This manual shows the parts that are not relevant to the virtual experiment on a grey background.

The low temperature properties of copper

Aims and Objectives

- Measure the temperature dependence of the resistivity of copper.
- Measure the temperature dependence of the heat capacity of copper.
- Understand the expected variations as a function of temperature of resistance and heat capacity.

Introduction

Theories explaining how and why materials behave in the way that they do must be tested against experiment. To do this, one usually needs to vary an environmental factor and see how the behaviour responds. A controllable way of doing this is by changing the temperature. In this experiment, you will be studying the temperature dependence down to 4.2 K of the resistivity and the heat capacity of copper. These quantities are not constant as a function of temperature, and explaining the way in which they vary provides crucial information for developing and testing any consistent theories of metals.

Why 4.2 K?

Background

The resistivity and heat capacity of metals are well-known properties, with well-known temperature dependences. In this experiment, you will measure these temperature dependences experimentally, and then explain the observed behaviour.

Resistivity

The electrical conductivity, σ, of a metal may be described by the following equation:

$$\sigma = \frac{ne^2\tau}{m}$$

where n is the number density of electrons, m is the electron mass, and τ is the collision time for the electrons. This equation may be derived by considering the free electrons in the metal and their motion in an applied electric field, assuming random collisions, as in the kinetic theory of gases. This gives rise to the collision time τ. This is typically dominated by collisions between the electrons and impurities, and between the electrons and phonons (quantized oscillations of the atoms in the crystal, like sound waves). Although the number of impurities usually remains constant as a function of temperature, this is not the case for the phonon population, and so the collision time will change as a function of temperature. This means that the temperature dependence of the resistivity is dominated by the electron-phonon interactions.

Heat capacity

The heat capacity of a material is a measure of the amount of heat required to change the temperature. A material has a number of potential sources of heat capacity, depending on the number of degrees of freedom. In all materials, the motions of the atoms (or phonons) are one source. This source of heat capacity is described by the Debye model. In metals, the free electrons also contribute some heat capacity independently. These two contributions have different temperature dependences, and you should be able to observe both parts in this experiment.

Suggest some other degrees of freedom.

Experimental Method

The experimental apparatus is installed inside a helium dewar. This is a pressurised container containing several litres of liquid helium. If liquid helium gets on your skin, it will freeze the flesh and cause localised frostbite. You will not be removing the experimental apparatus from the dewar, and so you will not be handling the liquid helium directly. The dewar is connected to the copper tubing on the walls, to provide a return line *for helium gas that boils off from the liquid. Do not disconnect this or close the yellow tap, as this will cause a pressure build up in the dewar. If this happens, one of the high pressure relief valves on the dewar will start releasing gas to avoid over-pressuring the dewar. If this happens, please avoid the stream of cold gas. Shaking the dewar can increase the boil-off rate - please move the dewar gently if you need to move it.*

Overview

A sample of fine copper wire has been wound into a coil. This is then suspended in vacuum in an insert into a helium dewar, providing weak thermal contact to the cold liquid helium. This acts to cool the sample. If a current is then passed through the coil, energy will be dissipated into the coil, causing heating of the coil. By measuring the current through the coil and the voltage across it, the resistance may be measured, and hence the resistivity extracted. This resistance will change as the coil is heated, providing a measure of the temperature dependence of the resistivity.

At the same time, the power put into the coil can also be calculated from the current and voltage. The heat capacity, $C(T)$ is the relationship between the heat put in and the temperature change observed, since

$$dQ = C(T)dT$$

where dQ is the small amount of heat supplied. The power corresponds to $\frac{dQ}{dt}$, which gives

$$C(T) = \frac{P}{dT/dt}.$$

This means that the heat capacity may be calculated if the temperature is also measured, so that the rate of heating of the sample is known.

What about heat losses?

Details

The sample is a copper coil, supported by nylon threads onto a holding structure, in a tube that can be evacuated (see Figure 1). This tube is then placed inside the helium dewar (see Figure 2). These figures identify the various connections that you can see on the top of the dewar.

Why evacuate it?

The copper coil is cooled by thermal contact with the liquid helium in the dewar. When the tube is evacuated, the copper takes about 10 hours to completely cool to equilibrium. To speed this up, a sorb [1] is placed on the very bottom, so that when it is heated, helium gas is released. This allows the copper to cool down faster.

Why is this?

