

Magneto-Electrical Transport in a Novel Material

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This paper examines the magneto-resistance (MR) of low resistance (10Ω at room temperature) thick films composed of mesoscopic size Pt-group oxide particles imbedded in a glass matrix. Measurements were made from 20mK to 1K at various magnetic fields from 0T to 8T. In measuring the MR, a metal-insulator quantum phase transition was observed. This transition happens at a critical temperature T_c that increases as the magnetic field increases.

I. Introduction

This research was motivated by the need for accurate thermometry in significant magnetic fields. Resistance thermometer detectors (RTDs) have been widely used for their ease of use, stability and accuracy over a wide range of temperature. They measure the electric resistance changes in metal or metal-oxide elements. In the presence of an electric field, electrical conduction causes the electrons that were moving randomly to move together in a net flow to a particular direction. In this net flow, the scattering of electrons is caused by thermal motion of ions making up the material. [1]. Thus, the net flow is impeded, causing metal resistance. Since a primary cause of resistance may be due to thermal motion, by measuring resistance, we can calculate temperature.

RTDs consists of two forms, the wire wound devices and the thick film elements. We are interested in the thick film RTDs. They consist of a very thin layer of the base metal-oxide ($25 \mu\text{m}$) which is deposited onto a ceramic substrate and then laser trimmed to the desired resistance value. However, since RTDs' construction includes metal components, there are some disadvantages. For one, they would read inaccurately in the

presence of a magnetic field. RTDs, which read independently of applied magnetic fields, are needed for research and many applications. One such is the study of quantum turbulence.

At the University of Florida, Professor Gary Ihas, in collaboration with the University of Lancaster (England), is studying the decay of turbulence in superfluid ^4He at 20mK. As a superfluid, ^4He flows with no viscosity (no resistance) and can flow without a pressure difference. In ordinary fluids, the Reynolds number (the ratio of inertial force by viscous force) can describe the flow. For a small Reynolds number, there is constant and smooth flow (e.g. pouring honey). For a large Reynolds number, we have turbulence (e.g. hurricane). However, in a quantum field, quantum mechanics restricts superfluids to rotate in quantized vortex filaments, at quantum ground state. That is what we mean by quantum turbulence.

^4He becomes a superfluid at 2.2K. At such low temperatures, we need to create turbulence in such a way that very little to no heat is produced. Therefore, a motor controlled by a magnetic field is used to pull a grid through the liquid helium to create turbulence. This poses a problem for accurate thermometry because most thermometers have metal components and, thus, read inaccurately in the presence of a magnetic field. Therefore, Prof. Ihas is examining different RTDs to find one with a very low magneto-resistance (MR). In one particular case, we are examining 10-ohm (RT) thick film resistors that are 25 μm that are composed of a “complex matrix of metal and metal oxide particles suspended in a glass” [2]. In order to attain this temperature range to test the RTDs, we attach our RTDs to a dilution refrigerator that reaches milliKelvin temperatures. We measure the resistance readings of four samples at varying temperatures from 20mK to 1K and varying magnetic fields from 0T to 8T. Two of our

samples are arranged with the film parallel to the magnetic field, while the other two are arranged with the film perpendicular to the field.

We have found that these RTDs have a very low MR above a critical temperature (T_c). However, below that T_c , we find that the resistance does not depend on temperature. In addition, T_c increases with increasing magnetic fields. Below T_c , we believed to have witnessed a metal-insulator quantum phase transition brought on by a 3D percolation process.

II. Background

Let us define some terms such as quantum phase transition, percolation process and define properties of a metal and insulator. First, a quantum phase transition (QPT) is a phase transition between two quantum phases (phases of matter at absolute zero temperature). The transition describes an abrupt change in the ground state of a many-body system due to its quantum fluctuations [3]. At absolute zero temperature, thermal fluctuations vanish while quantum fluctuations prevail. Although microscopic in nature, these quantum fluctuations are able to induce macroscopic phase transition in the ground state of a many-body system [4]. In addition, QPTs are only induced by varying a physical parameter – such as B-field or pressure – at absolute zero temperature [3].

