A Teachers Guide to

Superconductivity

for High School Students

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Preface

During the late 1980's the rapid succession of newly discovered superconductors with higher critical temperatures led to excitement. Much research and industrial developments of superconductive devices has advanced at a relatively slow rate since the first discovery of 1911. In part the reason for slowing advances was due to the cost and reliability of refrigeration needed to cool materials into superconductive states. Although liquid air is extremely cold by most peoples' standards, it is a relatively high temperature (and refrigeration is relatively easy) compared to what is needed for the many superconductive metals studied before 1986. Although many universities have regular sources for liquid helium, it is difficult for a high-school teacher to become involved with studies of classical superconductive metals. However, now that superconductivity can be observed rather easily in liquid nitrogen, kits for demonstrating the Meissner effect have become rather popular for classroom use. This handbook was prepared as an effort to help teachers learn to understand, teach, and demonstrate the basic features of superconductivity.

A historical background, fundamental physical features, and envisioned applications are discussed in this text. Although it is addressed to the teacher, this text may often be most useful to excited students embarking on science fair projects or personal interest. Three professional demonstrations and four student experiments are described. In addition, problems related to high-school chemistry and physics are listed. I hope that *Superconductivity* stimulates many high school students to further scientific education.

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INTRODUCTION:

Superconductivity is a fascinating and challenging field of physics. Scientists and engineers throughout the world have been striving to develop an understanding of this remarkable phenomenon for many years. For nearly 75 years superconductivity has been a relatively obscure subject. Until recently, because of the cryogenic requirements of low-temperature superconductors, superconductivity at the high school level was merely an interesting topic occasionally discussed in a physics class. Today however, superconductivity is being applied to many diverse areas such as: medicine, theoretical and experimental science, the military, transportation, power production, electronics, as well as many other areas. With the discovery of high-temperature superconductors, which can operate at liquid nitrogen temperatures (77 K), superconductivity is now well within the reach of high school students. Unique and exciting opportunities exist today for our students to explore and experiment with this new and important technological field of physics.

The materials in this handbook have been designed to help high school students better understand the basic concepts of superconductivity. This booklet discusses the history, physics, chemistry, and applications of superconductors. Instruction for several simple demonstrations and experiments, as well as safety considerations are included. This booklet has been prepared to serve as an introduction to superconductivity for students with diverse backgrounds and interests. Additional information may be obtained by individual students through various articles and books listed at the end of this booklet.

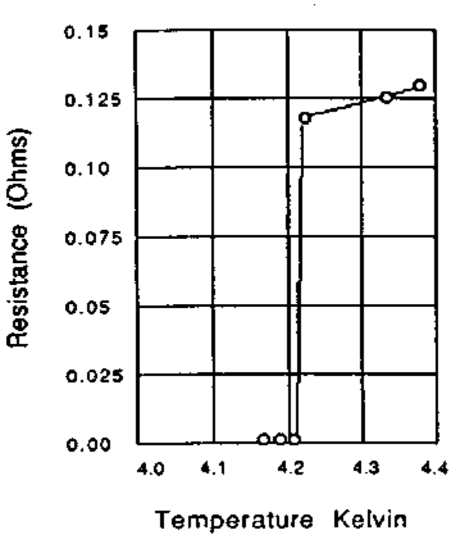
I hope this material will provide both teachers and students with a good starting point to explore the mysterious world of superconductivity. From the moment your students become entranced by observing a simple levitated magnet, to when they ask, "how does it work," and speculate what it can be used for, scientific inquiry has begun. Students' curiosities will be limited only by their imagination. The teacher need only move out of their way and let the minds of the future take over.

HISTORICAL BACKGROUND:

Major advances in low-temperature refrigeration were made during the late 19th century. Superconductivity was first discovered in 1911 by the Dutch physicist, Heike Kammerlingh Onnes. Onnes dedicated his scientific career to exploring extremely cold refrigeration. On July 10, 1908, he successfully liquified helium by cooling it to 452 degrees below zero Fahrenheit (4 Kelvin or 4 K). Onnes produced only a few milliliters of liquid helium that day, but this was to be the new beginnings of his explorations in temperature regions previously unreachable. Liquid helium enabled him to cool other materials closer to absolute zero (0 Kelvin), the coldest temperature imaginable. Absolute zero is the temperature at which the energy of material becomes as small as possible.

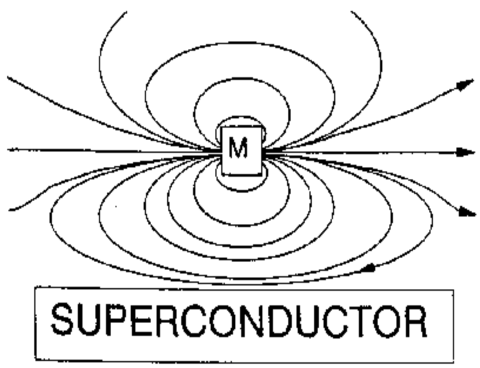
In 1911, Onnes began to investigate the electrical properties of metals in extremely cold temperatures. It had been known for many years that the resistance of metals fell when cooled below room temperature, but it was not known what limiting value the resistance would approach, if the temperature were reduced to very close to 0 K. Some scientists, such as William Kelvin, believed that electrons flowing through a conductor would come to a complete halt as the temperature approached absolute zero. Other scientists, including Onnes, felt that a cold wire's resistance would dissipate. This suggested that there would be a steady decrease in electrical resistance, allowing for better conduction of electricity. At some very low temperature point, scientists felt that there would be a leveling off as the resistance reached some ill-defined minimum value allowing the current to flow with little or no resistance. Onnes passed a current through a very pure mercury wire and measured its resistance as he steadily lowered the temperature. Much to his surprise there was no leveling off of resistance, let alone the stopping of electrons as suggested by Kelvin. At 4.2 K the resistance suddenly vanished. Current was flowing through the mercury wire and nothing was stopping it, the resistance was zero. (See Figure 1) According to Onnes, "Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state". The experiment left no doubt about the disappearance of the resistance of a mercury wire. Kamerlingh Onnes called this newly discovered state, **Superconductivity**.

Fig. 1



Onnes recognized the importance of his discovery to the scientific community as well as its commercial potential. An electrical conductor with no resistance could carry current any distance with no losses. In one of Onnes experiments he started a current flowing through a loop of lead wire cooled to 4 K. A year later the current was still flowing without significant current loss. Onnes found that the superconductor exhibited what he called ***persistent currents***, electric currents that continued to flow without an electric potential driving them. Onnes had discovered superconductivity, and was awarded the Nobel Prize in 1913.

Fig. 2



Whenever a new scientific discovery is made, researchers must strive to explain their theories. By 1933 Walther Meissner and R. Ochsenfeld discovered that superconductors are more than a perfect conductor of electricity, they also have an interesting magnetic property of excluding a magnetic field. A superconductor will not allow a magnetic field to penetrate its interior. It causes currents to flow that generate a magnetic field inside the superconductor that just balances the field that would have otherwise penetrated the material.

This effect, called the **Meissner effect**, causes a phenomenon that is a very popular demonstration of superconductivity. (See figure 2) The Meissner Effect will occur only if the magnetic field is relatively small. If the magnetic field becomes too great, it penetrates the interior of the metal and the metal loses its superconductivity.

In 1957 scientists began to unlock the mysteries of superconductors. Three American physicists at the University of Illinois, John Bardeen, Leon Cooper, and Robert Schrieffer, developed a model that has since stood as a good mental picture of why superconductors behave as they do. The model is expressed in terms of advanced ideas of the science of quantum mechanics, but the main idea of the model suggests that electrons in a superconductor condense into a quantum ground state and travel together collectively and coherently. In 1972, Bardeen, Cooper, and Schrieffer received the Nobel Prize in Physics for their theory of superconductivity, which is now known as the BCS theory, after the initials of their last names.

In 1986, Georg Bednorz and Alex Müller, working at IBM in Zurich Switzerland, were experimenting with a particular class of metal oxide ceramics called perovskites. Bednorz and Müller surveyed hundreds of different oxide compounds. Working with ceramics of lanthanum, barium, copper, and oxygen they found indications of superconductivity at 35 K, a startling 12 K above the old record for a superconductor. Soon researchers from around the world would be working with the new types of superconductors. In February of 1987, a perovskite ceramic material was found to superconduct at 90 K. This discovery was very significant because now it became possible to use liquid nitrogen as a coolant. Because these materials superconduct at significantly higher temperatures they are referred to as ***High Temperature Superconductors*.** Since then scientists have experimented with many different forms of perovskites producing compounds that superconduct at temperatures over 130 K. Currently, many governments, corporations and universities are investing large sums of money for research in High Temperature Superconductors. The ease of cooling new superconductors has greatly influenced vast efforts in the development of new materials, material fabrication, and changing theory of the behavior of superconductors at relatively high temperatures. In addition, electrical power applications for the high temperature superconductors are expected to now be practical, thanks to the increased machine reliability and decreased cost associated with the cooling of such devices at temperatures greater than 20 K. The history of superconductors is only just now beginning.

FUNDAMENTALS OF SUPERCONDUCTORS:

The theoretical understanding of superconductivity is extremely complicated and involved. It is far beyond the scope of this video booklet to attempt to discuss the quantum mechanics of superconductors. However, in this section fundamental terms and phenomena of superconductors will be discussed.

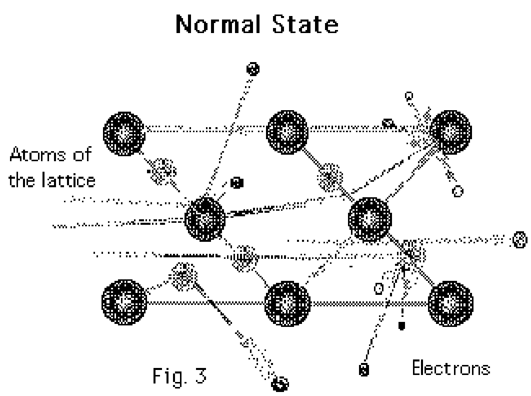


Fig. 3

Superconductors have the ability to conduct electricity without the loss of energy. When current flows in an ordinary conductor, for example copper wire, some energy is lost. In a light bulb or electric heater, the electrical resistance creates light and heat. In metals such as copper and aluminum, electricity is conducted as outer energy level electrons migrate as individuals from one atom to another. These atoms form a vibrating lattice within the metal conductor; the warmer the metal the more it vibrates. As the electrons begin moving through the maze, they collide with tiny impurities or imperfections in the lattice. When the electrons bump into these obstacles they fly off in all directions and lose energy in the form of heat.

Inside a superconductor the behavior of electrons is vastly different. The impurities and lattice are still there, but the movement of the superconducting electrons through the obstacle course is quite different. As the superconducting electrons travel through the conductor they pass unobstructed through the complex lattice. Because they bump into nothing and create no friction they can transmit electricity with no appreciable loss in the current and no loss of energy.

The ability of electrons to pass through superconducting material unobstructed has puzzled scientists for many years. The warmer a substance is the more it vibrates. Conversely, the colder a substance is the less it vibrates. Early researchers suggested that fewer atomic vibrations would permit electrons to pass more easily. However this predicts a slow decrease of resistivity with temperature. It soon became apparent that these simple ideas could not explain superconductivity. It is much more complicated than that.

The understanding of superconductivity was advanced in 1957 by three American physicists-John Bardeen, Leon Cooper, and John Schrieffer, through their Theories of Superconductivity, know as the ***BCS Theory***. The BCS theory explains superconductivity at temperatures close to absolute zero. Cooper realized that atomic lattice vibrations were directly responsible for unifying the entire current. They forced the electrons to pair up into teams that could pass all of the obstacles which caused resistance in the conductor. These teams of electrons are known as ***Cooper pairs***. Cooper and his colleagues knew that electrons which normally repel one another must feel an overwhelming attraction in superconductors. The answer to this problem was found to be in phonons, packets of sound waves present in the lattice as it vibrates. Although this lattice vibration cannot be heard, its role as a moderator is indispensable.

