

Measuring the Thermopower of the Chiral Helimagnet $\text{Cr}_{1/3}\text{NbS}_2$

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Summer Physics REU 2013

August 9, 2013

Abstract

A better understanding of the electrical transport properties of materials offers the potential for many interesting developments in the future, such as thermoelectrics being used to power satellites or reclaim waste energy from engines. The lab I worked in is studying the electrical transport properties of the Chiral Helimagnet $\text{Cr}_{1/3}\text{NbS}_2$. Over the summer I helped to account for the demagnetizing field in our results, prepare a cryostat for use in taking thermopower measurements, and to start taking thermopower measurements of a sample of $\text{Cr}_{1/3}\text{NbS}_2$.

Introduction

$\text{Cr}_{1/3}\text{NbS}_2$ is a crystal formed by the intercalation of Cr atoms between the trigonal prismatic layers of 2H-NbS_2 . The Intercalated Cr strengthens the bonds of the crystal and contributes charge which changes the electronic structure, contributes charges, and contributes magnetic moments [1]. It has multiple magnetic states including a helimagnetic state, a soliton lattice state, and a ferromagnetic state. Interest has been expressed in the possibility of applications for spintronics [1]. Before this summer the lab had been studying $\text{Cr}_{1/3}\text{NbS}_2$ by looking at its magnetization, magnetoresistance, and the Hall Effect. This summer we additionally wanted to be able to look at its thermopower while it is exposed to a magnetic field.

Thermopower is an interesting phenomenon by which a thermal gradient may be used to produce a voltage. By studying these electrical and magnetic properties it is hoped that we will gain a better understanding of how they arise and that this will open new opportunities for using these materials and producing more useful materials in the future.

Since we are largely interested in the electrical behavior inside the sample it was also helpful for us to figure out a way of accounting for the demagnetizing field in our sample in order to have a better idea what the magnetic field inside our sample was like. We used a paper by Aharoni to create Matlab code to calculate a demagnetization factor and to correct our internal field value based on magnetization data which had been taken [1].

We were able to prepare a cryostat for use in taking measurements and to take preliminary data on the thermopower of our sample.

The Demagnetization Correction

Since we are studying $\text{Cr}_{1/3}\text{NbS}_2$ while it is exposed to a magnetic field it is magnetized and it is useful for us to account for the demagnetizing field. The demagnetizing field is a field which occurs in ferromagnetic samples. It is caused by an apparent build up of north and south charges on the surface of the magnetized material [3]. It is called the demagnetizing field because these fictitious magnetic charges on the surface create a field that is in opposition to the field that led to the magnetization [3]. The demagnetizing field, H_D , is proportional to the magnetization and is given by $H_D = NM$, where N is the demagnetizing factor which is determined from the sample geometry and M is magnetization [3]. The internal magnetic field $H_i = H_e - H_D$ where H_i is the internal field and H_e is the external field (Figure 1). The demagnetizing factor is very dependent on the geometry of the sample. We used a long sample which is thin in the direction of magnetization which is a geometry for which the demagnetizing factor is larger.

Since our lab focuses on the electrical and magnetic properties inside the sample it is more useful for us to know the internal field, H_i , rather than the external field, H_e , which we directly controlled. We used an equation from the paper "Demagnetizing Factors for Rectangular Ferromagnetic

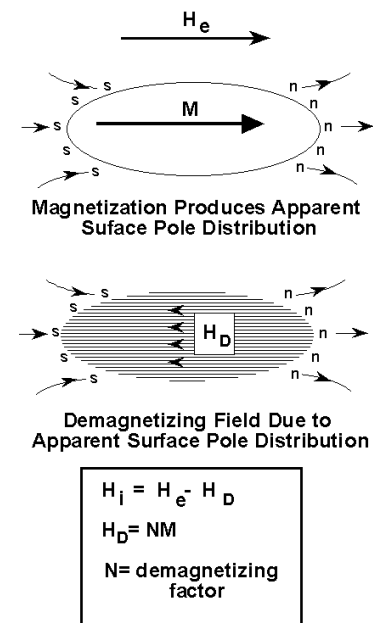


Figure 1 [1]: Illustration of the demagnetizing field; H_e is the external magnetic field, H_D is the demagnetizing field, H_i is the internal field, M is the Magnetization

