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HIGH-TEMPERATURE SUPERCONDUCTIVITY EXPERIMENT DEVELOPMENT

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Abstract

High-temperature superconductors are interesting metamaterials currently being researched around the world. Giving students easy access to an education-rich superconductivity experiment was the project goal. After over a year of hard work, the experiment will be available for the Fall 2015 Semester.

Introduction

Materials can be classified as (1) conductors or metals, (2) non-conductors or electrical insulators, (3) semiconductors or (4) superconductors according to their ability to move charge. **Superconductors** are solid elements, inter-metallic alloys or compounds that reach a superconducting phase transition at a specific **critical temperature** $\mathbf{T_C}$. Below this temperature, the superconductor's electromagnetic properties are altered appreciably without change in the crystal structure. While superconducting, they are known for (1) **Zero-Resistance:** no resistance to direct current (DC), allowing charge to flow without hindrance and (2) **Meissner-Ochsenfeld Effect:** expulsion of magnetic flux from the superconductor's interior.

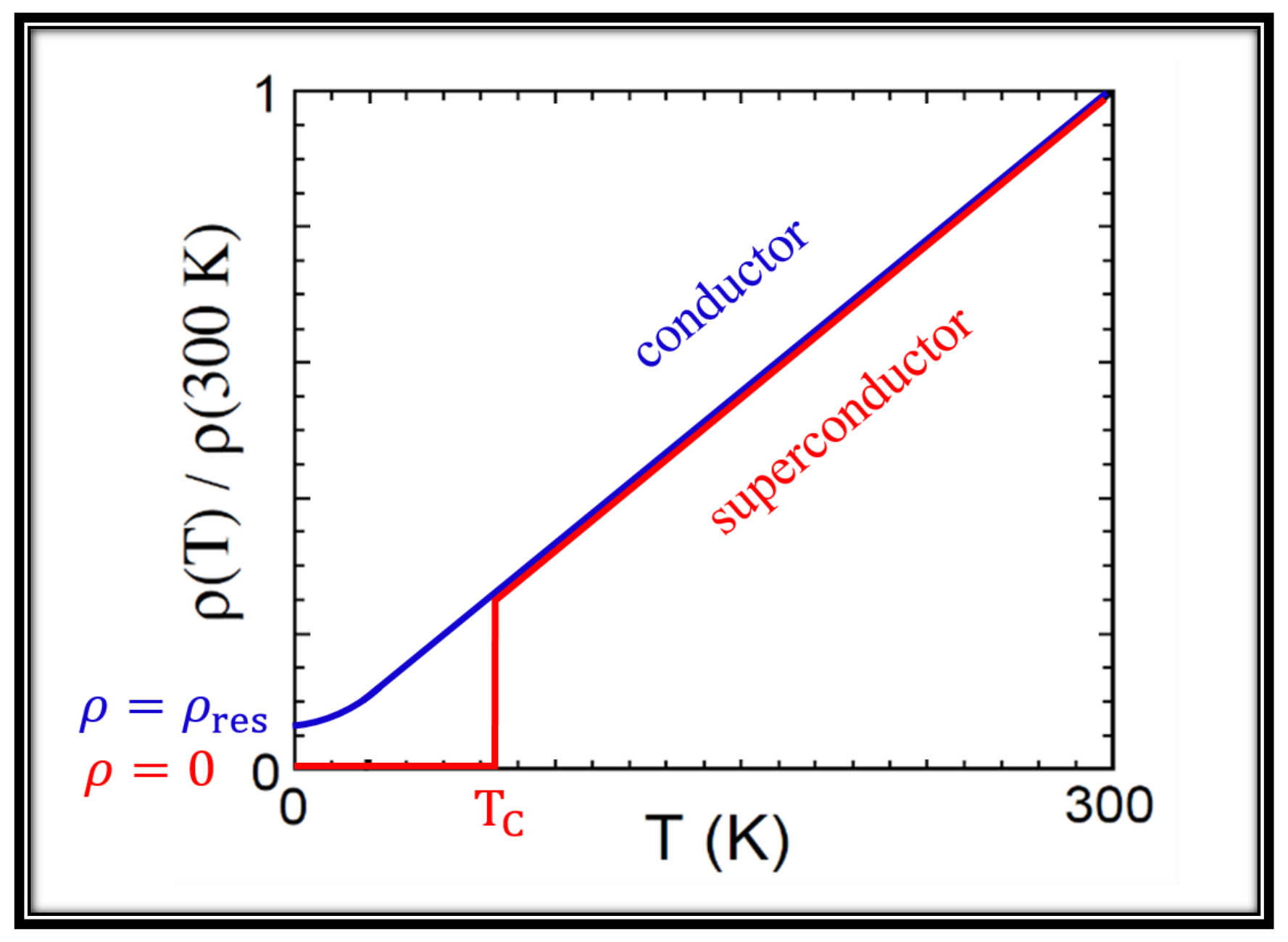


Figure 1: Resistivities ρ for superconductor vs. conductor

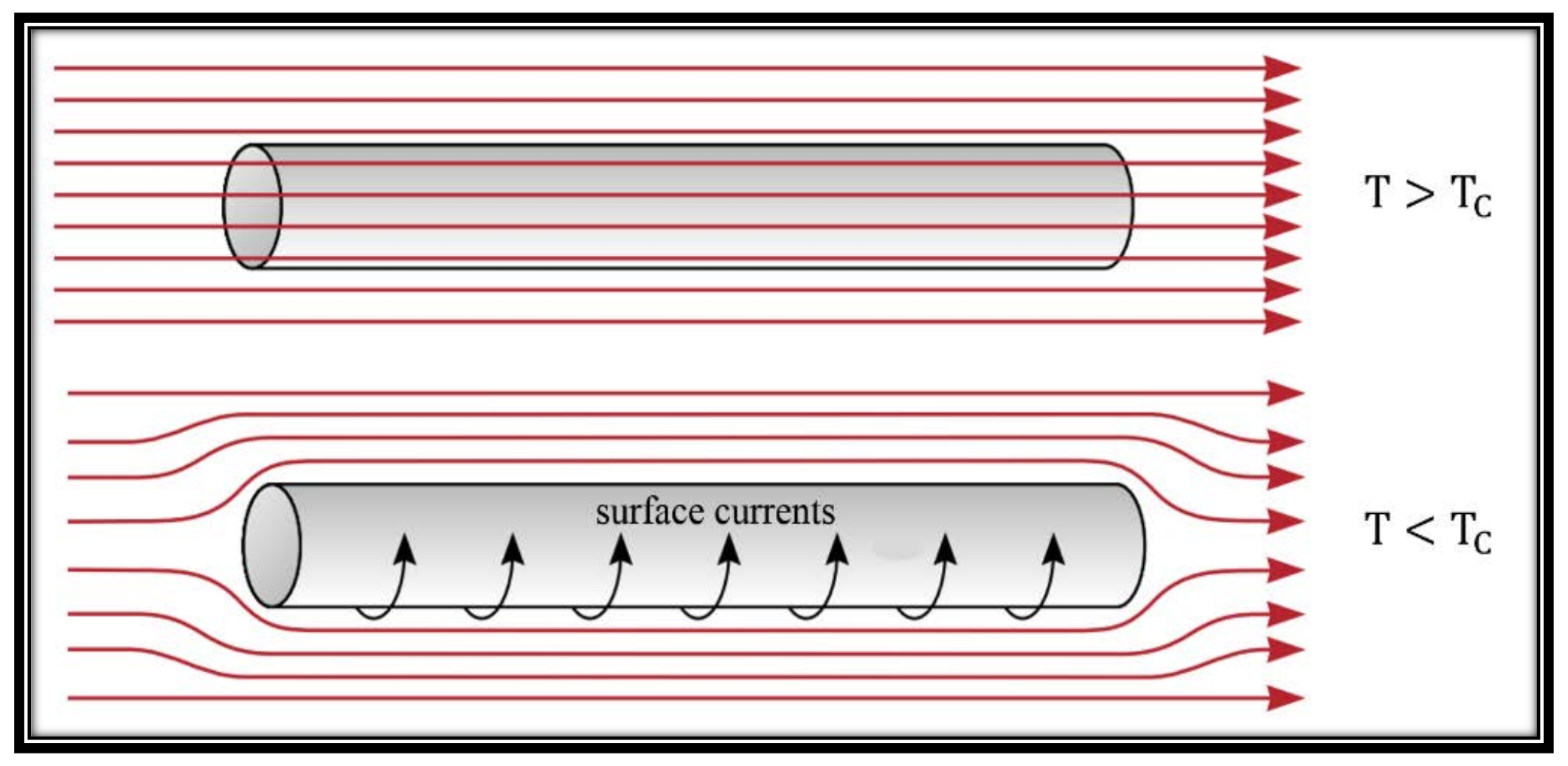


Figure 2: Meissner-Ochsenfeld Effect [1]

Superconductivity was discovered in 1911 by Heike Kamerlingh Onnes when he cooled a mercury sample and caused it to superconduct. He used **liquid helium** as the coolant which has a boiling point temperature of **4.2K** = -268.95℃ = -452.11℉. This was an important discovery, but much excitement was renewed in 1986 when Swiss scientists discovered that certain ceramics would superconduct around ~30K.

