

University of Toronto  
ADVANCED PHYSICS LABORATORY

**NEEL**  
**Phase Change in Chromium**  
**At the Néel Temperature**

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## INTRODUCTION

Many solids undergo structural transformation as the temperature is changed. These are analogous to phase changes from gas to liquid or from liquid to solid except that in a structural transformation both phases are solid. Some of these transformations result from the onset of magnetic order in the solid, for example the ordering of atomic magnetic moments which occurs at the Curie temperature of a ferromagnet.

Chromium is unique among metals in that the magnetic transition is from a paramagnetic (high temperature) phase to an anti-ferromagnetic<sup>1</sup> (low temperature) phase, at the Néel temperature,  $T_N \sim 37.5^\circ\text{C}$ . Also, the transformation is thermodynamically of the first order, which means that there is a latent heat ( $L = \Delta Q$ ) and a volume change ( $\Delta V$ ) at  $T_N$ . Most magnetic transitions are second order, with a change in the specific heat ( $dQ/dT$ ) and the thermal expansion ( $dV/dT$ ) at the transition temperature.

The magnetic transition in Chromium is more easily detected by the volume change,  $\Delta V$ , than by the small changes in the magnetic properties which occur when the metal becomes antiferromagnetic. In this experiment we measure the fractional length change,  $(\Delta \ell / \ell)$ , which is related to the volume change by

$$\frac{\Delta V}{V} = 3 \frac{\Delta \ell}{\ell} \quad (1)$$

We can calculate the latent heat per unit volume of the transition,  $L/V$ , using the Clausius-Clapeyron equation<sup>2</sup>,

$$\frac{dP}{dT_N} = \frac{L}{T_N \Delta V} = \frac{L/V}{T_N (\Delta V/V)} \quad (2)$$

and the fact that the Néel temperature is depressed by pressure and the rate of

$$\frac{dT_N}{dP} = -5.1 \text{K/kilobar} \quad (3)$$

As can be seen in the short article by Matsumoto and Mitsui, Chromium undergoes a contraction when it passes from the antiferromagnetic phase to the paramagnetic phase (Matsumoto and Mitsui Figure 1) and also the coefficient of thermal expansion is larger in the paramagnetic phase than it is in the antiferromagnetic phase (Matsumoto and Mitsui Figure 2).

## EXPERIMENT

A semiconductor strain gauge (“gauge” rhymes with “page”) has been glued to the Chromium sample and immersed in a Silicon oil bath for temperature stability. A copper-constantan thermocouple<sup>3</sup> is also held in place quite close to the sample, as shown in Figure 1. Preliminary temperature measurements may be done with a digital external thermometer dipped in the oil to give a rough indication of temperature.

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<sup>1</sup> “Introduction to Solid State Physics” by Charles Kittel (8th edition ©2004 by John Wiley & Sons) Chapter 15, sub-section on “Antiferromagnetic Order”

<sup>2</sup> “Heat and Thermodynamics” by Mark Zemansky and Richard Dittman (7<sup>th</sup> edition ©1996 by McGraw-Hill) Chapter 11, sub-section on Clapeyron equation

<sup>3</sup> Type T Cu versus Cu-Ni Alloy Thermocouples Data Tables, available on reserve in MP250

### Safety Reminders

- To avoid burns, do not touch the hot plate surface when it is on, or until it has cooled down after being turned off.
- Silicon oil is slippery and is very hard to wash out of your clothes. Clean up any spills promptly with paper towels.

*NOTE: This is not a complete list of all hazards; we cannot warn against every possible dangerous stupidity, e.g. opening plugged-in electrical equipment, juggling cryostats, .... Experimenters must constantly use common sense to assess and avoid risks, e.g. if you spill liquid on the floor it will become slippery, sharp edges may cut you, .... If you are unsure whether something is safe, ask the supervising professor, the lab technologist, or the lab coordinator. If an accident or incident happens, you must let us know. More safety information is available at <http://www.ehs.utoronto.ca/resources.htm>.*