According to the theory, as one negatively charged electron passes by positively charged ions in the lattice of the superconductor, the lattice distorts. This in turn causes phonons to be emitted which forms a trough of positive charges around the electron. Before the electron passes by and before the lattice springs back to its normal position, a second electron is drawn into the trough. It is through this process that two electrons, which should repel one another, link up. The forces exerted by the phonons overcome the electrons' natural repulsion. The electron pairs are coherent with one another as they pass through the conductor in unison. The electrons are screened by the phonons and are separated by some distance. When one of the electrons that make up a Cooper pair and passes close to an ion in the crystal lattice, the attraction between the negative electron and the positive ion cause a vibration to pass from ion to ion until the other electron of the pair absorbs the vibration. The net effect is that the electron has emitted a phonon and the other electron has absorbed the phonon. It is this exchange that keeps the Cooper pairs together. It is important to understand, however, that the pairs are constantly breaking and reforming. Because electrons are indistinguishable particles, it is easier to think of them as permanently paired.

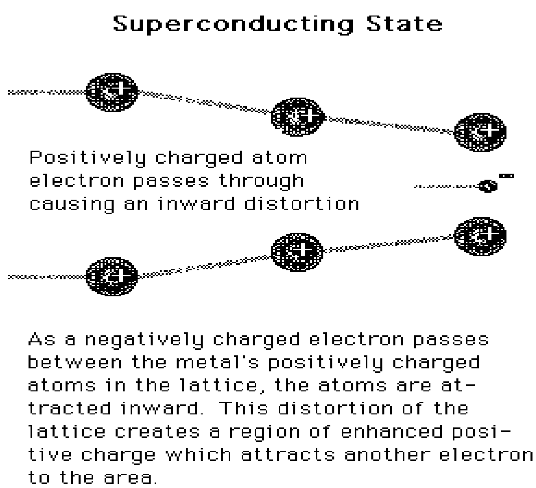


Fig. 4

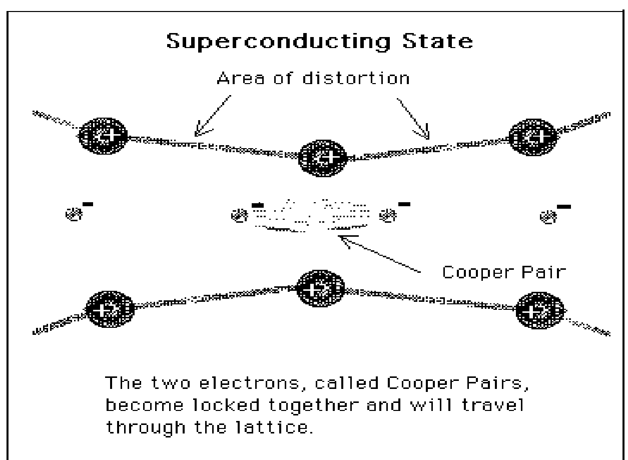


Fig. 5

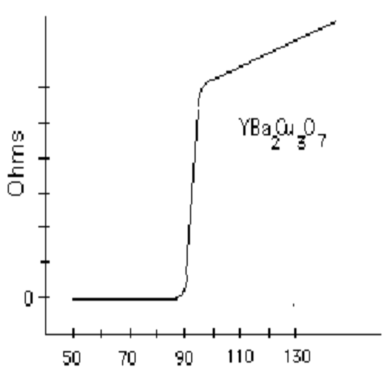
By pairing off two by two the electrons pass through the superconductor more smoothly. The electron may be thought of as a car racing down a highway. As it speeds along, the car cleaves the air in front of it. Trailing behind the car is a vacuum, a vacancy in the atmosphere quickly filled by inrushing air. A tailgating car would be drawn along with the returning air into this vacuum. The rear car is, effectively, attracted to the one in front. As the negatively charged electrons pass through the crystal lattice of a material they draw the surrounding positive ion cores toward them. As the distorted lattice returns to its normal state another electron passing nearby will be attracted to the positive lattice in much the same way that a tailgater is drawn forward by the leading car.

The electrons in the superconducting state are like an array of rapidly moving vehicles. Vacuum regions between cars locks them all into an ordered array as does the condensation of electrons into a macroscopic, quantum ground state. Random gusts of wind across the road can be envisioned to induce collisions, as thermally excited phonons break pairs. With each collision one or two lanes are closed to traffic flow, as a number of single-particle quantum states are eliminated from the macroscopic, many-particle ground state.

The BCS theory successfully shows that electrons can be attracted to one another through interactions with the crystalline lattice. This occurs despite the fact that electrons have the same charge. When the atoms of the lattice oscillate as positive and negative regions, the electron pair is alternatively pulled together and pushed apart without a collision. The electron pairing is favorable because it has the effect of putting the material into a lower energy state. When electrons are linked together in pairs, they move through the superconductor in an orderly fashion.

Fig. 6

Resistance vs. Temperature



As long as the superconductor is cooled to very low temperatures, the Cooper pairs stay intact, due to the reduced molecular motion. As the superconductor gains heat energy the vibrations in the lattice become more violent and break the pairs. As they break, superconductivity diminishes. Superconducting metals and alloys have characteristic transition temperatures from normal conductors to superconductors called ***Critical Temperature*** (T_c). Below the superconducting transition temperature, the resistivity of a material is exactly zero. Superconductors made from different materials have different T_c values. Among ceramic superconductors, $YBa_2Cu_3O_7$ T_c is about 90 K while for $H_gBa_2Ca_2Cu_3O_{8+x}$ it is up to 133 K.

Since there is no loss in electrical energy when superconductors carry electrical current, relatively narrow wires made of superconducting materials can be used to carry huge currents. However, there is a certain maximum current that these materials can be made to carry, above which they stop being superconductors. If too much current is pushed through a superconductor, it will revert to the normal state even though it may be below its transition temperature. The value of ***Critical Current Density*** (J_c) is a function of temperature; i.e., the colder you keep the superconductor the more current it can carry.

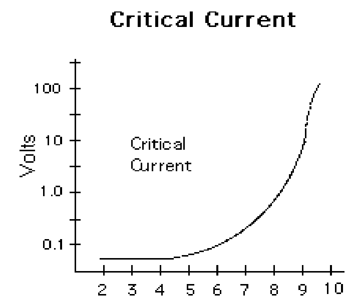
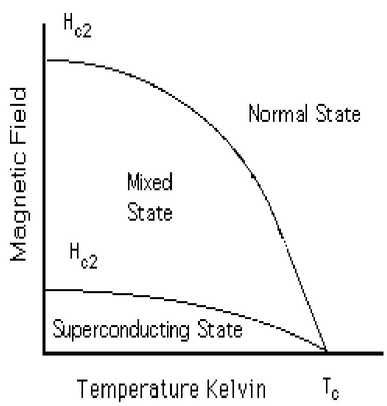


Fig. 7

Fig. 8

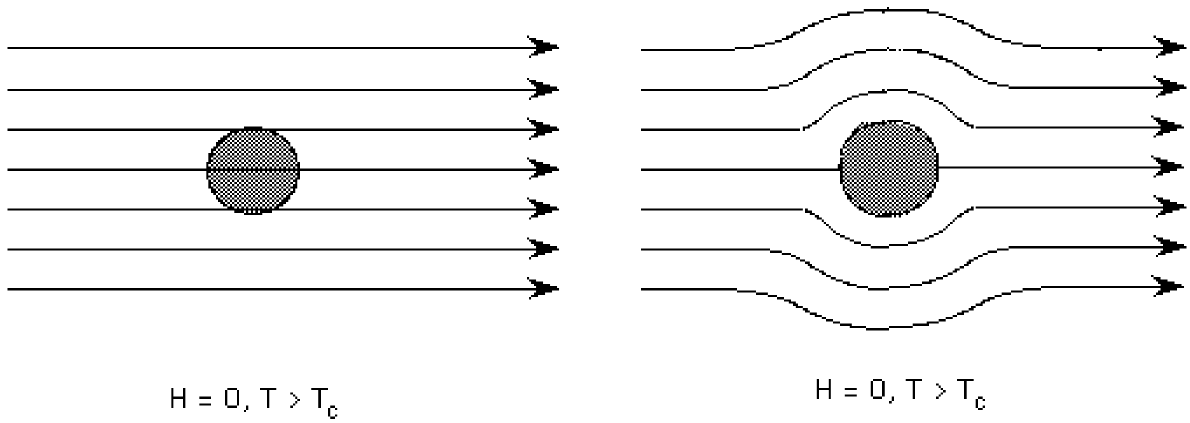


For practical applications, J_c values in excess of 1000 amperes per square millimeter (A/mm^2),are preferred.

An electrical current in a wire creates a magnetic field around a wire. The strength of the magnetic field increases as the current in the wire increases. Because superconductors are able to carry large currents without loss of energy, they are well suited for making strong electromagnets. When a superconductor is cooled below its transition temperature (T_c) and a magnetic field is increased around it , the magnetic field remains around the superconductor. Physicists use the capital letter *H* as the symbol for ***Magnetic Field***. If the magnetic field is increased to a given point the superconductor will go to the normal resistive state.
The maximum value for the magnetic field at a given temperature is known as the ***critical magnetic field*** and is given the symbol H_c. For all superconductors there exist a region of temperatures and magnetic fields within which the material is superconducting. Outside this region the material is normal. Figure (8) demonstrates the relationship between temperature and magnetic fields.

Figure (9) demonstrates what occurs as a superconductor is placed into a magnetic field. When the temperature is lowered to below the critical temperature, (T_c), the superconductor will "push" the field out of itself. It does this by creating surface currents in itself which produces a magnetic field exactly countering the external field, producing a “magnetic mirror”. The superconductor becomes perfectly diamagnetic, canceling all

Fig. 9



magnetic flux in its interior. This perfect diamagnetic property of superconductors is perhaps the most fundamental macroscopic property of a superconductor. Flux exclusion due to what is referred to as the Meissner Effect, can be easily demonstrated in the classroom by lowering the temperature of the superconductor to below its T_c and placing a small magnet over it. The magnet will begin to float above the superconductor. In most cases the initial magnetic field from the magnet resting on the superconductor will be strong enough that some of the field will penetrate the material, resulting in a nonsuperconducting region. The magnet, therefore, will not levitate as high as one introduced after the superconductive state has been obtained.

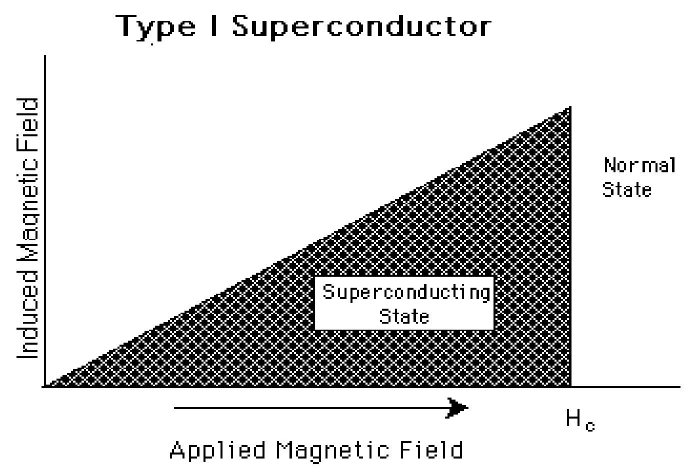


Fig. 10

There are two types of superconductors, Type I and Type II. Very pure samples of lead, mercury, and tin are examples of Type I superconductors. High temperature ceramic superconductors such as $YBa_2Cu_3O_7$ (YBCO) and $Bi_2CaSr_2Cu_2O_9$ are examples of Type II superconductors. Figure (10) shows that when an external magnetic field (horizontal abscissa) is applied to a Type I superconductor the induced magnetic field (vertical ordinate) exactly cancels that applied field until there is an abrupt change from the superconducting state to the normal state. Type I superconductors are very pure metals that typically have critical fields too low for use in superconducting magnets. Magnetic field strength is measured in units of gauss. The earth's magnetic field is approximately 0.5 gauss. The field strength at the surface of a neodymium-iron-boron magnet is approximately 16 kilogauss. The strongest type-I superconductor, pure lead has a critical field of about 800 gauss. The unit of a gauss is a very small unit. A much larger unit of field strength is the tesla (T). Ten kilogauss (1×10^4 gauss) is equal to 1 tesla.

