The Effect of Uniaxial Pressure on the Superconducting Transition Temperature of $CeMIn_5$

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Abstract. Uniaxial pressure applied to $CeCoIn_5$ and $CeIrIn_5$ along either the a or c axis changes the superconducting transition temperature, T_c. T_c is measured using both resistivity and susceptibility. It has been found that as pressure is applied to a $CeCoIn_5$ sample along the c axis T_c decreases.

1 Background

A class of heavy-fermion materials known as 1-1-5 metals, $CeMIn_5$, where M is a transition metal Co, Rh, or Ir, exhibit superconductivity properties similar to those of high temperature superconductors. One such property of these materials is that its crystal structure results in alternating layers (1) (Fig. 1), with a lattice constant a within each layer and a lattice constant c between layers such that the ratio c/a can be altered by applying uniaxial pressure along one of the axes. As this ratio changes, the critical temperature, T_c, at which the material becomes superconductive, changes. A previous study (2) found that as pressure is applied along the a axis of $CeCoIn_5$, T_c increases as it tends to do with most $CeMIn_5$, however it was also found that as pressure is applied along the c axis T_5 rises as well but at a slower rate. This is unusual behavior that differs from other $CeMIn_5$ materials. As a material becomes superconductive, its resistivity drops to 0 and its magnetic susceptibility increases from 0 as it begins to act as a diamagnet and any external magnetic field is expelled in what is known as the Meissner Effect. These two effects do not necessarily occur at the same temperature because the Meissner Effect requires the entire surface to become superconducting so external magnetic fields can be expelled but the measured resistivity of a sample dropping to 0 requires only a single line of superconducting material through the sample. In $CeIrIn_5$ is it known that the resistivity T_c is 3 times larger than the susceptibility T_c but it is not known how this changes under uniaxial pressure.

2 Procedure

2.1 Susceptibility Measurements

The susceptibility of a sample is measured using a susceptibility coil which consists of two nearly identical secondary coils wound in opposite directions placed inside a primary coil. A current is passed through the primary coil which creates a magnetic field which

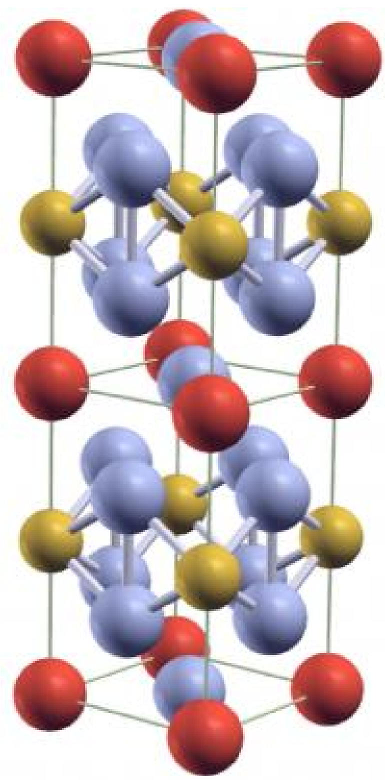

Figure 1. Unit cell for a 1-1-5 metal. The a axis is within each layer and the c axis is perpendicular to the layers

in turn induces emfs in both of the secondary coils that nearly cancel each other out. A sample is positioned inside one of the coils and as long as T > T_c, the sample has little effect on the magnetic field inside the coils, but at T < T_c the sample becomes diamagnetic and expels the external magnetic field beyond the secondary coil it is located in. When this occurs, the induced emf in the coil with the sample decreases and the difference in the induced emfs is a measure of the sample's susceptibility.

