THERMAL CONDUCTIVITY OF SINGLE MOLECULE MAGNETS

An Undergraduate Research Scholars Thesis

by

WELLS HERO

Submitted to the LAUNCH: Undergraduate Research office at
Texas A&M University
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by
Faculty Research Advisor: Dr. Rupak Mahapatra

May 2023

Major: Physics
Mathematics

RESEARCH COMPLIANCE CERTIFICATION

Research activities involving the use of human subjects, vertebrate animals, and/or biohazards must be reviewed and approved by the appropriate Texas A&M University regulatory research committee (i.e., IRB, IACUC, IBC) before the activity can commence. This requirement applies to activities conducted at Texas A&M and to activities conducted at non-Texas A&M facilities or institutions. In both cases, students are responsible for working with the relevant Texas A&M research compliance program to ensure and document that all Texas A&M compliance obligations are met before the study begins.

I, Wells Hero, certify that all research compliance requirements related to this Undergraduate Research Scholars thesis have been addressed with my Faculty Research Advisor prior to the collection of any data used in this final thesis submission.

This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

TABLE OF CONTENTS

ABSTRACT

Thermal Conductivity of Single Molecule Magnets

Wells Hero
Department of Physics & Astronomy
Department of Mathematics
Texas A&M University

Faculty Research Advisor: Rupak Mahapatra
Department of Physics & Astronomy
Texas A&M University

Single molecule magnets often abbreviated as SMMs are materials that demonstrate superparamagnetism below a certain temperature at the molecular scale. While superparamagnetism is (arguably) the defining feature of SMMs they have other important properties as well such as hysteresis (magnetic memory) and magnetic avalanche. Because of these properties in particular magnetic avalanche SMMs have interested physicists since their discovery in 1993. After investigating SMMs, physicists have determined that their unique properties have potential utility in both the search for Dark Matter as a low energy detector, and storing qubits for use in quantum computing. The most studied SMM sometimes referred to as the archetypal SMM is Mn_{12} acetate, often abbreviated as Mn_{12}, it is the target of the methods developed in this paper due to the extensive research already done on Mn_{12} for applications already discussed. This paper will utilize a dilution fridge provided by Infrared laboratories inc. that can reach temperatures of 280mK, an SNSPD as a temperature sensor, as well as copper wires and a copper base. Where copper was chosen since it is a metal with known thermal conductivity that is often used in thermal conductivity experiments. In order to investigate the thermal conductivity of Mn_{12} at low temperatures

where magnetic avalanches are possible this paper investigates SNSPDs in order to verify its utility as a temperature sensor. The point of this research is ultimately to better understand a material that will most likely be important in future technologies so that it can be utilized fully.

ACKNOWLEDGMENTS

Contributors

I would like to thank my faculty advisor, Dr. Mahapatra, for his guidance and support throughout the course of this research.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

I would also like to thank Mark Platt for fabricating parts, Paige Savage for doing the wiring, and Will Baker for teaching me how to use a dilution fridge.

All other work conducted for the thesis was completed by the student independently.

Funding Sources

This work was funded by the DOE under Grant Number DE-SC0021051. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the DOE.

1. INTRODUCTION

Manganese-12 acetate($Mn_{12}O_{12}(O_2CCH_3)_{16}(H_2O)_4$) often abbreviated Mn_{12} [1] is an example of what is known as a single molecule magnet(SMM). Single molecule magnets are metal complexes which act as magnetic domains at the single-molecule level. The nanosize dimensions and quantum nature of SMM systems brings to light several properties that link macroscopic phenomena with the quantum world [2]. Due to this SMMs have a variety of uses, such as being used to try and detect dark matter particles, or being used for qubit storage in quantum computers [1].

Dark matter is important because, at the foundations of physics there are 2 major theories: General relativity and the Standard model. However, at the scale of galaxies, galaxy clusters, etc. as well as the early stages of the universe these 2 theories don't fit observations. In order to fix this problem both Dark matter and Dark energy were introduced. Dark matter specifically has the ability to explain a wide variety of observations from galactic rotation curves to how the universe is structured [3]. In fact, without Dark matter new theories of gravity are necessary such as MOND, though the necessary general framework of Modified gravity for which MOND would be a limit of hasn't been worked out, or at least isn't agreed upon. Thus the discovery or absence of Dark matter is important for the foundation of physics.

The ability to detect dark matter particles relies on the ability to detect very low energy signals, specifically the ability to detect energy depositions as low as $\sim$ 10meV with high efficiency and low false positive (or dark count) rates [1]. Therefore exploring materials that allow for the detection of very low energy signals, so that these materials and their properties can be fully utilized in the detection of new particles is important in the hunt for dark matter particles. Where Mn_{12} comes in is that, in the 90s specific heat measurements were used to provide evidence that magnetic quantum tunneling occurs in Mn_{12} spin clusters [4]. Later the process of magnetic avalanche was attributed to thermal runaway caused by tunneling of molecular spin from the lowest state to an excited state [5]. Then the magnetic avalanche of Mn_{12} was used as a single quantum sensor to detect low mass dark-matter [1]. Notice how this started with the study of specific heat, which like thermal conductivity is a thermodynamic property.

Quantum computing is important because arguably computers are the single most revolutionary technology in human history. Having an impact on society comparable to other major technologies throughout history such as; the discovery of fire, development of agriculture, and the invention of the steam engine. Computers have had a major impact on education, business, entertainment, medicine, mass communication/social media, and data analysis to name a few. It should be clear then that further developing and improving computers is a major priority of companies, governments, and academia alike. While there are many ways to increase computing power, the most famous of which might be due to Moore's law i.e. adding more transistors per silicon chip. For physicists the most interesting way is probably through Quantum computing.

