

An Investigation of the Magneto-Resistance and Quantum Phase Transitions of Cryogenic Sensors

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Abstract

Using a ^3He - ^4He dilution refrigerator to obtain required, low temperatures, the quantum phase transition of a selected material was investigated. From a temperature range of approximately 25mK to 20K, the magnetic field imposed on a cryogenic sensor was varied from 0 to 8T to attempt to study and further characterize this quantum transition. Moreover, attention was given to the orientation of the sensor in the magnetic field induced upon it. After studies were completed, quantum phase transitions were assumed to be found as the magnetic field changed. These assumed transitions occurred at critical temperatures (T_c) that varied as the magnetic field changed. Finally, magneto-resistance was discovered in these sensors as the magnetic field was altered.

I. Introduction

Stimulated by the ongoing efforts to find a technique of measuring relatively low temperatures in considerable magnetic fields, this research also examines the quantum phase transition of the sensors used in this thermal study. These sensors are electrical resistance thermometers (or RTD's) that exploit the predictable change in electrical resistance of some materials with changing temperature [1]. Such thermometers function by measuring a voltage drop across a resistor while a constant current is passed through the resistor. Afterwards, a change in resistance can be measured. This change can then be associated with a temperature change after a temperature calibration has been performed.

Recent studies performed by Dr. Gary Ihas and a former REU physics student, Arthtiya (Annie) Thebprasith, revealed a quantum phase transition in a material used in commercial high-precision resistors. (The material was Caddock samples prepared by placing Pt-group particles in a matrix). These transitions occurred in these devices once they were introduced to varying magnetic fields ranging from 0 to 8 teslas. Taking advantage of the recent research, we will attempt to further explore the quantum phase transition in a selected material. For example, we are able to limit the range in which we take our data because recent studies have shown that the transitions occur at a particular temperature in a given magnetic field. Given that the sizes of the sensors used in recent studies are not identical, this presents the possibility of a slight variation in the location of the transitions.

II. Background

Magneto-Resistance

Magneto-resistance and orientation of the samples used in this study will be taken into consideration. Magneto-resistance is a property of materials that indicates how the resistance of the material changes as it is introduced to varying magnetic fields. In order to achieve the desired, accurate thermometry, our experiment will seek to expose sensors that show a deviation in temperature measurements as the magnetic field introduced to certain materials is varied up to 8 T. The sensors' accuracies will be based on how much a temperature calculation changes as the magnetic field varies. The

accepted temperature for a given resistance will be taken as the calibrated temperature, which is the temperature calculated from data taken at zero Tesla. If magneto-resistance occurs, this study will seek to explore the effects that the placement of the samples relative to the magnetic field has on temperature calculations. One of the samples will be placed parallel to the field, and the other sample will be placed perpendicular to the magnetic field. Nonetheless, orientation of the samples will be trivial if minimal magneto-resistance is observed in this study.

Quantum Phase Transitions

In the field of condensed matter physics, quantum phase transitions have become a topic of great interest [3]. Such transitions occur between different quantum phases, and quantum phases are the different phases of matter at absolute zero temperature [1]. Quantum phase transitions can be obtained only by varying a physical parameter such as magnetic field or pressure near zero temperature, and they are observed at a critical temperature (T_c). Opposed to the classical phase transitions, which are associated with changes in temperature, quantum phase transitions are caused by quantum fluctuations [4]. The transition describes an abrupt change in the ground state of a many-body system due to these fluctuations. Moreover, it must be noted that absolute zero has not yet been reported to be reached by any experimentalist. Thus, the near-zero temperatures reached in experiments

where quantum phase transitions are expected to occur are sufficient draw accurate conclusions.

Thermometry

The main method of thermometry used in this study is metallic resistance thermometry. Since the resistivity of pure metals varies temperature, metals have been widely used as simple and reliable temperature-measuring devices [2]. However, many elements or compounds are not suitable for use in low-temperature resistance thermometry because they lack some of the necessary properties of an ideal resistance thermometer [2]. These properties include a resistivity that varies linearly with temperature to simplify interpolation, high sensitivity, high stability of resistance so that its calibration is maintained over long periods of time and is not affected by thermal cycling, and the capability of being mechanically worked [2].

The RTD's introduced are optimal for this study because they possess some of these required properties. However, other forms of thermometry are required in order to obtain accurate temperature readings in different temperature regimes. Cerium magnesium nitrate (CMN) Thermometry is an example. CMN is a paramagnetic salt; thus, the CMN thermometer functions by measuring the magnetic susceptibility of the salt as it is exposed to different temperatures. This thermometer has been shown to be very sensitive in the temperature range of 27 mK to approximately 0.5 K. Beyond this range, other cryogenic

sensors have been tested to have relatively high sensitivities, and they will be used to take accurate temperatures in their respective regimes.