Figure (11) shows a Type II superconductor in an increasing magnetic field. You will notice that this graph has an H_{c1} and H_{c2}. Below H_{c1} the superconductor excludes all magnetic field lines. At field strengths between H_{c1} and H_{c2} the field begins to intrude into the material. When this occurs the material is said to be in the ***mixed state***, with some of the material in the normal state and part still superconducting. Type I superconductors have H_c too low to be very useful. However, Type II superconductors have much larger H_{c2} values. YBCO superconductors have upper critical field values as high as 100 tesla.

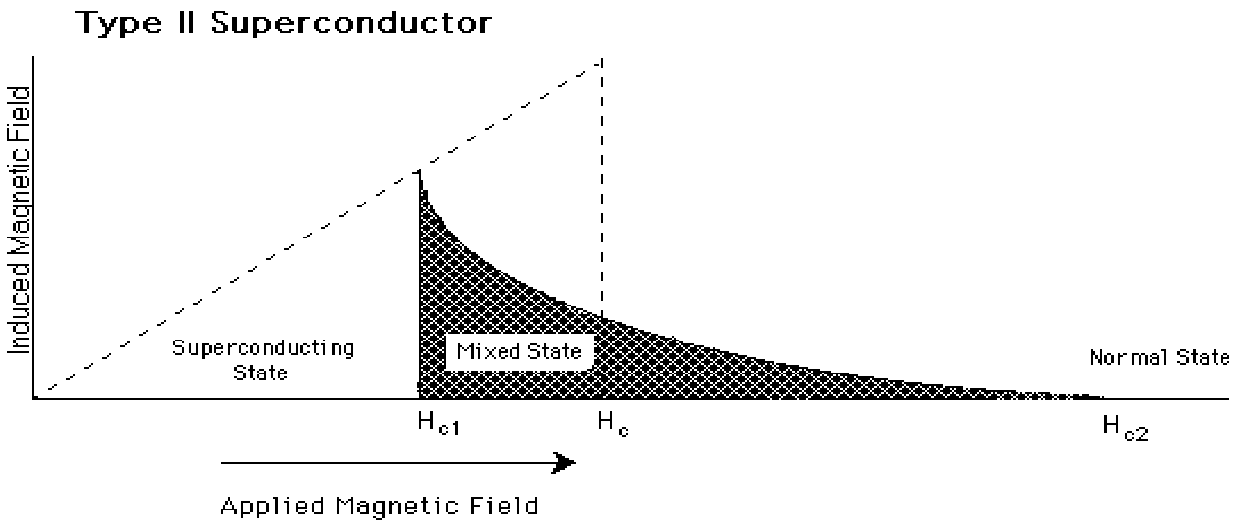


Fig. 11

Type II behavior also helps to explain the **Meissner effect**. When levitating a magnet with a Type I superconductor, a bowl shape must be used to prevent the magnet from scooting off the superconductor. The magnet is in a state of balanced forces while floating on the surface of expelled field lines. Because the field at the surface of a samarium-cobalt magnet is about 600 G, and the H_{c1} for the YBCO superconductor is less that 200 G the pellet is in the mixed state while you are performing the Meissner demonstration. Some of the field lines of the magnet have penetrated the sample and are trapped in defects and grain boundaries in the crystals. This is known as ***flux pinning***. This "locks" the magnet to a region above the pellet.

The superconducting state is defined by three very important factors: critical temperature (T_c), critical field (H_c), and critical current density (J_c). Each of these parameters is very dependant on the other two properties present. Maintaining the superconducting state requires that both the magnetic field and the current density, as well as the temperature, remain below the critical values, all of which depend on the material. The phase diagram in figure (12) demonstrates relationship between T_c, H_c, and J_c. The highest values for H_c and J_c occur at 0 K, while the highest value for T_c occurs when H and J are zero. When considering all three parameters, the plot represents a critical surface.

From this surface, and moving toward the origin, the material is superconducting. Regions outside this surface the material is normal or in a lossy mixed state. When electrons form Cooper pairs, they can share the same quantum wave-function or energy state. This results in a lower energy state for the superconductor. T_c and H_c are values where it becomes favorable for the electron pairs to break apart. The current density larger than the critical value is forced to flow through normal material. This flow through normal material of the mixed state is connected with motion of magnetic field lines past pinning sites. For most practical applications, superconductors must be able to carry high currents and withstand high magnetic field without reverting to its normal state.

Critical Surface Phase Diagram

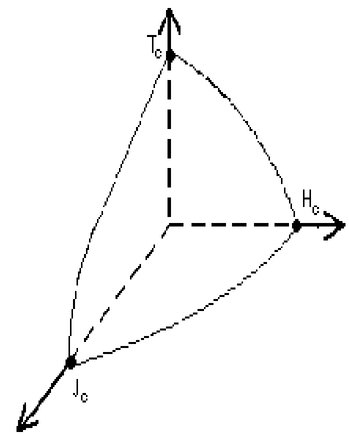


Fig. 12

Higher H_c and J_c values depend upon two important parameters which influence energy minimization, penetration depth and coherence length. Penetration depth is the characteristic length of the fall off of a magnetic field due to surface currents. Coherence length is a measure of the shortest distance over which superconductivity may be established. The ratio of penetration depth to coherence length is known as the Ginzburg-Landau parameter. If this value is greater than 0.7, complete flux exclusion is no longer favorable and flux is allowed to penetrate the superconductor through cores known as vortices. Currents swirling around the normal cores generate magnetic fields parallel to the applied field. These tiny magnetic moments repel each other and move to arrange themselves in an orderly array known as a ***fluxon lattice***. This mixed phase helps to preserve superconductivity between H_{c1} to H_{c2}. It is very important that these vortices do not move in response to magnetic fields if superconductors are to carry large currents. Vortex movement results in resistivity. Vortex movement can be effectively pinned at sites of atomic defects, such as inclusions, impurities, and grain boundaries. Pinning sites can be intentionally introduced into superconducting material by the addition of impurities or through radiation damage.

Up to this point those properties of superconductors which are commonly referred to as macroscopic properties, such as the Meissner effect and zero resistance have been discussed. We will now focus on those properties which are often referred to as quantum mechanical or microscopic properties. An example of microscopic properties is the phenomenon of electron tunneling in superconductors. ***Tunneling*** is a process arising from the wave nature of the electron. It occurs because of the transport of electrons through spaces that are forbidden by classical physics because of a potential barrier. The tunneling of a pair of electrons between superconductors separated by an insulating barrier was first discovered by Brian Josephson in 1962. Josephson discovered that if two superconducting metals were separated by a thin insulating barrier such as an oxide layer 10 to 20 angstroms thick, it is possible for electron pairs to pass through the barrier without resistance. This is known as the ***dc Josephson Effect***, and is contrary to what happens in ordinary materials, where a potential difference must exist for a current to flow. The current that flows in through a d.c. Josephson junction has a critical current density which is characteristic of junction material and geometry. A ***Josephson junction*** consists of two superconductors separated by a thin insulating barrier. Pairs of superconducting electrons will tunnel through the barrier. As long as the current is below the critical current for the junction, there will be zero resistance and no voltage drop across the junction. If it is placed next to a wire with a current running through it, the magnetic field generated by the wire lowers the critical current of the junction. The actual current passing through the junction does not change, but has become greater than the critical current which was lowered. The junction then develops some resistance which causes the current to branch off. Figures (13) and (14) demonstrate the Josephson effect and a Josephson junction.

The Josephson junction is a superfast switching devise. Josephson junctions can perform switching functions such as switching voltages approximately ten times faster than ordinary semiconducting circuits. This is a distinct advantage in a computer, which depends on short, on-off electrical pulses. Since computer speed is dependent on the time required to transmit signal pulses the junction devices' exceptional switching speed make them ideal for use in super fast and much smaller computers.

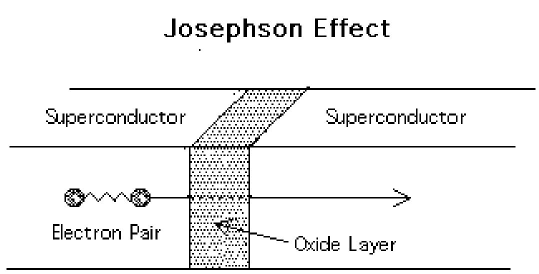


Fig. 13

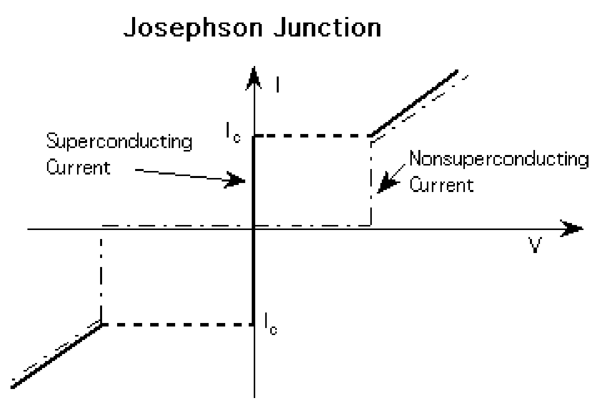


Fig. 14

APPLICATIONS OF SUPERCONDUCTORS:

Soon after Kamerlingh Onnes discovered superconductivity, scientists began dreaming up practical applications for this strange new phenomenon. Powerful new superconducting magnets could be made much smaller than a resistive magnet, because the windings could carry large currents with no energy loss. Generators wound with superconductors could generate the same amount of electricity with smaller equipment and less energy. Once the electricity was generated it could be distributed through superconducting wires. Energy could be stored in superconducting coils for long periods of time without significant loss.

The recent discovery of high temperature superconductors brings us a giant step closer to the dream of early scientists. Applications currently being explored are mostly extensions of current technology used with the low temperature superconductors. Current applications of high temperature superconductors include; magnetic shielding devices, medical imaging systems, superconducting quantum interference devices (SQUIDS), infrared sensors, analog signal processing devices, and microwave devices. As our understanding of the properties of superconducting material increases, applications such as; power transmission, superconducting magnets in generators, energy storage devices, particle accelerators, levitated vehicle transportation, rotating machinery, and magnetic separators will become more practical.

The ability of superconductors to conduct electricity with zero resistance can be exploited in the use of electrical transmission lines. Currently, a substantial fraction of electricity is lost as heat through resistance associated with traditional conductors such as copper or aluminum. A large scale shift to superconductivity technology depends on whether wires can be prepared from the brittle ceramics that retain their superconductivity at 77 K while supporting large current densities.

The field of electronics holds great promise for practical applications of superconductors. The miniaturization and increased speed of computer chips are limited by the generation of heat and the charging time of capacitors due to the resistance of the interconnecting metal films. The use of new superconductive films may result in more densely packed chips which could transmit information more rapidly by several orders of magnitude. Superconducting electronics have achieved impressive accomplishments in the field of digital electronics. Logic delays of 13 picoseconds and switching times of 9 picoseconds have been experimentally demonstrated. Through the use of basic Josephson junctions scientists are able to make very sensitive microwave detectors, magnetometers, SQUIDs and very stable voltage sources.

The use of superconductors for transportation has already been established using liquid helium as a refrigerant. Prototype levitated trains have been constructed in Japan by using superconducting magnets.

Superconducting magnets are already crucial components of several technologies. Magnetic resonance imaging (MRI) is playing an ever increasing role in diagnostic medicine. The intense magnetic fields that are needed for these instruments are a perfect application of superconductors. Similarly, particle accelerators used in high-energy physics studies are very dependant on high-field superconducting magnets. The recent controversy surrounding the continued funding for the Superconducting Super Collider (SSC) illustrates the political ramifications of the applications of new technologies.