Let us consider percolation. The percolation process suggests that as conductivity increases, the current begins to flow as the electron ‘hops around’ or percolates throughout the system causing the system to conduct (e.g. becomes metallic) [5]. Variable-range-hopping is a way that electrons percolate through the material, resulting in a higher conductivity. Perfect metals would have a crystal lattice where electrons can move in predictable patterns. However, since we are not working in a perfect metal, but

rather a “complex matrix of metal and metal oxide components,” the electrons do not have a predictable crystal lattice to move through, but a complex, if not random, lattice [6]. In 1968, Mott first pointed out that at low temperatures the most frequent hopping process would not necessarily be to the nearest neighbor. He argued that for the hopping process through a distance with lowest activation energy, there is an energy lost. In addition, the further the electron hops, the smaller the lost of energy. The variable range hopping probability is thus the conductivity [7].

In our case, we witnessed a metal-insulator QPT, where below T_0 , our RTDs acted like an insulator that was still conducting and above T_0 ; they conduct like a metal that has a resistivity that is thermally dependent. Now, insulators are believed not to have conductivity. However, in 1937, Buer and Verwey pointed out that a variety of transition metal oxides that were predicted to be conductors by band theory were, actually, insulators [8]. Mott insulators are a class of materials that are expected to conduct electricity under conventional band theories, but are actually insulators when measured. This effect is due to the electron-electron interaction (EEI), which is not considered in the formulation of conventional band theory [8].

III. Experimental Setup

To work in temperatures ranging from 20mK to 1K, we attached our samples to the mixing chamber of a ^3He - ^4He dilution refrigerator. In any dilute solution, the solute molecules can be considered as a gas whose pressure and volume correspond to the osmotic pressure and volume of the solution. In a dilution refrigerator, dilution of the solution by adding more solvent causes expansion of the solute gas, and cooling results. Since the density of ^3He is less than that of ^4He , at temperatures below 0.87K, solutions

of ^3He and ^4He exists in two liquid phases. During the phase transition of ^3He to ^4He at constant temperature, the entropy increases and heat is absorbed by the ^3He to increase its enthalpy [9]. That is the driving mechanism behind a ^3He - ^4He dilution refrigerator.

We attach Ge sensor thermometers that would help measure the temperature that would be part of our temperature calibration used to compare resistance readings. In addition to the Ge sensors, the fridge is also wired to a CMN thermometer that measures the magnetic susceptibility (approximately T^{-1}), which we also use to compare to the resistance readings. We surround the fridge and our samples with an 8T coil magnet. This magnet, designed and built by Prof. Ihas, has two coil sections, the top and bottom sections. The magnetic field induced in each section is opposite to the other, thus the net effect is to be able to apply up to 8 Tesla on the samples while having zero field on the thermometers and refrigerator. The Ge sensors are arranged to be in this upper section so that it would not be influenced by the magnetic field. Of our four RTDs, two of our samples are placed with films perpendicular to the magnetic field while the other two are arranged parallel to the magnetic field.

In order to obtain a temperature reading from our RTDs, a resistance must be measured so that we can calculate the temperature. Ideally, we can measure the resistance by passing a current through the RTDs and measuring the potential across it. If the current is known, the voltage can be calculated using Ohm's law and the temperature can be determined by the resistance temperature characteristics. However, for accuracy, two more commonly used methods are used: potentiometric and bridge methods [10]. In our case, we have used a Picowatt Bridge to measure the resistance in a two-lead wire arrangement. We measure the resistances from 20mK to 1K and at varying magnetic fields from 0 to 8T.

IV. Results

Without the presence of a magnetic field, we measured the resistances from 20mK to 20K. At these conditions, we observed the thermal-resistance relationship and calibrated the RTDs. We are able to express the thermal-resistance relationship as:

$$R(T) = 10^A T^B \quad \text{or;} \quad (1)$$

$$T(R) = (R/10^A)^{1/B} \quad (2)$$

where A and B are constants determined by a linear fit of the calibration plot (which depends on a particular sample). Figure 1 shows the calibration for Sample 4 at 0T, where A is 1.092 and B = -0.0316.

