Synthesis of High-Temperature YBCO Superconductors

Simon Ji, '23

Follow this and additional works at: https://works.swarthmore.edu/theses

Part of the Engineering Commons

Recommended Citation
https://works.swarthmore.edu/theses/286

Please note: the theses in this collection are undergraduate senior theses completed by senior undergraduate students who have received a bachelor's degree. This work is brought to you for free by Swarthmore College Libraries' Works. It has been accepted for inclusion in Senior Theses, Projects, and Awards by an authorized administrator of Works. For more information, please contact myworks@swarthmore.edu.
Synthesis of High-Temperature YBCO Superconductors

Simon Ji

Advisor: Prof. Lynne Molter
Abstract

Superconductors are a fascinating class of materials that seem to defy physics. For my project, I attempted to create one of the most famous types of superconductor, Yttrium Barium Copper Oxide (YBCO), using commonly available chemicals found online and equipment that already exists on campus. This report gives a short description of the theory behind superconductors, and outlines the synthesis procedures I followed that involved citrate pyrolysis and high-temperature treatment using a tube furnace. I succeeded in creating YBCO samples that exhibited superconducting behaviors, and also designed a small magnetic track that can be used for demonstration purposes.
Introduction

When certain materials are cooled to cryogenic temperatures below a certain “critical temperature,” quantum interactions between the electrons and the material lattice allow the material to conduct electricity with zero energy loss. The term “superconductivity” was coined to these materials by their original discoverer, Heike Kamerlingh Onnes, in 1911. In 1986, Bednorz and Muller discovered a ceramic material that exhibited superconductivity at temperatures far higher than was previously possible, and subsequently won the 1987 Nobel Prize in Physics. One year later, Chu et al. discovered $\text{YB}_2\text{Cu}_3\text{O}_{7-d}$ (YBCO) superconductors that reached a critical temperature of 92 K, above the boiling point of liquid nitrogen. Decades of research since then has revealed many more high-temperature superconductors with similar electronic structures as YBCO, but there are still no physics models that can accurately predict superconductivity. A superconductor that can operate at or near room temperature remains elusive, but if it is ever discovered, will completely transform the world in fields such as energy generation and transfer, transportation and computing.
In order to study these superconducting materials, I attempt to create YBCO superconductor pellets using the synthesis steps laid out by Blank et al. (1988). Popular youtuber NileRed has previously followed the same procedure and successfully created the samples using readily available reagents purchased online, as well as equipment commonly found in most chemistry labs. A lab-grade tube furnace was also accessed at Prof. Hillary Smith’s lab in the Swarthmore Physics Department in order to complete an important high-temperature heating step.

---

1 Image taken from Pia Jensen Ray, Structural Investigation of La_{2-x}Sr_xCuO_{4+y} http://fys.bozack.dk/docs/master/thesis.pdf
**Theory**

The temperature-dependence of electrical conductivity in materials had been an important field of research throughout the 19th and early 20th century. With the successful liquefaction of helium in 1908 by Heike Kamerlingh Onnes, physicists began to probe the electrical behavior of materials at temperatures near absolute zero. For most materials tested, it seemed that the resistivity continued to drop and plateaued to a non-zero value at lower temperatures. In 1911, however, Onnes put mercury through this test and the resistivity dropped to a level below what the instrument could detect. As shown in Figure 2, the transition to this “superconductive state” also seemed very sudden and occurred at a specific temperature. This temperature is later known as the critical temperature (Tc), and further tests also confirmed that the resistance is indeed zero and not a very small non-zero value.

![Image taken from the University of Cambridge, Department of Materials Science and Metallurgy](https://www.doitpoms.ac.uk/tlplib/superconductivity/discovery.php)

Figure 2: Temperature vs Resistivity for normal metal vs superconductor

---

2 Image taken from the University of Cambridge, Department of Materials Science and Metallurgy [https://www.doitpoms.ac.uk/tlplib/superconductivity/discovery.php](https://www.doitpoms.ac.uk/tlplib/superconductivity/discovery.php)
In the following decades since the discovery of superconductivity of mercury, several more materials such as lead and niobium were found to be superconductive. However, no real working theory of this phenomenon was found until 1957, when Bardeen, Schrieffer and Cooper developed the BCS Theory of superconductivity (the acronym is formed from their last initials).