What is quantum computing and how does it differ from ordinary classical computing? This comes down to the difference between classical bits and quantum bits, also known as qubits, a term that originated in an acknowledgement section of a 1993 paper but since has taken over to become the normal nomenclature [6]. Qubits are similar to classical bits. A single bit of both consists of a two-state system. For classical bits these 2 states are "on" corresponding to "1" or "off" corresponding to "0", what on and off mean physically depends on the physical system in question but typically means that the voltage is either higher or lower than some threshold voltage within a transistor. Similarly for a quantum system these 2 states are the spin-up corresponding to $|1\rangle$ and spin-down corresponding to $|0\rangle$ states of a spin-$\frac{1}{2}$ elementary particle. However, there are 2 important differences between classical bits and qubits. The first one is that classical bits have a definite state "1" or "0" whereas qubits are a superposition of both states [7]. This difference presents a problem when trying to store bits.

While there are various possible methods proposed to store qubits, each with pros and cons, SMMs are one of the most promising ones. Specifically SMMs with strong uniaxial magnetic anisotropy such as Mn_{12} or $Fe_8O_2(OH)_{12}(tacn)_6]Br_8 \cdot 9H_2O$ commonly referred to as Fe_8. These SMMs demonstrate hysteresis (i.e. magnetic memory) near liquid Helium temperatures. In addition, SMMs show intriguing quantum phenomena such as resonant spin tunneling and Berry phase interferences between different tunneling paths. Of particular note for qubit storage are; the ability to tune their properties (such as spin, magnetic anisotropy, resonance frequencies, etc), their high spins (e.g. the spin for both Fe_8 and Mn_{12} is S = 10), large densities (typically $\sim$ 1020 - 1021 spins/cm^3), and the fact that, in many SMM crystals, the anisotropy axes of each magnetic center are aligned parallel to each other, which might enable the attainment of stronger couplings than those previously achieved with other natural spin systems [8].

My thesis is that understanding the thermal conductivity of single molecule magnets, namely Mn_{12}, will be important in future application of single molecule magnets such as in quantum computers and quantum sensors. My project is different from other previous projects in that within low temperature physics the study of thermal conductivity is rare. For single molecule magnets it simply hasn't been done yet.

An important question to ask is what is thermal conductivity. Thermal conductivity is defined by the equation below.

$$\vec{q} = -k\vec{\nabla}T \tag{1}$$

This equation is known as Fourier's law. It relates the heat released or absorbed to the gradient of the temperature. Where $\vec{q}$ is referred to as either the heat flux or the heat current. Though normally if it is being referred to as the heat current it will be represented by $\vec{J}$ instead of $\vec{q}$ which is done in order to parallel common notation for electrical current density. Physically it refers to the energy flowing in or out of the material and the direction in which it is flowing. The gradient of the temperature is a vector field, i.e. a function that places a vector at every point in 3D space, that tracks the maximum change of temperature. The direction of the gradient is the direction of the greatest change in temperature in 3D space. The thermal conductivity is the constant k that is greater than zero. The negative sign is there due to a fundamental thermodynamic property that heat flows from higher temperature regions to lower temperature regions but never from lower temperature regions to higher temperature regions. For a one dimensional homogeneous object, the heat current is therefore determined by the temperature difference of the two heat baths ΔT, and the object length L. The formula is then is.

$$q = -k \cdot \frac{T_2 - T_1}{L} \tag{2}$$

It is this formula that most experimentalists use in practice when determining an object's thermal conductivity. This is fundamentally a classical picture chosen mostly as a tool to properly explain thermal conductivity. However, it should be known that generally, the validity of Fourier's law does not seem to be strictly linked to the classical or quantum nature of the system. [9]

2. METHODS

2.1 Tools

In order to study the thermal conductivity of Mn_{12} this paper will investigate Superconducting Nanowire Single-Photon Detectors or SNSPDs as thermal sensors. Superconductivity is when certain materials are cooled to "near" absolute zero then any current running through the material will encounter no electric resistance and any magnetic field will be rejected from the material. Another important property of superconductors is that while normally the resistance decreases gradually, superconductivity is an abrupt change. This will be important when attempting to measure the critical current. The property of superconductors that SNSPDs utilize is that the superconducting state is sensitive to incident radiation at optical wavelengths. What SNSPDs are, are superconducting devices based on a niobium nitride nanowire that is sensitive at visible and infrared wavelengths, with recovery times and timing precision orders of magnitude faster than other existing single-photon detectors based on superconducting materials. [10]

In order to test the thermal conductivity of Mn_{12} the main piece of equipment is a dilution fridge. A dilution fridge is a fridge that reaches near 0 K temperatures using a mixture of ^3He diluted in ^4He, which is where it gets its name. The dilution fridge has several flanges that correspond to different stages of cooling.

Note that most low temperature physics labs have a Bluefors setup. For the BlueFors dilution refrigerator the stages are the room temperature flange, the 50 K flange, the quasi 4 K flange, the still flange (which has a temperature range of .8 - 1.2 K), the cold plate (.08 - .1 K), and the mixing chamber (0 - .01 K, note it can't ever reach 0 K). To get from room temperature to 50 K the first stage of the pulse tube cooler is used. From 50 K to 4 K the second stage of the pulse tube cooler is used. (Note that after the quasi 4 K flange the support structure between the flanges becomes a heat switch.) Between the 4 K and the still flange flow impedance causes both the temperature and pressure to drop as well as condenses the mixture, this occurs due to the Joule-Thompson effect.

Then a heat exchanger is used to get us from the still flange to the cold plate. The mixer utilizes a special property of the superfluid ^{3}He, ^{4}He mixture. At temperatures below .8 K the Helium mixture will separate into a ^{3}He rich phase, with practically no ^{4}He, and ^{3}He poor/dilute phase which contains 6.4% ^{3}He. A pump line will continually bring the ^{3}He rich and poor phase into contact and ^{3}He from the rich phase will start to seep into the poor phase, because the enthalpy is greater in the poor phase the mixture must take heat from the environment, cooling the bottom of the mixer.