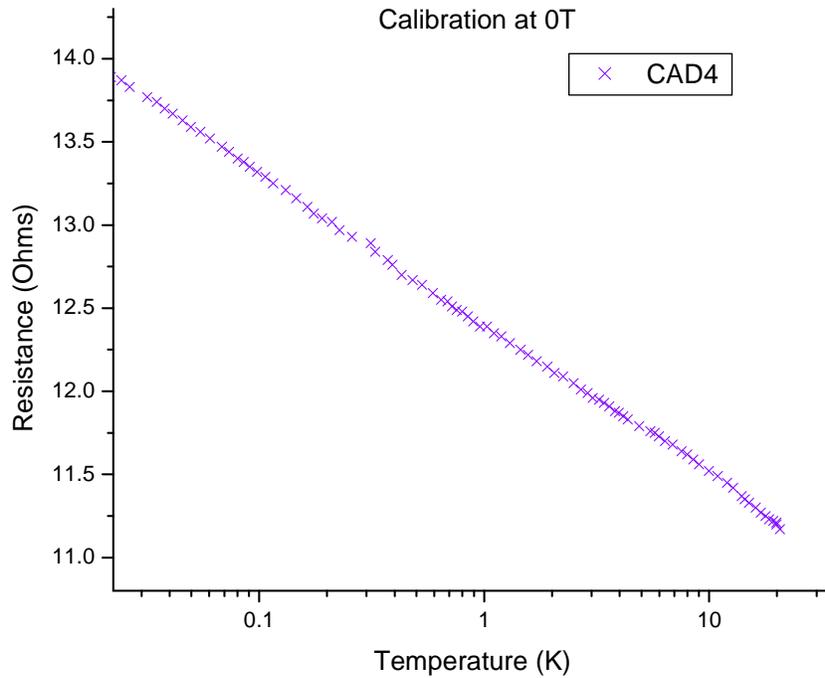


Figure 1: Zero-field resistance vs. $\log(T)$ for Sample 1.

Due to different arrangements of the samples in accordance with the magnetic field, we have grouped Samples 1 and 2 together to represent the perpendicular

arrangement. Figure 2 shows the resistance measured by Caddock Samples 1 and 2 at various temperatures at 0T. Since Sample 1 shows more electrical noise than Sample 2 data, we took Sample 2 to represent the perpendicular arrangement to the magnetic field. The noise may be due to insufficient settling time between changing the temperature to measuring the resistance. Figure 3 shows the resistance measured by Samples 3 and 4 at various temperatures at 0T. The data shows little noise and we see that both samples read almost identical resistances at various temperatures. We will study Sample 4 as a representative of the parallel arrangement.

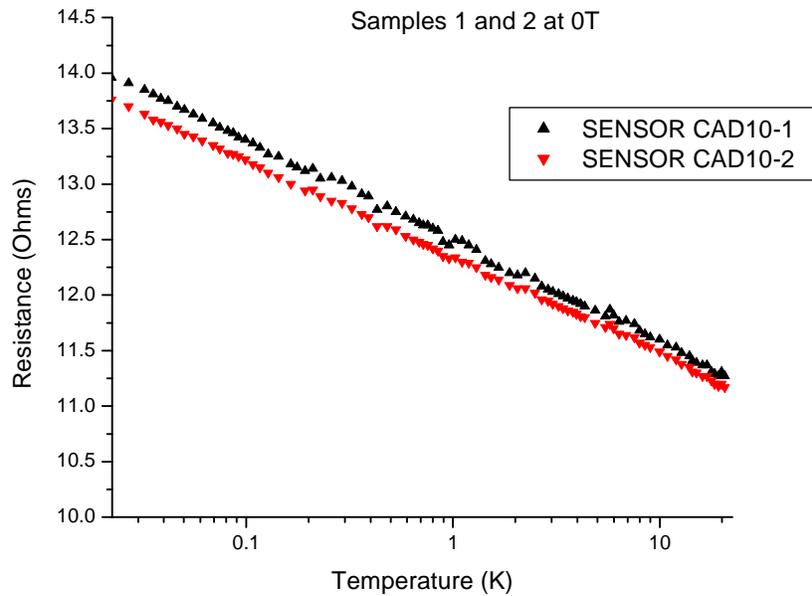


Figure 2: Zero-field resistance vs. $\log(T)$ for Sample 1 (black) and Sample 2 (red). Due to electric noise, Sample 1 data is less linear than that of Sample 2.