III. Experimental Arrangement

In order to obtain the temperature range that this experiment required (25 mK to 20 K), our RTD samples were attached to the mixing chamber of a ^3He - ^4He dilution refrigerator, and a sample was also placed on the cryostat of the refrigerator. This sample was a dual-function sensor thermometer (DFST). A dilution refrigerator is a cryogenic device that uses a mixture of two isotopes of helium: helium-3 and helium-4. When cooled below 700 mK, the mixture undergoes spontaneous phase separation to form a ^3He -rich phase and a ^3He -poor phase [5]. Energy is required to transport helium-3 atoms from the ^3He -rich phase into the ^3He -poor phase, and if the atoms can be made to continuously cross this boundary, they effectively cool the mixture [5]. This is the mechanism that enables the refrigerator to achieve the low temperatures required in cryogenics. Also, a Burns thermometer is attached to the mixing chamber to assist in calibrations and resistive comparisons. Additionally, the refrigerator is equipped with a CMN thermometer, attached to the mixing chamber as well, that measures magnetic susceptibility (which is close to T^{-1}). These measurements are used to make a 0-T calibration, and they are used to compare resistance/temperature readings at different magnetic fields. The dilution refrigerator is surrounded by an 8-T coil magnet built by Prof. Ihas. Because of its unique design of opposing sections, up to 8 teslas can be applied

on the samples while having zero field on the thermometers and refrigerator[6]. The Caddock RTD samples were arranged with one sensor being perpendicular (“vertical”) to the magnetic field and the other sensor being parallel (“horizontal”) to the magnetic field.

The RTD’s used in this study required a way of measuring resistances from these samples in order to compute a temperature value for these samples. The traditional way of measuring the samples’ resistances is to pass a current through the RTD’s and measure the voltage drop across them. Using Ohm’s laws, the resistance can be calculated if the value of the current used is known [6]. Then the temperature can be computed from the temperature resistive properties of the samples [6]. However, this method’s accuracy is not acceptable in the realm of modern cryogenics. A more accurate method that was used in this project was the bridge method. Using a picowatt bridge, the resistances in two lead wire arrangements were measured from 25 mK to 20 K while varying the magnetic field from 0 T to 8 T [6].

IV. Results

In the absence of a magnetic field, resistance readings were taken over a temperature range of 25 mK to 20 K. These resistances were then used to make a calibration for the RTD Caddock samples that were oriented parallel and perpendicular to the magnetic field. The calibration was divided into three different temperature ranges: (1) 25.34-315.31 mK, (2) 346.58 mK-4.697 K, and

(3) 5.95 to 19.64 K. The temperature-resistance relationships for these ranges can be expressed respectively as:

$$\text{Regions 1 and 2: } T(R) = y_0 + (2A/\pi) * (w / (4(R-x_0)^2 + w^2))$$

$$\text{Region 3: } T(R) = A_2 + (A_1 - A_2) / (1 + e^{((R-x_0)/dx)})$$

In Regions 1 and 2, y_0 , A , x_0 , and w are parameters that were determined by Lorentz fits for these regions. In Region 3, A_1 , A_2 , x_0 , and dx are parameters that were obtained from a Boltzmann fit. Figure 1 gives a calibration for both Caddock samples at 0T where all the parameters in each region, for each orientation, are nonzero numbers.

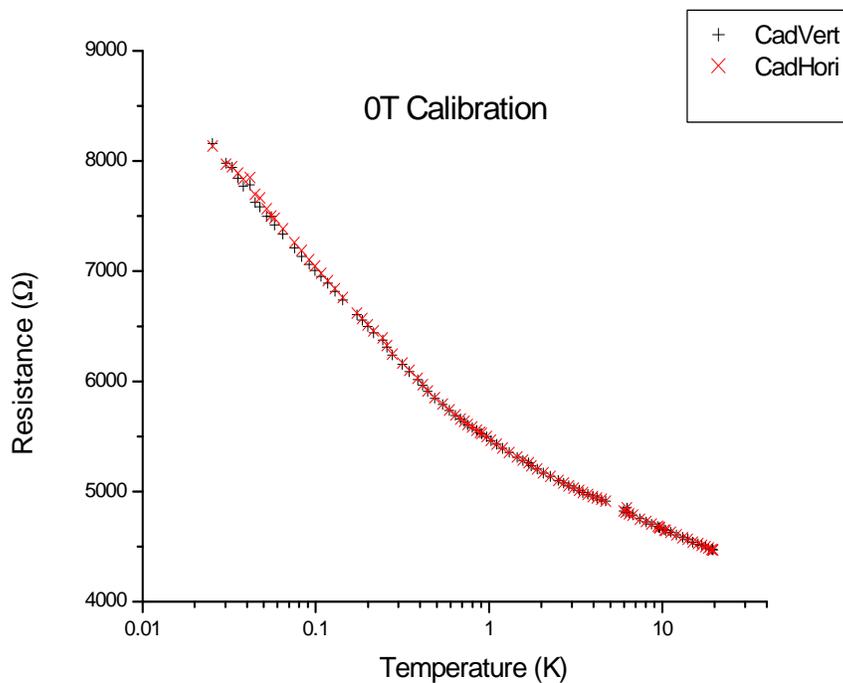


Figure 1: Resistance-temperature relationship for both Caddock samples at 0 T over a temperature range of 25 mK to 20 K on a linear(R) vs. log(T) plot.