2.2 Resistivity Measurements

In order to measure the resistivity of a sample, a standard 4-wire measurement set-up is used. Four wires are attached to the sample and a current is passed through two of them while voltage is measured across the other two and using Ohm's Law the resistance can be found. The 4 wire measurement is necessary instead of a simple 2 wire measurement because the resistance of the samples are on the order of $10^{-2}\Omega$ while the resistance of the wires is around 300Ω, so the change in the total resistance as the sample becomes superconductive would be negligible. Several different methods of attaching leads to the samples were tried but the most effective was silver epoxy and silver paint. Copper wire is stripped and flattened so it can lie against the sample with maximum contact. Both the sample and the wires are cleaned with acetone and dilute HCl to ensure clean surfaces with minimum resistance. The sample is varnished on a spacer and the wires are lined up against the sample and held in place with varnish. A small dab of silver epoxy is put over each wire and side of the sample, leaving most of the stripped wire exposed. After the epoxy dries, silver paint is applied over the rest of each exposed wire touching the sample to decrease the contact resistance. The ideal contact resistance is around 1Ω, however if it is higher, it has been found that passing AC current between 100-1000 Hz and 1-2 V through the leads can lower the resistance (3). It is important to note that the samples used for the resistivity measurements should be as long and as thin as possible so that the total resistance of the sample is maximized.

2.3 Samples

The two materials being studied are $CeCoIn_5$, T_c = 2.3K, and $CeIrIn_5$, T_c = 0.4K, using susceptibility and resistivity measurements respectively to find Tc of each. X-ray diffraction is used to initially select the desired orientation of the sample being used. Either the $CeCoIn_5$ susceptibility or the $CeIrIn_5$ resistivity sample is polished flat such that uniform pressure can be applied to it. X-ray diffraction is then used again to confirm the orientation of the sample so it is known which axis is being compressed. The $CeCoIn_5$ sample is then placed between stainless steel spacers, using varnish to hold it to the lower spacer, and inserted into a susceptibility coil, whereas the $CeIrIn_5$ sample with the 4 leads attached is simply placed between the spacers and held in place with varnish (Fig. 2). Once the sample is mounted between the spacers, the spacers are placed inside the pressure column on a dilution refrigerator.

2.4 Fridge

The samples are secured such that they are in good thermal contact with the fridge, which is made of stainless steel for durability but coated with copper foil to increase thermal conductivity. The fridge is cooled using a 1K pot and a ^{3}He-^{4}He mixing chamber. The 1K pot works by pumping on a container of liquid helium and is sufficiently cold to measure the T_c of $CeCoIn_5$. In order to achieve the temperature needed to observe the $CeIrIn_5$ T_c, a mixing pot which evaporates ^{3}He into ^{4}He is needed. A heater at the mixing chamber allows temperature control so it can be scanned across T_c multiple times at a controlled rate. The cooling elements and the sample are put in good thermal contact with each other using copper foil. There are also thermometers placed both at the mixing chamber and at the sample. The fridge is sealed in a vacuum chamber and placed in a Dewar of liquid ^{4}He.

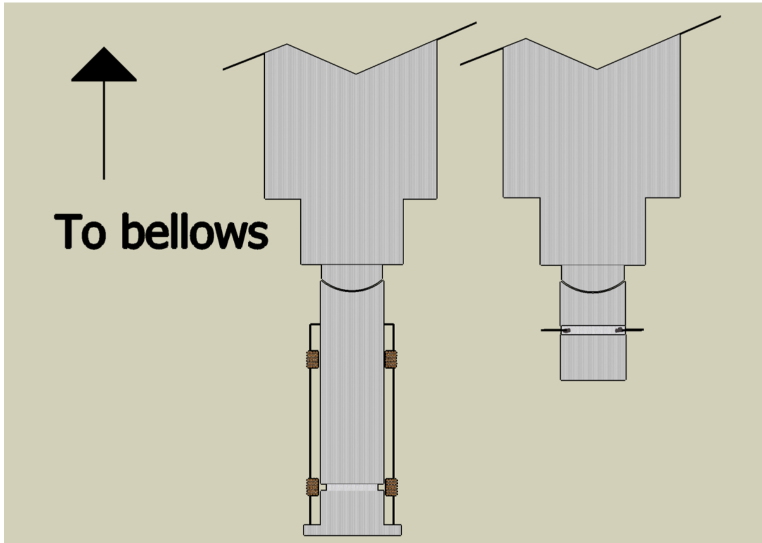

Figure 2. Susceptibility sample mounted between spacers inside coil (left) and resistivity sample between spacers (right)

2.5 Uniaxial Pressure

The sample is located at the bottom of the refrigerator inside a pressure column with a bellows at the top. ^{4}He gas is put into bellows above the pressure column and the resulting force is measured using a piezoelectric. The force measurement is converted into a pressure based on the surface area of the sample.