According to the BCS Theory, superconductivity first starts with the formation of “cooper pairs”, which are pairs of electrons interacting together and behaving as the same particle. This is normally not possible as the electrons would repel each other due to their electrical charge, but as shown in Figure 3, in a superconductor lattice, the positive nuclei are attracted to the electrons and move slightly closer, resulting in a local positively charged area that then can overcome the repulsion force between electrons.

![Figure 3: Formation of Cooper Pairs.](https://www.doitpoms.ac.uk/tlplib/superconductivity/cooper.php)
When on their own, electrons have non-integer spins ($\frac{1}{2}$, $-\frac{1}{2}$) and obey the Pauli Exclusion Principle, meaning that they cannot occupy the same energy state. When electrons form Cooper pairs, the quantum behavior completely changes as they now have integer spins and can all be in the same energy level. In conventional conductors, resistance occurs as momentum transfers to the lattice from the electrons. However, when an electric field is applied to a superconductor, all the Cooper pairs must all gain the same amount of momentum as they all exist in the same quantum state. In contrast to classical resistance, individual cooper pairs cannot easily transfer the momentum to the lattice as all pairs must all gain or lose the same momentum. At higher temperatures, the random energy fluctuations would allow these Cooper pairs to break apart and transfer momentum, breaking the superconductivity.

Since the discovery of ceramic superconductors, scientists have realized that superconductors can be split into two classes: Type I and Type II. As shown in Figure 4, Type I superconductors are typically pure elements that only have a single state below the critical temperature, which repels all the magnetic field present. Type II superconductors, however, have a “mixed state” where the superconductors still have zero resistance, but “bundles” of field lines are able to penetrate the superconductor.
Figure 4: Type I vs Type II superconductors; x-axis is temperature and y-axis in magnetic field strength. Meissner state means that the field is completely repelled from the material. When the magnetic field becomes too strong, both types will lose superconductivity.\(^4\)

While in this mixed state, a phenomenon called “flux pinning” can occur where magnetic field bundles are able to lock the superconductor in a certain orientation, as shown in Figure 5. The force from this effect is strong enough to overcome the force of gravity, and allows the magnet or superconductor to float without being completely pushed away by the repelling force. This is the principle behind some maglev train designs which allows trains to run on tracks without wheels, and will also be the way I test my superconductors by exposing it to a magnetic field created by small neodymium magnets.

\(^4\) Image taken from Kechik et al. Effect of Yb2O3 Nanoparticle Addition on Superconducting Properties of BSCCO (2223)/Ag Tapes by Acetate Precipitation Method, Figure 2
Figure 5: Flux pinning effect demonstrated with a superconductor sample floating on neodymium magnets, and field lines are sketched out to show some penetration while most are repelled. This can also be reversed to have magnets float on superconductors instead.\(^5\)

**Procedure**

**Procuring Chemical Reagents and lab Equipment**

Several reagents are required to create the YBCO lattice. Due to budget constraints, most chemicals were sourced from online markets like Ebay and Amazon with no guarantee of their purities. One chemical, Yttrium Nitrate, is too expensive and difficult to store, so I purchased a precursor chemical (Yttrium Oxide) instead to synthesize this reagent myself.

In addition to the chemical reagents, a supply of pure oxygen is required in the sintering step. We managed to obtain a large shop-grade tank from J’s workshop that was originally used for oxy acetylene torches. In order to test the final YBCO samples, I also reached out to Dr. Paul Jacobs from the Physics Department to regularly refill a liquid nitrogen container from their nitrogen reservoir meant for experimental physics research.