When a magnetic field was introduced to the Caddock samples, there was a difference between the plots of these magnetic field data and the data taken at 0 T. For the data taken at magnetic fields other than zero, the plots show a step in the data, and this is where it was conjectured that a quantum phase transition occurred. As the magnetic field was increased, the assumed transition became more apparent. Moreover, the occurrence of the suspected transition was independent of the orientation of the Caddock samples. This is why we cannot confidently conclude that the steps in the plots refer to quantum phase transitions. Thus, these steps may indicate a discontinuity of thermal contact in samples as the data was taken. The relatively small changes in resistance up until the jump in the data may be indicative of such an event. Figures 2 and 3 show a plot of the resistances of the vertical Caddock sample at 4 T and 8 T.

In both figures, the assumed quantum phase transition occurred at critical temperatures in the millikelvin range, which was expected because of the nature of quantum phase transitions. These critical temperatures T_c were respectively 47.47 mK and 57.28 mK for the 4-T and 8-T data recorded for the vertical Caddock samples. In these figures, the resistances were not dependent upon the temperatures until after the critical temperature was passed, and beyond the critical temperature, the 4-T and 8-T data behaved similar to the data at 0 T (a linear temperature-resistance relationship).

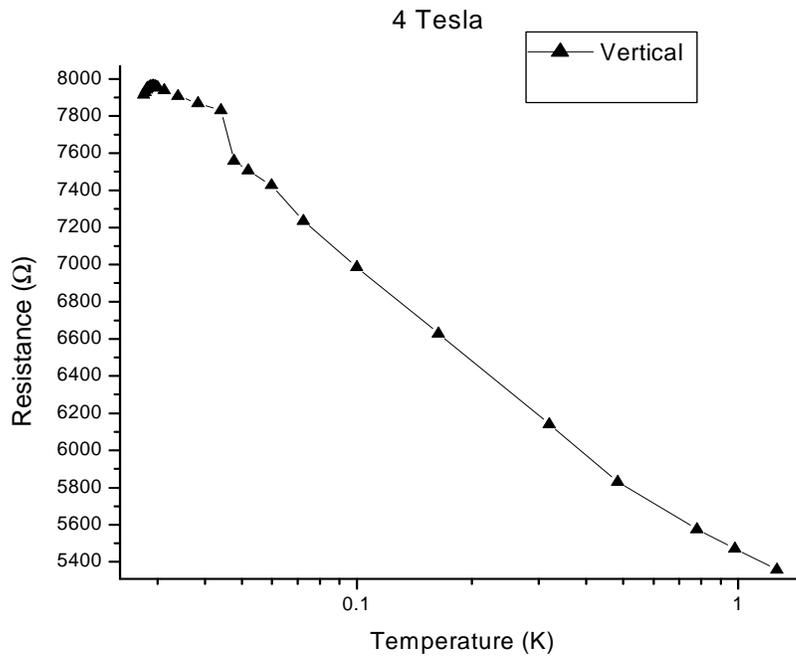


Figure 2: Resistance-temperature relationship in the vertical Caddock sample at 4T from 27 mK to 1.26 K on a Linear(R) vs. Log(T) plot.