Prisms" by Amikam Aharoni in order to calculate the demagnetizing factors for our samples. Using those demagnetizing factors and data on magnetization as a function of applied field we were then able to calculate what the internal field was when an external magnetic field was applied during a measurement. For most of the data we are analyzing, the magnetization can be treated as linear to the applied field, and the internal field. This allows H_i to be rewritten as

$$H_i = H_e - N\chi_a H_e = H_e - N\chi_i H_i$$

where χ_a and χ_i are the volume magnetic susceptibilities (slope of Magnetization vs H) for the applied and internal fields respectively. Which may be rewritten as,

$$\frac{H_i}{H_e} = \frac{1}{1 + N\chi_i}$$

This allows us to calculate a correction factor, C_f , such that

$$H_i = C_f H_e$$

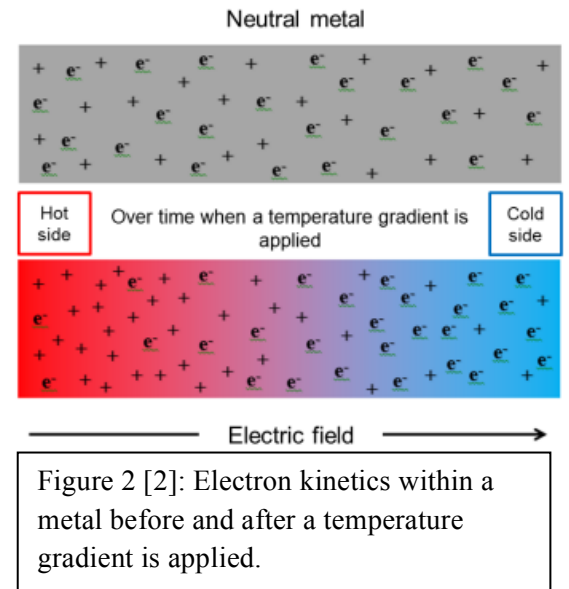
I created a Matlab function to calculate this correction factor which allows us to easily calculate the internal magnetic field for our measurements once we have taken the magnetization data for the sample.

Thermopower Background

Thermopower, also known as the Seebeck effect, is an effect that arises from the fact that charge carriers may also carry thermal energy [4]. This means that charge mobility may be influenced by the thermodynamic state of the system. In particular the Seebeck effect is when a thermal gradient causes charges on one side of a material to have more kinetic energy than those on the other side and to move until there is a charge gradient creating an electric field that causes a force to oppose the further movement of more charges [4]. The Seebeck coefficient, α , is the negative of the ratio of the voltage developed to the temperature gradient ($-\Delta V / \Delta T$), however this ratio is not constant but depends on the temperature of the sample [4, 5].

This process may also be reversed such that thermal energy can be made to be transported by charges moved by electric energy and used to establish a thermal gradient in an effect known as the Peltier effect [4]. The connection between the Seebeck effect and the Peltier effect can be seen in the definition of the Peltier coefficient (Π).

