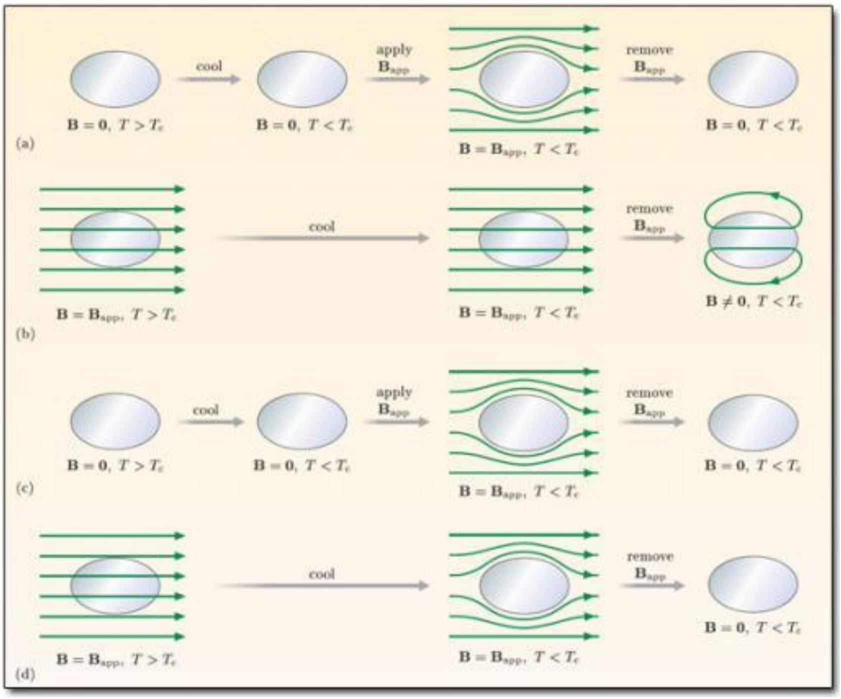


Figure (3.8) A comparison of the response of a perfect conductor, (a) and (b), and a superconductor, (c) and (d), to an applied magnetic field.

In part (a) of this figure, a perfect conductor is cooled in zero magnetic field to below the temperature at which its resistance becomes zero. When a magnetic field is applied, screening currents are induced in the surface to maintain the field at zero within the material, and when the field is removed, the field within the material stays at zero. In contrast, part (b) shows that cooling a perfect conductor to below its critical temperature in a uniform magnetic field leads to a situation where the uniform field is maintained within the material. If the applied field is then removed, the field within the conductor remains uniform, and continuity of magnetic field lines means there is a field in the region around the perfect conductor. Clearly, the magnetization state of the perfect conductor depends not just on temperature and magnetic field, but also on the previous history of the material[66].Contrast this with the behavior of a superconductor, shown in Figure (3.8) parts (c) and (d). Whether a material is cooled below its superconducting critical temperature in zero field, (c), or in a finite field, (d), the magnetic field within a superconducting material is always zero. The magnetic field is always expelled from a superconductor. This is achieved spontaneously by producing currents on the surface of the superconductor. The direction of the currents is such as to create a magnetic field that exactly cancels the applied field in the superconductor. It is this active exclusion of magnetic field – the Meissner effect – that distinguishes a superconductor from a perfect conductor, a material that merely has zero resistance. Thus we can regard zero resistance and zero magnetic field as the two key characteristics of superconductivity.

3.6 Thermal Properties of Superconductors

Superconductivity is a startling departure from the properties of normal (i.e., nonsuperconducting) conductors of electricity. In materials that are electric conductors, some of the electrons are not bound to individual atoms but are free to move through the material; their motion constitutes an electric current. In normal conductors these so-called conduction electrons are scattered by impurities, dislocations, grain boundaries, and lattice vibrations (phonons). In a superconductor, however, there is an ordering among the conduction electrons that prevents this scattering. Consequently, electric current can flow with no resistance at all. The ordering of the electrons, called Cooper pairing, involves the momenta of the electrons rather than their positions. The energy per electron that is associated with this ordering is extremely small, typically about one thousandth of the amount by which the energy per electron changes when a chemical reaction takes place. One reason that superconductivity remained unexplained for so long is the smallness of the energy changes that accompany the transition between normal and superconducting states. In fact, many incorrect theories of superconductivity were advanced before the BCS theory was proposed. For additional details on electric conduction in metals and the effects of temperature and other influences [67].Hundreds of materials are known to become superconducting at low temperatures. Twenty-seven of the chemical elements, all of them metals, are superconductors in their usual crystallographic forms at low temperatures and low (atmospheric) pressure. Among these are commonly known metals such as aluminum, tin, lead, and mercury and less common ones such as rhenium, lanthanum, and protactinium. In addition, 11 chemical elements that are metals, semimetals, or semiconductors are superconductors at low temperatures and high pressures. Among these are uranium, cerium, silicon, and selenium. Bismuth and five other elements, though not superconducting in their usual crystallographic form, can be made superconducting by preparing them in a highly disordered form, which is stable at extremely low temperatures. Superconductivity is not exhibited by any of the magnetic elements chromium, manganese, iron, cobalt, or nickel[68].Most of the known superconductors are alloys or compounds. It is possible for a compound to be superconducting even if the chemical elements constituting it are not; examples are disilver fluoride (Ag_2F) and a compound of carbon and potassium (C_8K). Some semiconducting compounds, such as tin telluride (SnTe), become superconducting if they are properly doped with impurities. Since 1986 some compounds containing copper and oxygen (called cuprates) have been found to have extraordinarily high transition temperatures, denoted T_c. This is the temperature below which a substance is superconducting. The properties of these high-T_c compounds are different in some respects from those of the types of superconductors known prior to 1986, which will be referred to as classic superconductors in this discussion. For the most part, the high-T_c superconductors are treated explicitly toward the end of this section. In the discussion that immediately follows, the properties possessed by both kinds of superconductors will be described, with attention paid to specific differences for the high-T_c materials. A further classification problem is presented by the superconducting compounds of carbon (sometimes doped with other atoms) in which the carbon atoms are on the surface of a cluster with a spherical or spheroidal crystallographic structure. These compounds, discovered in the 1980s, are called fullerenes (if only carbon is present) or fuller ides (if doped). They have superconducting transition temperatures higher than those of the classic superconductors. It is not yet known whether these compounds are fundamentally similar to the cuprates high-temperature superconductors.