Starting in 1987, several groups discovered materials that would superconduct at temperatures over 77K. These new materials are called **high-temperature** or **high-**$\mathbf{T_C}$ superconductors. Their discovery was a major breakthrough because **liquid nitrogen** could be used as the coolant which has a boiling point temperature of **77K** = -196.15℃ = -321.07℉. Liquid nitrogen can be distilled from air, and is relatively cheap.

3-D Phase Space

Superconductivity can be **quenched** (destroyed) with certain parameters. Usually this occurs when the maximum current density $\mathbf{J_C}$ the superconductor can conduct or the maximum magnetic field $\mathbf{B_C}$ ($\mathbf{B_{C2}}$ for Type-II) it can withstand is reached. This gives rise to a three-dimensional (3D) phase space.

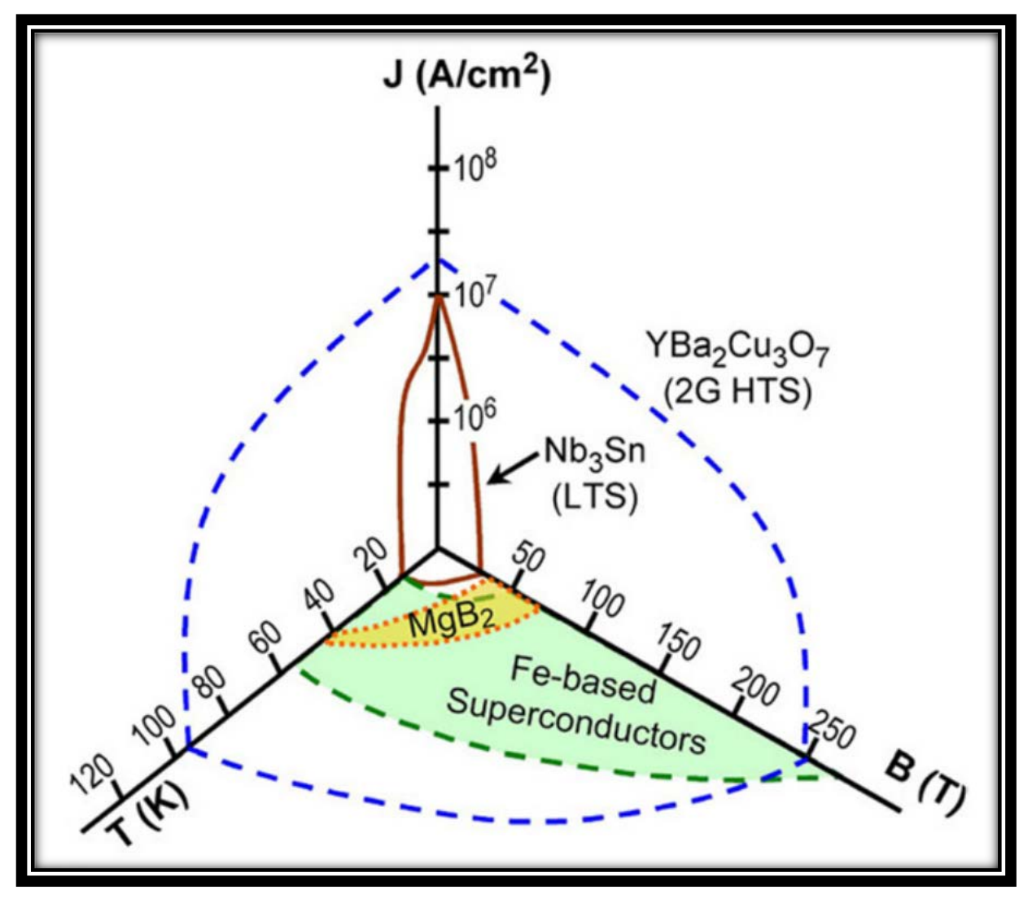
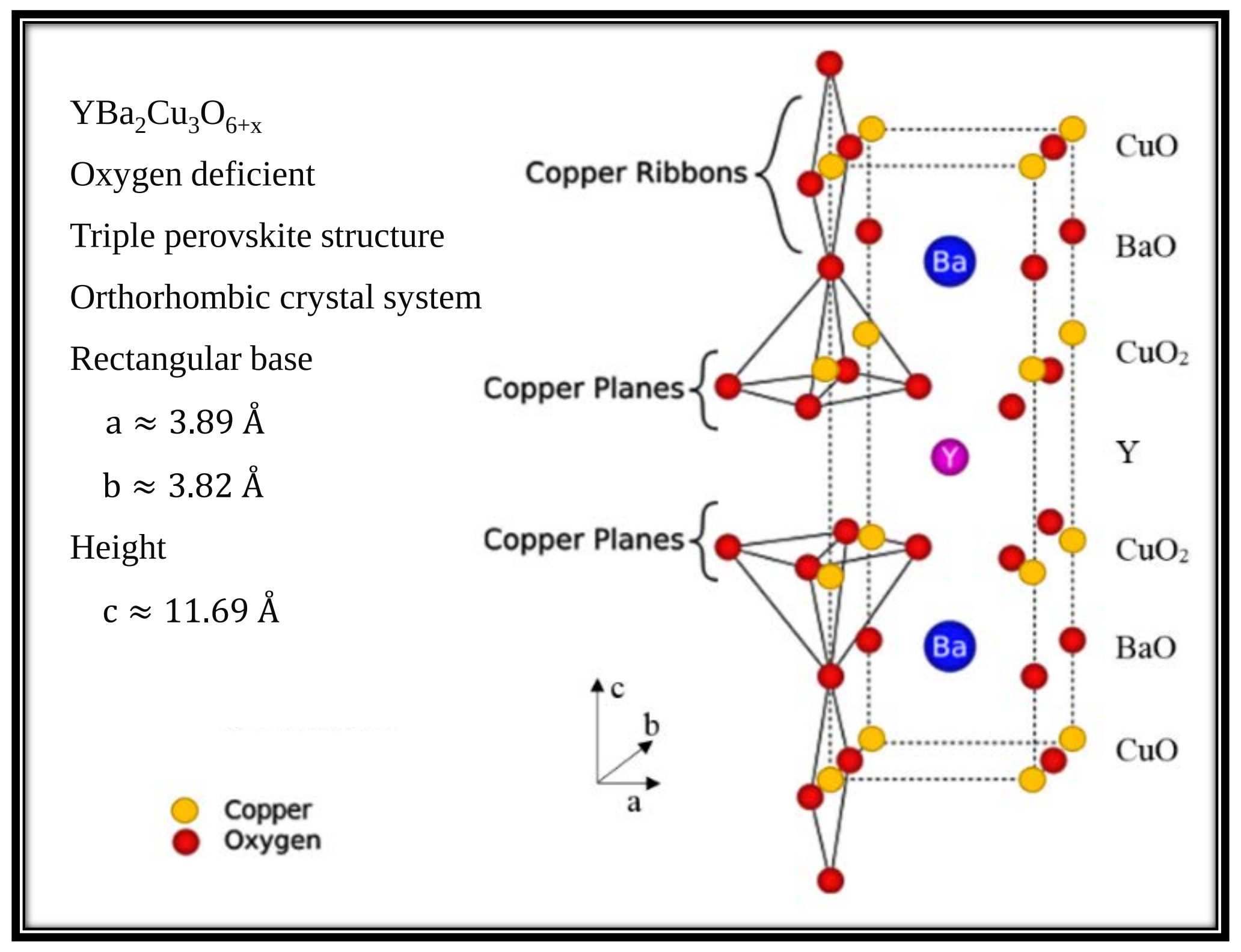