However the dilution fridge used in this experiment uses a slightly different setup provided by infrared laboratories inc. that has a few important differences. First of all as reported by infrared laboratories inc the setup should be able to reach 250mK. However, experimentally I have only seen temperatures as low as 280mK and more often than not in practice it is even higher in the range of 300mK - 500mK. This doesn't pose a problem for this experiment because the necessary temperature is 1K-2K. Second, while the room temperature and 50K flanges are practically identical, and the 4K flange is mostly the same, lower sections are where differences in the designs can be seen. Despite the differences the theory behind how the mixer works is still how the last stage works since this is why it is called a dilution fridge.

In order to utilize the SNSPD we need to know the critical current (explained later in this paragraph) and to measure the critical current we need to be able to measure the resistance of the SNSPD. In order to measure the resistance of the SNSPD this experiment utilizes a Keithly 2636. This is important because when using a Keithly 2636 to measure resistance it utilizes Ohm's law to get a reading of the resistance. This means that the Keithly inputs a current and then reads the voltage difference. However there are problems with this methodology, first inputting a current into a wire causes the wire to heat up. This is especially a problem because we need to keep the temperature so low. However, it was originally thought that since we need the temperature we need is in the 1K-2K range and the fridge can go down to 280mK with a small current the heating power generated by the current should be smaller than the cooling power the fridge outputs. Though later on we found there were issues related to the current heating the wire. Another problem is the fact that in order for the SNSPD to function properly it must be superconducting and strong enough currents can destroy the superconducting state. The point when currents become strong enough to destroy the superconducting state is called the critical current. Because of this my research began with trying to precisely determine where the critical current was for SNSPDs produced at the Texas A&M fabrication lab, however due to complications written about later this became the focus of my research. The last problem is that Ohm's law is in reality just an approximation, an approximation that gets better as the current increases up to a point. This discrepancy can be quite large as during research after calculating the resistance of a piece of Aluminum wire using the resistivity of Aluminum and the dimensions of the wire determined its resistance to be 40 Ω. However, with sufficiently low current, around 1 micro Amp, using the Keithley to measure the resistance the measured resistance could be as high as 30 MΩ, about a factor of a million off. This is a problem because in order to measure the critical current we need to measure when the resistance has a sudden jump indicating that the superconducting state has been destroyed. However, if the measured resistance is order of magnitudes bigger than the jump then the jump in resistance will be indistinguishable from error or noise.

The critical current is important because in order to have the SNSPD able to detect photons, phonons, and free electrons, the SNSPD must have current (specifically a DC current) going through it that is near the critical current. This is because how SNSPDs work is that when photons hit the SNSPD since the superconducting state is sensitive to incident radiation at optical wavelengths when a photon is absorbed by the nanowire creating a small resistive hotspot. The supercurrent is forced to flow along the periphery of the hotspot. Since the NbN nanowires are narrow, the local current density around the hotspot increases, exceeding the superconducting critical current density. This in turn leads to the formation of a resistive barrier across the width of the nanowire, which due to Ohm's law produces a voltage. Joule heating (via the DC bias) aids the growth of the resistive region along the axis of the nanowire until the current flow is blocked and the bias current is shunted by the external circuit. This allows the resistive region to subside and the wire becomes fully superconducting again. The bias current through the nanowire returns to the original value. The time it takes for this process to complete is called the time constant and is denoted by τ. [10]