3 Results

3.1 $CeCoIn_5$ Susceptibility

One set of susceptibility data was collected for a $CeCoIn_5$ sample.

3.1.1 Sample Temperature

The sample thermometer was not attached for the run so the only temperature data was from the fridge thermometer which is not equal to the sample temperature. I wrote a program that numerically solved for the sample temperature with Newton's Law of Cooling

$$-k(T_{sample} - T_{fridge}) = \frac{dT}{dt} \approx \frac{T_{sample}(t + \Delta t) - T_{sample}}{\Delta t} \tag{1}$$

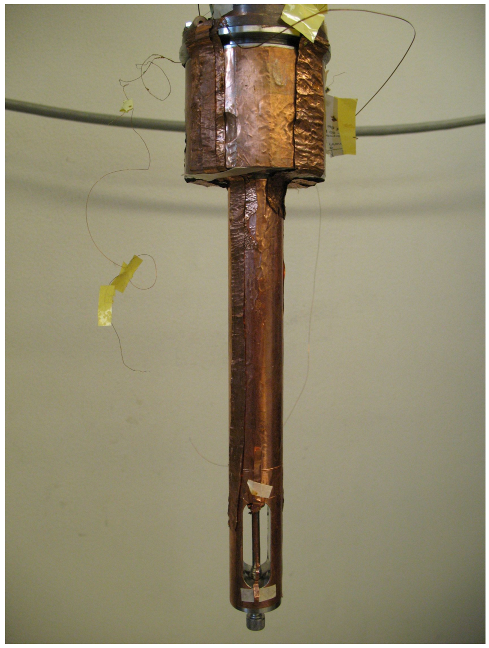

Figure 3. Pressure column located at the bottom of the refrigerator. The bellows is the wide part at the top and the sample is located in the open space near the bottom

which was rearranged to be

$$T_{sample}(t + \Delta t) = \frac{T_{fridge}(t + \Delta t) + \frac{k * T_{sample}(t)}{\Delta t}}{1 + \frac{k}{\Delta t}} \qquad (2)$$

where the time constant was found to be 160 sec. This was found by using a data set where the temperature oscillated back and forth such that the susceptibility vs. temperature graph had loops. The sample temperature was simulated using different time constants until the loops lined up.

Fig. 4 shows the fridge thermometer data in blue and the simulated sample temperature in red.

3.1.2 Transition Temperature

Fig. 5 shows the susceptibility vs. temperature graph of $CeCoIn_5$ as it passes through its T_c of around 2.3 K. T_c is measured as the point where the susceptibility first begins to deviate from 0. T_c is found for several different pressures and plotted as such to yield a graph that shows how T_c changes as $\frac{c}{a}$ varies (Fig. 6).