3.7 Transition Temperatures

The vast majority of the known superconductors have transition temperatures that lie between 1 K and 10 K. Of the chemical elements, tungsten has the lowest transition temperature, 0.015 K, and niobium the highest, 9.2 K. The transition temperature is usually very sensitive to the presence of magnetic impurities. A few parts per million of manganese in zinc, for example, lowers the transition temperature considerably.

3.8Specific Heat and Thermal Conductivity

The thermal properties of a superconductor can be compared with those of the same material at the same temperature in the normal state. (The material can be forced into the normal state at low temperature by a large enough magnetic field.)When a small amount of heat is put into a system, some of the energy is used to increase the lattice vibrations (an amount that is the same for a system in the normal and in the superconducting state), and the remainder is used to increase the energy of the conduction electrons. The electronic specific heat (C_e) of the electrons is defined as the ratio of that portion of the heat used by the electrons to the rise in temperature of the system. The specific heat of the electrons in a superconductor varies with the absolute temperature (T) in the normal and in the superconducting state (as shown in Figure 1). The electronic specific heat in the superconducting state (designated C_{es}) is smaller than in the normal state (designated C_{en}) at low enough temperatures, but C_{es} becomes larger than C_{en} as the transition temperature T_c is approached, at which point it drops abruptly to C_{en} for the classic superconductors, although the curve has a cusp shape near T_c for the high-T_c superconductors. Precise measurements have indicated that, at temperatures considerably below the transition temperature, the logarithm of the electronic specific heat is inversely proportional to the temperature [69]. This temperature dependence, together with the principles of statistical mechanics, strongly suggests that there is a gap in the distribution of energy levels available to the electrons in a superconductor, so that a minimum energy is required for the excitation of each electron from a state below the gap to a state above the gap. Some of the high-T_c superconductors provide an additional contribution to the specific heat, which is proportional to the temperature. This behavior indicates that there are electronic states lying at low energy; additional evidence of such states is obtained from optical properties and tunneling measurements. The heat flow per unit area of a sample equals the product of the thermal conductivity (K) and the temperature gradient ΔT: $J_Q = -K \Delta T$, the minus sign indicating that heat always flows from a warmer to a colder region of a substance. The thermal conductivity in the normal state (K_n) approaches the thermal conductivity in the superconducting state (K_s) as the temperature (T) approaches the transition temperature (T_c) for all materials, whether they are pure or impure. This suggests that the energy gap (Δ) for each electron approaches zero as the temperature (T) approaches the transition temperature (T_c). This would also account for the fact that the electronic specific heat in the superconducting state (C_{es}) is higher than in the normal state (C_{en}) near the transition temperature: as the temperature is raised toward the transition temperature (T_c), the energy gap in the superconducting state decreases, the number of thermally excited electrons increases, and this requires the absorption of heat [70].

3.9 Energy Gaps

As stated above, the thermal properties of superconductors indicate that there is a gap in the distribution of energy levels available to the electrons, and so a finite amount of energy, designated as delta (Δ), must be supplied to an electron to excite it. This energy is maximum (designated Δ_0) at absolute zero and changes little with increase of temperature until the transition temperature is approached, where Δ decreases to zero, its value in the normal state. The BCS theory predicts an energy gap with just this type of temperature dependence [71].According to the BCS theory, there is a type of electron pairing (electrons of opposite spin acting in unison) in the superconductor that is important in interpreting many superconducting phenomena. The electron pairs, called Cooper pairs, are broken up as the superconductor is heated. Each time a pair is broken, an amount of energy that is at least as much as the energy gap (Δ) must be supplied to each of the two electrons in the pair, so an energy at least twice as great (2Δ) must be supplied to the superconductor. The value of twice the energy gap at 0 K (which is $2\Delta_0$) might be assumed to be higher when the transition temperature of the superconductor is higher. In fact, the BCS theory predicts a relation of this type—namely, that the energy supplied to the superconductor at absolute zero would be $2\Delta_0 = 3.53\ kT_c$, where k is Boltzmann's constant (1.38×10^{-23} joule per kelvin). In the high-T_c cuprates compounds, values of $2\Delta_0$ range from approximately three to eight multiplied by kT_c.The energy gap (Δ) can be measured most precisely in a tunneling experiment (a process in quantum mechanics that allows an electron to escape from a metal without acquiring the energy required along the way according to the laws of classical physics). In this experiment, a thin insulating junction is prepared between a superconductor and another metal, assumed here to be in the normal state. In this situation, electrons can quantum mechanically tunnel from the normal metal to the superconductor if they have sufficient energy. This energy can be supplied by applying a negative voltage (V) to the normal metal, with respect to the voltage of the superconductor[68].Tunneling will occur if eV—the product of the electron charge, e (-1.60×10^{-19} coulomb), and the voltage—is at least as large as the energy gap Δ. The current flowing between the two sides of the junction is small up to a voltage equal to $V = \Delta/e$, but then it rises sharply. This provides an experimental determination of the energy gap (Δ). In describing this experiment it is assumed here that the tunneling electrons must get their energy from the applied voltage rather than from thermal excitation.