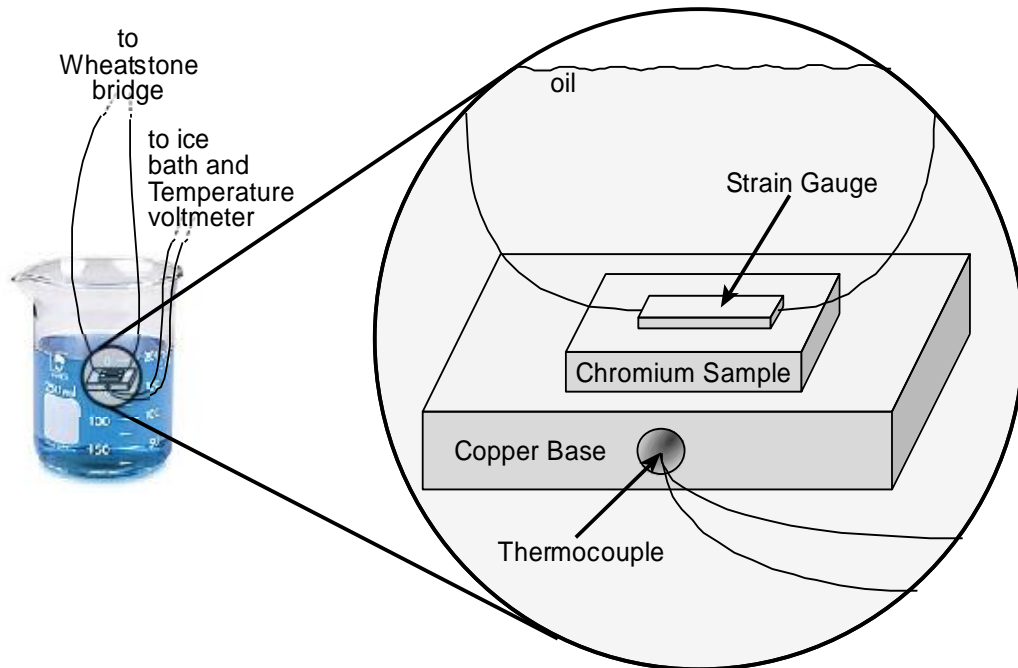


Figure 1: Arrangement of the Chromium Sample, Strain Gauge and Thermocouple in the Silicon oil bath. The Strain gauge is glued to the top of the Chromium Sample. The Chromium Sample sits on the Copper Base. The entire apparatus is immersed in the oil bath in a glass beaker.

As the bath temperature is raised, the output of a Wheatstone bridge is plotted versus temperature, and the appearance and approximate magnitude of the singularity due to  $D\ell/\ell$  at  $T_N$  is noted. After preliminary setup runs have been performed a final run should be made with decreasing temperature and with the bath wrapped in cloth to ensure that the temperature decreases very slowly.

## The Strain Gauge

This information on the BCM BCM semiconductor strain gauge is taken from the manufacturer specification<sup>4</sup>

BCM Gauge Type Number	SN5-120-P-1 / SN-120-5-P
Doping of semiconductor	p-type
Effective length at zero strain	5 mm
Resistance at 23°C	120 ± 5% Ω
Temperature Coefficient of Resistance	<0.15%/°C
Gauge Factor at 23°C	110 ± 5%
Temperature Coefficient of Gauge Factor	<0.15%/°C

The gauge factor relates strain to fractional change in resistance, and is defined as

$$F = \frac{DR/R}{D\ell/\ell} \quad (4)$$

In fact the gauge factor depends on temperature, and is given by

$$F = F_0 + m_F (T - T_0) \quad (5)$$

where  $T_0=21^\circ\text{C}$ . Similarly, the total resistance of the gauge at zero strain was measured to have a slight dependence on temperature, so that the total resistance is given by:

$$R = R_0 + m_R (T - T_0) \quad (6)$$

## Measuring the Coefficient of Thermal Expansion

Since the gauge expands as the chromium expands, the strain we measure is due to the difference in the coefficients of thermal expansion of chromium and the silicon from which the gauge is made. The measurement of the strain is obtained from the change in the resistance as the temperature rises but the resistance of the gauge itself is a function of temperature so this effect must be considered as well. Strain is defined as  $D\ell/\ell$ . The apparent strain we measure over a change in temperature,  $\Delta T$ , which does not include a phase change, is

$$\frac{D\ell/\ell}{DT} = a_{Cr} - a_{Si} + \frac{m_R}{R_0 F} \quad (7)$$

where the coefficient of thermal expansion of the Silicon strain gauge is  $\alpha_{Si}=2.52 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ , and  $\alpha_{Cr}$  is to be determined. Note that in Chromium the coefficient of thermal expansion above the Néel Temperature may be different than that below.