Figure 3: The T_C*–*B_{C2} *-* J_C *3D phase diagram [2]*

As an external magnetic field $\mathbf{B_0}$ **increases**, a superconductor's critical temperature $\mathbf{T_C}$ **decreases**. As the current density in the superconductor **J increases**, its critical temperature $\mathbf{T_C}$ **decreases**.

Sample

$YBa_2Cu_3O_{6+x}$ is the selected Type-II, unconventional, high-temperature, ceramic, cuprate superconductor for study. It is commonly abbreviated as **YBCO** composed of yttrium ${}^{88.9}_{39}Y$, barium ${}^{137.3}_{56}Ba$, copper ${}^{63.6}_{29}Cu$ and oxygen ${}^{16.0}_{8}O$ atoms.



$YBa_2Cu_3O_{6+x}$

Oxygen deficient

Triple perovskite structure

Orthorhombic crystal system

Rectangular base

a ≈ 3.89 Å

b ≈ 3.82 Å

Height

c ≈ 11.69 Å

Figure 4: YBCO structure and composition [2]

$YBa_2Cu_3O_7$ superconductor was **derived from semiconducting** $\mathbf{YBa_2Cu_3O_6}$ **by doping** it with O_2 charge carriers, but the crystal is not actually completely saturated with oxygen atoms. Since there are oxygen vacancies in the lattice, the superconducting material is often written as $YBa_2Cu_3O_{7-\delta}$ or $YBa_2Cu_3O_{6+x}$ where x and δ are quantities of doping. Cuprates have highly **anisotropic resistivities** (different values measured in different directions) and **high upper critical magnetic fields**.

Methods

Ohm's Law gives a relation between electric potential deference (voltage) ΔV, electric current I and electrical resistance R:

$$\Delta V = IR \tag{1}$$

When the voltage drop across the superconductor falls to zero, there is no resistance to the current.

Methods (cont.)