Table 1: List of Reagents/Supplies Sourced

<table>
<thead>
<tr>
<th>Chemical Reagents and Other Supplies</th>
<th>Item</th>
<th>Source</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Yttrium Oxide</strong>, 250g</td>
<td>Ebay</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Citric Acid</strong>, 1lb</td>
<td>Amazon (Food Grade)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Barium Nitrate</strong>, 500g</td>
<td>Lab Alley</td>
<td>Poison Hazard</td>
</tr>
<tr>
<td></td>
<td><strong>Copper Nitrate</strong>, 500g</td>
<td>Ebay</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ammonium Hydroxide</td>
<td>Lab Alley</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>68% Nitric Acid</strong></td>
<td>Walmart</td>
<td>Very Corrosive</td>
</tr>
<tr>
<td></td>
<td>Oxygen Supply</td>
<td>Engineering Department</td>
<td>Fire Hazard</td>
</tr>
<tr>
<td></td>
<td>Liquid Nitrogen</td>
<td>Physics Department</td>
<td>To cool YBCO down to</td>
</tr>
<tr>
<td></td>
<td>Neodymium Magnets</td>
<td>Amazon/Physics Department</td>
<td>critical temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Test Superconducting</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Abilities</td>
</tr>
</tbody>
</table>
Figure 6: Pictures of several reagents (Citric Acid, NH₄OH, Ba(NO₃)₂, Cu(NO₃)₂)

Figure 7: Picture of the liquid nitrogen reservoir located in the basement of Science Center (left) and picture of the cryogenic dewar used to contain the liquid nitrogen (right). The dewar can keep the liquid nitrogen for around 5 hours before everything boils off.
<table>
<thead>
<tr>
<th>Item</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>500mL Beakers (5x)</td>
<td>Used to perform most preparation reactions. Must be pyrex to</td>
</tr>
<tr>
<td></td>
<td>withstand high temperatures.</td>
</tr>
<tr>
<td>Scale</td>
<td>Used to measure the powdered reagents.</td>
</tr>
<tr>
<td>Stirring Rod</td>
<td></td>
</tr>
<tr>
<td>pH Paper</td>
<td></td>
</tr>
<tr>
<td>Hotplate</td>
<td>For pyrolysis reactions and synthesis of Yttrium Nitrate.</td>
</tr>
<tr>
<td>Drying Chamber</td>
<td>To dry the Yttrium Nitrate reagent. Available at Singer 127.</td>
</tr>
<tr>
<td>Fume Hood</td>
<td>For pyrolysis reactions and the oxygen insertion step; prevent</td>
</tr>
<tr>
<td></td>
<td>harmful gases from building up in the lab.</td>
</tr>
<tr>
<td>Tube Furnace</td>
<td>High-temperature reaction chamber. Prof. Hillary Smith has one</td>
</tr>
<tr>
<td></td>
<td>in her lab.</td>
</tr>
<tr>
<td>25mm Pellet die set</td>
<td>Make YBCO pellets.</td>
</tr>
<tr>
<td>Hydraulic Press</td>
<td>Compress the powder into pellets using the die set.</td>
</tr>
<tr>
<td>Oxygen Flowmeter</td>
<td>Measure up to 100 mL per minute. A model from Omega is purchased as available flowmeters cannot measure flow rates this low.</td>
</tr>
</tbody>
</table>
Chemical Synthesis

The first step of the chemical synthesis is to convert Yttrium Oxide into a water-soluble form, Yttrium Nitrate. The procedure steps are as follows:

1. Add 200mL deionized water and 100mL 68% concentrated nitric acid into a 500mL beaker
2. Turn the hotplate to low-mid heat and stir bar on
3. Add around 30g yttrium oxide powder. The solution turned cloudy until a certain temperature is reached, then the following reaction occurs:

   \[ Y_2O_3 + 6 HNO_3 \rightarrow 2 Y(NO_3)_3 + 3 H_2O \]

4. \( Y(NO_3)_3 \) was dissolved in water and the solution turned clear. To destroy the remaining nitric acid, continue to add in more \( Y_2O_3 \) until the solution stayed cloudy. Slowly add drops of concentrated nitric acid until the solution becomes clear again.