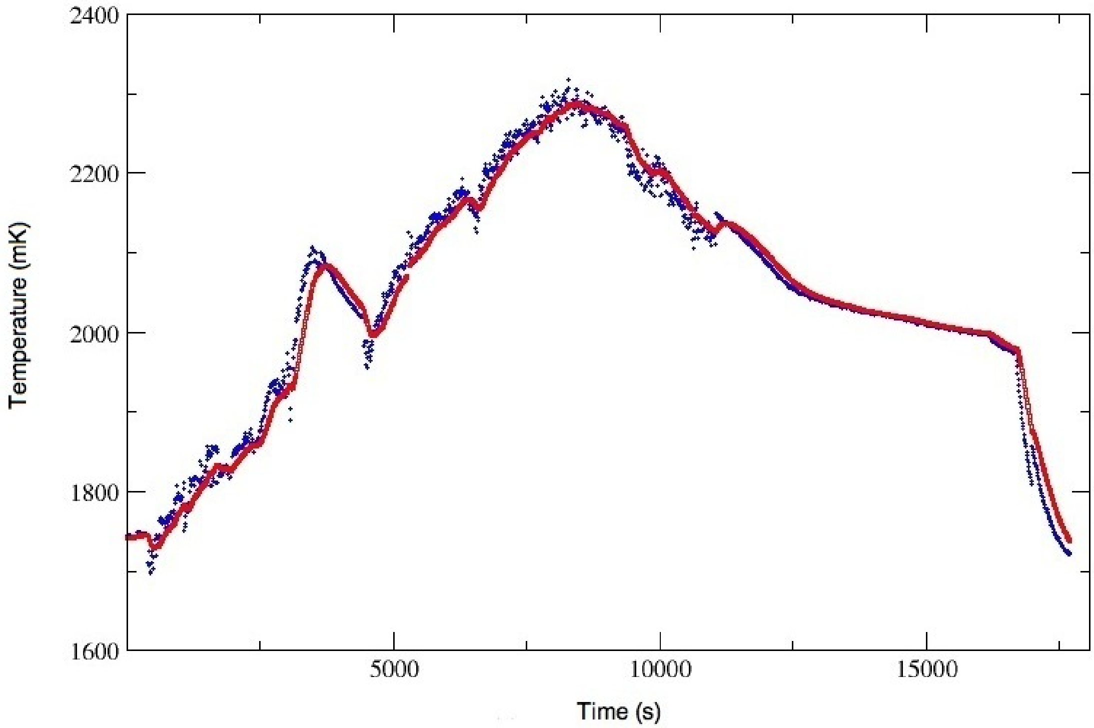

Figure 4. Fridge thermometer data (blue) and simulated sample temperature (red)

3.2 $CeIrIn_5$ Susceptibility

Ultra pure titanium has a T_c of around 0.4K, which is the same as $CeIrIn_5$'s T_c which makes it impossible to determine which material's T_c is registering. The titanium used in the spacers had impurities which changes its T_c to around 1K (4). This too makes measurement of $CeIrIn_5$'s T_c impossible because when the spacers become superconductive, the magnetic field from the primary coil is expelled beyond the secondary coils, leaving no field to be expelled by the sample. This problem is solved by replacing the titanium spacers with spacers made of stainless steel which does not become superconductive. Data collection needs to be done using the new spacers.

3.3 $CeIrIn_5$ Resistivity

A sample of $CeIrIn_5$ was polished to be a rectangular prism of with $l = 0.127$cm and $w = h = 0.03048$cm. The resistivity of the material has been found to be $\rho = 35\mu\Omega$cm