New applications of superconductors will increase with critical temperature. Liquid nitrogen based superconductors has provided industry more flexibility to utilize superconductivity as compared to liquid helium superconductors. The possible discovery of room temperature superconductors has the potential to bring superconducting devices into our every-day lives.

High-temperature superconductors are recent innovations from scientific research laboratories. New commercial innovations begin with the existing technological knowledge generated by the research scientist. The work of commercialization centers on the development of new products and the engineering needed to implement the new technology. Superconductivity has had a long history as a specialized field of physics. Through the collaborative efforts of government funded research, independent research groups and commercial industries, applications of new high-temperature superconductors will be in the not so distant future. Time lags however, between new discoveries and practical applications are often great. The discovery of the laser in the early 60's has only recently been appreciated today through applications such as laser surgery, laser optical communication, and compact disc players. The rapid progress in the field of superconductivity leads one to believe that applications of superconductors is limited only by one’s imagination and time.

The table on the next page shows both present and potential applications of superconductors. As you can see application of superconductors is only just beginning.

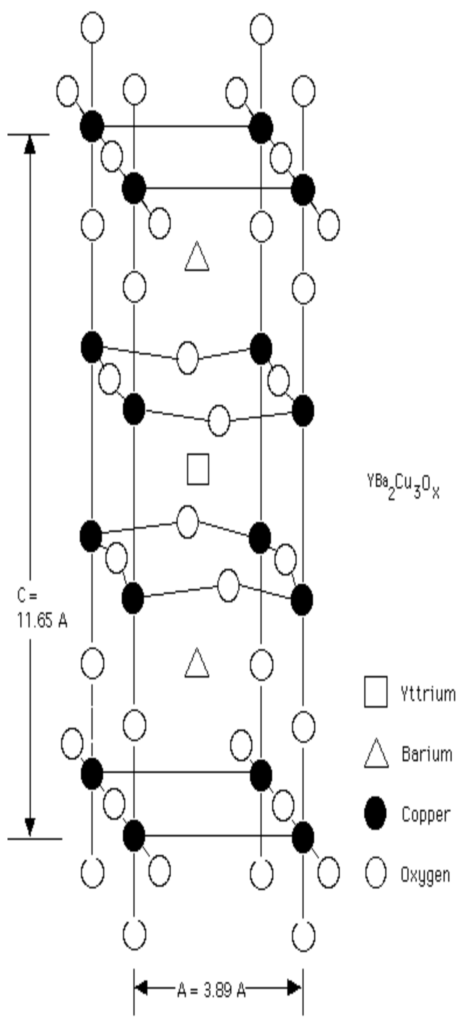
APPLICATIONS OF SUPERCONDUCTORS:

Application	*Current*	*Emerging*
medical		
magnetic resonance imaging	X	
biotechnical engineering		X
electronics		
SQUIDs	X	
transistors		X
Josephson Junction devices		X
circuitry connections		X
particle accelerators	X	
sensors	X	
Industrial		
separation	X	
magnets	X	
sensors and transducers		X
magnetic shielding		X
Power Generation		
Motors		X
Generators		X
Energy Storage		X
Transmission		X
Fusion		X
Transformers and Inductors		X
Transportation:		
Magnetically levitated vehicles		X
Marine propulsion		X

The Chemistry of Superconductors:

The high-temperature superconductors known as Perovskites are a mixture of metal oxides which display the mechanical and physical properties of ceramics. $YBa_2Cu_3O_x$, (YBCO) is a very common Type II superconductor. A key element to the behavior of these materials is the presence of planes containing copper and oxygen atoms chemically bonded to each other. The special nature of the copper-oxygen chemical bond permits materials to conduct electricity very well in some directions. See figure (15).

Fig. 15

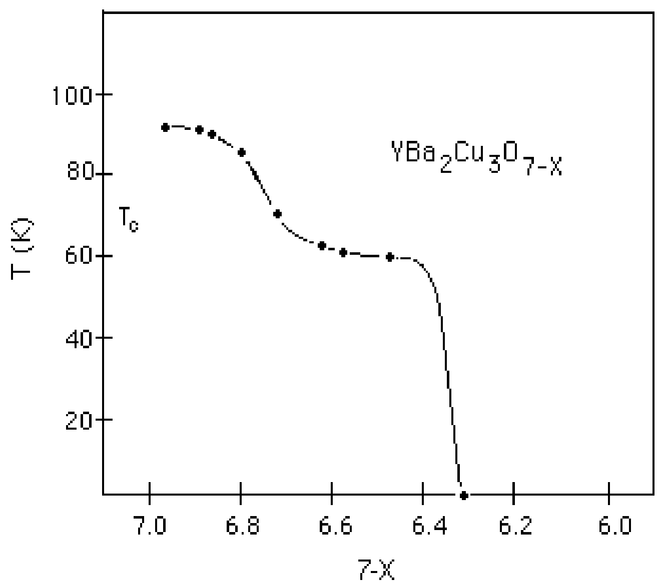


Most ceramic materials are considered good electrical insulators. YBCO compounds, also known as 1-2-3 compounds, are very sensitive to oxygen content. They change from semiconductors at $YBa_2Cu_3O_{6.5}$ to superconductors at $YBa_2Cu_3O_7$ without losing their crystalline structure. The high sensitivity of superconductors to oxygen content is due to the apparent ease to which oxygen can move in and out of the molecular lattice. Using the standard valance charges for the metallic elements, one would expect a formula of $YBa_2Cu_3O_{6.5}$. However, it has been found that these superconductors usually have more oxygen atoms than predicted. According to the formula, $YBa_2Cu_3O_7$, the metals are in a mole ratio of 1-2-3.

$YBa_2Cu_3O_7$ was the first material found to be superconducting above liquid nitrogen temperature. It exhibits a very interesting and complex relationship between its chemistry, crystal structure and physical properties. A very subtle electronic charge balance exists between the one dimensional copper-oxygen chains, which have variable oxygen content, and the two dimensional copper-oxygen pyramidal planes, where superconductivity originates.

In oxygen deficient $YBa_2Cu_3O_{7-x}$, oxygen is removed from the CuO chains. A 90 K superconductor is obtained for $0<x<0.2$, a 60 K superconductor for $0.3<x<0.55$, and an antiferromagnetic semiconductor for $0.55<x<1.0$. These changes in T_c as a function of x are shown in figure (16).

Fig. 16



T_c as a function of oxygen content in $YBa_2Cu_3O_{7-x}$

Since perovskites are ceramics, the procedure for making them is very similar to making other ceramics. All that is needed is a mortal and pestle, a die cast mold, a well-ventilated kiln or furnace and the necessary chemicals. Oxides, carbonates, and nitrates are good sources for the metals needed to make YBCO. The following recipe for making YBCO superconductors allows ambitious and outstandingly competant readers to make their own superconductors. Excellent quality commercially produced superconductors may be purchased at very reasonable cost through various vendors.

Temperature Measurements:

Measuring temperatures of -10 to 150° C can be accomplished quite easily by means of an ordinary laboratory thermometer. However, measuring temperatures in the range of liquid nitrogen can prove to be very difficult with an ordinary thermometer. ***Thermocouple thermometers*** however, are fairly accurate over a wide range of temperatures. A thermocouple is an electrical junction between two dissimilar metals. This junction produces a small voltage at different temperatures. By calibrating the voltage with known temperatures, an accurate thermocouple thermometer can be made. Commercial thermocouples of various types are usually already calibrated and are readily available.

When working with very low temperatures it is inconvenient to work with the Celsius or Fahrenheit scales because of their inherent negative numbers. The K scale, with 0 K representing the temperature where a substance has zero heat energy, is a more appropriate temperature scale to use. This scale is very convenient for measuring the very low temperatures of liquid nitrogen. On this scale liquid nitrogen would have a temperature of
77 K.

The three main temperature scales used for measuring temperature are Fahrenheit, Celsius, and Kelvin. The Kelvin scale is used for most scientific work because it is proportional to the kinetic energy in a substance. The following formulas may be used to convert from one temperature scale to another.

Formulas:

Degrees Fahrenheit = (9/5 * Celsius) + 32

Degrees Celsius = 5/9(Degrees Fahrenheit - 32)

Degrees Kelvin = Degrees Celsius + 273

Common Temperature Reference Points:

	Fahrenheit	**Celsius**	**Kelvin**
Absolute Zero	-460	-273	0
Liquid Helium	-452.1	-268.8	4.2
Liquid nitrogen	-321	-196	77
Water (Fp)	32	0	273
Water (Bp)	212	100	373

Materials:

Dust mask and safety goggles
Mortar and pestle
50 ml acetone
1.00g yttrium oxide, Y_2O_3
2.11g cupric oxide wire, CuO
3.50g barium carbonate $BaCO_3$
Alumina boat, 90x17x11.5 mm
Tongs
Heat-proof gloves
Tube furnace, 1 in. diameter
Pellet press
Quartz tube (24 mm o.d.) equipped with air-tight connections made at one end for attachment to an oxygen tank and the other end for attachment to an oil-filled bubbler.
Tank of oxygen, with regulator and tubing
Krylon No 11303, acrylic resin spray

Procedure for Pellet Preparation

Wear a dust mask and safety goggles at all time, and conduct grinding operations in a fume hood. In the mortar and pestle, grind together the yttrium oxide, copper oxide, and barium carbonate with enough acetone to make a thick slurry. Allow the acetone to evaporate completely in air; at this point the mixed powder will flow freely. Place the powder in the alumina boat and heat in the tube furnace at 950°C for one hour. Wearing heat-proof gloves and tongs, remove the boat containing the mixed oxides from the tube furnace. Allow the mixture to cool to room temperature. It will be black or green-black at this time.

When cool, regrind the dry powder in the mortar and pestle (do not use acetone). Return the powder to the boat, and heat it in the furnace for five hours at 950°C. Again, cool it to room temperature. Grind the now black powder for a third time in the mortar and pestle, this time using acetone. Allow the acetone to evaporate completely.

Use a pellet press to form pellets at about 50,000 lb/in^2 pressure. The pellets should be approximately 13 mm in diameter and 3 mm thick. There should be enough mixed oxide to make three pellets.

Place the pellets in the alumina boat, and place the boat inside the quartz tube. Place the assembly in the tube furnace and heat at 950 for one hour in order to sinter (heat just below the melting point to increase strength and density and to promote intergranular bonding) the pellets. Allow the furnace to cool to 500-600^{o}C for the crucial "sensitization" step. At this point the ceramic is ***oxygen deficient***. This means that there is not enough oxygen in the crystalline structure to superconduct. Pass pure oxygen through the quartz tube, over the pellets, at a rate of about 10ml/min for 3 hours. At the conclusion of the 3 hour period turn off the furnace and allow it to cool to room temperature while maintaining the flow of oxygen over the pellets. Oxygen will enter the YBCO compound as it ***slowly cools***, between 600 and 400^{o} C. By allowing oxygen to circulate in the oven as the sample cools your sample will become oxygenated. Several annealing procedures, heating and cooling cycles, seem to improve the quality of 1-2-3 ceramic superconductors.

Spray coat the pellets with an acrylic resin such as Krylon No 1303. This will protect the pellets from chemical decomposition, which can occur from prolonged exposure to water or water vapor.

Once cooled, the final material should be hard and black in color, any green coloration will indicate that you have an insulator rather than a superconductor. If the material exhibits the Meissner effect, it is a true superconductor. Remember the production of superconductors is still very much an experimenters game.

Electrical Contacts: ***Advanced Topic***

One of the greatest advantages of superconductors is their ability to carry large currents through small areas. A major problem however, is getting the current in and out. Consider a large water main for a major metropolitan city. If the ends of the pipe were small and difficult to attach, the limiting factor would be the connecting pipes not the main. This can be a significant problem with superconductors. They may have very high current densities, but if there is too much resistance in the electrical contacts the current flow will cause heating at the contacts. Power dissipation as heat is equal to the current flow multiplied by the voltage drop. Since superconductivity exists only at low temperatures, this heating causes easy flow of electrical current to be limited. Attaching contact leads to bulk superconductors can be difficult. Many commercially produced superconductors can be purchased with electrical leads already attached. The contact resistance of commercial superconductors are usually superior to contacts that are made in a high school lab.