5. At this point, the solution should only contain the aqueous form of yttrium nitrate. If undissolved impurities are visible, then the solution should be first filtered through a vacuum filter. In my case, no visible impurities were seen so this step was skipped.

6. To obtain crystals of \( Y(NO_3)_3 \), the solution was left on the hotplate for around 3 hours which reduced the volume from 350 mL to around 120 mL. The viscosity seemed to have increased, and the yttrium nitrate started to crystallize once the beaker was removed from the hotplate. After around 30 minutes, all of the \( Y(NO_3)_3 \) crystallized out of the solution and the mixture has a consistency of shaved ice. A slight ammonia-like smell could also be detected close to the mixture when it was outside of the fume hood, likely due to the
degradation of unreacted nitric acid into NO₂ gas. Extra caution was therefore taken as NO₂ gas is toxic.

7. To completely dry the $Y(NO_3)_3$, the beaker was placed in a drying chamber located in Singer 127. The chamber was set to 60 degrees celsius and continuously ran for 5 days. The mixture formed large clumps that were hard to break apart and trapped a lot of moisture, so the chamber was opened everyday to manually stir the mixture and attempt to break large clumps into smaller ones to speed up the process. After five days, over 60 g of yttrium nitrate was obtained in the form of completely dried white powder, which is more than what was needed for the rest of the experiment steps.

Figure 8: Picture of the drying chamber in Singer 127
*Note* Yttrium nitrate seems to be a very good drying agent, and actively draws moisture from the air to turn itself back into the aqueous form. Unfortunately this became apparent a few weeks after making the dried powder, and the drying process had to be repeated to recreate the crystals. It is therefore recommended to only make this reagent when needed and continuously store it in a humidity-controlled chamber.

Figure 9: Cup containing yttrium nitrate powder (left) synthesized from yttrium oxide (right)

To obtain the ratios consistent with the YBa$_2$Cu$_3$O$_{7-d}$ structure, I completed stoichiometric calculations to determine the amount of each reagent required, as shown in table 3.

Table 3: Stoichiometric Calculations

<table>
<thead>
<tr>
<th>Element</th>
<th>Element Molar Mass (amu)</th>
<th>Source Reagent</th>
<th>Source Reagent Molar Mass (amu)</th>
<th>Mass Reagent added (g)</th>
<th># moles of Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>88.91</td>
<td>Y(NO$_3$)$_3$</td>
<td>274.92</td>
<td>13.75</td>
<td>0.05</td>
</tr>
<tr>
<td>Ba</td>
<td>137.32</td>
<td>Ba(NO$_3$)$_2$</td>
<td>261.34</td>
<td>26.13</td>
<td>0.10</td>
</tr>
<tr>
<td>Cu</td>
<td>63.546</td>
<td>Cu(NO$_3$)$_2$·3H$_2$O</td>
<td>241.60</td>
<td>36.24</td>
<td>0.15</td>
</tr>
</tbody>
</table>
To create a highly homogeneous mixture of fine powder to serve as precursors for the structure, a technique called citrate pyrolysis is used (Senzaki et al, 2021). Under high heat, citric acid degrades and the released carbon atoms spontaneously combust in the nitrate-rich mixture and generate carbon dioxide gas. The volatiles released from the combustion then cause the mixture to rise into a light foam structure that breaks apart into fine powder when a small force is applied. The goal for the next step of the chemical synthesis is to create a solution with the correct mixture of reagents to undergo citrate pyrolysis, and the procedure is as follows.

1. To a 500 mL beaker, add 150 mL of water and 36.24 g of copper nitrate. The salt quickly dissolved and the solution immediately turned bright blue.

2. Add 26.13 g of barium nitrate. This salt took much longer to dissolve and required some heat from the hotplate. Some solid barium nitrate could still be seen after 30 minutes of mixing but most seem to have gone into solution.

3. At this point, add 13.75 g of yttrium nitrate and let the mixture stir for 15 minutes.

4. Add 60 g of citric acid and let the mixture stir for another 15 minutes.

5. Using the pH paper, the pH of the solution was tested which shows to be around pH = 1. The pH should be around 7 before continuing to the pyrolysis.