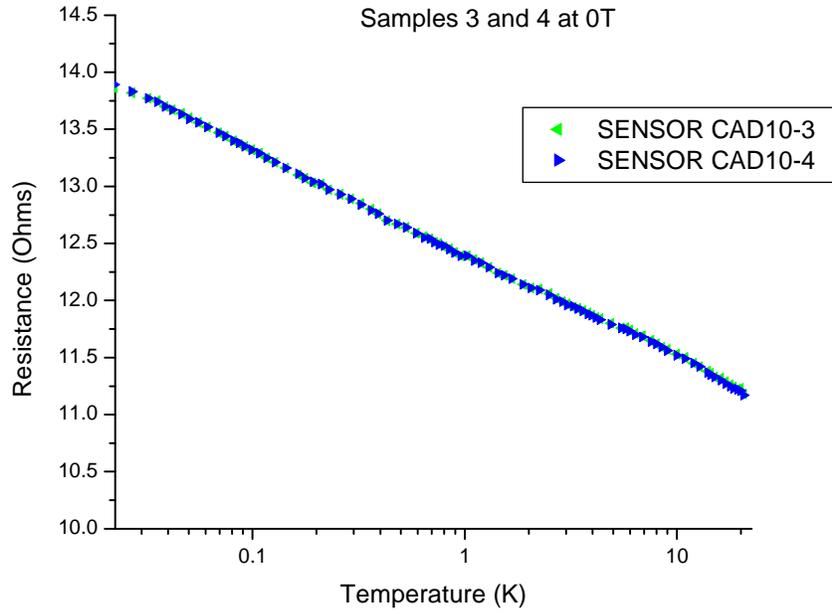


Figure 3: Zero-field resistance vs. $\log(T)$ for Sample 3 (green) and Sample 4 (blue).

In the presence of a magnetic field, we notice a step in our data. Figure 4 represents the resistances measured by Samples 2 and 4 at various temperatures in the presence of a 1T magnetic field. The step is most visible in Sample 4. We see that below 45mK, Sample 4 (parallel) shows a step in the resistance. Below 35mK (our critical temperature T_c in this case), we see that the resistance seems to be independent of temperature. Above T_c , the resistance seems to drop rapidly before returning to its original behavior seen at 0T. However, Sample 2, which is set perpendicular to the magnetic field, does not seem to show a point where the resistance is independent of temperature. There seems to be constant behavior for Sample 2 at 1T.

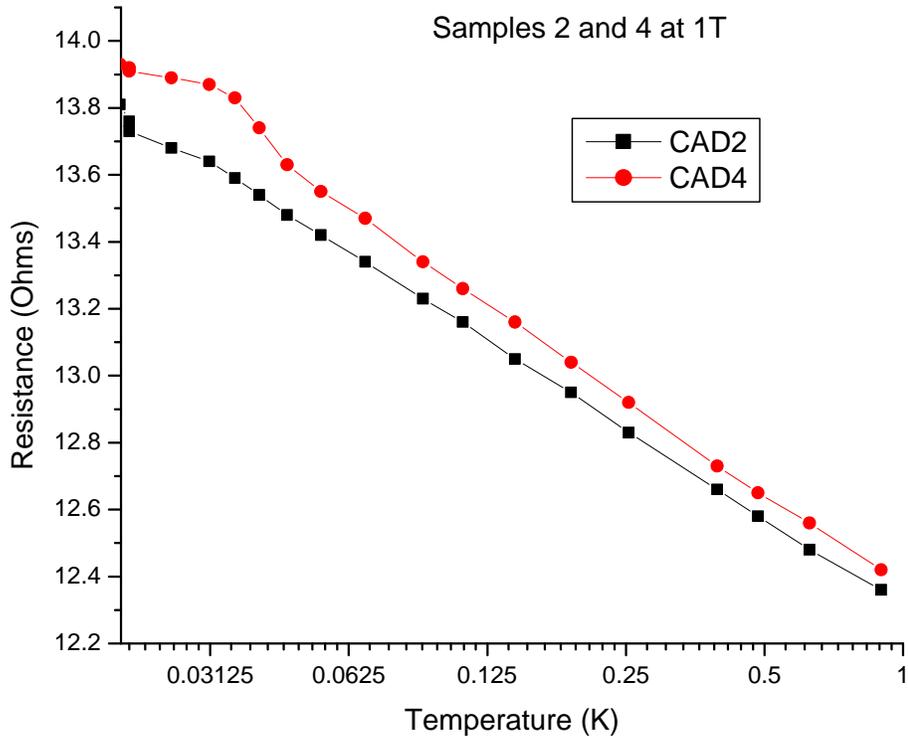


Figure 3: Resistance at 1T vs. $\log(T)$ for Sample 2 (black) and Sample 4 (red). Below 45mK, the resistance of Sample 4 is not linear in $\log(T)$, like it is at higher temperatures.