## Temperature Measurement: Ni-Cu Thermocouple

The thermocouple applies the Seebeck effect, which is the production of a small voltage across the length of a wire due to a difference in temperature along that wire. This effect is most easily observed and applied with a junction of two dissimilar metals in contact, each metal producing a different Seebeck voltage along its length, which translates to a voltage between the two unjoined wire ends, as shown in Figure 2.

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<sup>4</sup> [https://www.physics.utoronto.ca/apl/neel/Semiconductor\\_Strain\\_Gauges\\_2015.pdf](https://www.physics.utoronto.ca/apl/neel/Semiconductor_Strain_Gauges_2015.pdf)

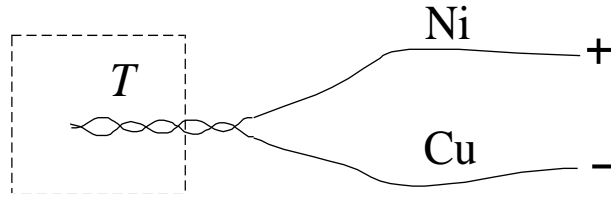


Figure 2: A single junction of two different metals (Nickel and Copper), which produces a small voltage between the free ends. This voltage increases with the temperature of the junction,  $T$ .

The problem with this effect is that it is impossible to measure for a single junction. Once you attach a voltmeter to the free ends, you will always create another junction of dissimilar metals. For example, if your voltmeter uses copper leads, there will be a new Nickel-Copper junction which will also produce a voltage. For this reason, a thermocouple is always composed of two junctions, and only temperature differences can be measured, not absolute temperature. Figure 3 shows the setup used in this experiment, where  $T_1$  is the temperature of an ice-water bath, and  $T_2$  is the temperature of the oil in the beaker that contains the Chromium sample.

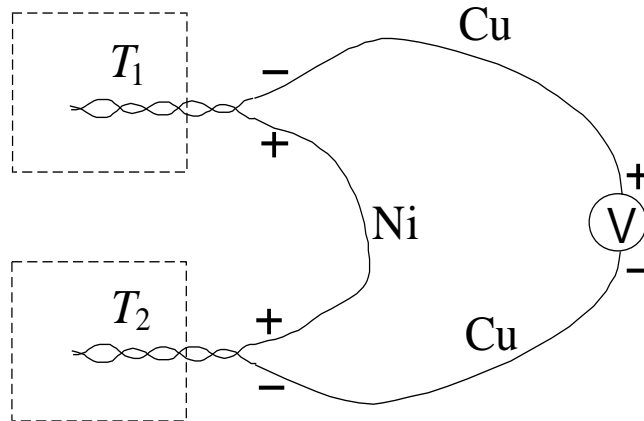


Figure 3: Two junctions combined in a circuit with a voltmeter.  $T_1$  is a reference temperature,  $T_2$  is the temperature we wish to measure. The measured voltage is proportional to the difference  $T_2 - T_1$ .

The voltage produced by the thermocouple is on the order of a milli-Volt. To measure this with the computer, it is first amplified by the high impedance voltmeter. You must calibrate the output of the voltmeter by comparing it to the reading on the dial, and perhaps adjusting the “isolated output” and “zero” dials on the voltmeter. You may assume that the dial is calibrated properly.

### Strain Gauge Resistance Measurement: The Wheatstone Bridge

There are several acceptable arrangements of the Wheatstone Bridge which can produce usable results for measurement of strain gauge resistance. The suggested arrangement shown in Figure 4 was designed to give maximum sensitivity to departures from equilibrium.