6. To the beaker, the neutralization process started by adding 50 mL of ammonium hydroxide solution. This reaction created lots of heat, and the solution became visibly darker. The pH was tested regularly and ammonium hydroxide continued to be added until the solution was at around pH 7.
7. Since there are still some undissolved solids at this stage, I filtered the solution through filter paper. Around 250 mL of dark-blue colored solution was left after the filtration.

8. To a new 500 mL beaker, add around 70 mL of the solution and start to heat the beaker under a hotplate. Once the solution starts to boil, lower the heat to low until most of the water boils off and viscous bubbles start to form.

9. At this point, turn the heat to high. Some strong splattering occurred for a brief period, and the solution continues to darken into pitch black.

10. When the mixture is almost fully dried, pyrolysis begins as the citric acid self-combusts.

   A porous black material begins to form and grows into a 3D structure. The reaction lasts for about a minute, and lots of water vapor was initially formed from the remaining water in the mixture.

11. Steps 8-10 were repeated until all of the solution was used up. The pyrolysis product was then scraped off of the beaker and collected together in preparation for the next step.

In contrast to the procedure seen on NileRed, I had a lot of problems with splattering in steps 8-9. Higher heating levels sped up the process, but also caused very strong splatters and resulted in a large amount of yield loss in my first two runs. I found that it is best to be patient and start with the lowest setting until almost all the water boils off. This made the process take much longer to around 1 hour per 70 mL of solution, but resulted in a much higher yield.
Figure 10: Snapshots of the Pyrolysis reaction. The left picture is a top down view from the experiment conducted at Singer 125; the right picture is a side view taken from NileRed⁶ that better displays foam growth.

⁶ Video link: [https://www.youtube.com/watch?v=RS7gyZJg5nc&t=6s&ab_channel=NileRed](https://www.youtube.com/watch?v=RS7gyZJg5nc&t=6s&ab_channel=NileRed). Time stamp at 14:55
Sintering and Insertion of Oxygen

To make the YBCO superconductor, the pyrolysis product (YBa$_2$Cu$_3$O$_6$) has to first incorporate additional oxygen atoms into its lattice, and then undergo sintering at extremely high temperatures to transform into the correct lattice structure (YBa$_2$Cu$_3$O$_7$). These two steps were achieved using a tube furnace borrowed from physics Prof. Hillary Smith’s lab, capable of heating up to 1100 °C and programmable to create custom heating and cooling curves.

Figure 11: Left structure (YBa$_2$Cu$_3$O$_6$) is the pyrolysis product and is not superconducting, while the right structure (YBa$_2$Cu$_3$O$_7$) contains extra oxygen atoms and is the actual superconducting structure.\footnote{Image source website: https://www.ch.ic.ac.uk/rzepa/mim/century/html/ybco.htm}
According to Blank et al. (1988), the ideal heating temperature appears to be at 920°C, at which the material is able to readily absorb oxygen into its structure. The heating curve was then programmed as shown in Figure 12, consistent with the curve used in NileRed’s procedure. The oxygen source is turned on at a rate of 70 mL per minute for the first 11 hours of the heating process, then turned off during the cooling phase as it is no longer needed at that time.

Figure 12: Heating curve input for the tube furnace. The temperature increases from 20°C to 920°C in the first hour of operation, then the furnace stays at 920°C for 10 hours. At minute 660, the chamber starts to slowly cool from 920°C down to 20°C for the next 11 hours to complete the sintering process. Both steps used the same heating curve.
Figure 13: Sintering/Oxygenation Setup. Oxygen tank supplies a constant flow of oxygen into the tube furnace placed inside a fume hood.

Figure 14: Glowing red color within the tube indicates that the furnace is definitely very hot.
Figure 15: The powdered sample before and after oxygenation. The sample is visibly darker after this step, and appears to loosely clump together.