3.10 Magnetic and Electromagnetic Properties of Superconductors

3.10.1Critical Field

One of the ways in which a superconductor can be forced into the normal state is by applying a magnetic field. The weakest magnetic field that will cause this transition is called the critical field (H_c) if the sample is in the form of a long, thin cylinder or ellipsoid and the field is oriented parallel to the long axis of the sample. (In other configurations the sample goes from the superconducting state into an intermediate state, in which some regions are normal and others are superconducting, and finally into the normal state.) The critical field increases with decreasing temperature. For the superconducting elements, its values (H_0) at absolute zero range from 1.1 Oersted for tungsten to 830 Oersted for tantalum [72].These remarks about the critical field apply to ordinary (so-called type I) superconductors. In the following section the behavior of other (type II) superconductors is examined.

3.10.2 High-Frequency Electromagnetic Properties

The foregoing descriptions have pertained to the behavior of superconductors in the absence of electromagnetic fields or in the presence of steady or slowly varying fields; the properties of superconductors in the presence of high-frequency electromagnetic fields, however, have also been studied[73].The energy gap in a superconductor has a direct effect on the absorption of electromagnetic radiation. At low temperatures, at which a negligible fraction of the electrons are thermally excited to states above the gap, the superconductor can absorb energy only in a quantized amount that is at least twice the gap energy (at absolute zero, $2\Delta_0$). In the absorption process, a photon (a quantum of electromagnetic energy) is absorbed, and a Cooper pair is broken; both electrons in the pair become excited. The photon's energy (E) is related to its frequency (ν) by the Planck relation, $E = h\nu$, in which h is Planck's constant (6.63×10^{-34} joule second)[74]. Hence the superconductor can absorb electromagnetic energy only for frequencies at least as large as $2\Delta_0/h$.

3.10.3 Magnetic-Flux Quantization

The laws of quantum mechanics dictate that electrons have wave properties and that the properties of an electron can be summed up in what is called a wave function. If several wave functions are in phase (i.e., act in unison), they are said to be coherent [75]. The theory of superconductivity indicates that there is a single, coherent, quantum mechanical wave function that determines the behavior of all the superconducting electrons. As a consequence, a direct relationship can be shown to exist between the velocity of these electrons and the magnetic flux (Φ) enclosed within any closed path inside the superconductor. Indeed, inasmuch as the magnetic flux arises because of the motion of the electrons, the magnetic flux can be shown to be quantized; i.e., the intensity of this trapped flux can change only by units of Planck's constant divided by twice the electron charge. When a magnetic field enters a type II superconductor (in an applied field between the lower and upper critical fields, H_{c1} and H_{c2}), it does so in the form of quantized fluxoids, each carrying one quantum of flux. These fluxoids tend to arrange themselves in regular patterns that have been detected by electron microscopy and by neutron diffraction. If a large enough current is passed through the superconductor, the fluxoids move. This motion leads to energy dissipation that can heat the superconductor and drive it into the normal state. The maximum current per unit area that a superconductor can carry without being forced into the normal state is called the critical current density (J_c)[76]. In making wire for superconducting high-field magnets, manufacturers try to fix the positions of the fluxoids by making the wire inhomogeneous in composition.

3.10.4 Josephson Currents

If two superconductors are separated by an insulating film that forms a low-resistance junction between them, it is found that Cooper pairs can tunnel from one side of the junction to the other. (This process occurs in addition to the single-particle tunneling already described.) Thus, a flow of electrons, called the Josephson current, is generated and is intimately related to the phases of the coherent quantum mechanical wave function for all the superconducting electrons on the two sides of the junction. It was predicted that several novel phenomena should be observable, and experiments have demonstrated them. These are collectively called the Josephson effect or effects [77].The first of these phenomena is the passage of current through the junction in the absence of a voltage across the junction. The maximum current that can flow at zero voltage depends on the magnetic flux (Φ) passing through the junction as a result of the magnetic field generated by currents in the junction and elsewhere. The dependence of the maximum zero-voltage current on the magnetic field applied to a junction between two superconductors [78]. A second type of Josephson Effect is an oscillating current resulting from a relation between the voltage across the junction and the frequency (ν) of the currents associated with Cooper pairs passing through the junction. The frequency (ν) of this Josephson current is given by $\nu = 2eV/h$, where e is the charge of the electron. Thus, the frequency increases by 4.84×10^{14} hertz (cycles per second) for each additional volt applied to the junction. This effect can be demonstrated in various ways. The voltage can be established with a source of direct-current (DC) power, for instance, and the oscillating current can be detected by the electromagnetic radiation of frequency (ν) that it generates. Another method is to expose the junction to radiation of another frequency (ν') generated externally. It is found that a graph of the DC current versus voltage has current steps at values of the voltage corresponding to Josephson frequencies that are integral multiples (n) of the external frequency ($\nu = n\nu'$); that is, $V = nh\nu'/2e$. The observation of current steps of this type has made it possible to measure h/e with far greater precision than by any other method and has therefore contributed to knowledge of the fundamental constants of nature. The Josephson Effect has been used in the invention of novel devices for extremely high-sensitivity measurements of currents, voltages, and magnetic fields[79].