2.2 First Sample

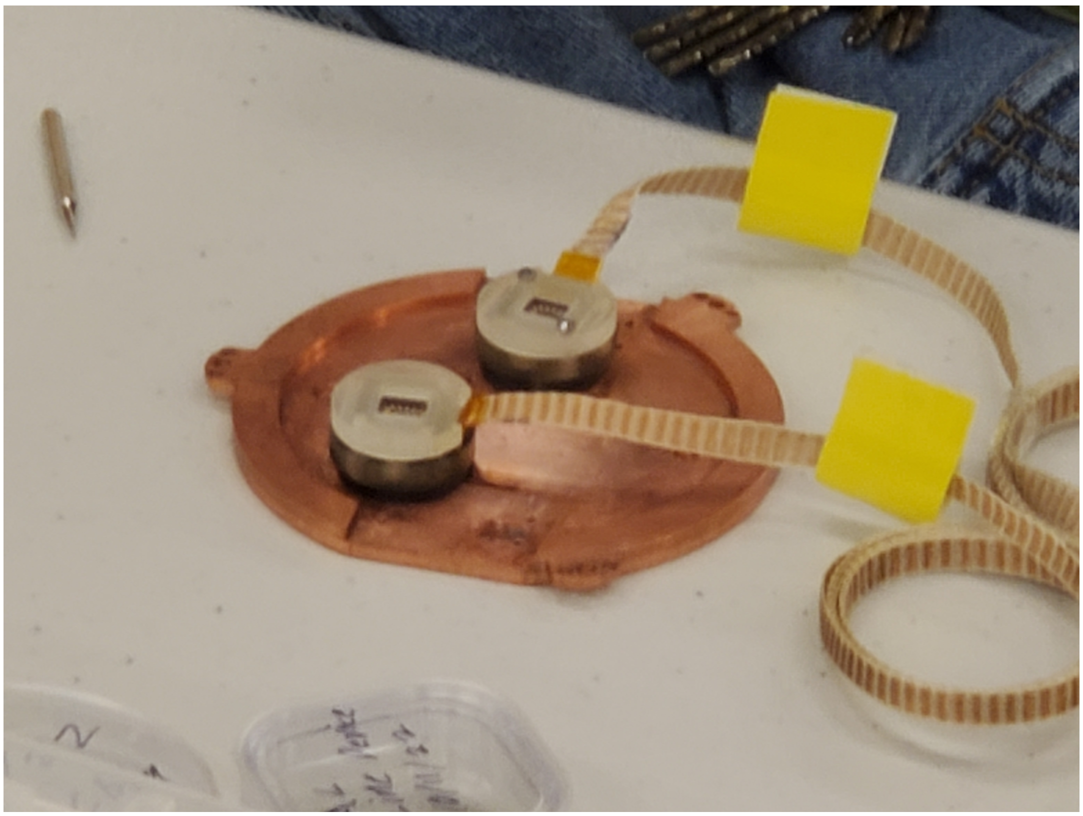

Figure 1: Picture of the first sample

This is the first sample that was experimented on. It was fabricated by Mark Platt. There are several important qualities about this first sample. The first thing to note is that one puck holds an SNSPD and the other puck holds pure Aluminum. Next is the base. The base is copper, copper was chosen because it is a common material, probably the most common material, used in conductivity experiments. The reason why copper is a commonly used material in thermal conductivity experiments is because copper has a very high thermal conductivity so when measuring the thermal conductivity of most materials the additional delay in the release of heat through the copper is negligible. The wires are a Beryllium-Aluminum composite, this is important because pure Beryllium has a critical temperature of 26mK which is a lower temperature than what the infrared laboratories inc. dilution fridge used for this experiment can achieve (see the dilution fridge section for more details). The Beryllium-Aluminum composite however has a critical temperature in the 1-2K range. It should be noted that Niobium–titanium is the industry standard for superconducting material, which is important since in order to be able to ensure that the SNSPD is superconducting the wire must have no resistance. The reason for this decision was mostly economic as this was expected to not be the final sample and the Beryllium-Aluminum composite was sufficient for the purposes of this experiment. The next quality that's relevant is the pucks. It should be noted that the top part of the puck is plastic. This is an imperfection of the original design that was at first thought to be negligible. Inside the puck is a silicon wafer that holds either the aluminum or the SNSPD. The little screws visible are stainless steel. The sample utilizes a 4 point method of resistance measurement in an attempt to reduce the effect of the resistance of the wires on the measurement of the resistance of the SNSPD and the Aluminum.

3. RESULTS

3.1 First Round of Experiments

First run of the fridge failed due to not giving the liquid enough time to condense. Second Run was able to get down to .470K, which is .200K more than expected. We were not able to see the transition to superconducting. The Aluminum was 65.5Ω at $\sim$ 2.8K. Then we switched to measure the SNSPD (see graph). When we switched back at .7K the resistance was still 65.5Ω. Even at .470K the resistance was 65.5Ω The superconducting temperature of Aluminum is 1.2K. Why was the final temperature .470K? One reason as to why the final temperature was so high was that the wires aren't thermalized because they aren't connected to an intermediary stage. This is made worse by the fact that Beryllium isn't superconducting at these temperatures, superconducts at .026K. We are not sure why we couldn't see the transition of Aluminum, possible explanations are. One possible reason is that the sample "pucks" are made of plastic may have worse thermal conductivity causing either. Another reason is it takes a much longer time for the aluminum itself, not the sample stage, to reach superconducting temperature. The last reason is that the thermal conductivity of the plastic is so slow the heat that increased the final temperature is keeping the Aluminum from reaching superconducting temperature.

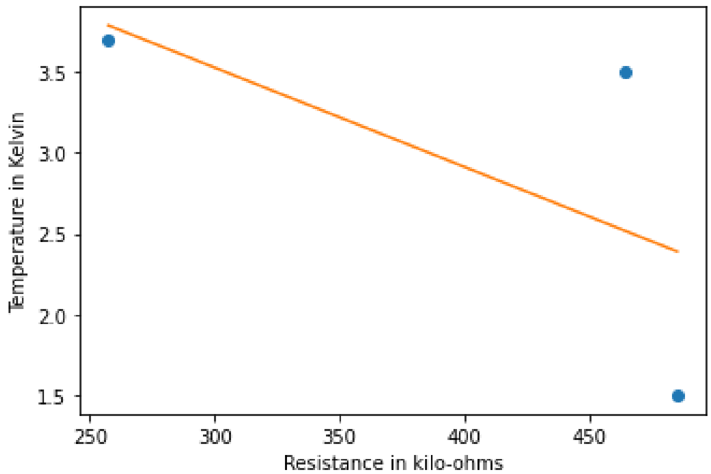

Figure 2: Picture of a Python plot of the first experiment of the first round of Experiments

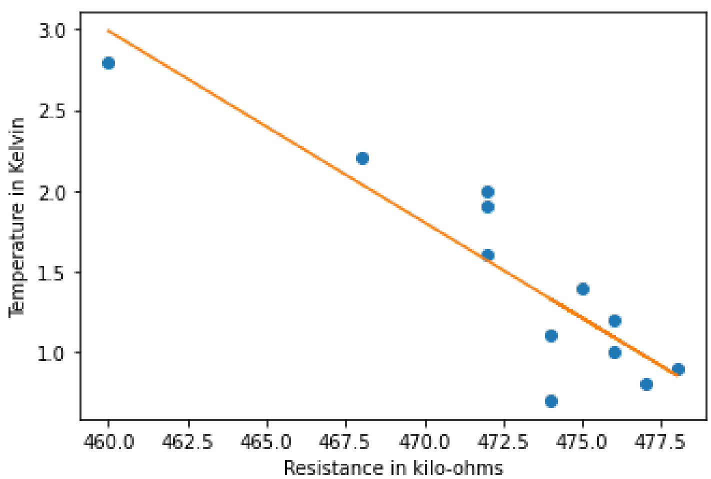

Figure 3: Picture of a Python plot of the second experiment of the first round of Experiments