Hence, as the sample's resistance R_s decreases, the voltage ΔV_S measured decreased as well. Four wires were attached to the sample using the **four point probe method** with a conductive adhesive. A **lock-in amplifier** was used to make accurate measurements of a weak signal with a prime number frequency of $f = 13$ Hz despite a noisy environment. A **signal generator** produced a root-mean-squared voltage of $\Delta V_{SG} = 5$ V which caused alternating current (AC) to flow through the circuit. A **load resistor** with a high resistance $R_L = 1000\ \Omega$ compared to R_s was placed in the circuit, and the following approximation was made:

$$I = \frac{\Delta V_S}{R_s} = \frac{\Delta V_{SG}}{R_S + R_L} \approx \frac{\Delta V_{SG}}{R_L} \tag{2}$$

This lead to an accurate measurement of the sample's resistance:

$$R_S = \frac{\Delta V_S}{\Delta V_{SG}} R_L \tag{3}$$

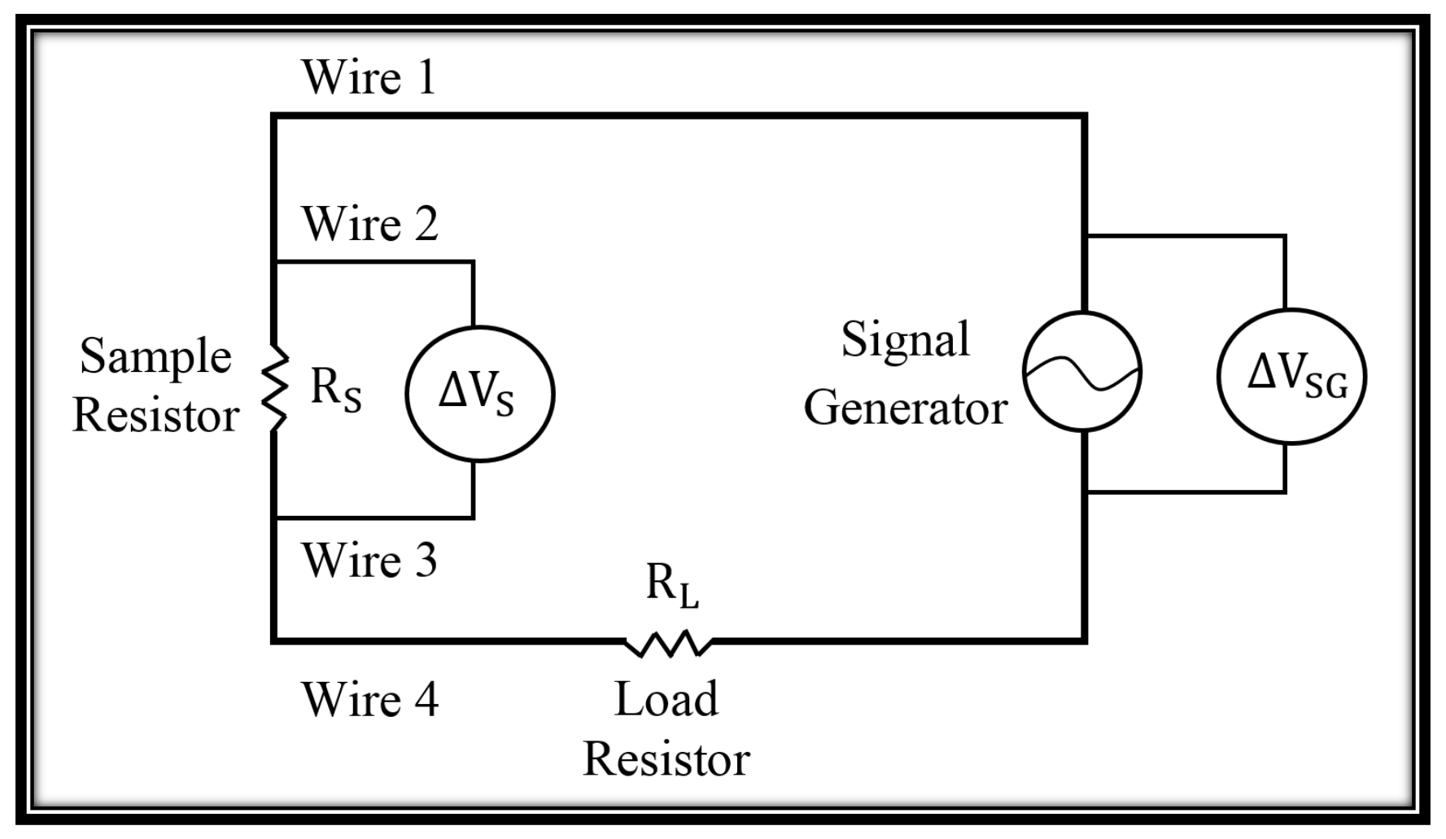


Figure 5: Circuit schematic for the experiment

An **Autotuning Temperature Controller (Model 330)** was used to control the temperature of the sample in this experiment. Liquid nitrogen was used as the coolant and heater coils were used to counteract the cooling and set the temperature at a specific value.