After the oxygenated powder was created, I then needed to compress the sample into small coin-sized solids. This is typically done with a scientific pellet press die set that requires very small tolerance on part sizes and commercially costs over $300 per set, which is far beyond my available budget. Luckily, J. was able to make one using the CNC machine and steel cylinders available in the workshop (Figure 16). There is also a hand-operated hydraulic press that can achieve up to 12 tons available for use.
Figure 16: Setup for the pellet die set under the hydraulic press.
The first attempt at creating these pellets was not successful, as the die set parts got stuck together due to powder trapped between the ram rod and the walls (Figure 17). The die set parts were pulled apart again after some effort, but the hard powder had scratched the steel and caused permanent damage to the set. The die therefore had to be remade by J., with a new design that allows the use of the hydraulic press to push the parts apart and careful cleaning was done after each press. We found that 6 tons of pressure had the best result and was enough to create a pellet that stayed together, as higher pressures only led to more damage to the die set with powder being forced into the crevices.

![Image of a pellet with powder residue](image)

Figure 17: Powder residue can be seen on the spacers after a press is completed.

The compressed pellets at this stage were extremely fragile and could break apart under any slight external force. The surface also behaved like charcoal and left a black powder residue when it interacted with other surfaces like paper and skin. These pellets are also not superconducting at this stage yet, as the particle sizes are too small and need to be sintered into a more aligned lattice structure.
Figure 18: Physics principle of sintering. The loose powder is heated to a temperature below its melting point, but it is enough to cause the atoms in materials to diffuse across particle boundaries and fuse together.

The sintering process is done by putting the pellets back into the tube furnace and applying the same heating curve shown in Figure 17 without the oxygen exposure. No significant changes in color or appearance seem to occur after sintering, but the pellets no longer leave a residue when rubbed against a surface and did not break apart when small external forces were applied.

At this stage, the samples were completed and should exhibit superconducting behavior when cooled.

\[8\]

Image taken from article by Mark Saline: https://www.industrialheating.com/articles/94932-sintering-and-additive-manufacturing
Addressing Safety Concerns

Due to the safety issues involved with the oxygen tank and the expensive tube furnace borrowed from physics Prof. Hillary Smith’s lab, this step required lots of logistical planning ahead of time. Swarthmore College’s Safety Officer, Colleen Bautista, was consulted throughout the process to ensure that the procedure complied with the safety code.

The rate of oxygen flow had to be monitored carefully to make sure that it was at the desired level (50-100 mL per minute) as instructed by the procedure. This rate is extremely low for most applications, and the available flowmeters in J’s workshop cannot measure rates in this range. We therefore needed to purchase our own Omega Flow Meter that measures up to 100 mL of oxygen per minute. A portable oxygen detector was also present in the room, which was used regularly during the run to ensure that the room’s oxygen levels did not increase significantly. Warning signs were also pasted outside the lab, and Prof. Molter and my phone number were posted in case of any emergencies.
Figure 19: Picture of the pressure gauges along with the oxygen flowmeter
Figure 20: Warning signs pasted at the door of Singer 125
**Results**

During the synthesis steps, there was no way for me to verify the identity and purity of intermediate products except to check if the products’ color looked similar to the video by NileRed. The only way I can determine the success of my procedure is to test its superconductivity with liquid nitrogen at the end. If no superconductivity was detected, I would not know which exact step had gone wrong and would have to completely restart the process.

Figure 21: The four samples that were made. The cracked pellet on the left is the first sample, and three more samples on the right of the Figure were made later. All samples exhibited superconducting behavior.
I was therefore relieved to find that despite having an imperfect shape, my first test sample (shown in the left in Figure 20) exhibited superconductivity through the quantum locking effect as shown in Figure 21, marking the success of my project. I went on to repeat the pellet-making process again with an improved die set, and made a thicker sample without any cracks which also worked as a superconductor.

Figure 22: Demonstration showing a cube neodymium magnet floating on top of a YBCO superconductor I synthesized and cooled to 77 K. The magnet does not move in position unless external force is applied, but can spin freely around an axis parallel to the YBCO disk.
Attempts at creating a magnetic track

While waiting for approval to conduct my synthesis experiments, I started attempting to design physics demonstrations that better highlight the quantum levitation effect. One cool demonstration I attempted to make is the concept of a Mobius strip magnetic track, where a superconductor can slide across it with minimal friction and spend part of the time upside down.