These two images above are Python plots of data from 2 different runs from the first round of data collection. Some things to note about the data are that the first Python plot only has 3 data points, with the orange line being a least squares polynomial fit produced using the polyfit function of the numpy library of those 3 data points. Because there are so few data points it is reasonable to ask if the fit presented is actually representative of an actual trend or just the result of having so few points and assuming a linear fit. However, the second run was identical to the first, the first experiment being cut short due to time restraints, but instead of just 3 points it has 12. It is clear from the second plot that the linear regression is indeed justified. While there are deviations from the fit, that is just because real data is never perfectly linear. What is clear is that a linear fit is the simplest model to explain what in the second plot is a clear trend, that as temperature increases resistance decreases. However, this presents a problem. The expected behavior was that temperature and resistance would be directly proportional until the critical temperature below which the resistance should jump to zero. This discrepancy indicates that there is something wrong with the wiring and that instead of measuring the resistance of the SNSPD and the Aluminum we are actually measuring the resistance of the silicon wafer.

3.2 Second round of Experiments

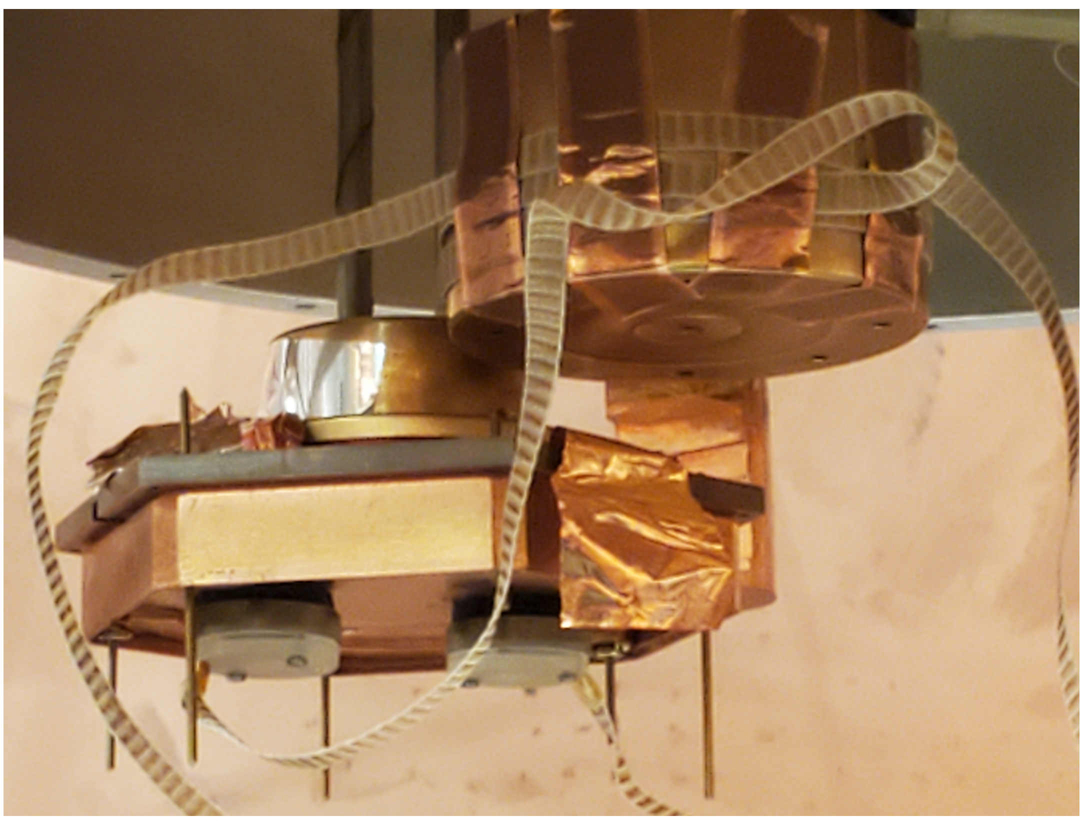

Figure 4: Picture of the rewired first sample using copper wire to address deficiencies

This is a picture of the second round of experiments. In response to the problems of the first round of experiments, namely not measuring the resistance of the SNSPD and the Aluminum as well as having the final temperature of the sample being 200mK higher than predicted, this experimental setup has been completely rewired and we have attempted to thermalize the wires by using copper tape to tape the beryllium wire to the second to last cooling stage. The result of implementing these changes is that the recorded temperature is 313mK, a 157mK improvement over the first round of experimentation. Secondly we didn't observe the "troubling" trend that resistance increases as temperature decreases, and instead noticed the "normal" trend of the temperature and resistance being directly proportional. This second round of experimentation had its own set of problems. Once we verified the sample was acting as expected we began to calculate the expected resistance of the Aluminum wire. To do this we used the dimensions of the Aluminum measured when the wire was fabricated at the Texas A&M fabrication lab. As well as the resistivity of Aluminum at low temperatures but not superconducting, which has already been studied. With this information we were able to measure the resistance as 40 Ω. This gives us an idea of the discontinuous jump we can expect to see when the aluminum becomes superconducting. To measure the resistance we used the Keithly 2636. As was written about earlier in the experimentation section the Keithly uses Ohm's law to measure resistance but at low current the approximation is order of magnitudes off. The other issue written about earlier in the experimentation section is that utilizing Ohm's law results in Joule heating which can destroy superconductivity. Initially we set the current between 1 - 2 μA and found that in this current range we could get the resistance in the range of 10 - 30 MΩ. Obviously this is too high a resistance to be useful. Then the temperature of the sample began to increase uncontrollably. This thermal runaway presented a big issue. It interrupted data collection because often it did not give us enough time to collect and write down the data. Even when we did have enough time to write down data there was the problem that with so few data points per run in order to get a plot with a trend we would need to pull data from completely different runs of the fridge. This would be a problem because variables that should be controlled variables might not be and thus any trend might not be due to either the independent or dependent variables. Therefore instead of plotting the data I have decided to put the data into a table in order to give the reader a more quantitative understanding of the problems encountered in this second round of experiments.