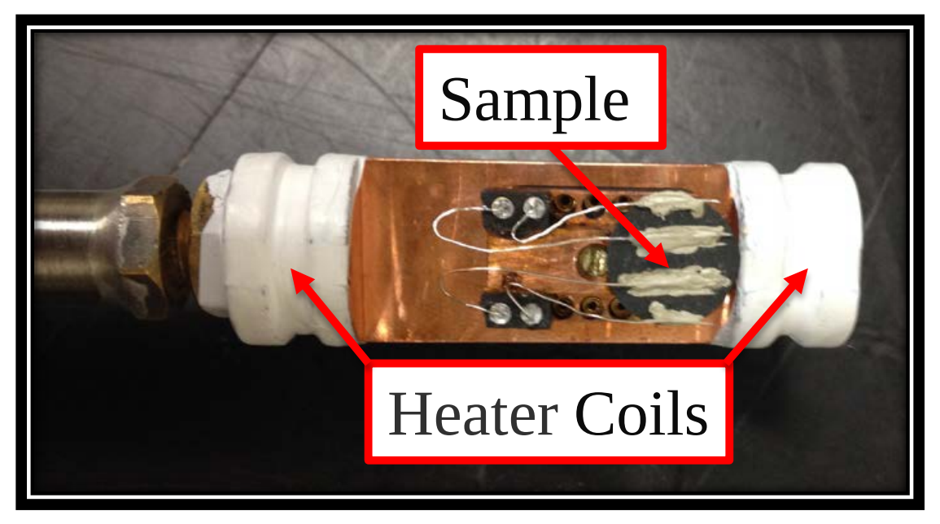


Figure 6: Mounted sample with heater coils

An **electromagnet** produced uniform external magnetic field of around $B_0 = 90$ mT for the cryostat to sit in. The sample was inserted into the cryostat and helium gas was used to exchange thermal energy between the sample space and liquid nitrogen.