My first design attempted to use 18 mm ceramic disk magnets I purchased for a cheap price on Amazon. Using Fusion 360, I created a Mobius Strip with a width of 20 mm and diameter of 300 mm (as seen in Figure 22). To fit the structure on the available 3D printers in the Makerspace, I cut the track into four roughly equal sections. The twisting 3D structure turned out to be quite difficult to print on the cheaper Ultimaker S3 and S5 models, and I decided to switch to the Markforged instead which created a much better support structure for the print. With the magnets pressure fitted into the printed holes, I then brushed on a thin layer of epoxy resin to fully secure the magnets and strengthen the strip.

Figure 23: CAD design of the Mobius strip track, with circular holes generated to house magnets. The strip is split into quarters in order to fit the print bed in the available 3D printers.
Figure 24: Picture of a printed track using the Markforged 3D printer. The circular magnets are installed in the holes, and the surface is coated in a thin layer of epoxy.

Unfortunately, this test strip did not work very well when tested on a superconductor. The ceramic magnets were far too weak to create the magnetic field required for the quantum levitation effect, and I had to look for stronger magnets to replace them. After looking at options online, I settled on 20x8x1.5 mm neodymium magnets from Amazon that seem to offer the largest surface area to price ratio, while also being small enough pieces to help them conform into a twisted structure. I was able to re-use the track I already printed, and attached the magnets temporarily using double-sided tape. When tested against the superconductor, I found that these magnets are still not enough to fully float the samples, likely due to their small thickness making them still too weak. Larger thick magnets are out of my budget range, and the superconductors also warms up too quickly that they risk losing the locking effect while moving upside-down on the track and causing them to break upon impact with the ground.
With the remaining magnets and time I had, I decided to scale down on my Mobius strip track ambitions and moved to an easier linear track design. Using a scrap piece of acrylic sheet from Makerspace, I again used double-sided tape to hold the magnets in place. The flat geometry made the process much easier, as the magnets naturally wanted to move into the correct place so that the poles could properly align. I double layered the magnets this time to increase the field strength, and increased the track width to 4 magnet-widths so the superconductor was fully confined to the track.

This design actually managed to levitate the two thin samples I had, and I was able to effortlessly move the superconductors linearly across the track while they were hovering mid-air. This however only worked on the thin samples and not the thicker ones, which I suspect will need an even stronger magnetic field to support their own weight. I can get around 20 seconds of levitation before the thin samples warm back up and lose their superconductivity.

Figure 25: Picture of the linear track and a demonstration showing a superconductor floating on it. The thin magnets were stacked in two layers to generate enough field strength to overcome gravity.
Discussion

Testing the necessity of oxygen source

During the synthesis procedure, the oxygen insertion step was by far the most dangerous and expensive. While looking into the purchase of an oxygen flowmeter, I was surprised by how low the flow rate was (less than 100 mL per minute). This is lower than the smallest increment of measurements in the flowmeters available on campus and sold online. Although NileRed suggested the additional oxygen as a necessary step within the procedure, I was a bit skeptical about its necessity and decided to run an extra trial run with some leftover pyrolysis product I had. Using the exact same heating curve, I simply kept the oxygen valve turned off during the oxygen insertion step and then created a sintered pellet from this new product. This new sample also turns out to be superconducting, confirming my suspicions that ambient air is enough as a source of oxygen in this reaction.

With a lab-grade tube furnace already available on campus, I was able to complete the oxygen insertion and sintering step with minimal costs. However, for a typical student or hobby chemist, a tube furnace would be inaccessible and an alternative needs to be found. Youtube Channel Applied Science managed to do this procedure using a cheap kiln, but had some trouble holding the heating curve to the tube furnace’s level of precision. This is a process that I would like to potentially recreate in the future with the available kilns on campus.