Table 1: Data for the second round of experiments

Temperature	**Resistance**	**Source Current**
3.4 K	100 MΩ	300 μA
3.8 K	.136 MΩ	50 μA
1.6 K	.144 MΩ.	50 μA
1 K	.144 MΩ	50 μA
N\A	30 kΩ	500 μA
N\A	25 kΩ	500 μA

When looking at table 1 one can see that even at the relatively high current of 500 μA the lowest resistance measured was 21 kΩ. This is a problem because as previously mentioned the predicted resistance when not superconducting is 40 Ω and in order to see the jump the measured resistance can't be over 1,000 Ω preferably less than 100 Ω. So it is currently impossible to detect the jump in resistance due to losing superconductivity as it would be indistinguishable from noise. The cause of the thermal runaway is believed to be caused by the current heating up the Beryllium wire, instead of the sample directly, and the heat from the Beryllium wire is what causes the thermal runaway. In order to address the thermal runaway and to while we're at it to get rid of the imperfections caused by the plastic part of the pucks for the third round of the experiment we decided that the sample should be remade completely.

3.3 Third Round of Experiments

For the third round of experiments the sample was completely remade. With copper wires that would be better thermalized replacing the Beryllium wire that was believed to be causing the thermal runaway issue in the second round of experiments. There was a new SNSPD with more precise wire bonding. This sample was believed to be by my faculty research advisor a "high confidence sample" meaning that any issues in measuring the critical current would be a result of a bad experimental setup and not due to some issue involving the SNSPD. As I installed the new SNSPD the setup wasn't properly housed and the copper wires got caught on one of the screws. I didn't notice this and ripped the copper wires from the sample. Afterwards I gave the sample to Mark Platt who tried to repair the sample but was unable to re-do the wire bonding leaving this sample unviable.

3.4 Fourth Round of Experiments

For the fourth round of experiments, because of the third round of experiments, we didn't have a new sample to experiment on. Later we would get a new sample but we didn't want to do nothing and wait so we took an SNSPD sample that was being tested for another experiment for use in our experiment. An important distinction between this sample and the previous sample was that instead of having 4 wire measurements this sample had 2 wire measurements. This is important because the 4 wire measurement accounted for the resistance of the wires whereas the 2 wire measurements do not. Because of the low temperature the resistance of the wires should be very low. Will Baker thought it should still be possible to see the jump that occurs when hitting the critical current. Learning from the previous mistake we properly housed the SNSPD and the installation didn't encounter any issues. I personally wired the installation into the fridge. After installing the SNSPD into the fridge, data collection was delayed due to the fact that utilizing the 300mK fridge for my experiment created noise for the adjacent fridge, the Blue Fors fridge that was being used by grad students for their experiments. Because of this if the grad students needed to collect data I could not. This caused delays of about a week in trying to collect data. Once I was able to collect data a bigger issue took the forefront. The issue being that it seemed that the circuit was open. We figured this out by comparing the ground current against the source or input current in the Keithly 2636. Because the ground current was 5-20 times smaller than the input or source current this indicated that the circuit was open. The cause of this was due to my miswiring of the installation. I plugged the male connector pins into the wrong female connector pins. Another issue was that my faculty research advisor Mahapatra said that with a 2 wire measurement a SQUID to do precisely, and there was no squid installed at the time of data collection. We had planned to just fix the wiring and take data but then a new SNSPD with high confidence was given to us to test so we switched over to the new device.