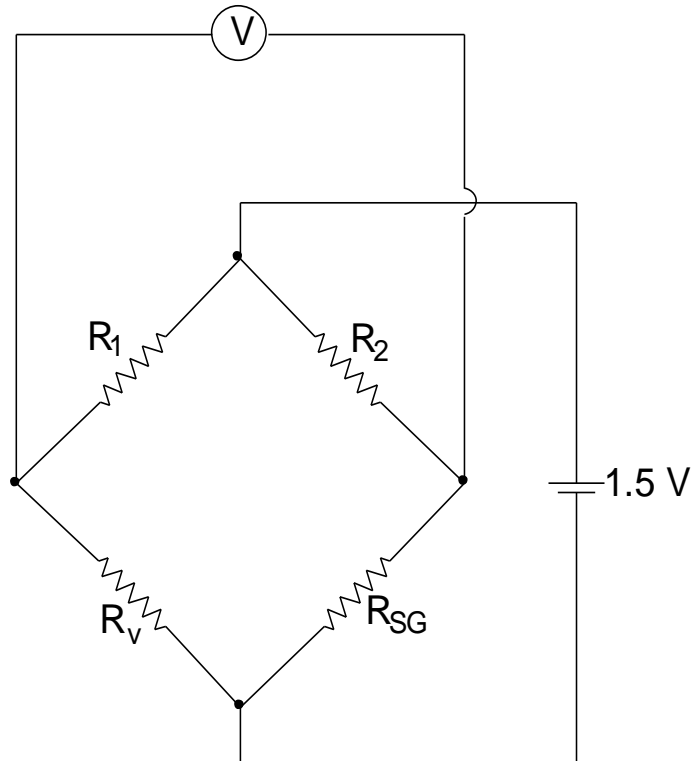


Figure 4: Wheatstone Bridge

When  $R_1 = 10 R_2$ , and  $R_V = 10 R_{SG}$ , the voltage across the bridge read by the voltmeter will read zero. Small changes in  $R_{SG}$  due to strain will lead to easily measureable voltages across the bridge. In this particular system, the two fixed resistances are  $R_1=1000 \Omega$  and  $R_2=100 \Omega$ , the resistance of the strain gauge is approximately  $R_{SG} \approx 120 \Omega$ , so variable decadal resistor should be set to approximately  $R_V \approx 1200 \Omega$ . To aid in calibration of the system, it may be noted that a change of  $1 \Omega$  in the variable resistor,  $R_V$ , causes a voltage change from equilibrium which is almost identical in magnitude to a change of  $0.1 \Omega$  in the strain gauge. Finally, the condition that the power dissipated in the strain gauge ( $6 \text{ mW}$ ) is less than  $20 \text{ mW}$  is fulfilled with this setup.

The voltage you wish to measure is on the order of milli-Volts, and should first be amplified by the milli-microvoltmeter. You should check the output is calibrated properly, so that the computer readings match that of the dial on the milli-microvoltmeter.

In this experiment, the computer is being used as a two-channel volt-meter. The first channel voltage, which is related to the strain gauge resistance, is plotted on the  $y$ -axis. The second channel voltage, which is related to the temperature difference of the two ends of the thermocouple, is plotted on the  $x$ -axis. Data may be printed directly or saved in text format and read into an analysis program, such as Excel.

### Measurements to be Made

The following points could be considered in presenting and discussing your experimental data:

- The magnitude of  $D\ell/\ell$  at  $T_N$  should be determined with as high accuracy as possible, since this is the main purpose of the experiment.

- The sign of  $D\ell/\ell$  should be shown to be consistent with the sign of  $dT_N/dP$  and a positive latent heat,  $L$ , in going from the low temperature antiferromagnetic phase to the high temperature paramagnetic phase. Evaluate  $L$  from equation  $\frac{DV}{V} = 3\frac{D\ell}{\ell}$  (1).
- Determine  $T_N$ .
- Determine the width of the transition by changing the temperature very slowly through  $T_N$ .
- Use equation  $\frac{D\ell/\ell}{DT} = a_{Cr} - a_{Si} + \frac{m_R}{R_0F}$  to evaluate the coefficient of thermal expansion of Chromium,  $\alpha_{Cr}$ , both above and below the Néel temperature.
- Is there thermal hysteresis<sup>5</sup> in the system? For example, does a plot of  $\Delta\ell/\ell$  versus temperature depend on whether the temperature is rising or falling?

## BIBLIOGRAPHY

T. **Matsumoto** and T. **Mitsui**, *Thermal Expansion of Chromium Single Crystals at the Néel Temperature*, Journal of the Physical Society of Japan, 27 (1969) 786;  
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<sup>5</sup> I. S. **Williams** and R. **Street**, *Investigation of thermal hysteresis near the Neel transition in chromium*, Journal of Physics F: Metal Physics 10 (1980) 2551-2553; <http://iopscience.iop.org/article/10.1088/0305-4608/10/11/026/pdf>