Chapter Four

Technological Applications of Superconductivity

4.1 Introduction

Superconducting magnets are some of the most powerful electromagnets known. They are used in MRI/NMR machines, mass spectrometers, the beam-steering magnets used in particle accelerators and plasma confining magnets in some tokamaks[80]. They can also be used for magnetic separation, where weakly magnetic particles are extracted from a background of less or non-magnetic particles, as in the pigment industries.

Fig (4.1)Play media Video of superconducting levitation of YBCO

In the 1950s and 1960s, superconductors were used to build experimental digital computers using cryotron switches. More recently, superconductors have been used to make digital circuits based on rapid single flux quantum technology and RF and microwave filters for mobile phone base stations. Superconductors are used to build Josephson junctions which are the building blocks of SQUIDs (superconducting quantum interference devices), the most sensitive magnetometers known. SQUIDs are used in scanning SQUID microscopes and magnetoence phalography. Series of Josephson devices are used to realize the SI volt. Depending on the particular mode of operation, a superconductor-insulator-superconductor Josephson junction can be used as a photon detector or as a mixer[78]. The large resistance change at the transition from the normal- to the superconducting state is used to build thermometers in cryogenic micro-calorimeter photon detectors. The same effect is used in ultrasensitive bolo meters made from superconducting materials[81].Other early markets are arising where the relative efficiency, size and weight advantages of devices based on high-temperature superconductivity outweigh the additional costs involved. For example, in wind turbines the lower weight and volume of superconducting generators could lead to savings in construction and tower costs, offsetting the higher costs for the generator and lowering the total LCOE. Promising future applications include high-performance smart grid, electric power transmission, transformers, power storage devices, electric motors (e.g. for vehicle propulsion, as in vactrains or maglev trains), magnetic levitation devices, fault current limiters, enhancing spintronic devices with superconducting materials, and superconducting magnetic refrigeration. However, superconductivity is sensitive to moving magnetic fields so applications that use alternating current (e.g. transformers) will be more difficult to develop than those that rely upon direct current. Compared to traditional power lines superconducting transmission lines are more efficient and require only a fraction of the space, which would not only lead to a better environmental performance but could also improve public acceptance for expansion of the electric grid[82].

4.2Uses for Superconductors

Magnetic-levitation is an application where superconductors perform extremely well. Transport vehicles such as trains can be made to "float" on strong superconducting magnets, virtually eliminating friction between the train and its tracks. Not only would conventional electromagnets waste much of the electrical energy as heat, they would have to be physically much larger than superconducting magnets. A landmark for the commercial use of MAGLEV technology occurred in 1990 when it gained the status of a nationally-funded project in Japan. The Minister of Transport authorized construction of the Yamanashi Maglev Test Line which opened on April 3,

1997. In April 2015, the MLX01 test vehicle (shown above) attained an incredible speed of 374 mph (603 kph)[83,84].Although the technology has now been proven, the wider use of MAGLEV vehicles has been constrained by political and environmental concerns (strong magnetic fields can create a bio-hazard). The world's first MAGLEV train to be adopted into commercial service, a shuttle in Birmingham, England, shut down in 1997 after operating for 11 years. A Sino-German maglev is currently operating over a 30-km course at Pudong International Airport in Shanghai, China. The U.S. plans to put its first (non-superconducting) Maglev train into operation on a Virginia college campus.

Fig (4.2) The Yamanashi MLX01 MagLev train.

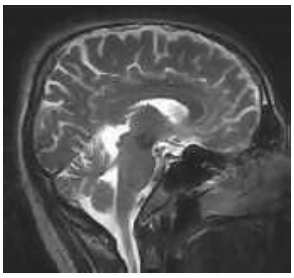


Fig (4.3) MRI of a human skull.

An area where superconductors can perform a life-saving function is in the field of diamagnetism. Doctors need a non-invasive means of determining what's going on inside the human body. By impinging a strong superconductor-derived magnetic field into the body, hydrogen atoms that exist in the body's water and fat molecules are forced to accept energy from the magnetic field. They then release this energy at a frequency that can be detected and displayed graphically by a computer. Magnetic Resonance Imaging (MRI) was actually discovered in the mid 1940's. But, the first MRI exam on a human being was not performed until July 3, 1977. And, it took almost five hours to produce one image! Today's faster computers process the data in much less time. A tutorial is available on MRI at this link[85]. Or read the latest MRI news at this link. The Korean Superconductivity Group within KRISS has carried diamagnetic technology a step further with the development of a double-relaxation oscillation SQUID (Superconducting Quantum Interference Device) for use in Magnetoence paleography. SQUID's are capable of sensing a change in a magnetic field over a billion times weaker than the force that moves the needle on a compass (compass: 5e-5T, SQUID: e-14T.). With this technology, the body can be probed to certain depths without the need for the strong magnetic fields associated with MRI's

Probably the one event, more than any other, that has been responsible for putting "superconductors" into the American lexicon was the Superconducting Super-Collider project planned for construction in Ellis County, Texas. Though Congress cancelled the multi-billion dollar effort in 1993, the concept of such a large, high-energy collider would never have been viable without superconductors. High-energy particle research hinges on being able to accelerate sub-atomic particles to nearly the speed of light.