One method for attaching contact leads to your superconductor requires small gauge silver or copper wire and electrical silver paint. These items are readily available at any electronic supply store. By attaching the leads to the sample with the silver paint as shown in figure (17) you should have a good four point probe. If the contact resistance is too high, scrape the silver paint away and then try resintering the sample by annealing it again in your oven. When a simple measurement of electrical resistance is made by a two probe connection, you unintentionally also measure the resistance of the contact points. In a normal conductor the resistance of the contact points is relatively small compared to the resistance of the conductor. However, when measuring the resistance of a superconductor, which has very low or no resistance, the contact resistance is very significant.

The effect of the contact resistance can be diminished by the use of a four point probe. Figure (17) shows a four point probe attached to a superconducting sample. A constant current flows through the wires labeled C_1 and C_2. A power supply capable of providing 0.5 amperes is needed. If an ammeter is not built into the power supply an ammeter should be wired into the circuit to monitor the current flow.

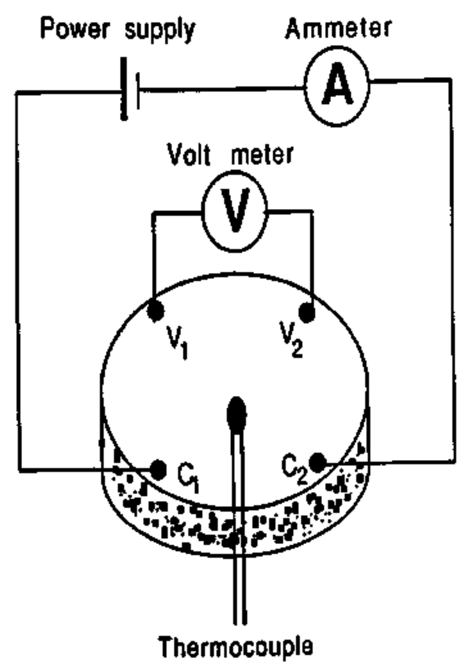


Fig. 17

If there is any resistance in the sample, a voltage drop will occur between the contact points of current leads as the current spreads and flows. Wires V_1 and V_2 are connected to a digital volt meter to detect any voltage drop between their contact points. If these two contacts are physically removed from the current contacts (wires labeled C_1 and C_2), the resistance of the superconductor between wires V_1 and V_2 is the ratio of the voltage to the output current of the power supply, according to Ohm's Law $V=IR$. If wires V_1 and V_2 contact wires C_1 and $_2C$, the measured resistance R is the sum of the sample resistance and the two contact resistances.

HANDLING LIQUID NITROGEN:

Liquid nitrogen is manufactured by cooling down air to a temperature of 77 K. Liquid nitrogen is very common and easy to obtain, if you know where to look. It is used by hospitals, physicians, cattle breeders, universities, factories, and welding shops. Liquid nitrogen can be obtained from these sources for a minimal cost.

Small quantities of liquid nitrogen can be stored in Dewar bottles. Dewar bottles are hollow-walled glass-lined containers which provide excellent insulation. Dewar bottles will keep liquid nitrogen for a fairly long period of time. If you do not have a dewar, a standard *Thermos* bottle with a stainless steel shell will work fine for transporting and storing small amounts of liquid nitrogen for a short time. *Thermos* bottles have screw-on caps. CAUTION !!! **THE CAP MUST NEVER BE SCREWED ON AT ANY TIME LIQUID NITROGEN IS IN THE BOTTLE**. If the cap is not vented the liquid nitrogen will boil and build up pressure until the bottle **EXPLODES.**

Safety procedures for handling liquid nitrogen:

Liquid nitrogen is a hazardous substance. If misused it may cause, *frostbite, eye damage, torn flesh, or asphyxiation.* **FOLLOW THE FOLLOWING SAFETY RULES:**

* Keep away from students.

* Always wear safety goggles at all times.

* Use tweezers to handle superconductors, magnets, or other small, cold objects. Plastic tweezers are useful but should be tested for embrittlement (see last caution) before use in classroom.

* Wear insulating gloves when handling liquid nitrogen or large, cold objects.

* Use liquid nitrogen only in well ventilated places.

* Do not allow any liquid nitrogen to touch any part of your body.

* Item in contact with liquid nitrogen becomes **Extremely Cold**. Do not touch any item that has been immersed in liquid nitrogen until it has warmed to room temperature.

* Do not store liquid nitrogen in any container with a tight fitting lid. A tightly sealed container will build up pressure as the liquid boils and may **EXPLODE** after a short time.

* Many substances become brittle and may shatter when cold, sending pieces of the material flying. Avoid common glass and large, solid plastics.

Demonstration # 1:

The Meissner Effect

Levitation of a magnet above a cooled superconductor, the ***Meissner Effect***, has been well known for many years. If a superconductor is cooled below its critical temperature while in a magnetic field, the magnetic field surrounds but does not penetrate the superconductor. The magnet induces current in the superconductor which creates a counter-magnetic force that causes the two materials to repel. This can be seen as the magnet is levitated above the superconductor. Keep in mind that this will occur if the strength of the applied magnetic field does not exceed the value of the critical magnetic field (H_c) of the superconductor. If the magnetic field becomes too strong, it can penetrate the interior of the material and lose its superconductivity. In addition the force of repulsion must exceed the weight of the magnet.

Materials:

- superconducting disk
- neodymium-iron-boron (or other strong) magnet
- liquid nitrogen
- dewar
- petri dish
- styrofoam cup
- non-magnetic tweezers
- gloves

Procedure:

1. Carefully fill the styrofoam cup with liquid nitrogen. (This will help to keep the liquid nitrogen in the petri dish from boiling away too fast).

2. Place the petri dish on top of the styrofoam cup and carefully pour in enough liquid nitrogen until the liquid is about a quarter inch deep. The liquid will boil rapidly for a short time. Wait until the boiling subsides.

3. Using non-metallic tweezers, carefully place the superconducting disk in the liquid nitrogen in the petri dish. Wait until the boiling subsides.

4. Using non-metallic tweezers, carefully place a small magnet about 2 mm above the center of the oxide pellet. Upon releasing the magnet it should be levitated approximately 3 mm above the pellet.

The magnet should remain suspended until the superconducting pellet warms to above its critical temperature, at which time it will no longer be levitated. It may either settle to the pellets surface or "jump" away from the pellet.

This demonstration can also be done by placing the magnet on top of the superconducting pellet before it is cooled in the liquid nitrogen. The magnet will levitate when the temperature of the superconductor falls below the critical temperature (T_c).

Another interesting phenomenon can be observed, while the magnet is suspended above the superconducting pellet, by gently rotating the magnet. The rotating magnet acts like a frictionless bearing as it is suspended in the air.

Demonstrating the Meissner Effect to a large class sometimes may prove to be difficult. One way to help students better see the effect is by placing the superconductor into a plastic petri dish which is resting on a styrofoam cup filled with liquid nitrogen. See figure (19). Other methods to address larger audiences can be accomplished by the use of video projection or the use of an overhead projector. By placing an overhead projector on its side such that it still projects onto a screen, an image of the levitated magnet can be seen. Place the superconducting disk with the levitated magnet in front of the glass plate so that its silhouette can be seen. The magnet should be as close to the glass plate as possible for best results. Another method for projecting an image of the levitated magnet can be accomplished by setting up your demonstration as shown in figure (19). Position mirrors so that the total distance from the upper focussing lense and reflector to the levitating magnet is the same as to the glass plate normally used for transparency support.

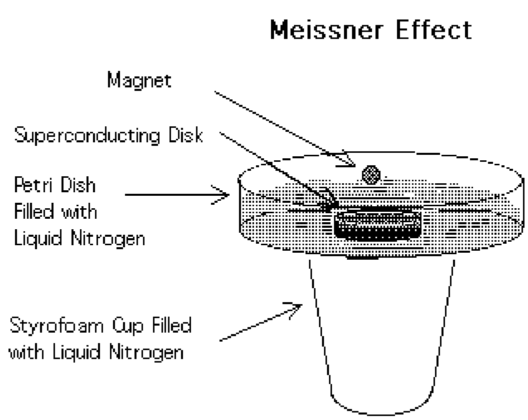


Fig. 18

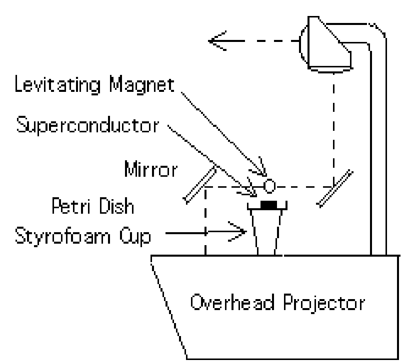


Fig. 19

Demonstration # 2

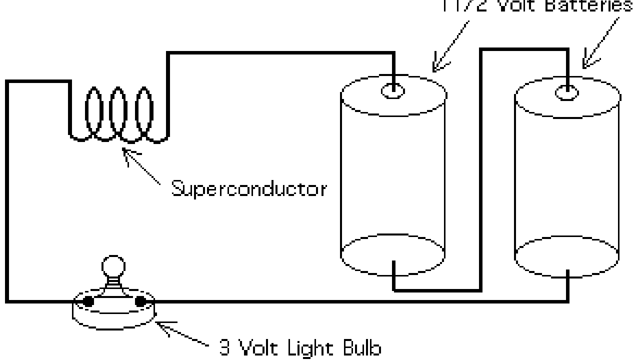
A Superconductive Switch

When a superconductor is in the normal state the resistance to the flow of current is quite high compared to the superconducting state. Because of this, a simple resistance switch can be easily demonstrated.

Material:

- YBCO superconductive wire with attached leads—Ceranova Corporation sells a suitable wire coil.
- 2 C batteries with holder
- 3 volt flash light bulb with holder
- liquid nitrogen
- dewar or styrofoam cup

Fig. 20



Procedure:

1. Connect superconductor, light bulb and batteries as shown in figure (20).

2. When the superconductor is at room temperature it is in the normal state and will have high resistance. The bulb will not light.

3. Place the superconductor into the liquid nitrogen. The bulb will light as the resis tance decreases.

4. Remove the superconductor from the liquid nitrogen. The bulb will begin dim and eventually go out as the resistance increases.

Caution: This demonstration requires low-resistance contacts to the superconductor. If the switch fails to provide change in light intensity, repeat contact construction as described on page 19. The superconductor may well need an anneal.

Demonstration #3

Voltage Drop using an Oscilloscope ***Advanced Topic***

The voltage drop that occurs when a superconductor goes from the normal state to the superconducting state can be easily demonstrated on an oscilloscope. The nonlinear current-voltage relation of a superconductor in its mixed state may also be observable if a hand-held magnet can apply enough magnetic field.

Materials:

- Oscilloscope
- superconductor with attached leads
- AC power supply
- liquid nitrogen
- dewar or styrofoam container

Procedure:

1. Connect the power supply, superconductor, and oscilloscope as shown in figure (21). Figure (23) shows a circuit diagram for an ac ramp power supply made from readily available components.

2. The voltage drop across the voltage leads (V_1, V_2) will be seen on the "*Y*" axis if connected to the vertical input terminals. Note that the ac power supply floats with respect to the ground at the oscilloscope input. If you wish to use a commercial supply with a grounded output, use a differential input amplifier available on many oscilloscopes. Figure 24 shows the circuit diagram for a differential amplifier that can be built from readily available components.

3. Set the oscilloscope trigger to display one sweep across the screen for each ac cycle.

4. Adjust the input voltage sensitivity setting on the oscilloscope as needed to obtain an image similar to figure (22).

5. Place the superconducting disk into the liquid nitrogen. As the disk cools and begins to superconduct the voltage drop across the voltage leads (V_1, V_2), will go to zero. This will cause the image to rotate to a horizontal line.

6. Remove the superconductor from the liquid nitrogen. The resistance increases causing the voltage drop to increase again.