3.5 Fifth Round of Experiments

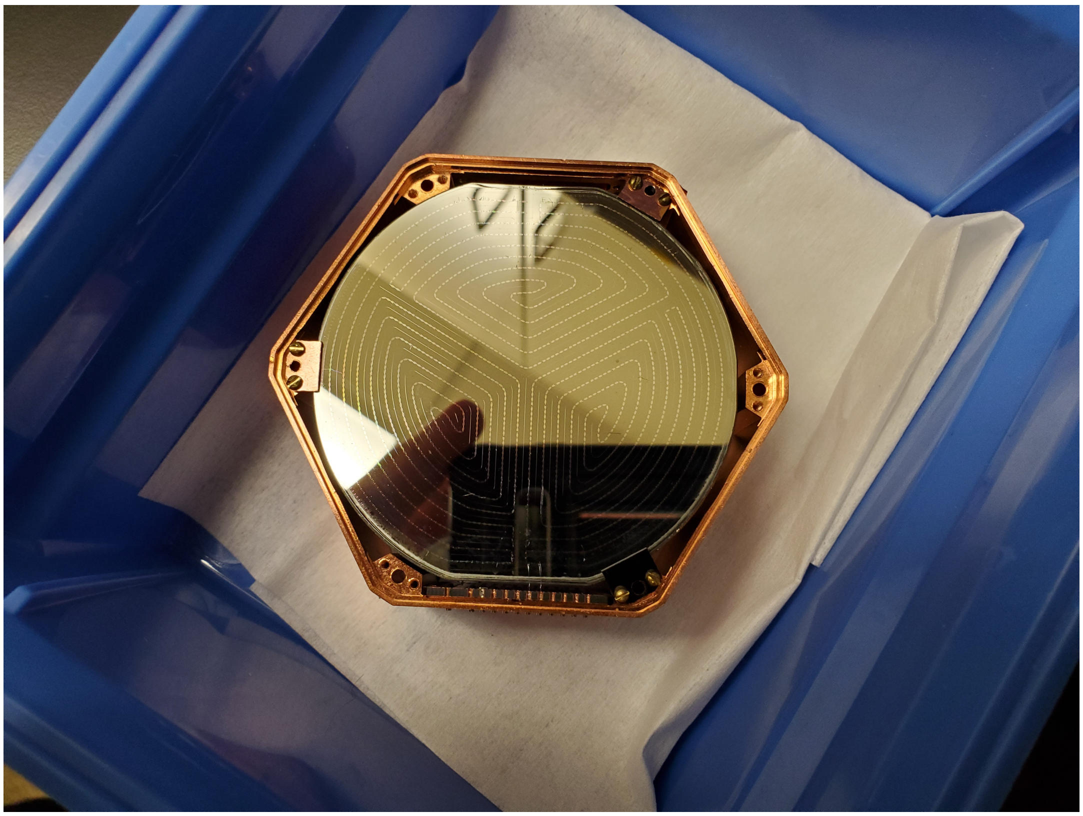

Figure 5: Picture of the detector used for the fifth round of experiments

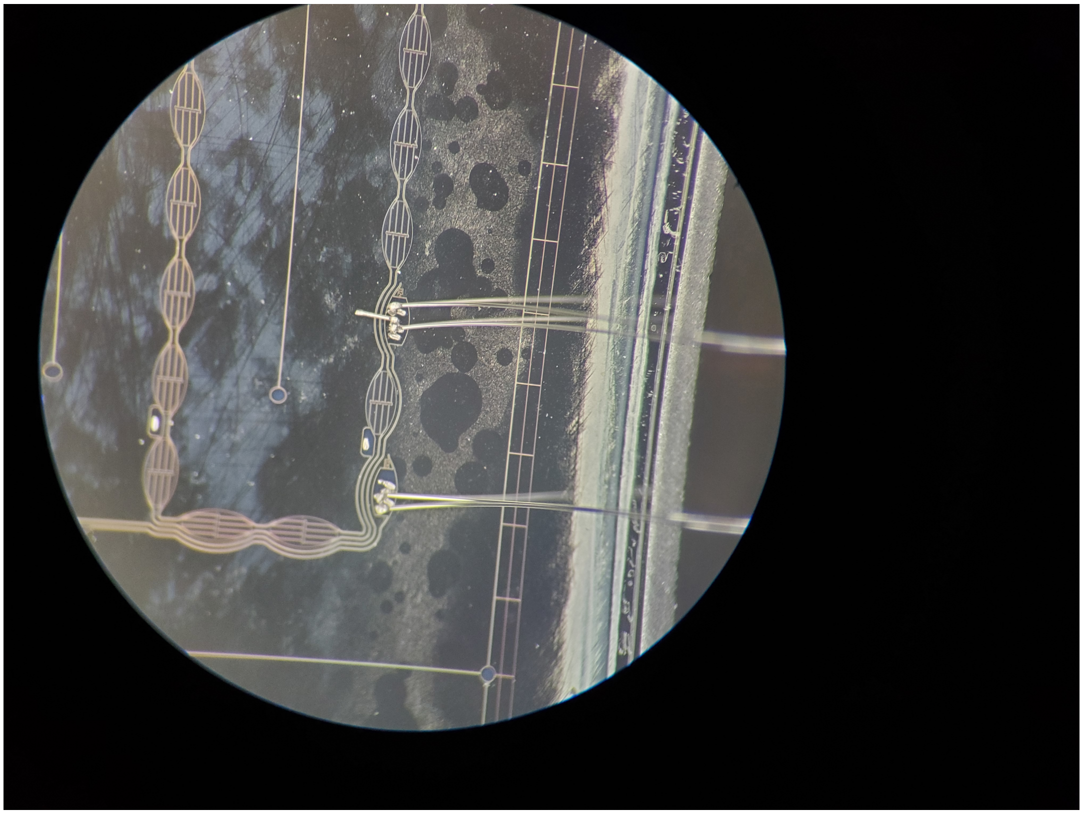

Figure 6: A zoomed in picture at the microscopic scale of figure 5

For the fifth round of experiments we used figure 6 as the SNSPD. It looks dramatically different from the SNSPD samples because the SNSPD was put onto a detector that is normally meant to try and detect potential Dark Matter particles. This change meant that the mass of the sample was much bigger than previous samples, around 800g. This had the unexpected effect that it was harder to cool down. This meant having to do several cycles of turning the He Switches and He Pumps on and off in order to get the Helium to condense. This required being more vigilant than previous runs and caused some time delay. The SNSPD is on top of a Germanium wafer. The wires are Aluminum. If you look more closely at the 2 locations where wires come out they don't come in contact. Instead in the picture the wires are parallel, though this is somewhat misleading as eventually the wires do meet closer to the center of the wafer. Initially the sample was ready for a 2 point measurement but Will Baker adjusted it so that it would be a 4 point measurement. It should be noted that this detector is part of a collaboration and that unlike the other experiments two experiments with 2 separate housings were placed in the dilution fridge for this experiment. My sample was attached to the 300mK stage while the collaborators sample was attached to the 900mK. The collaborators experiment was meant to try and measure the inductance of a small loop while it is superconducting.