---

9 Video link: https://www.youtube.com/watch?v=sLFaa6RPJIU&ab_channel=AppliedScience
Future Work

With the time I had over the past semester, I was able to achieve my main goal of producing a working YBCO superconductor sample. There are aspects of my project that I was unable to complete due to time and budget constraints, as well as future directions I would like to expand my work into.

Although the samples I made did exhibit superconducting behavior, I did see signs of impurities including blue and gray specks scattered within the pellets that should have been uniformly charcoal black. In order to find out the purity of my sample and the identity of the impurities, I would like to test the samples using X-Ray diffraction technique, which can provide insights to the lattice structure of the YBCO and its constituent elements. The data for a pure YBCO sample can be found online, which I can then compare with the result of my own samples. I would also like to use similar techniques to check out my pyrolysis product, as well as chemical tests on my reagents to see which steps introduced the impurities. An X-ray diffractometer may be available for use in the Swarthmore Chemistry Department if approval is granted. A Scanning Electron Microscope (SEM) image of my samples also would be useful in determining the size of particles before and after sintering.
As mentioned in the procedure section, my initial attempts at creating a working Mobius strip magnetic track unfortunately did not work very well. With the proof-of-concept through the linear track and more budget for stronger magnets, a full-scale curved track should be possible to be built easily in the future. To create a stronger flux pinning effect, it would also be beneficial to make a new pellet die set that can make larger diameter flat disks that allow more magnetic field bundles to penetrate and lock the superconductor onto the track. To reduce the warming rate of the superconductor, I can use the idea from the Royal Institution Lecture (see right image from Figure 27) where a small liquid nitrogen reservoir made of styrofoam is attached to the sample while it goes around the track.

---

Figure 26: X-ray diffraction pattern of a pure YBCO Sample (Dughaish et al, 2016) 

---

10 Image taken from Dughaish et al. Effect of Annealing and Addition of Fine Metal Powders on the Mechanical Properties of YBa$_2$Cu$_3$O$_7$ High Temperature Superconductor (HTS), Figure 2
Figure 27: Pictures of large-scale Mobius strip tracks built by other institutions in the past. Left image shows a $3\pi$ track created by Ithaca College Physics Department\textsuperscript{11}; right image shows an actively-cooled sample floating on a track created by the Royal Institute.\textsuperscript{12}

\textsuperscript{11} Video Link: https://www.youtube.com/watch?v=Vxror-fnOL4&ab_channel=IthacaCollegePhysics
\textsuperscript{12} Video Link: https://www.youtube.com/watch?v=zPqEEZa2Gis&ab_channel=TheRoyalInstitution
**Engineering Design**

The constraints for my engineering design for this project mostly revolves around completing a complex manufacturing procedure with limited equipment and budget. The requirements include completing within a $400 budget and before the May 2nd deadline, identifying and addressing all potential safety hazards, as well as producing a final sample that exhibits superconducting behavior. I have completed these requirements, with the exception of the budget which I had gone slightly over due to the necessity of the oxygen flowmeter (part of the safety requirement).

**Acknowledgements**

This project was made possible by the resource and financial support from the Swarthmore Engineering Department. I would like to specifically thank Prof. Lynne Molter for being a great advisor and helping me throughout each step of the project, and J. Johnson for coming up with a solution to the oxygen flow and pellet press on short notice. I would also like to thank Prof. Hillary Smith and Dr. Paul Jacobs from the Physics Department for providing me with the tube furnace and supply of liquid nitrogen, as well as Ian McGarvey from the Chemistry Department for the lab supplies, all of which were crucial in the successful completion of my project.
References


Department of Materials Science and Metallurgy, “Superconductivity”, *Dissemination of IT for the Promotion of Materials Science*, 2008
https://www.doitpoms.ac.uk/tplib/superconductivity/index.php

https://www.youtube.com/watch?v=RS7gyZJg5nc&t=895s&ab_channel=NileRed

Applied Science, “Making YBCO Superconductor”, *Youtube*, 2018
https://www.youtube.com/watch?v=sLFaa6RPJlU&t=2s&ab_channel=AppliedScience