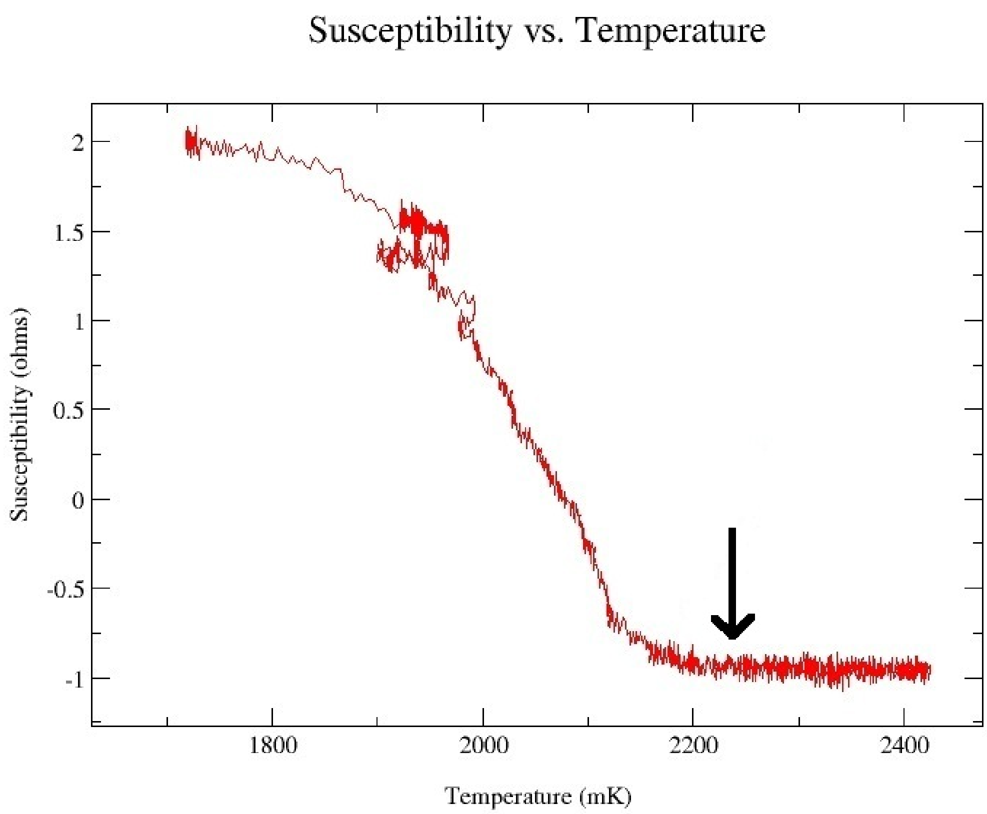

Figure 5. Susceptibility vs. temperature graph showing T_c

(5) and so using the equation:

$$R = \rho \frac{l}{wh} \tag{3}$$

the total resistance of the sample is $4.7 \times 10^{-3}\Omega$. Four copper leads were attached using the method described above with the smallest possible contacts to use as much of the sample for resistance as possible. The best contact resistance I was able to achieve was 5Ω. Perhaps the sample will yield useable data, otherwise larger contacts need to be made to achieve lower contact resistances.

4 Discussion

1-1-5 metals have a crystal structure that is made of alternating layers. The superconductive transition temperature, T_c, can be altered by changing the ratio of the bond

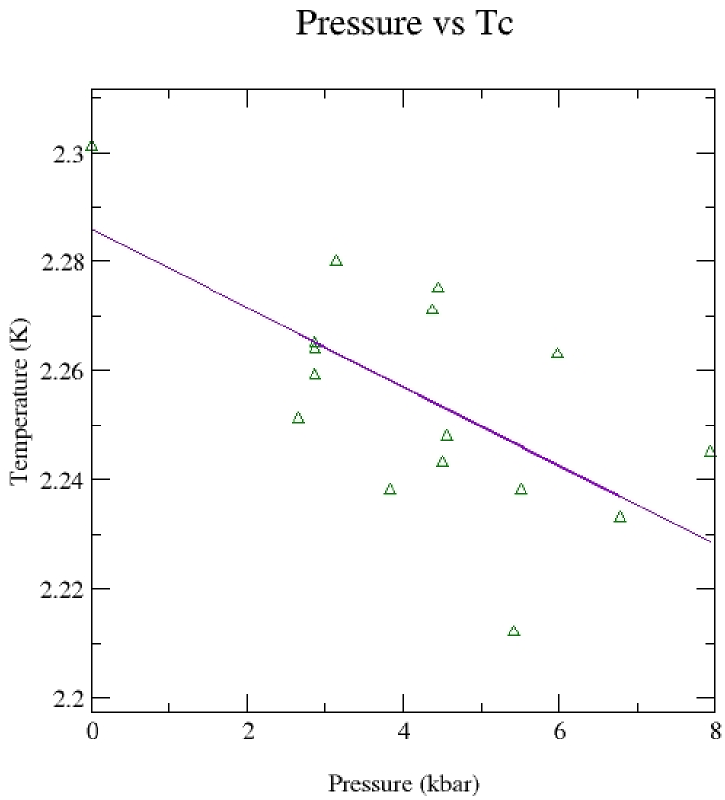

Figure 6. T_c plotted as a function of c-axis pressure

length between layers to the bond length within each layer, $\frac{c}{a}$ by applying uniaxial pressure to the material. It was found through a thermal expansion experiment that by applying pressure to the a-axis and increasing $\frac{c}{a}$ T_c will increase and that it will increase, but not as quickly when pressure is applied along the c-axis (2). The trend from the susceptibility measurements while applying pressure to the c-axis of $CeCoIn_5$ (Fig. 6) is that T_c simply decreases with $\frac{c}{a}$.