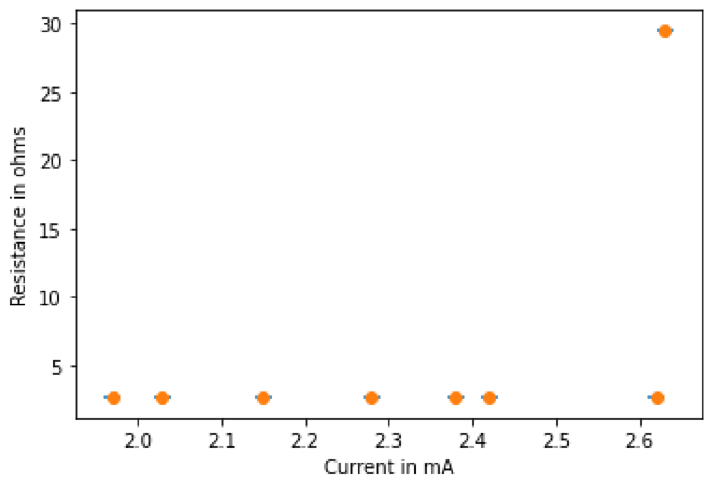

Figure 7: Python Plot of the current versus resistance data or the fifth round of experiments. Note the orange points are the actual data and the blue barely visible lines are the error bars, note that both the x and y axis have error bars though they are barely visible

This plot shows the sudden jump in resistance exactly in line with the theoretical prediction of how a critical current should behave. Notice that the resistance below 2.6mA isn't exactly zero. This is despite both the SNSPD being superconducting and using 4 wire measurements to account for the resistance of the wires. This is because of a phenomenon called parasitic resistance, which is the resistance of things in between the SNSPD and the wire. This resistance is not accounted for by the 4 wire measurement.

As can be seen in table 3 the average is 2.58 mA and the standard deviation is .029mA. The small standard deviation is a good sign that the measurement is highly precise.

Table 2: Critical current data for the fifth round of experiments

Critical Current
2.6 mA
2.63 mA
2.528 mA
2.550 mA
2.564 mA
2.567 mA
2.580 mA
2.586 mA

Table 3: Mean and Standard deviation of table 2

Mean	**Standard Deviation**
2.58mA	.029 mA

4. CONCLUSION

In conclusion we were not successful in being able to get to the point of utilizing SNSPDs for the purpose of measuring the thermal conductivity of SMMs due to problems arising during the testing of SNSPDs. SNSPDs were produced in house to lower costs however this involved having to make and test them. We were however successful in eventually building and testing a SNSPD's critical current so that it may be used in future experiments.

During the 8 month period during which this paper was written errors could be broadly categorized into 2 camps errors due to the SNSPD and errors in the measuring of the critical current. The errors due to the SNSPDs themselves, such as the Beryllium wires not being superconducting at these temperatures causing thermal runaway, were corrected during the course of the experiment and will aid future students who pick up this research later. However, issues in the measuring of the critical current were not addressed. The main issue in this respect is that the data was taken by hand. This potentially has a huge effect on the precision. A way for future experimenters to address this issue is that the keithley 2636 has a Test Script Builder and a processor scripting engine called Lua. This would allow a basically continuous taking of data. A note about this while technically it seems to be possible to use a RS-232 to USB connection we weren't able to get them to work and looking online it seems to be a common problem. Instead we had success using GPIB to USB cable. The reason why this wasn't employed is because someone needs to practice and then create the Lua code to do this and due to more pressing concerns about the SNSPD sample themselves time was not carved out to do this. Another error is the fact that table 2 only has 8 data points. This was due to time constraints and sharing equipment and lab space. Future experiments could improve on this by greatly increasing the data points.

Possible future experiments include utilizing the SNSPD for use in measuring the thermal conductivity of SMMs. This can be done because the size of the Mn12 created at Texas A&M are about 1 mm x 3mm while the SNSPD are microscopic. Because of this the SNSPD, in theory, can be stuck to the SMM. Then while the SNSPD is usually used to measure photons it can also be used to measure phonons. Due to now knowing the critical current a setup with the SNSPD and SMM in a circuit with a current just below critical will be sensitive enough to measure to a high degree of accuracy the thermal conductivity of the SMM.

REFERENCES

[1] H. Chen, R. Mahapatra, G. Agnolet, M. Nippe, M. Lu, P. C. Bunting, T. Melia, S. Rajendran, G. Gratta, and J. Long, "Quantum detection using magnetic avalanches in single-molecule magnets," 2020.

[2] J. Hellerstedt, A. Cahlík, M. Švec, B. de la Torre, M. Moro-Lagares, T. Chutora, B. Papoušková, G. Zoppellaro, P. Mutombo, M. Ruben, R. Zbořil, and P. Jelinek, "On-surface structural and electronic properties of spontaneously formed tb_2pc_3 single molecule magnets," *Nanoscale*, vol. 10, no. 33, pp. 15553–15563, 2018.

[3] M. Roos, "Dark matter: The evidence from astronomy, astrophysics and cosmology," 2010.

[4] A. M. Gomes, M. A. Novak, R. Sessoli, A. Caneschi, and D. Gatteschi, "Specific heat and magnetic relaxation of the quantum nanomagnet mn_{12}ac," *Phys. Rev. B*, vol. 57, pp. 5021–5024, Mar 1998.

[5] M. P. Sarachik, "Magnetic avalanches in molecular magnets," 2013.

[6] B. Schumacher, "Quantum coding," *Phys. Rev. A*, vol. 51, pp. 2738–2747, Apr 1995.

[7] D. P. DiVincenzo, "Quantum computation," *Science*, vol. 270, no. 5234, pp. 255–261, 1995.

[8] M. Jenkins, T. Hümmer, M. J. Martínez-Pérez, J. García-Ripoll, D. Zueco, and F. Luis, "Coupling single-molecule magnets to quantum circuits," *New Journal of Physics*, vol. 15, p. 095007, sep 2013.

[9] D. Manzano, M. Tiersch, A. Asadian, and H. J. Briegel, "Quantum transport efficiency and fourier's law," *Physical Review E*, vol. 86, dec 2012.

[10] C. M. Natarajan, M. G. Tanner, and R. H. Hadfield, "Superconducting nanowire single-photon detectors: physics and applications," *Superconductor Science and Technology*, vol. 25, p. 063001, apr 2012.