The copper coil

A test example of the coil is available for you to look at. The coil is made from 34 SWG wire, and after being coiled, it is dried in Bostik glue to hold it in place. A Cernox thermometer, of mass 0.05 g, is buried inside the coil. Figure 3 shows the coil installed in the holding structure. To use this thermometer, the resistance across it is measured in a 4-point measurement. The relationship between resistance and temperature has been calibrated, and the conversion is handled by the CTC100 Temperature Controller. The

[1] A sorb is an absorbant material that releases substances when heated

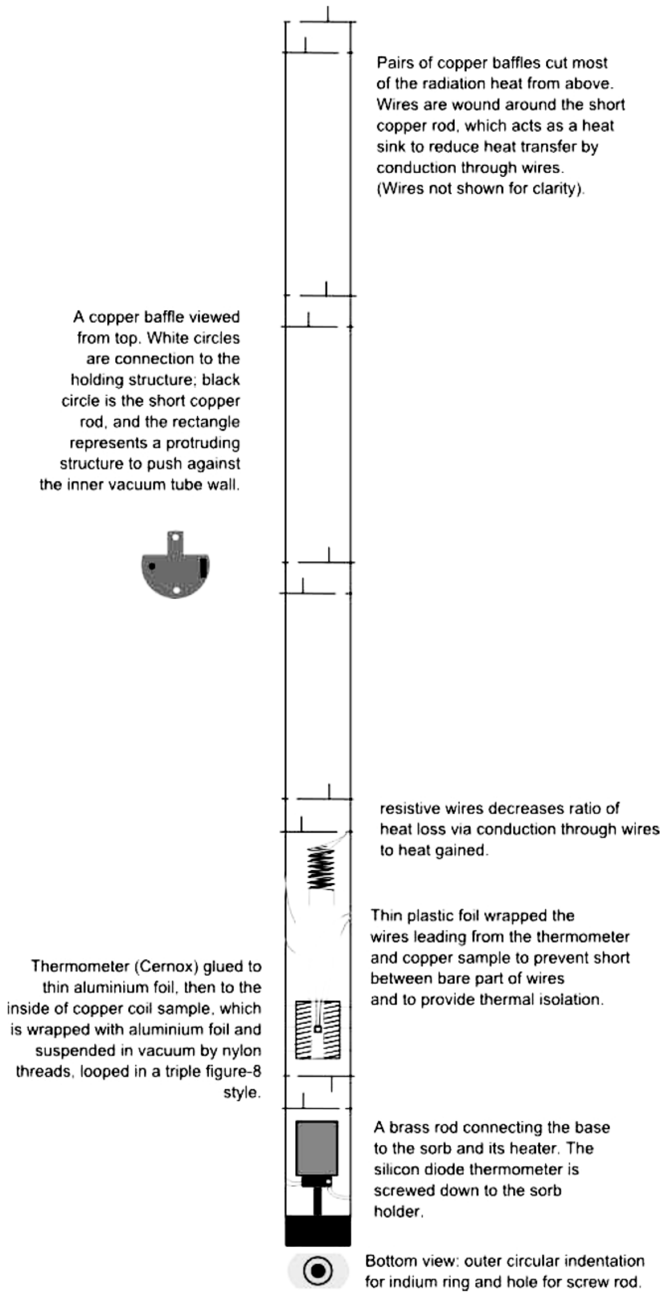

Figure 1: The holding structure, along with the components which will fit in it.