We see the phenomenon more clearly at a higher magnetic field. Figure 5 shows the same samples at 8T. The Sample 4 resistance readings show an independency to up to 125mK (T_c), and the resistance does not return to its original behavior (seen at 0T) until about 0.2K. Sample 2 readings shows a similar behavior but is not as dramatic as the Sample 4 readings.

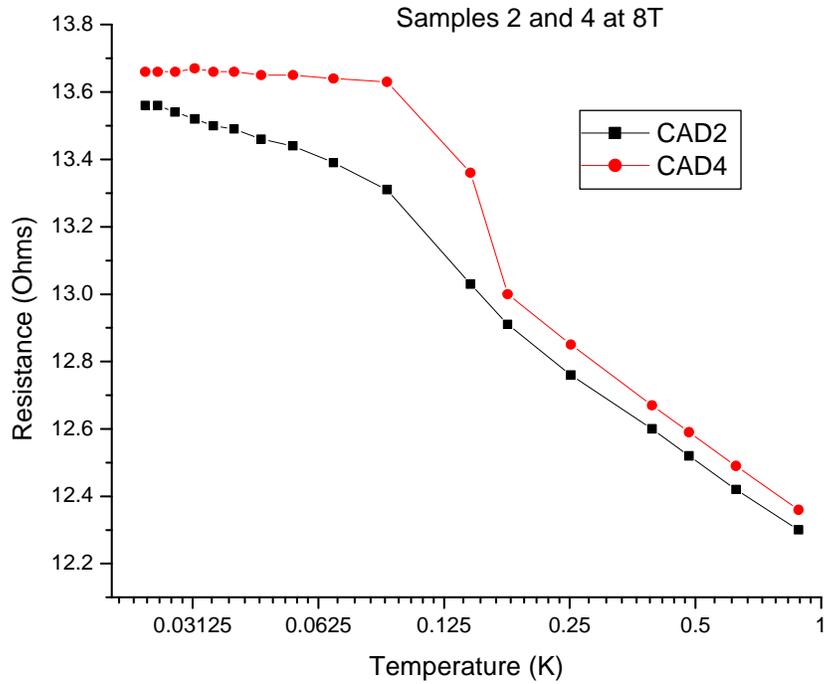


Figure 4: Resistance at 8T vs. $\log(T)$ for Sample 2 (black) and Sample 4 (red).