The reason both susceptibility and resistivity are used to measure T_c is because they can yield different results due to the mechanism by which the corresponding phenomena occur. In order for the resistivity to drop to 0, there simply must be a single path through the sample that acts as a superconductor and any parts of the sample that still have resistance are shorted out. The susceptibility transition, however requires that the entire surface of the sample act as a superconductor so the magnetic flux can be expelled. This means that the resistive T_c tends to be higher than the susceptibility T_c because a single superconducting path can occur at a higher temperature than the entire surface becoming superconducting.

Mounting a sample for susceptibility measurements is easy because it only needs to be polished flat and be placed inside a coil. Mounting a sample for resistivity measurements is, however, is more difficult because the sample must be polished to a geometry that has a high resistance, namely long and thin, and yet still be thick enough to attach 4 wires with large enough contacts to have a low resistance.

$CeIrIn_5$ samples are fairly easy to work with for any measurement because they are relatively large in all directions and thus can be polished to a variety of shapes with different axis orientations. The main difficulty in polishing samples is the presence of pockets of In that form within the material. When these are uncovered, they must be polished away because irregularities on the surface can lead to the sample breaking while under pressure. $CeCoIn_5$ is more difficult because the samples are very thin as they are made of only a few layers in the crystal lattice. This means pressure can easily be applied to the c-axis for susceptibility measurements. The problem lies in applying pressure along the a-axis or attaching leads to the sample for resistivity measurements. Perhaps this issue could be resolved by varnishing several samples together to provide some thickness along the c-axis.

5 Conclusions and Future Work

As pressure is applied along the c-axis, the superconducting transition temperature decreases at a rate of $\frac{dT_c}{dP_c}$ = -0.007258 K/kbar. A previous study (2) found $\frac{dT_c}{dP_c} = 0.0075 \pm 10^{-3}$ K/kbar. The only difference between the two results is the change in sign which indicates that T_c continues to decrease with $\frac{c}{a}$, opposite of what was previously thought.

There is still much work left to be done on this project. We have collected one set of data for the susceptibility T_c for $CeCoIn_5$ with pressure applied to the c-axis which needs to be repeated. Also samples need to be prepared that allow a-axis pressure to be applied, as well as leads to be attached for resistivity measurements. For the $CeIrIn_5$ samples the most vital task is to attach the wires with as small a contact resistance as possible. Otherwise, it is necessary to take c-axis and a-axis resistivity and susceptibility measurements with $CeIrIn_5$.

References

[1] J. D. Thompson et al. *Magnestism and unconventional superconductivity in* $Ce_nM{-}mIn_3n + 2m$ *heavy-fermion crystals* Physica B 329–333 (2003) pp. 446–449.

[2] N. Oeschler et al. *Uniaxial Pressure Effects on* $CeIrIn_5$ *and* $CeCoIn_5$ *Studied by Low-Temperature Thermal Expansion* Phys. Rev. Lett. 91. 076402 (2003).

[3] J. C. Cooley *High Pressure Transport Measurements on the Rare Earth Systems* SmB_6 $Ce_3Bi_4Pt_3$ *and* EuB_6 (1997) p. 195, University of Michigan.

[4] A. Peruzzi et al. *Investigation of the titanium superconducting transition as a temperature reference point below 0.65 K* Metrologia 37 (2000) pp. 229–233.

[5] C. Petrovic et al. *A new heavy-fermion superconductor* $CeIrIn_5$*: A relative of the cuprates?* Europhysics Letters 53 (1 Feb 2001) p. 356.