Superconductor magnets make this possible. CERN, a consortium of several European nations, is doing something similar with its Large Hadron Collider (LHC) recently inaugurated along the Franco-Swiss border [86]. Other related web sites worth visiting include the proton-antiproton collider page at Fermilab. This was the first facility to use superconducting magnets. Get information on the electron-proton collider HERA at the German lab pages of DESY (with English text). And Brookhaven National Laboratory features a page dedicated to its RHIC heavy-ion collider. Electric generators made with superconducting wire are far more efficient than conventional generators wound with copper wire. In fact, their efficiency is above 99%

and their size about half that of conventional generators. These facts make them very lucrative ventures for power utilities. General Electric has estimated the potential worldwide market for superconducting generators in the next decade at around $20-30 billion dollars. Late in 2002 GE Power Systems received $12.3 million in funding from the U.S. Department of Energy to move high-temperature superconducting generator technology toward full commercialization. Other commercial power projects in the works that employ superconductor technology include energy storage to enhance power stability. American Superconductor Corp. received an order from Alliant Energy in late March 2000 to install a Distributed Superconducting Magnetic Energy Storage System (D-SMES) in Wisconsin. Just one of these 6 D-SMES units has a power reserve of over 3 million watts, which can be retrieved whenever there is a need to stabilize line voltage during a disturbance in the power grid. AMSC has also installed more than 22 of its D-VAR systems to provide instantaneous reactive power support.

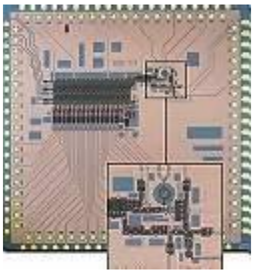
Fig (4.5) The General Atomics/Intermagnetics General superconducting Fault Current Controller, employing HTS superconductors.

Recently, power utilities have also begun to use superconductor-based transformers and "fault limiters". The Swiss-Swedish company ABB was the first to connect a superconducting transformer to a utility power network in March of 1997. ABB also recently announced the development of a 6.4MVA (mega-volt-ampere) fault current limiter - the most powerful in the world.

This new generation of HTS superconducting fault limiters is being called upon due to their ability to respond in just thousandths of a second to limit tens of thousands of amperes of current. Advanced Ceramics Limited is another of several companies that makes BSCCO type fault limiters. Inter magnetics General recently completed tests on its largest (15kv class) power-utility-size fault limiter at a Southern California Edison (SCE) substation near Norwalk, California [87]. And, both the US and Japan have plans to replace underground copper power cables with superconducting BSCCO cable-in-conduit cooled with liquid nitrogen. (See photo below.) By doing this, more current can be routed through existing cable tunnels. In one instance 250 pounds of superconducting wire replaced 18,000 pounds of vintage copper wire, making it over 7000% more space-efficient.

Fig(4.6) power cables with superconducting BSCCO cable-in-conduit cooled with liquid nitrogen.

An idealized application for superconductors is to employ them in the transmission of commercial power to cities. However, due to the high cost and impracticality of cooling miles of superconducting wire to cryogenic temperatures, this has only happened with short "test runs". In May of 2001 some 150,000 residents of Copenhagen, Denmark, began receiving their electricity through HTS (high-temperature superconducting) material. That cable was only 30 meters long, but proved adequate for testing purposes. In the summer of 2001 Pirelli completed installation of three 400-foot HTS cables for Detroit Edison at the Frisbie Substation capable of delivering 100 million watts of power. This marked the first time commercial power has been delivered to customers of a US power utility through superconducting wire. Intermagnetics General has announced that its IGC-Superpower subsidiary has joined with BOC and Sumitomo Electric in a $26 million project to install an underground, HTS power cable in Albany, New York, in Niagara Mohawk Power Corporation's power grid. Sumitomo Electric's DI-BSCCO cable was employed in the first in-grid power cable demonstration project sponsored by the U.S. Department of Energy and New York Energy Research & Development Authority. After connecting to the grid successfully on July 2006, the DI-BSCCO cable has been supplying power to approximately 70,000 households without any problems. Currently the longest run of superconductive power cable was made in the AmpaCity project near Essen, Germany, in May 2014. That cable was a kilometer in length.



Fig(4.8) Hypres SuperconductinMicrochip,Incorporating 6000 Josephson Junctions**.**

The National Science Foundation, along with NASA and DARPA and various universities are currently researching "petaflop" computers. A pet flop is a thousand-trillion floating point operations per second [88]. Currently the fastest in the world is the Chinese Sunway TaihuLight Supercomputer, operating at 124.5 pet flops per second. It has been conjectured that devices on the order of 50 nanometers in size along with unconventional switching mechanisms, such as the Josephson junctions associated with superconductors, will be necessary to achieve the next level of processing speeds. These Josephson junctions are incorporated into field-effect transistors which then become part of the logic circuits within the processors. Recently it was demonstrated at the Weizmann Institute in Israel that the tiny magnetic fields that penetrate Type II superconductors can be used for storing and retrieving digital information. It is, however, not a foregone conclusion that computers of the future will be built around superconducting devices. Competing technologies, such as quantum (DELTT) transistors, high-density molecule-scale processors, and DNA-based processing also have the potential to achieve pet flop benchmarks. In the electronics industry, ultra-high-performance filters are now being built. Since superconducting wire has near zero resistance, even at high frequencies, many more filter stages can be employed to achieve a desired frequency response. This translates into an ability to pass desired frequencies and block undesirable frequencies in high-congestion rf (radio frequency) applications such as cellular telephone systems. ISCO International and Superconductor Technologies are companies currently offering such filters. Superconductors have also found widespread applications in the military. HTSC SQUIDS are being used by the U.S. NAVY to detect mines and submarines. And, significantly smaller motors are being built for NAVY ships using superconducting wire and "tape". In mid-July, 2001, American Superconductor unveiled a 5000-horsepower motor made with superconducting wire (below). An even larger 36.5MW HTS ship propulsion motor was delivered to the U.S. Navy in late 2006

fig(4.9) :motor made with superconductor wire

The newest application for HTS wire is in the degaussing of naval vessels. American Superconductor has announced the development of a superconducting degaussing cable. Degaussing of a ship's hull eliminates residual magnetic fields which might otherwise give away a ship's presence.

