Investigation into Superconductor Formation

I. Introduction

In 1911 a Dutch physicist named Heike Kamerlingh-Onnes discovered that the resistivity of mercury below a critical temperature of 4.3 Kelvin drops precipitately to zero.[2] This fairly peculiar phenomenon was termed superconductivity, and has been tested to be found in various classes of metals. Prior to this discovery, the conductivity of copper wire was considered the standard (or zero resistivity mark). However, recent literature on superconductors below their critical temperatures alludes to resistivity measurements 10^{17} times smaller than that of copper. In 1913, Onnes was awarded the Nobel Prize in physics for his low temperature metal work.[2]

Traditionally, resistivity of metals has been known to be directly related to temperature; as the temperature of the sample increases, the resistivity of the sample also increases. When the temperature of the metal sample is lowered to around absolute zero, there is a deviation from this linear trend and the resistivity approaches a finite value. [1] Superconductor metals or ceramic mixtures also illustrate this linear relationship between temperature and resistivity; however near a low, critical temperature there is a sharp drop in resistivity to zero rather than a leveling off to a finite resistance. The indigenous resistivity of a typical metal is best described as being residual of various electron collisions with impurities and structural imperfections in a particular metal. [1] This classical model of natural resistance of a substance, no matter the temperature, does not coincide with the observed science of superconductors. In 1957, Bardeen, Cooper, and Schrieffer theorized the peculiar superconducting property of zero resistance by suggesting that there is a net attractive force between negatively charged electrons that are moving through a positively charged lattice structure.[1] One passing electron will create a positively charged wake behind it, thereby attracting a second passing electron to chase after the wake and thus indirectly attract it to the first electron. This system of electron movement allows for a linkage of two electrons into a *Cooper pair*, and it is at low temperatures that the momentum of the sum of these pairs moving in conjunction with each other is too reduced to cause lattice scattering. [1] Without this type of scattering that occurs normally in traditional metals, there will be no native resistance to the sample.

There are presently known to be two types of superconductors: type I and type II.

The first type of superconductor is elemental in nature and includes Al, Hg, Pb, Ti, Zn, and others.[1] Yet another startling aspect of superconductivity besides its apparent lack of resistance is the relationship that a superconducting sample has with magnetism. About twenty years after Onnes' pioneering work (1933), W. Hans Meissner and Robert Ochsenfeld explored the expulsion of weak magnetic flux from the interior of the Type I superconductor.[1] In essence, a small magnet can be suspended and spun over the superconducting sample as a result of this magnetic flux diversion. This *Meissner* effect is a unique property to type I superconductor samples and can be used as a test to see if a prepared sample has reached its superconducting state or needs further cooling.[1] It is theorized that small surface currents are the reason that the magnetic field lines cannot penetrate the interior of a superconducting sample. Nevertheless, a magnetic field can still be discerned to a certain depth (penetration depth) of the type I sample since these currents do not exist in a minutely thin layer on the surface. A magnetic field can indeed pass wholly through the sample prior to it reaching its superconducting state and thus, for instance, generating a traditional current in a loop sample. Although the magnetic field will be expelled from the interior of the sample upon it reaching the critical temperature, the current that was established will propagate indefinitely in the loop in a manner known as persistent current.[1] It should also be noted that the critical temperature for Type I conductors have been found to decrease in the presence of an increasing magnetic field. It should be noted that if a substantially higher magnetic field is applied to the sample, the superconducting state of the sample is lost and the magnetic field lines penetrate the sample.[1]

Type II superconductors exhibit this same threshold magnetic field value, although they has two limits instead of a single limit. Above the B_{c2} (uppermost critical magnetic field) the superconducting state of the sample is lost just as is seen in the Type I samples. Below the B_{c1} (the lower critical magnetic field) the superconducting state of the sample is wholly analogous in properties and effects to Type I samples.[1] However the applied magnetic fields between these two critical values creates a *vortex* region whereas the sample does completely lack resistance; however the presence of vortex columns known as filaments allow the penetration of magnetic field lines through the sample.[1] This penetration of magnetic flux while superconducting is in direct contrast to the observed Meissner effect observed in Type I superconductors.

II. Materials and Methods

This experiment called for the preparation of an approximated 5-gram sample of Yttrium Barium Copper Oxide ($YBa_2Cu_3O_7$). Stoichiometric assessment of reaction conditions was needed in order to determine the needed amount of each of the reactants, Y_2O_3, $BaCO_3$, and CuO. The powder was mixed in an argon-flushed glove box, ground and pressed into a small pellet, and sintered at 940˚ C in an oxygen flushed oven for approximately 70 hours. One intermission period was permitted for further grinding and a repress. A slow cooling time for the sample was essential for emphasizing complete oxidation.

Liquid nitrogen was poured across the sample in order to cool it below the critical temperature of the $YBa_2Cu_3O_7$ and thus allow it to superconduct. In order to test the effectiveness of the superconducting state, the application of the Meissner effect was employed by levitating a small magnet over the cooled sample.

III. Results and Discussion

In order to prepare the sample, stoichiometric analysis of the reaction was performed.

$$Y_2O_3 + 4BaCO_3 + 6CuO \rightarrow 2YBa_2Cu_3O_7 + 3.5CO_2$$

From this equation the gram values for each of the reactants was determined: .845 g Y_2O_3, 2.964 grams of $BaCO_3$, and 1.788 grams of CuO. After mixing these in the glove box it was very important to thoroughly grind the powders with the pestle so as to mix the Yttrium fully. The pellet was formed and oxygenated while sintered per instructions given. A dark gray, pelleted powder was observed at the sintering intermission, and a more deeply blackened sample was noted after the final annealing. After this final annealing, the compound was placed with plastic tweezers into a Pyrex Petri dish. Liquid nitrogen was poured over the compound, thus cooling it to the temperature of liquid nitrogen, 77 degrees Kelvin, which is well below the critical temperature of the Yttrium compound, around 95 degrees Kelvin.[1] A very small permanent magnet was adjusted to be right on top of the compound, and it was observed to levitate.

It should be noted that attempts were made to attach short copper leads to the sample via silver paste. This was done in an attempt to monitor resistivity levels of the compound as it was cooled and during its superconducting state. However, these attempts to lodge the copper leads onto the compound proved unsuccessful.

IV. Conclusion

The purpose of this experiment—to observe the superconducting state of Yttrium barium copper oxide—was achieved. Although achievement of the exact zero resistivity of the compound could not directly be determined, the Meissner effect test proved to us that indeed the compound reached superconductor activity. Overall this experiment was successful and extremely engaging.

V. References

[1] Serway, Moses C., and Moyer, C. (1997). *Modern Physics.* Fort Worth, TX: Saunders Company.

[2] Serway, Raymond A., and Beichner, Robert J. (2000). *Physics for Scientists and Engineers.* Philadelphia, PA: Saunders Company.