7. Place the superconductor back into the liquid nitrogen and watch the voltage drop back to zero. Now place a strong magnet near the superconductor and observe the voltage drop. Under the right conditions, resistivity will again appear. The supercurrent vortices move (indicated by the observed voltage that is not quite proportional to electrical current) in reponse to a driving force due to the current flow.

Fig. 21

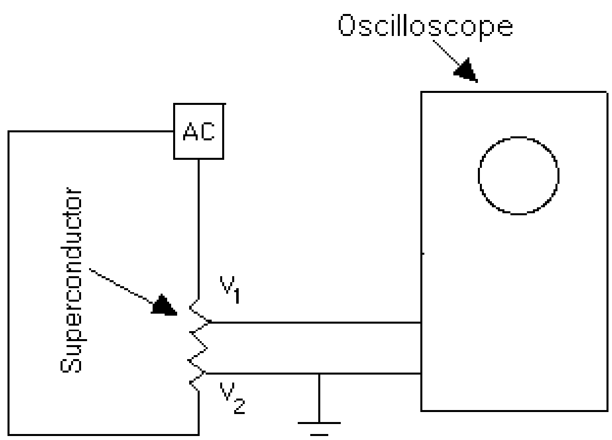
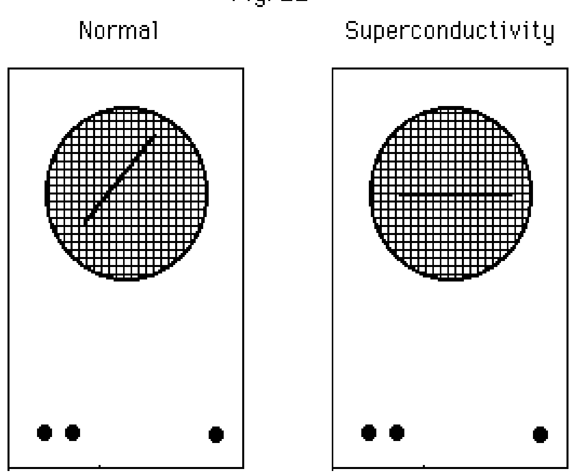


Fig. 22



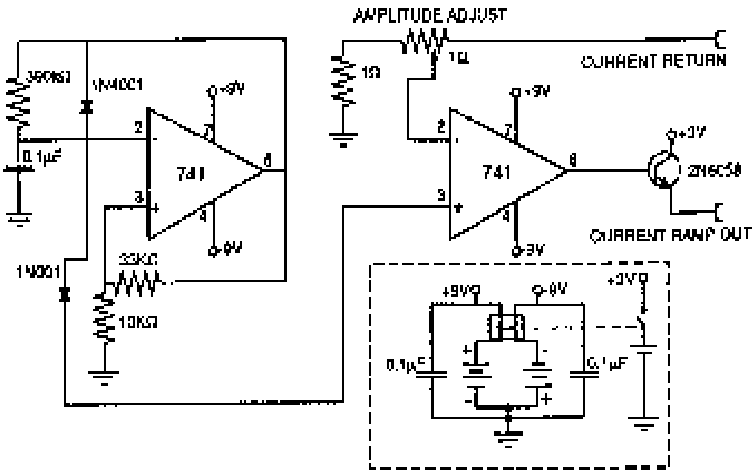


Fig. 23

Figure (23) shows a simple circuit diagram for an ac ramp power supply. It can be built with inexpensive and readily available 741 operational amplifiers, a 2N6058 transistor, two 1N4001 diodes, two 0.1 μF capacitors, two ordinary 9-V batteries, and various resistors. This ramping current supplies current that increases linearly with time up to an adjustable maximum value (amplitude). Then it drops to zero and repeats the ramp at an adjustable frequency.

DIFFERENTIAL AMPLIFIER

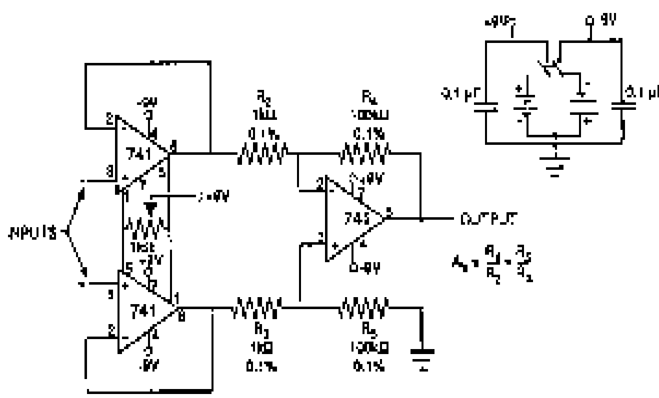


Fig. 24

Figure (24) is a schematic diagram of a simple differential amplifier. Connecting the superconductor directly to grounded oscilloscope input gives a terribly inaccurate voltage measurement for the oscilloscope's vertical deflection, the *Y* value of the displayed graph. Voltage connections V_1 and V_2 give approximately the same voltages at both inputs to the amplifier. These voltages must be rejected except for their small difference, the voltage drop within the superconductor. An ordinary oscilloscope with two inputs that can be subtracted for display will show graphical values of the difference that includes "common mode" error. The gains for the inputs that are electronically subtracted are R_4/R_2 and R_5/R_3.

Experiment # 1

Determining T_c using the Meissner Effect:

One very simple method for measuring the critical temperature of a superconductor is by using the Meissner Effect. Remember when the temperature of a superconductor is lowered to below the critical temperature, (Tc), the superconductor will "push" the field out of itself. It does this by creating surface currents in itself which produces a magnetic field exactly countering the external field, producing a "magnetic mirror". The superconductor becomes perfectly diamagnetic, canceling all magnetic flux in its interior. This perfect diamagnetic property of superconductors is perhaps the most fundamental macroscopic property of a superconductor. When your material is superconducting the magnet will begin to float above the superconductor. If you monitor the temperature as the Meissner effect occurs you can obtain a good approximation of the critical temperature.

Objective:

1. To determine the approximate value of a YBCO superconductor using the Meissner Effect.

Materials:

- YBCO superconductor with attached thermocouple
- small magnet
- millivolt meter
- liquid nitrogen

Procedure:

1. Attach the thermocouple lead from the superconductor to a digital voltmeter. The voltmeter should be set to the millivolt range.
2. Completely immerse the superconducting disk in liquid nitrogen with the thermocouple on the bottom. Calibrate your thermocouple according to the manufacturer's specifications.
3. Carefully balance your magnet above the superconducting material and observe the Meissner Effect. When the liquid nitrogen has almost completely boiled away the temperature will begin to increase.
4. Observe the magnet as the disk warms. The magnet will stay levitated as long as the disc is superconducting. As the disk warms the magnet will slowly begin to fall. Record the temperature when the magnet comes to a complete rest on the superconducting disc.

Remember the disk will not be warming equally throughout. The top of the superconductor will warm up before the bottom of the disk which is still in liquid nitrogen. Because YBCO disks are bulk superconductors, the Meissner effect will diminish as the top of the disk warms until the entire superconductor is above the critical temperature.

Experiment # 2

Resistance / Temperature Relationship

Objective:

1. To obtain a resistivity vs. temperature curve:
2. To determine the critical temperature of a YBCO superconductor;

Materials:

- YBCO superconductor with four point probe and thermocouple
- millivolt meter
- constant current supply
- ammeter
- liquid nitrogen

Procedure:

1. Attach current leads, (C_1,C_2) to the power supply.
2. Attach millivolt meter to leads V_1 and V_2.
3. Attach thermocouple to millivolt meter and calibrate.
4. Carefully immerse the superconductor into liquid nitrogen.
5. When the boiling stops carefully adjust the current to 0.5 amps.
6. Record the temperature and the voltage across V_1 and V_2. This voltage is expected to be the same with or without current flow because it is the thermal electromotive force (EMF).
7. Allow the liquid nitrogen to slowly boil away permitting the superconductor to slowly warm.

* 8. Record the voltage drop and temperature as the superconductor warms. The electrical power supply should be turned off and/or disconnected periodically and thermal EMF recorded.

By knowing the voltage drop across leads V_1 and V_2, and the current flowing through the circuit the resistance of the superconductor can be calculated according to Ohm's Law.

- Make a graph plotting the resistance in ohms on the *Y* axis and the Kelvin temperature on the *X* axis.
- Determine the critical temperature for your superconductor.
- Repeat this experiment using 0.2 amps.
- Calculate the resistivity of your sample. (ohms-cm)

* Note: Results from this experiment can be greatly improved if the temperature and voltage drop values can be recorded by a strip chart or by interfacing with a computer.

Experiment # 3

Determination of Critical Current:

There is a certain maximum current that superconducting materials can be made to carry, above which they stop being superconductors. If too much current is pushed through a superconductor, it will revert to the resistive mixed state even though it is below its transition temperature. The value of ***Critical Current Density*** (J_c) is a function of temperature, the colder you keep the superconductor the more current it can carry.

Objective:

1. To determine the critical current of a YBCO superconductor.

Materials:

- YBCO superconductor with four point probe and thermocouple
- millivolt meter
- 10 watt power supply capable of a 10 ampere output (for use with a disk superconductor) or a 1 watt supply capable of a 1 ampere output (for use with a superconductor coil).
- ammeter
- liquid nitrogen

Procedure:

1. Attach current leads, (C_1, C_2) to the power supply.
2. Attach millivolt meter to leads V_1 and V_2.
3. Attach thermocouple to millivolt meter and calibrate.
4. Carefully immerse the superconductor into liquid nitrogen.
5. When the boiling stops carefully adjust the current to 0.1 ampere.

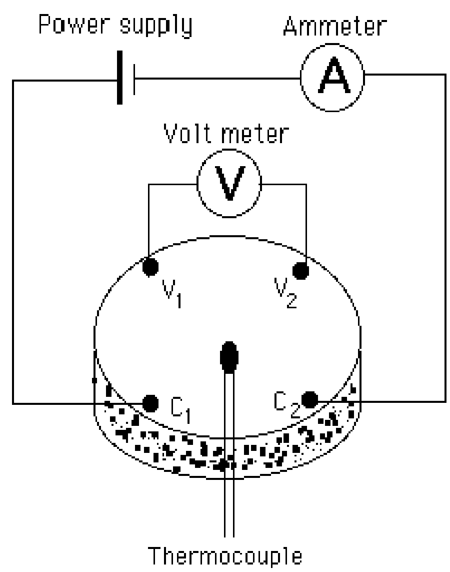


Fig. 17 (repeated)

6. Record voltage and current.
7. Keep the superconductor in the liquid nitrogen at all times during this experiment to prevent it from heating up.
8. Increase the current in 0.5 ampere intervals (for disk) or .05 ampere intervals (for coil) and record the voltage drop and current for each trial. Repeat this step until the sample heating produces noticeable liquid boiling.
9. Do not remove the superconductor from the liquid nitrogen until you have turned off the power supply.

- Make a graph plotting the voltage drop on the *Y* axis and the current on the X axis.
- Determine the critical current for your superconductor at 77 K
- Calculate the critical current density, (A/mm^2), for your superconductor

CAUTION !!! Excessive electrical heating can damage samples even while they are immersed in liquid nitrogen. Teacher must try this experiment and set a clear limit to electrical current students can use.

Experiment # 4

Determination of the Critical Magnetic Field:

Objective:

To determine the critical field, H_{c2}, of a YBCO superconductor.