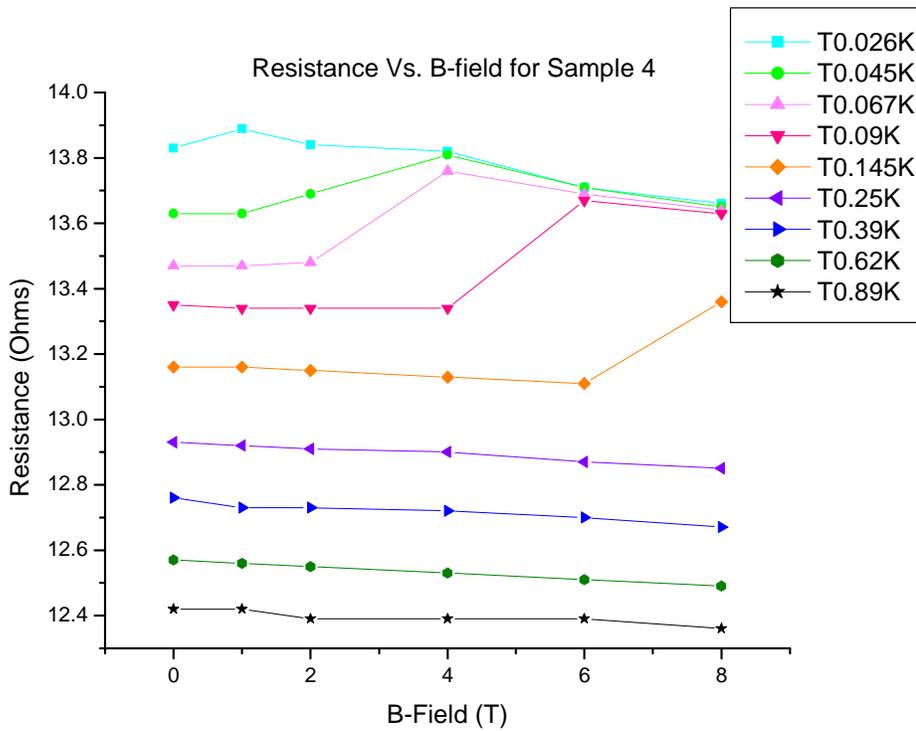


Figure 5: Resistance vs magnetic field for Sample4. Each line shows the variation of resistance with magnetic field at a fixed temperature between 26 and 890 mK.

We also examined the change in resistance with respect to magnetic field at constant temperatures seen in Figure 6. Figure 6 shows that for temperatures above 0.25K, there is little MR (resistance dependency on magnetic field). The resistances measured by Sample 4 at those temperatures seem to decay slightly as we increase the magnetic field. However, above 0.25K, we see that the resistances seem to converge to one value at 6T and 8T. This is because at those low temperatures and at those high magnetic fields, the resistances at that point are independent of temperature; therefore, they converge to the same point.

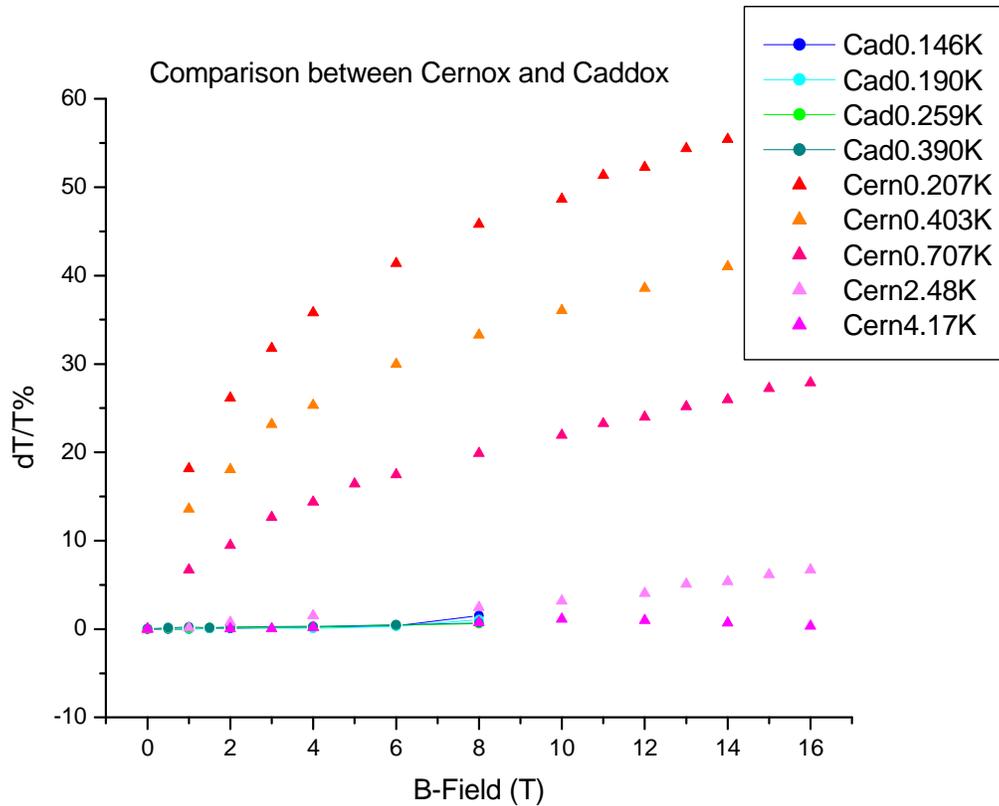


Figure 6: Magnetoresistance of Caddock Sample 4 and a Cernox sample at various temperatures.