In addition to reduced power requirements, HTS degaussing cable offers reduced size and weight [89].

The military is also looking at using superconductive tape as a means of reducing the length of very low frequency antennas employed on submarines. Normally, the lower the frequency, the longer an antenna must be. However, inserting a coil of wire ahead of the antenna will make it function as if it were much longer. Unfortunately, this loading coil also increases system losses by adding the resistance in the coil's wire. Using superconductive materials can significantly reduce losses in this coil. The Electronic Materials and Devices Research Group at University of Birmingham (UK) is credited with creating the first superconducting microwave antenna. Applications engineers suggest that superconducting carbon nanotubes might be an ideal nano-antenna for high-gigahertz and terahertz frequencies, once a method of achieving zero "on tube" contact resistance is perfected. The most ignominious military use of superconductors may come with the deployment of "E-bombs". These are devices that make use of strong, superconductor-derived magnetic fields to create a fast, high-intensity electro-magnetic pulse (EMP) to disable an enemy's electronic equipment. Such a device saw its first use in wartime in March 2003 when US Forces attacked an Iraqi broadcast facility.

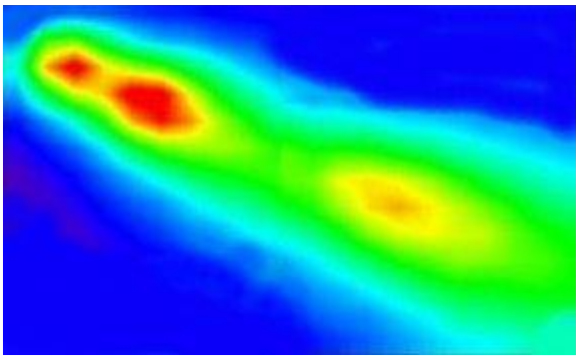
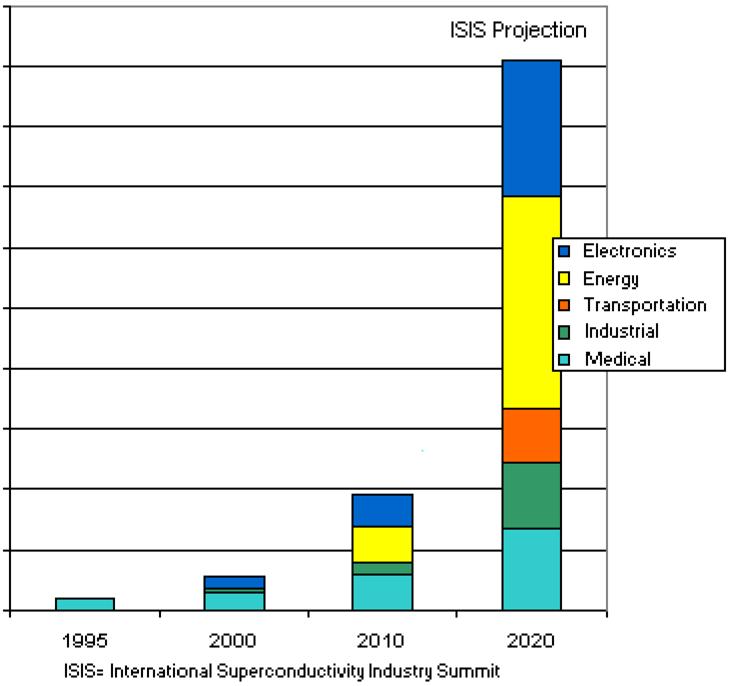


Fig (4.10)A photo of Comet 73P/Schwassmann-Wachmann 3, in the act of disintegrating,taken with the European Space Agency S-CAM.

Among emerging technologies is a stabilizing momentum wheel (gyroscope) for earth-orbiting satellites that employs the "flux-pinning" properties of imperfect superconductors to reduce friction to near zero. Superconducting x-ray detectors and ultra-fast, superconducting light detectors are being developed due to their inherent ability to detect extremely weak amounts of energy. Already Scientists at the European Space Agency (ESA) have developed what's being called the S-Cam, an optical camera of phenomenal sensitivity (see above fig). And, superconductors may even play a role in Internet communications soon. In late February, 2000, Irvine Sensors Corporation received a $1 million contract to research and develops a superconducting digital router for high-speed data communications up to 160 GHz. Since Internet traffic is increasing exponentially, superconductor technology may be called upon to meet this *super* need.



Fig(4.11) :show international superconductivity industry summit.

According to June 2002 estimates by the Conectus consortium, the worldwide market for superconductor products is projected to grow to near US $38 billion by 2020. Low-temperature superconductors are expected to continue to play a dominant role in well-established fields such as MRI and scientific research, with high-temperature superconductors enabling newer applications. The above ISIS graph gives a rough breakdown of the various markets in which superconductors are expected to make a contribution [90]. All of this is, of course, contingent upon a linear growth rate. Should new superconductors with higher transition temperatures be discovered, growth and development in this exciting field could explode virtually overnight. Another impetus to the wider use of superconductors is political in nature. The reduction of green-house gas (GHG) emissions has becoming a topical issue due to the Kyoto Protocol which requires the European Union (EU) to reduce its emissions by 8%. Physicists in Finland have calculated that the EU could reduce carbon dioxide emissions by up to 53 million tons if high-temperature superconductors were used in power plants [91]. The future melding of superconductors into our daily lives will also depend to a great degree on advancements in the field of cryogenic cooling. New, high-efficiency magnetocaloric-effect compounds such as gadolinium-silicon-germanium are expected to enter the marketplace soon. Such materials should make possible compact, refrigeration units to facilitate additional HTS applications.