Materials:

- YBCO superconductor with attached leads
- power supply
- electromagnetic coil
- millivoltmeter
- liquid nitrogen
- dewar or styrofoam container

Procedure:

1. Connect current probes and voltage probes as done for Experiment # 3. For study of a disk superconductor adjust the current to 0.5 ampere (or 0.05 anpere for coil).
2. Connect power supply to electromagnetic coil and place the coil into liquid nitrogen. The value of the magnetic field can be determined by knowing the geometry of the coil and the current passing through it. The coil must be large enough to place the superconductor in it.
3. Place the superconductor into the coil in the liquid nitrogen. Record the voltage drop (V_1, V_2) and the magnetic field applied. This field strength must be determined by multiplying the current supplied by a calibration constant for the coil used. An approximate expression is:

   $$H = 4\pi NI(1+d^2/L^2)^{-1/2}/10L$$

   where the solenoidal coil of diameter d has NL turns over its length L. The magnetic field H is in units of Oersteds and lengths are in centimeters.
4. Gradually increase the magnetic field placed on the superconductor. Record the voltage and magnetic field for each setting.
5. The voltage (V_1, V_2) will show an abrupt increase at some value of the applied magnetic field strength. This value represents the critical magnetic field H_{c2}, for the superconductor at 77 K.

- Make a graph plotting applied magnetic field strength on the Y axis and resistance on the X axis.
- Determine the critical magnetic field strength for the superconductor at 77 K.

SUPERCONDUCTIVITY CHEMISTRY PROBLEMS:

The following twenty problems are selected questions dealing with general chemistry and the chemistry of the YBCO superconductor.

Give the formula weights of the following compounds.

1. CO_2 2. O_2 3. CuO 4. $BaCO_3$

5. H_20 6. Y_2O_3 7. $YBa_2Cu_3O_7$ 8. $Bi_2Sr_2CaCu_2O_8$

9. If a student wants to make 250 grams of $YBa_2Cu_3O_7$, how many moles of each element will be needed ?

10. How many grams of each element will the student need in problem #9?

11. When yttrium oxide, barium carbonate and copper(II) oxide are mixed, annealed and cooled in an oxygen atmosphere, a YBCO compound can be formed. Give the balanced equation for the formation of $YBa_2Cu_3O_7$. (NOTE: When $BaCO_3$ is heated BaCO and CO_2 are formed.)

12. How many additional moles of O_2 need to be added to the YBCO compound formed in problem #11 to make it superconducting?

13. Why does the YBCO material need to be cooled in a stream of oxygen gas?

14. What color should the YBCO superconductor be after it has been annealed?

15. What type of superconductor is the YBCO material?

16. What is the name of the crystal structure found in YBCO ceramics?

17. What is the critical temperature T_c for $YBa_2Cu_3O_7$?

18. Which atoms occupy the corners of the crystal lattice of the YBCO compound?

19. If a YBCO superconductor is left unprotected in the air a chemical reaction can occur with CO_2 and water resulting in deoxygenation of the sample. How can you prevent this from happening?

20. $Bi_4(Sr,Ca)_6Cu_4O_{16}$ is another high temperature superconductor. Write the balance equation for the formation of $Bi_4(Sr,Ca)_6Cu_4O_{16}$ from its metal oxides.

over

(NOTE: the moles of Sr and Ca may vary but the total mole of Sr and Ca is equal to six).

21. Briefly describe the formation of Cooper Pairs according to the BCS Theory.

Solutions for Superconductivity Chemistry Problems:

1. 44.0 g/mole 2. 32.0 g/mole 3. 79.6 g/mole 4. 197.4 g/mole

5. 18.0 g/mole 6. 225.8 g/mole 7. 666.2 g/mole 8. 888.4 g/mole

9. 0.375 mole Y, 0.750 mole Ba, 1.13 mole Cu, 2.63 mole O

10. 32.9g Y, 103g Ba, 71.8g Cu, 42.1g O

11. $BaCO_3$ -----> $BaO + CO_2$

$Y_2O_3 + 4BaO + 6CuO$ ---> $2YBa_2Cu_3O_{6.5}$

12. 1/4 mole per mole $YBa_2Cu_3O_7$

13. To oxygenate the YBCO to make it superconducting.

14. Black

15. Type II

16. Perovskites

17. 92 K

18. Copper

19. The YBCO can be kept in a closed container along with anhydrous $CaSO_4$, which absorbs water vapor.

20. $2Bi_2O_3$ + (X)SrO + (Y)CaO + 4CuO --> $Bi_4(Sr,Ca)_6Cu_4O_{16}$ Where (X)+(Y)=6

21. See pages 5-7.

SUPERCONDUCTIVITY PHYSICS PROBLEMS:

The following problems are selected questions dealing with general physics and the physics of the superconductivity. The rationalized mks system of electromagnetic units is used.

1. What is the resistance of a superconductor in the normal state if 300 milliamps of current are passing through the sample and 4.2 millivolts are measured across the voltage probes?

2. What is the resistivity of the rectangular sample in problem # 1, if the material is 2.5 mm wide, 3.4 mm high and the distance between the probes is 2.5 cm?

3. Imagine connecting rectangular samples of copper and stainless steel as in problem #3. Typical resistivities of these materials are 1.8×10^{-8} and 12×10^{-8} Ω-m, respectively. What resistances will be measured?

4. Consider wiring the superconductor of problems # 1 and # 2 in series with a 10-ohm resistor and connected to a 1.5-V battery. How much electrical current will flow through the superconductor? What is the critical density required for loss-free current flow?

5. Explain why the electric field inside a superconductor must be equal to zero.

6. A flat superconductor plate levitates magnets by acting as a mirror of magnetic fields. How high will fully magnetized, 1-g blocks of nickel, iron, and neodymium-iron-boron ($Nd_2Fe_{14}B$) levitate? Their saturation magnetizations are 0.005, 0.17, and 1.0 A-m^2/kg, respectively. (These magnetizations give surface magnetic fields of 54, 1700, and 16,000 gauss, respectively.) Note that the repulsive force between two (parallel) magnetic moments of identical values *m* separated by the distance *r* is given by $F=3m^2/r^4$.

7. Electrical current *I* through a circular wire loop of self inductance $L=\mu_0 b(ln 8b/a-7/4)$ decays over time *t* according to $I=I_0 exp(-tR/L)$. Two wires of radius a=0.2 mm (0.4-mm thick), length $2\pi b$=19 cm, and resistances, R=10 mΩ and 25 μΩ, were wound as circles. Graph the current as a function of time *t*.

8. The electrical potential around such a loop in the presence of an alternating magnetic field, $B cos(\omega t)$ is $E=\pi b^2 B\omega sin(\omega t)$. At 60 Hz what are the resulting current flows against the complex electrical impedance, $R+i\omega L$?

9. The following data was obtained from a YBCO bulk sample. Calculate the resistance for each trial given that a constant current of 100 mA was flowing through the sample.

Voltage	T (K)	R (Ohm)	Voltage	T (K)	R (Ohm)
0.0010370	118.2		0.0008440	93.5	
0.0010270	116.1		0.0007830	93.2	
0.0010600	114.8		0.0006390	93	
0.0010490	112.9		0.0005050	92.6	
0.0010350	110.9		0.0003790	92.3	
0.0010220	109.1		0.0002430	92.1	
0.0010090	106.9		0.0000930	91.7	
0.0010010	105		0.0000100	91.4	
0.0009890	103.5		0.0000030	91	
0.0009750	102.2		0.0000002	90.8	
0.0009670	100		-0.0000002	90.1	
0.0009510	97.9		-0.0000001	89.9	
0.0009440	95.8		0.0000003	89.5	
0.0009180	95		-0.0000001	88.8	
0.0009110	94.3		0.0000001	88.5	
0.0008920	93.8				

10. Using the data from problem # 9 make a graph plotting resistance as a function of the temperature.

11. What is the first derivative of the normal, resistive part of the graph?

12. Estimate the critical temperature T_c from your graph.

13. List and discuss two applications of superconductors that are currently in use today.

14. Discuss the problems that scientists must overcome before superconductors can be used effectively.

Solutions for Superconductivity Physics Problems:

1. $V=IR$, therefore $R=V/I$ so 4.2 millivolts/300 miliamps = 0.014 Ω

2. R×(area / length) = resistivity (ρ)
   ρ = (0.014Ω)×(2.5mm×3.4mm)/2.5cm = 0.000476 Ω-cm

3. $R = \rho\times$(2.5cm)/(2.5mm×3.4mm) = 5.3×10^{-7}Ω for copper and 3.5×10^{-6}Ω for stainless steel.

4. If the contacts are excellent, the current is simply I=(1.5 V)/(10 Ω)=0.15 ampere when the two are in series. There is no voltage drop across the superconductor until I exceeds the sample's critical current, of density $J_c=I_c/(2.5\text{mm}\times3.4\text{mm})\geq .018\text{A/mm}^2$.

5. According to Ohm's Law, $E=\rho J$. If ρ (resistivity) is equal to zero inside the superconductor while the current is flowing, the electric field must be zero. Similarly, $V=IR$, the voltage is a result of a potential difference which infers the existence of an electric field.

6. Magnetic moments are expected to be the saturation magnetizations (per unit mass) multiplied by sample masses. The forces must be equal to sample weights (masses multiplied by gravitational acceleration, g=9.8 m/s^2). Solving for the magnet's separation x from the reflector, twice the distance, r, from the image gives $x=½[3M^2\times(10^{-3}\text{ kg})^2/g]^{1/4}=½[3\times(1.0\text{ A-m}^2/\text{kg})^2\times(10^{-3}\text{ kg})^2/(9.8\text{ m/s}^2)]^{1/4}$ = 12 mm for $Nd_2Fe_{16}B$. For Fe or Ni no levitation is observed because $x=½[3\times(5\text{ mA-m}^2/\text{kg})^2\times(10^{-3}\text{ kg})^2/(9.8\text{ m/s}^2)]^{1/4}$=0.8mm and $½[3\times(0.17\text{A-m}^2/\text{kg})^2\times(10^{-3}\text{ kg})^2/(9.8\text{ m/s}^2)]^{1/4}$ = 5 mm respectively, both less than 6 mm, their minimum sizes, the diameters $2[(3\times(1\text{ g})/4\times\pi\times(8\text{ or }9\text{ g/cm}_3)]^{1/3}$ of spheres.

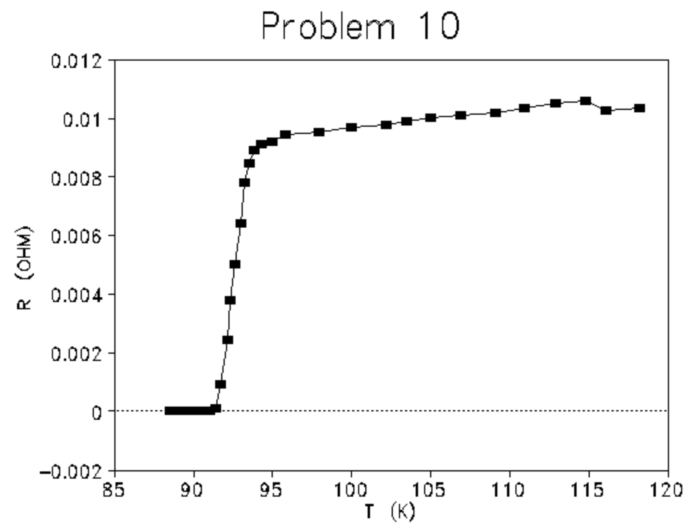
7. The current beginning at I_0 when t=0 decays to $I_0/e = 0.368I_0$ after the characteristic time $L/R=(4\pi\times10^{-7}\text{ V-s/A-m})\times(.03\text{ m})\times[\ln(8\times.03\text{m}/2\times10^{-4}\text{m})$ $-7/4]/(0.01\Omega)$=20 microseconds or $(4\pi\times10^{-7}\text{ V-s/A-m})\times(0.03\text{ m})$ $\times[\ln(8\times0.03\text{m}/2\times10^{-4}\text{m})-7/4]/(2.5\times10^{-5}\Omega)$=8 milliseconds.

8. The current $I=\pi b^2B\omega[R\cos(\omega t)-i\omega L\sin(\omega t)]/(R^2+\omega^2L^2)=\pi(0.03\text{m})^2B$ $\times2\pi\times60\text{s}^{-1}\times[(10\text{ m}\Omega\text{ or }2.5\ \mu\Omega)\cos(\omega t)-i(2\pi\times60\text{s}^{-1}\times2\times10^{-7}\text{Henry}$ $\times\sin(\omega t)]/[(10\text{m}\Omega\text{ or }2.5\mu\Omega)^2+(240\pi\times10^{-7}\Omega)^2] = B\sin(\omega t)\times106$ A/T or ×1.9 MA/T. One Tesla (T) equals 10,000 Gauss (G) of magnetic field.