$$\Pi = \alpha T$$

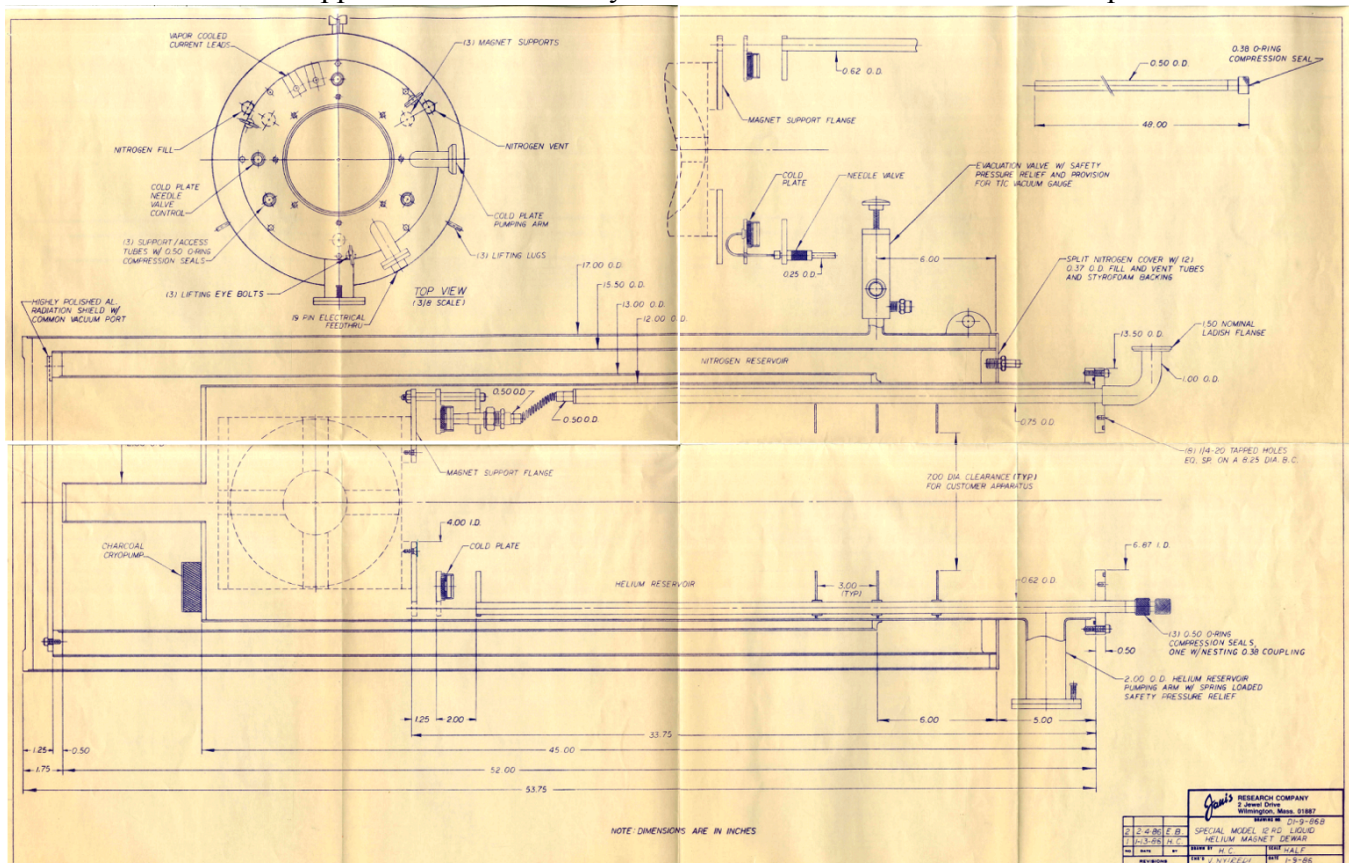


where α is the Seebeck coefficient and T is the temperature in kelvin [5].

Modifying a Cryostat

$\text{Cr}_{1/3}\text{NbS}_2$ has a magnetic ordering below about 130K and we want to study it under strong magnetic fields so we needed to use a cryostat. A cryostat is a device that uses cryogenic fluid, such as liquid nitrogen and liquid helium, to maintain low temperatures and which is used to take measurements. Liquid nitrogen can be used to keep the cryostat at around 77 kelvin and liquid helium at about 4 kelvin. Using a cryostat allows us to both study these materials at these low temperatures and to use a superconducting coil to study the sample under strong magnetic fields. To take thermopower measurements we need to both control the base temperature of the sample and the temperature gradient across it. This required that our sample be at vacuum (less than 10^{-5} torr), so that surrounding gas will not thermally sink the sample.