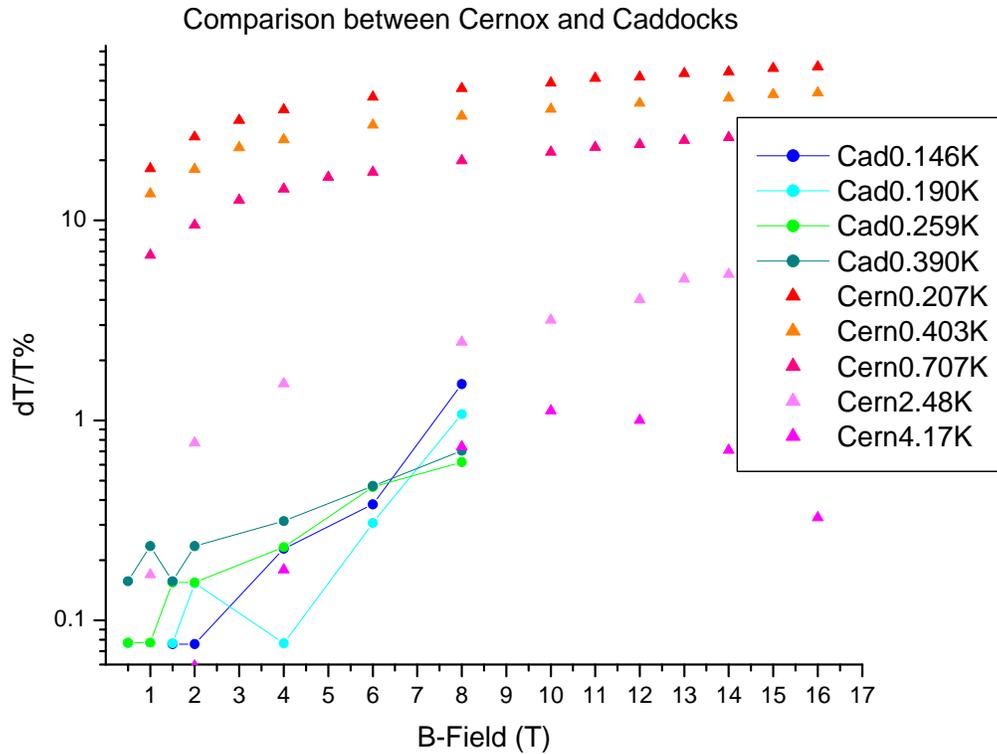


Figure 7: Data from Figure 7 shown on a log-linear plot, which magnifies the data closest to zero.

We have compared the MR of the Caddock samples to Cernox RTDs (previously observed by Prof. Ihas). Figure 7 compares the MR of the Caddock Sample 4 to a Cernox sample at various temperatures as a function of magnetic field. Normally, as temperature is lowered, MR increases. We see that at low temperatures, the Caddock samples have low MR effects compared to the Cernox samples. The Caddocks sample at 190mK has less than 1 dT/T% MR effect, while the Cernox sample at 207mK starts with an 18 dT/T% and increases as the magnetic field increases. The complex behavior of the Caddocks samples may be due to electric noise.

V. Conclusion

Originally, our goal was to find RTDs with little to no MR effects. We were successful, in that we found MR effects of less than 1 dT/T%. This is incredibly low compared to Cernox samples. The Caddock samples showed little MR effects at high temperatures and at low temperatures and high magnetic fields. However, at low temperatures (below 0.25K) and at high magnetic fields (above 4T), the resistances are independent of temperature but dependent on the magnetic field.

We think that this phenomenon is a metal-insulator quantum phase transition. It is a metal-insulator QPT because at temperatures below T_c , the RTDs have Mott insulator characteristics where they have low electric and thermal conductivity and a high resistance. The drop from the plateau of thermal independent resistivity may be representing the percolation process, where the electrons have migrated to another band conduction, changing the phase of the system from insulator to metal. Further investigation of this phenomenon may result in more a comprehensible explanation. Further study would open many new perspectives to quantum computing as well as a better understanding for strongly correlated systems, which are fundamental to effects such as conductivity.

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