9.

Voltage	T (K)	R (Ohm)	Voltage	T (K)	R (Ohm)
0.0010370	118.2	0.010368	0.0008440	93.5	0.008439
0.0010270	116.1	0.010266	0.0007830	93.2	0.007831
0.0010600	114.8	0.010597	0.0006390	93	0.006393
0.0010490	112.9	0.010493	0.0005050	92.6	0.005046
0.0010350	110.9	0.010351	0.0003790	92.3	0.003789
0.0010220	109.1	0.010216	0.0002430	92.1	0.002431
0.0010090	106.9	0.010095	0.0000930	91.7	0.000934
0.0010010	105	0.010011	0.0000100	91.4	0.000097
0.0009890	103.5	0.009894	0.0000030	91	0.000030
0.0009750	102.2	0.009755	0.0000002	90.8	0.000002
0.0009670	100	0.009673	-0.0000002	90.1	-0.000002
0.0009510	97.9	0.009511	-0.0000001	89.9	-0.000001
0.0009440	95.8	0.009439	0.0000003	89.5	0.000003
0.0009180	95	0.009176	-0.0000001	88.8	-0.000001
0.0009110	94.3	0.009112	0.0000001	88.5	0.000001
0.0008920	93.8	0.008916			

10.



11. The first derivative is represented by the slope of the graph in the normal phase.
slope = *dR/dT* = *Δ*rise/*Δ*run = (0.01065 - 0.009263)/(118.2 - 95)
slope = 5.98 x 10_{-5}Ω/K

12. T_c = 92 K. This is experimental data that shows the curved low-temperature tail of a transition. Within the narrow temperature range of the tail, individual grains of $YBa_2Cu_3O_7$ superconductive. Resistance in not zero because the grain boundaries, surface area where the particles were sintered together, must be cooled further to become superconductive.

13. See pages 13-15.

Appendix A

SUPERCONDUCTIVITY MILESTONES:

1911 Dutch physicist Heike Kamerlingh Onnes discovers superconductivity in mercury at temperature of 4 K.

1913 Kamerlingh Onnes is awarded the Nobel Prize in Physics for his research on the properties of matter at low temperature.

1933 W. Meissner and R. Ochsenfeld discover the Meissner Effect.

1941 Scientists report superconductivity in niobium nitride at 16 K.

1953 Vanadium-3 silicon found to superconduct at 17.5 K.

1962 Westinghouse scientists develop the first commercial niobium-titanium superconducting wire.

1972 John Bardeen, Leon Cooper, and John Schrieffer win the Nobel Prize in Physics for the first successful theory of how superconductivity works.

1986 IBM researchers Alex Müller and Georg Bednorz make a ceramic compound of lanthanum, barium, copper, and oxygen that superconducts at 35 K.

1987 Scientific groups at the University of Houston and the University of Alabama at Huntsville substitute yttrium for lanthanum and make a ceramic that superconducts at 92 K, bringing superconductivity into the liquid nitrogen range.

1988 Allen Hermann of the University of Arkansas makes a superconducting ceramic containing calcium and thallium that superconducts at 120 K. Soon after, IBM and AT&T Bell Labs scientists produce a ceramic that superconducts at 125 K.

1993 A. Schilling, M. Cantoni, J. D. Guo, and H. R. Ott from Zurich, Switzerland, produces a superconductor from mercury, barium and copper, ($HgBa_2Ca_2Cu_3O_8$) with maximum transition temperature of 133K.

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Appendix C

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Appendix D

SUPERCONDUCTOR DEMONSTRATION KITS

Edmund Scientific sells superconducting ceramic discs for educational laboratory demonstrations. The kit includes a disk of $YBa_2Cu_3O_7$, holder, instructions and bibliography. Contact Edmund Scientific, 101 East Gloucester Pike, Barrington, New Jersey 08007; telephone (609) 573-6250.

Sargent-Welch Scientific sells a superconductivity demonstration kit, which includes experiments demonstrating the Meissner effect, zero-resistance and quantum mechanical effects, and the variables of T_c, J_c, and H_c. Contact Sargent-Welch Scientific Company, 7300 N Linden Ave., Skokie Illinois 67007; telephone (800) SARGENT.

Colorado Superconductor, Inc. sells several superconducting kits which demonstrate the Meissner effect, as well as measurement of T_c, H_c, and current density. Contact Colorado Superconductors Inc. at P.O. Box 8223, Fort Collins, Colorado 80526; telephone (303) 491-9106.

Futurescience, Inc. sells a variety of superconducting kits for classroom demonstration and student use. Kits fit nicely on your bookcase and hold the necessary items. One kit has a videotape with extensive safety content, simple cryogenic demonstrations, and examples of activities that can be performed with other kits. Contact Futurescience, P. O. Box 17179, Colorado Springs, CO, 80935, 303-797-2933, 719-634-0185, Fax 719-633-3438

CeraNova Corporation produces helical coils of YBCO. These coils are useful in laboratory superconductivity demonstrations, especially where high resistances above liquid nitrogen temperatures are needed. Contact CeraNova at 14 Menfi Way, Hopedale, MA 01747; phone or fax (508) 473-3200

Appendix E

GLOSSARY:

absolute zero - The lowest temperature theoretically possible; the temperature at which the thermal energy of random motion of the particles of a system in thermal equilibrium is zero. 0 K = -273.15^{o} C = -459.69 ^{o}F

ampere - The unit of electrical current in the MKS system of units. Abbreviated a; A; amp.

ampere meter squared - The SI unit of electromagnetic moment. Abbreviated Am^2.

angstrom - A linear dimensional unit, equal to one-ten thousandth micron or 10^{-10} meters.

BCS theory - A theory advanced in 1957 by three researchers, John Bardeen, Leon Cooper, and J.R. Schrieffer, that explained how low-temperature superconductors work.

ceramic- Any product made from earth derived materials such as clays, silicates, or sand, usually requiring the application of high temperature in a kiln or oven at some stage of the process.

conductor- A substance or body that offers a relatively small resistance to the passage of an electrical current.

Cooper Pairs - The term given to pairs of bound electrons which occur in superconducting material according to the Bardeen-Cooper-Schrieffer (BCS) theory.

coulomb - The SI unit of electrical charge, defined as the charge transported in one second by an electric current of one ampere. Symbol: *C*

critical current - Cooled material experiences superconductivity properties up to a critical current, above which the material exhibits resistance.

critical current density J_c - The maximum value of electrical current per unit of cross-sectional area that a superconductor can carry without resistance. For practical applications, J_c values in excess of 1000 amperes per square millimeter (A/mm^2), are desirable in both bulk conductors and thin film superconductors.

critical magnetic field (H_c) - Above this value of an externally applied magnetic field a superconductor becomes nonsuperconducting. When an external magnetic field is applied to a Type I superconductor the transition from superconducting to normal is sharp. Type-II superconductors do not possess perfect diamagnetism (flux penetration of the material is possible). When an external magnetic field is applied to Type II superconductors the transition to the normal state is over a much broader region between a lower critical field, H_{c1}, and an upper critical field, H_{c2}.

critical temperature (T_c) - The highest temperature at which superconductivity occurs in a material. Below this transition temperature T_c the resistivity of the material is equal to zero.

cryogenics - A branch of physics dealing with the properties of matter at extremely low temperatures.

current - The rate of flow of electrons, measured in amperes, in a conductor. The conduction of current of 1 ampere is equal to the flow of about 10^{18} electrons per second.

dewar - A double-walled flask with a vacuum between the walls that are silvered on the inside, used specifically for the storage of liquified gases.

electric field - The space surrounding an electric charge. The area in which it is capable of exerting a perceptible force on another charge.

electromagnet - An iron core encircled by coils of wire that become magnetic when current flows through the wire.

fluxoid - Circulating vortices of current and flux contained in the vortices.

flux - To "flow". Referring to the rate of flow of radiation from a given source.

flux pinning - Superconducting material properties are altered locally by the presence of defects in the material. A fluxoid adjacent to such a defect in the material has its energy altered and its free motion through the superconductor is inhibited. Flux pining causes a field gradient in the superconductor and gives rise to a net current in the material.

gauss - The CGS-electromagnetic unit of magnetic flux density. 1 G = 10^{-4} tesla. Symbol: G

helium - The element helium, (Greek, meaning the sun) was named so because it was first discovered in the sun by spectrographics in 1868. Helium gas does not become liquid until the temperature reaches 4.2 K, about -269°C.

high temperature superconductor (HTS) - Refers to materials with much higher transition temperatures than previously known superconductors.

insulator - A substance that does not conduct electricity.

Josephson effect - Electrons crossing an insulating barrier in a Josephson Junction, a process called tunneling, that creates a "supercurrent"

Josephson Junction - Consists of two superconductors separated by a thin insulating barrier. Is in fast electronic switches or sensitive magnetometers.

Kelvin - A scale of temperature measured form absolute zero. 1 K = 1 deg C.
0 K = -273^{o}C.

lattice - A three dimensional grid-like pattern of the arrangement of atoms in a solid.

lower critical field - Above this value of an externally applied magnetic field a superconductor is in a mixed state. Below this value it is in the Meissner state.

magnetic flux - A measure of the total size of a magnetic field, defined as the scaler product of the flux density and area.

magnetic flux density - The magnetic flux passing through unit area of a magnetic field in a direction at right angles to the magnetic force. The vector product of the magnetic flux density and the current in a conductor gives the force per unit length of the conductor. It is measured in teslas.

MRI- Acronym for Magnetic Resonance Imaging. MRI is a diagnostic imaging technique that produces cross-sectional images. Its primary use is for organic materials and soft body tissue.

magnetic field strength - The magnitude of a magnetic field, measured in A m^{-1}

magnetic flux - A measure of the total size of a magnetic field, defined as the scaler product of the flux density and the area. It is measured in webers.

magnetometer - An instrument for detecting magnetic fields.

Meissner effect - The expulsion of magnetic fields from a superconductor.

Meissner state - The regime of temperature and magnetic fields where the Meissner effect can be observed.

mixed state - The regime of magnetic fields between the lower critical field, H_{c1}, and the upper critical field, H_{c2}. Diamagnetism is less than perfect because supercurrent vortices confine magnetic field within quantized filaments of normal-state material that pass through the superconductor.

ohm- The SI unit of electrical resistance, defined as the resistance between two points on a conductor through which a current of one ampere flows as a result of a potential difference of one volt applied between the points.

Ohm's law - The electrical current in any conductor is proportional to the potential difference between its ends. Ohm's law is often expressed as $I=E/R$, where I is the current, E is the potential difference, and R the resistance.

perovskite- A type of crystal. Referring to the crystal structure shared by the 1-2-3 and other high-temperature superconductors.

phonon- Quantized atomic lattice vibration. It is the mechanism causing electron pairing in the BCS theory.

quantum mechanics - The modern theory of action. It applies primarily to atomic motion.

resistance - The opposition to the flow of electrons in a conductor. Measured in ohms.

semiconductor - An element or compound whose electrical properties are midway between a conductor and insulator. A substance with relatively high resistance and corresponding low conductivity.

superconductor, Type-I - Material with perfect electrical conductivity for direct current that also possesses perfect diamagnetism. When an external magnetic field is applied on this superconductor, the transition temperature from superconducting to normal is sharp.

superconductor, Type-II - Material with perfect electrical conductivity for direct current that possesses moderate diamagnetism at high field. When an external magnetic field is increased, the transition from superconducting to normal state occurs after going through a broad "mixed state" region.

SQUID - Acronym for Superconducting Quantum Interference Device.

tesla - A unit used to describe the strength of magnetic fields in the MKS system.

upper critical field - Above this value of an externally applied magnetic field, a type-II superconductor is in the normal state. Below this value it is in the mixed state.

volt - The unit of potential difference or electromotive force in the MKS system.

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