We used a Janis Liquid Helium Magnet Dewar from the mid-80s that the department had. This cryostat can be used to produce a field up to 7 Tesla. The lab was able to make a probe so that the sample can be put in a canister that could be pumped down to vacuum and the sample mount has wires wrapped around it that may be used as a heater to control the temperature.



These were not the only modifications made to the cryostat. Since liquid helium is an expensive resource we tried to increase the cryostat's insulating ability and decrease the helium boil off rate. As can be seen in Figure 3, the top section of the helium reservoir of the cryostat has a section at the top that is exposed to air without the benefit of the nitrogen reservoir or the vacuum jacket. We also observed that the cryostat built up a layer of frost and ice in this region. We better insulated this region by coating it in a commercially available insulating foam. We also attempted to limit the air flow in the cryostat to help keep it cool. We did this by decreasing the three 7 inch clearance baffles to 2 inch clearance baffles and by making and installing two additional baffles in the upper uninsulated region. We also created small baffles to put in the transfer lines when they are not in use. We additionally raised the helium meter approximately 3.5 inches so that we can reliably fill the helium to a higher level and have a longer period during which we can run the superconducting magnet.

Thermopower Measurement Procedure

As mentioned previously in order to take the thermopower measurement we need to control the temperature of the sample and to create a thermal gradient across it. In order to control the temperature we wrapped a wire around the copper base of the probe, as seen on either side of Figure 4(a), so that by changing the current we may control the temperature of the base of the sample. In order to create the thermal gradient we attach the sample so that it is standing up, as can be seen in Figure 4 (b), so that the gradient can be created without the whole sample being thermally sunk to the copper. In order to create the temperature gradient we used a small resistor attached to the top of the sample as a heater.

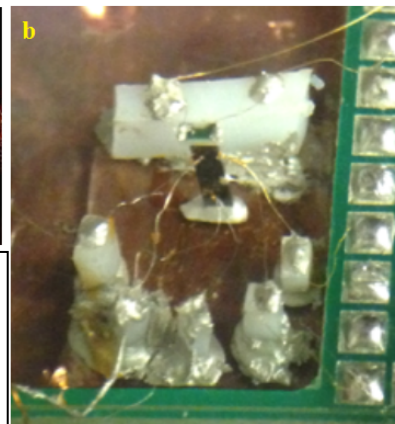
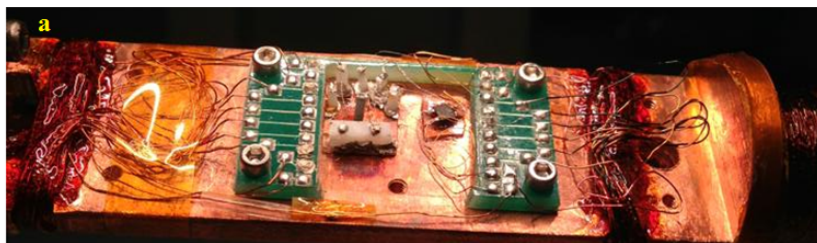


Figure 4: a) Probe with sample attached and heating wire visible on right. b) Better view of sample, with heater on top, and thermocouples and voltage wires attached with Teflon support structures

Interestingly in order to measure the temperature gradient generated we used thermocouples, a sensor which actually uses the Seebeck effect. Thermocouples are a sensor which is composed of two wires each made out of different materials and which are used to measure temperature. Thermocouples use the fact that the two different metals produce a different thermopower voltage when exposed to the same temperature gradient. The voltage measured across the two ends of the thermocouple can then be converted into a temperature if the proper function of the thermocouple is known. By combining two thermocouples with their voltages going in opposite direction, as illustrated in Figure 5, we were able

to directly measure the temperature gradient between the two points. Each thermocouple produces a voltage based on the temperature; by having each voltage measured in the opposite direction we are able to measure the voltage difference between the two points and to convert that into the corresponding temperature gradient. Using a fit of the thermopower voltage verses temperature, supplied by the Omega company that produced the thermocouples, I was able to create a Matlab program to calculate dT/dv . dT/dv is the ratio of the change of temperature to a change of voltage at a given temperature, calculated as the inverse of the derivative of the function of the voltage with respect to temperature. This value may be used to calculate the temperature gradient, ΔT , from the measured voltage difference, ΔV .