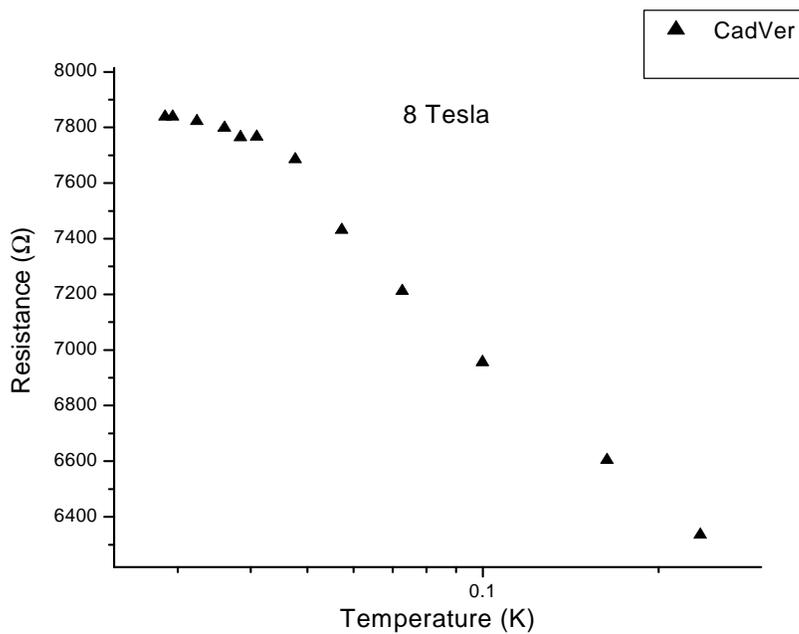


Figure 3: Resistance-temperature relationship in the vertical Caddock sample at 8 T from 27 mK to 1.26 K on a Linear(R) vs. Log(T) plot.

In order to test for magneto-resistance in the Caddock samples, the 0-T calibration was compared to temperature-resistance readings of the Caddock samples in different magnetic fields. Thus, the percent change between the temperature calculated from a 0-T calibration fit and the temperature calculated from the fit of another magnetic field was plotted to show magneto-resistance. Figure 4 shows the effects of magneto-resistance in a 6-T field for a Caddock sample placed perpendicular to the field.

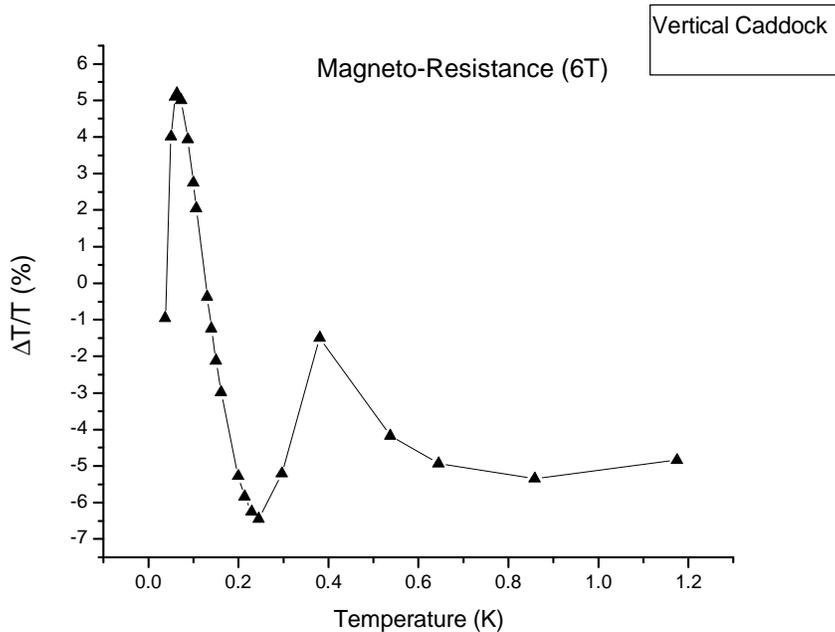


Figure 4: Percentage in temperature that a Caddock, placed vertical to a 6-T magnetic field, would deviate from true temperature if it were to be used as a thermometer from 37.44 mK to 1.175 K in this field.

A Caddock placed horizontal to a 6-T magnetic field was found to read at most 6.5% lower and 5.4% higher than the true temperature within temperature range from 37 mK to 1.2 K. The data did not reveal any organized pattern as to how a Caddock sample would be magneto-resistant in this 6-T field. However,

it must be noted that the Caddock sample consistently read temperature values that were lower than the true temperatures for given resistances for the temperature range of 130 mK to 1.2 K.

V. Conclusion

In an effort to further explore quantum phase transitions discovered in RTD's by previous studies, this research was conducted using a dilution refrigerator to operate at temperatures ranging from 25 mK to 20 K. At magnetic fields of 4 T and 8 T, the data showed consistent, possible quantum phase transitions. However, these transitions were not as apparent as the ones discovered in previous studies, and they occurred in both perpendicular and parallel orientations to the magnetic field. Therefore, firm conclusions could not be made about these assumed transitions. Nonetheless, these supposed transitions occurred at different temperatures when different magnetic fields were induced on the Caddock samples. Moreover, after the critical temperatures were passed for each supposed transition, the data at each magnetic field resumed behavior similar to the 0-T calibration for the samples. Also, it is possible that the relatively small resistance changes up until the critical temperatures at the different magnetic fields were due to a discontinuity of thermal contact. Additionally, once introduced to a 6-T magnetic field, magneto-resistant behavior was observed in the Caddock sample placed perpendicular to the magnetic field.

Further studies in this area of research may involve an attempt to reproduce robust quantum phase data and a closer look at the effects of varying magnetic field on RTD's. Afterwards, better thermometry can possibly be developed in cryogenics, and this may be pivotal to the advances that this field of research is yet to experience.

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