4.2.1 A Summary for Superconductor Applications

Superconducting Magnets	Josephson Devices	SQUID Magnetometer
Power transmission	Fault-current limiters	Electric motors
Maglev trains	MRI imagers	

4.2.1.1 Superconducting Magnets

Type II superconductors such as niobium-tin and niobium-titanium are used to make the coil windings for superconducting magnets. These two materials can be fabricated into wires and can withstand high magnetic fields. Typical construction of the coils is to embed a large number of fine filaments (20 micrometers diameter) in a copper matrix. The solid copper gives mechanical stability and provides a path for the large currents in case the superconducting state is lost. These superconducting magnets must be cooled with liquid helium. Superconducting magnets can use solenoid geometries as do ordinary electromagnets. Most high energy accelerators now use superconducting magnets[92]. The proton accelerator at Fermilab uses 774 superconducting magnets in a ring of circumference 6.2 kilometers. They have also found wide application in the construction of magnetic resonance imaging (MRI) apparatus for medical imaging.

4.2.1.2 Superconducting Transmission Lines

Since 10% to 15% of generated electricity is dissipated in resistive losses in transmission lines, the prospect of zero loss superconducting transmission lines is appealing. In prototype superconducting transmission lines at Brookhaven National Laboratory, 1000 MW of power can be transported within an enclosure of diameter 40 cm. This amounts to transporting the entire output of a large power plant on one enclosed transmission line. This could be a fairly low voltage DC transmission compared to large transformer banks and multiple high voltage AC transmission lines on towers in the conventional systems. The superconductor used in these prototype applications is usually niobium-titanium, and liquid helium cooling is required [93]. Current experiments with power applications of high-temperature superconductors focus on uses of BSCCO in tape forms and YBCO in thin film forms. Current densities above 10,000 amperes per square centimeter are considered necessary for practical power applications, and this threshold has been exceeded in several configurations.

4.2.1.3 Superconducting Maglev Trains

While it is not practical to lay down superconducting rails, it is possible to construct a superconducting system onboard a train to repel conventional rails below it. The train would have to be moving to create the repulsion, but once moving would be supported with very little friction. There would be resistive loss of energy in the currents in the rails[94]. Ohanian reports an engineering assessment that such superconducting trains would be much safer than conventional rail systems at 200 km/h. A Japanese magnetically levitated train set a speed record of 321 mi/h in 1979 using superconducting magnets on board the train. The magnets induce currents in the rails below them, causing a repulsion which suspends the train above the track.

4.2.1.4 Fault-Current Limiters

High fault-currents caused by lightning strikes are a troublesome and expensive nuisance in electric power grids. One of the near-term applications for high temperature superconductors may be the construction of fault-current limiters which operate at 77K. The need is to reduce the fault current to a fraction of its peak value in less than a cycle (1/60 sec). A recently tested fault-current limiter can operate at 2.4 kV and carry a current of 2200 amperes. It was constructed from BSCCO material.

4.2.1.5 Superconductors in NMR Imaging

Superconducting magnets find application in magnetic resonance imaging (MRI) of the human body. Besides requiring strong magnetic fields on the order of a Tesla, magnetic resonance imaging requires extremely uniform fields across the subject and extreme stability over time. Maintaining the magnet coils in the superconducting state helps to achieve parts-per-million special uniformity over a space large enough to hold a person, and ppm/hour stability with time[95].

4.2.1.6 SQUID Magnetometer

The superconducting quantum interference device (SQUID) consists of two superconductors separated by thin insulating layers to form two parallel Josephson junctions. The device may be configured as a magnetometer to detect incredibly small magnetic fields -- small enough to measure the magnetic fields in living organisms. Squids have been used to measure the magnetic fields in mouse brains to test whether there might be enough magnetism to attribute their navigational ability to an internal compass[96].

Threshold for SQUID: 10^{-14} T

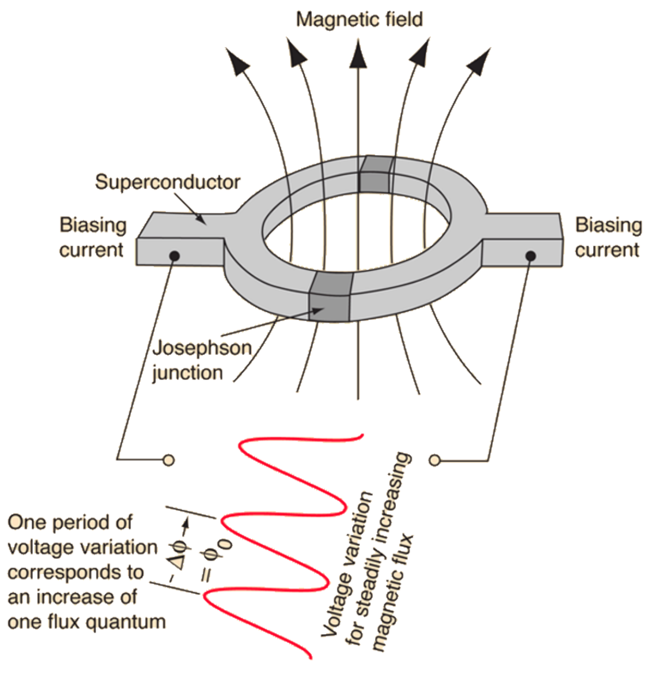
Magnetic field of heart: 10^{-10} T

Magnetic field of brain: 10^{-13} T

The great sensitivity of the SQUID devices is associated with measuring changes in magnetic field associated with one flux quantum. One of the discoveries associated with Josephson junctions was that flux is quantized in units

$$\Phi_0 = \frac{2\pi\hbar}{2e} \cong 2.0678x10^{-15}\,tesla \cdot m^2 \tag{4.1}$$

If a constant biasing current is maintained in the SQUID device, the measured voltage oscillates with the changes in phase at the two junctions, which depends upon the change in the magnetic flux. Counting the oscillations allows you to evaluate the flux change which has occurred.