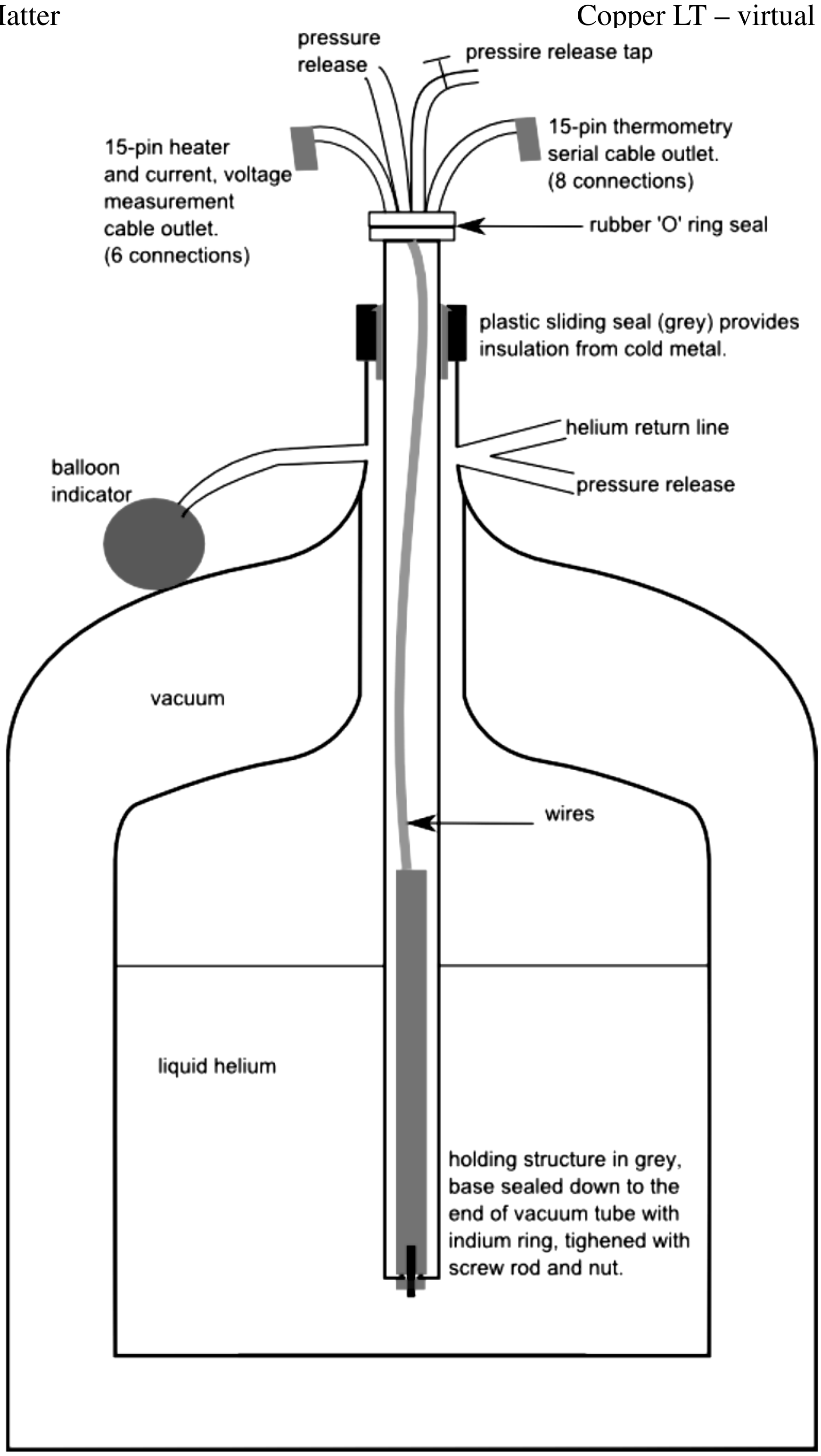

Figure 2: Holding structure within the tube, inserted into the helium dewar.

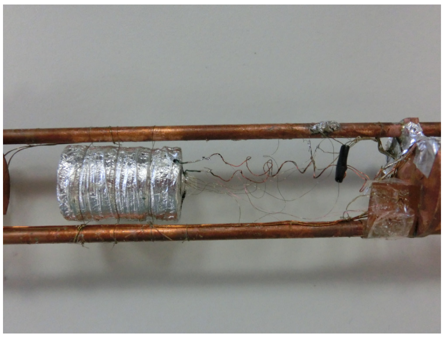

Figure 3: The copper coil, as mounted in the holding structure.

mass of the coil and thermometer is 18.72 g. The insulation is estimated to form 2.76% of the mass of the copper wire - this was estimated by taking a piece of the wire and dissolving off the insulation using concentrated hydrochloric acid.

What is the purpose of the box marked '25 Ω'?

To heat the coil, a current is supplied through the coil, so that it acts as its own heater. This current is supplied by the CTC100, as 'Out 1'. The current through the coil and the voltage across the coil are measured independently by the two Keithley multimeters.

The sorb

The sorb is made from crushed-up 87955 Alfa Aesar molecular sieve packed between layers of copper plates, surrounded by copper wire gauze, as shown in Figure 4. The sorb is screwed onto the brass rod on the bottom of the holding structure. The whole process, from packing the molecular sieve to fixing it into the structure takes place just before the holding structure is put into the tube and sealed to prevent unnecessary exposure to atmospheric water vapour, which reduces the capacity of the sorb to hold helium gas. The vacuum inside the evacuated tube has been spoiled with a small amount of helium gas. When the sorb is at base temperature ($\sim$ 4.2 K), all of this gas is absorbed in the sorb. On heating the sorb, this gas leaves the sorb, and can act as an exchange gas. Heating the sorb to 10 K will release less gas than heating it to 20 K, and this will alter the cooling power of the cryostat. The sorb heater has been set so that it cannot be heated above 40 K. This heating is done by means of a resistive wire, which is controlled as 'Out 2' on the CTC100. The sorb temperature is monitored by a silicon diode.