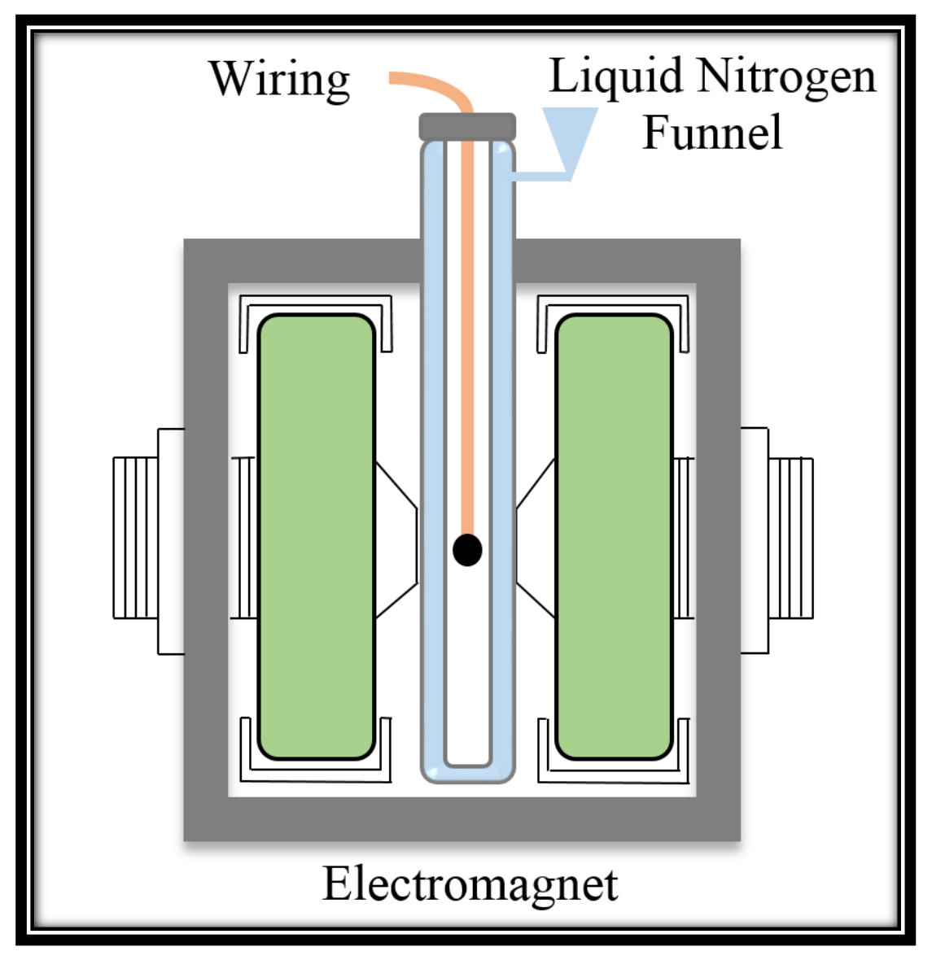


Figure 7: The electromagnet and cryostat setup

Data

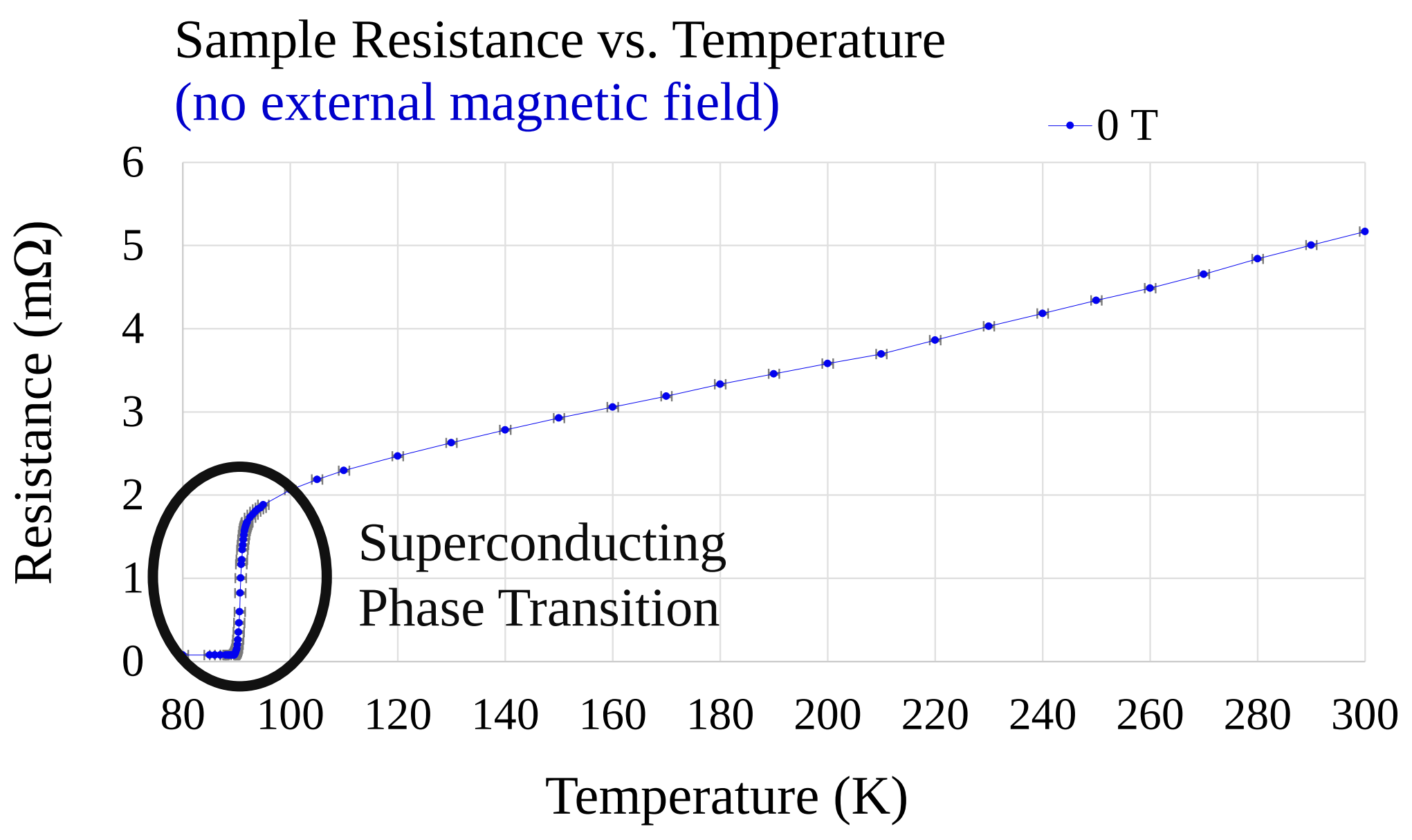


Figure 8: Plot of resistance with no external magnetic field

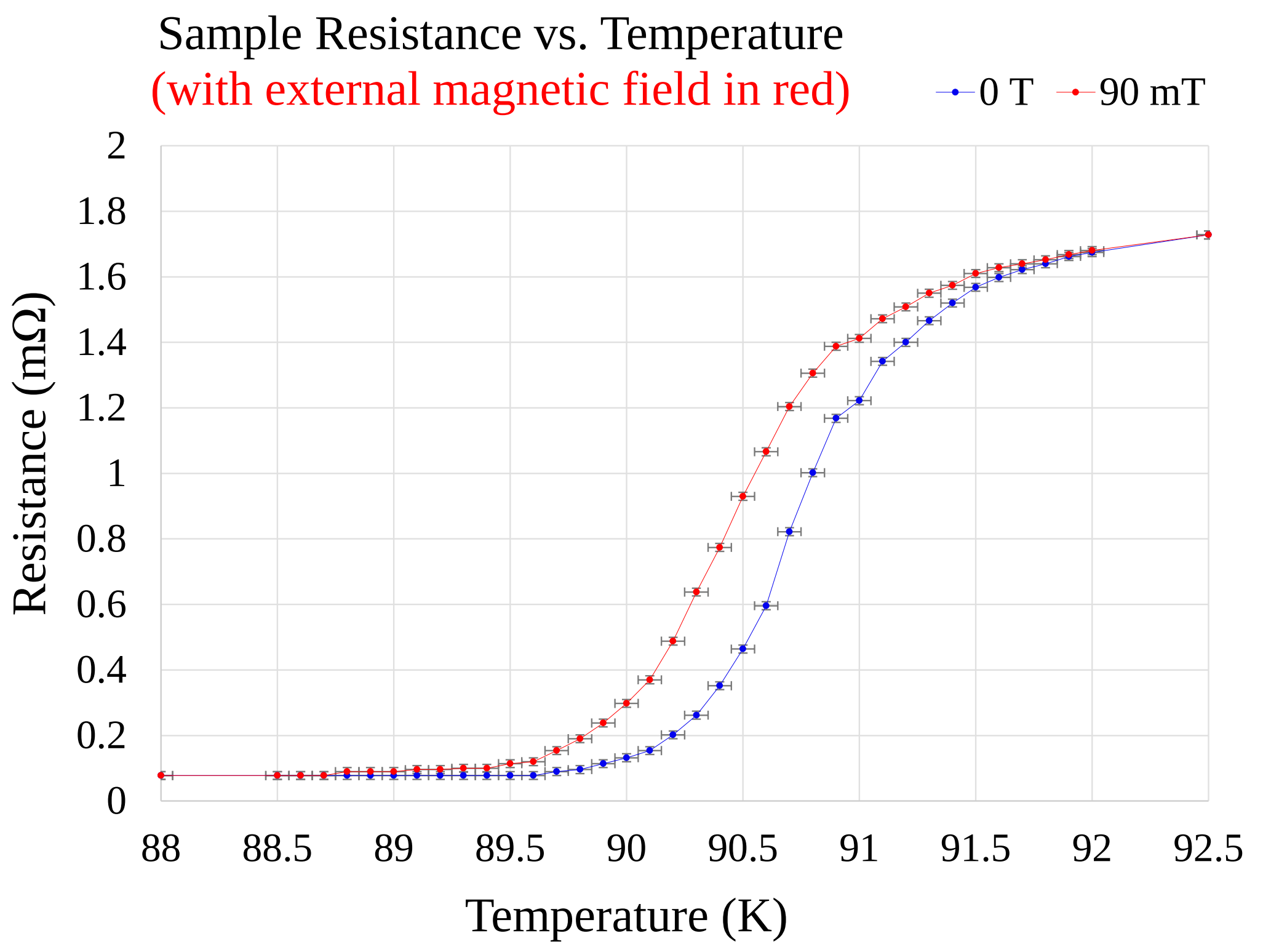


Figure 9: Plot of resistance with external magnetic field

Conclusion

- The four point probe method with the appropriate equipment and approximations allowed an accurate determination of the YBCO sample's decreased resistance with temperature.
- Attaching the current and voltage leads to the sample was extremely sensitive. If the surface degraded, measurements actually displayed semiconducting properties and resistance increased with temperature.
- The YBCO sample had its superconducting phase transition between 89 K and 92 K. The resistance falls to near-zero as it enters the superconducting state. Any residual resistance represents the experiment's measurement limitations.
- An external magnetic field shifts the superconducting phase transition to a lower temperature, but does not significantly affect the superconducting or normal region.

Further Work

- Resistivity calculations
- Magnetic susceptibility measurements
- Current density effect on critical temperature
- Improved method of attaching current and voltage leads

References

[1] R. Serway, C. Moses, C. Moyer (2004). The Solid State. *Modern Physics*. Belmont: Brooks/Cole.

[2] Lei, H. C. *et al.* (2012). Iron chalcogenide superconductors at high magnetic fields. *Sci. Technol. Adv. Mater.* **13**, 054305.

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