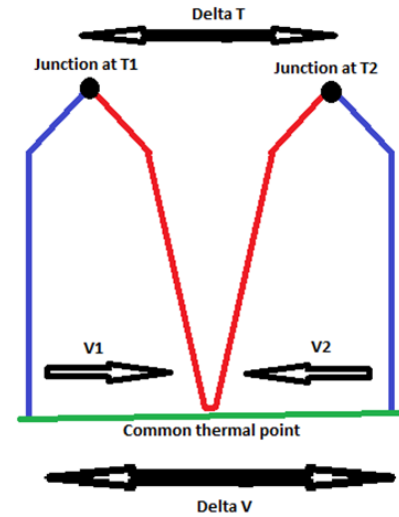


Figure 5: Illustration of how two thermocouples were used to measure a temperature gradient

$$\Delta T = \Delta V * dT/dV$$

Using this measurement and a measurement of a voltage generated across the sample we are then able to calculate the Seebeck coefficient.

$$\alpha = -\Delta V / \Delta T$$

Using these methods we are able to measure the Seebeck coefficient at multiple temperature gradients at several different temperatures.

Results

We were able to start taking data using this system. Initially we cooled down using liquid nitrogen in the liquid helium reservoir. This supplied the data shown as Scan3 WarmUp and Scan3 Cooldown in Figure 6. This data is promising. It has a distinct kink around 130 K which we know to be the Currie Temperature, the temperature below which it has magnetic ordering. T alignment of the data on the up and down temperature sweeps is good; however above 200K we do see a discontinuity that we believe to be related to our method of heating. We hope to be able to identify the cause of this offset and to eliminate it in future measurements. We then proceeded to take data, seen as Scan4 WarmUp and Scan4 Cooldown in Figure 6, at lower temperatures by replacing the liquid nitrogen in the liquid

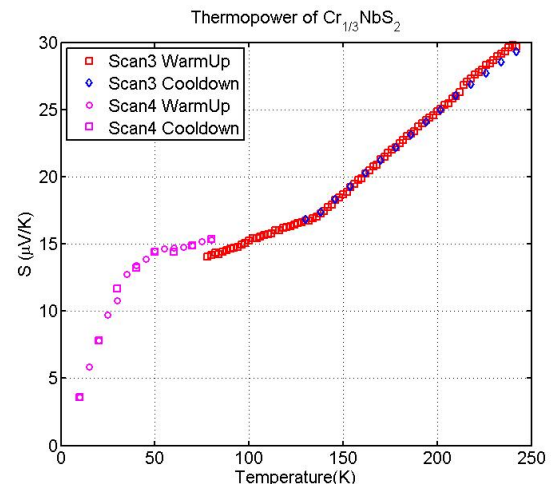


Figure 6: Initial thermopower measurements taken of Cr_{1/3}NbS₂ with no applied magnetic field

helium reservoir with liquid helium. This data shows thermopower going to zero as temperature goes to zero as expected. This data shows has a discontinuity with the previous data. We also believe this to be an effect of how we are heating the probe and that we will be able to improve upon this for future measurements.

Conclusion

Over this summer we were able to prepare a cryostat for taking thermopower measurements in order to study the electrical transport properties of $\text{Cr}_{1/3}\text{NbS}_2$. The system is functional and we are taking preliminary data that should allow the lab to improve the system and to proceed to take measurements of thermopower with the sample exposed to magnetic fields.

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Figure References

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