Why two types of thermometer?

Figure 4: The sorb packed with molecular sieve.

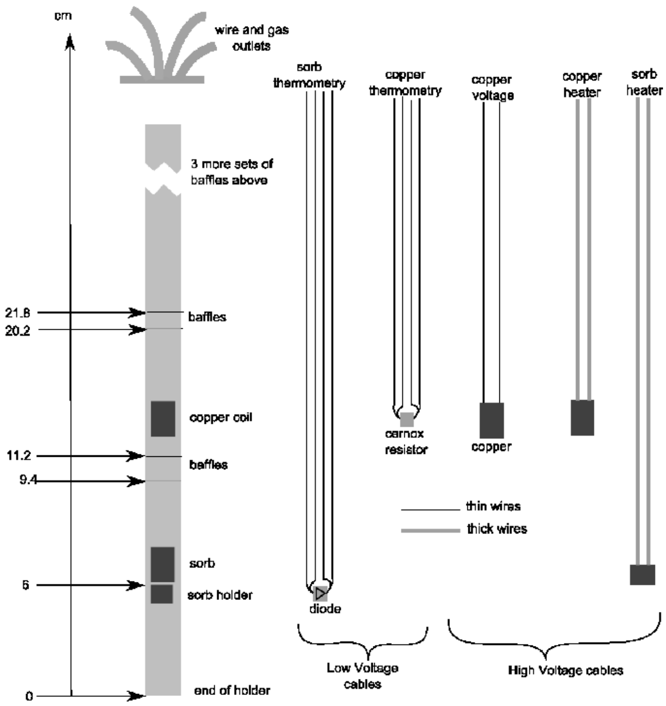

Figure 5: schematic of the wiring connections.

Measurements

To alter the temperature of either the sorb or the copper coil, heat must either be supplied or taken away. In this experiment, there is a constant ‘cooling’ power supplied by the surrounding liquid helium. This cooling power may be increased by introducing exchange gas, or reduced by removing it, but it is always present. Heat is input by means of resistive heating. The CTC100 temperature controller is given a particular setpoint temperature to reach and then stabilize at, and can actively control the heater by adjusting the power input. The cooling power may or may not be constant as a function of temperature.

To control the temperature requires a feedback loop, and the method used for this is commonly referred to as ‘PID feedback’. In PID control, there are three algorithms applied to determine how much power should be applied to the heater. This approach is used for many other automation problems, not just temperature control.

The P term is the proportional term. This calculates a heater output that is proportional to the difference between the setpoint and the actual temperature (the *error*). A large P value indicates that more heat will be put in. However, as one approaches the setpoint, the heater output will tend to zero, and it is unlikely that a zero heat output will be able to maintain the desired temperature.

This leads us to the I, or integral, term. The integral constant I is multiplied by the error and added to the previous value of the integral heater output. As one approaches the setpoint, the rate of change goes to zero, leaving a constant heater output to maintain the desired temperature. In many cases, the P and I terms are sufficient to control the temperature. However, the approach can be improved by including a D, or derivative, feedback term, which gives a heater output equal to the rate of temperature change multiplied by D.

The values for P, I and D can vary quite considerably. You can access the PID control on the CTC100 through the Setup panel for the two heater outputs. The choice of PID can make a big difference to the time it takes to reach a particular temperature. Further sources of information about PID control are given in the Recommmended Reading.

Initial investigations

- The apparatus should be sitting with the sorb and the copper coil both at ~ 4 K at the beginning of the experiment. Using the Labview control program, start warming up to 100 K. The software records the resistance and the heat capacity as a function of temperature.

- Now try to cool down the copper coil by turning off the heater ‘Out 1’. Experiment with the effect of heating the sorb on the cooling power of the instrument.
- Try to stabilize the copper coil at a given temperature. Investigate the PID feedback controls.

Possible investigations

- Measure the resistance as a function of temperature, and compare this with values in the literature. Investigate the functional form of the curve.
- Measure the heat capacity as a function of temperature, and compare this with values in the literature. Investigate the functional form of the curve.
- Investigate the effect of different heating rates on your results.

Recommended Reading

DoITPoMS, *Introduction to thermal and electrical conductivity*,
`http://www.doitpoms.ac.uk/tlplib/thermal_electrical/index.php`,
University of Cambridge (2014).

CTC100 User Manual, p.27, *Using PID feedback*, Stanford Research Systems, (2011).

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