Fig(4.12)SQUID Device

4.2.1.7 Superconducting Motors

Superconducting motors and generators could be made with a weight of about one tenth that of conventional devices for the same output. This is the appeal of making such devices for specialized applications. Motors and generators are already very efficient, so there is not the power savings associated with superconducting magnets. It may be possible to build very large capacity generators for power plants where structural strength considerations place limits on conventional generators[97]. In 1995 the Naval Research Laboratory demonstrated a 167 hp motor with high-T_c superconducting coils made from Bi-2223. It was tested at 4.2K and at liquid neon temperature, 28K with 112 hp produced at the higher temperature.

Chapter Five

Conclusion & Recommendations

5.1 Discussion

5.1.1Advantage One: Transforming the Electricity Grid

The electric power grid is among the greatest engineering achievements of the 20th century. Demand, however, is about to overwhelm it. For example, the North American blackout of 2003, which lasted about four days, affected over 50 million persons and caused about $6 billion in economic loss. Superconductor technology provides loss-less wires and cables and improves the reliability and efficiency of the power grid. Plans are underway to replace by 2030 the present power grid with a superconducting power grid. A superconducting power system occupies less real estate and is buried in the ground, quite different from present day grid lines.

5.1.2Advantage Two: Improving Wide-Band Telecommunication

Wide-band telecommunications technology, which operates best at gigahertz frequencies, is very useful for improving the efficiency and reliability of cell phones. Such frequencies are very difficult to achieve with semiconductor-based circuitry. However, they have been easily achieved by Hypres's superconductor-based receiver, using a technology called rapid single flux quantum, or RSFQ, integrated circuit receiver. It operates with the aid of a 4-kelvin cry cooler. This technology is showing up in many cell phone receiver transmitter towers.

5.1.3Advantage Three: Aiding Medical Diagnosis

One of the first large-scale applications of superconductivity is in medical diagnosis. Magnetic resonance imaging, or MRI, uses powerful superconducting magnets to produce large and uniform magnetic fields inside the patient's body. MRI scanners, which contain liquid helium refrigeration system, pick up how these magnetic fields are reflected by organs in the body. The machine eventually produces an image. MRI machines are superior to x-ray technology in producing a diagnosis. Paul Leuterbur and Sir Peter Mansfield were awarded the 2003 Nobel prize in physiology or medicine, "for their discoveries concerning magnetic resonance imaging," underlying the significance of MRI, and by implication superconductors, to medicine.

5.1.4 Disadvantages of Superconductors

Superconducting materials superconduct only when kept below a given temperature called the transition temperature. For presently known practical superconductors, the temperature is much below 77 Kelvin, the temperature of liquid nitrogen. Keeping them below that temperature involves a lot of expensive cryogenic technology. Thus, superconductors still do not show up in most everyday electronics. Scientists are working on designing superconductors that can operate at room temperature.

5.2 conclusion

Superconductivity is in the right place at the right time to address grand challenges of energy delivery and use:

Major increase in energy efficiency and capacity.

Higher efficiency grid equipment.

Electrification of transport.

Breaking power bottlenecks for reorganization.

Secure and ultra-reliable grid through Power flow control Fault current control.

Environmentally green and clean technology

5.3 Recommendations

*Successfully used for high energy physics, MRI, laboratory magnets.

*For electric power, many demonstrations Ac cabled Cable, motors, and generators.

*Enhancing Efficiency in the Electric Power Grid-7-10% of 1 Terawatt US electric power now lost in grid, superconductor equipment could cut this by half, save 50 Gigawatts!

*Superconductor cables bringing 50%-efficient generation to cities, replacing 30%-efficient “reliability-must-run” generators Dc super grid: a radical leap in grid efficiency.

*Reduced I^2R loss by efficient transformers, high voltage superconductor break this paradigm $I^2R = 0$ enables high Dc current, low voltage.

*Superconductors -“smart” materials, switch to resistive state above critical current.

*Superconducting power equipment avoids use of oil a contaminant and fire hazard.

*Superconductor’s high efficiency reduces unnecessary pollution and CO_2emission at energy source.

*Most desired superconductor functionalities (high current density, robust mechanical properties) have already been achieved, but still at too low a temperature with processes which could be simplified. The main challenge is the cost.

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9. (The displacement is ignored because it is assumed that electric field only varies slowly with respect to time, and the term is already suppressed by a factor of c.)
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69. perpetual motion (*in* perpetual motion)
70. quantum theory of conduction (*in* electricity: Conductors, insulators, and semiconductors)
71. traveling-wave linear accelerators (*in* particle accelerator: Linear electron accelerators)
72. ceramics (*in* conductive ceramics: Superconductors)
73. electrical resistance (*in* resistance (electronics)) (*in* crystal: Resistivity)
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