Estimate the Curie Temperature of a Ferromagnetic Material

Muhammad Hamza Humayun, Muhammad Umar Hassan and Muhammad Sabieh Anwar

LUMS School of Science and Engineering

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Atoms can have magnetic dipole moments that behave like small magnets. In ferromagnetic materials, these small magnets are spontaneously aligned in a particular direction, creating magnetic domains without any external impetus. The ferromagnetic properties of materials depend on the temperature. By varying the temperature, we can modify the thermal agitation and impact the magnetization of the material. At a certain temperature called the Curie temperature, the ferromagnetic material loses its magnetic domains, all atoms are then oriented in random direction and the material becomes paramagnetic. This experiment investigates the feromagnetic to paramagnetic transition through an extremely useful technique called extrapolation.

KEYWORDS

Ferromagnetism · Phase transition · Curie temperature · Extrapolate

1 Learning outcomes

In this experiment, we will:

1. familiarize ourselves with the Peltier effect and use a Peltier module to heat or cool a material,

2. familiarize ourselves with the use of sensors such as thermocouple and instruments such as those to measure magnetic field and temperature,

3. learn the relationship between magnetization and temperature, and

4. comprehend and practise the convenience of extrapolating experimental data.

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2 Introduction

2.1 Ferromagnetic materials

Electrons revolving around a nucleus are akin to the current flowing in a loop, and thus act as magnetic dipole moments. The net magnetic moment of an atom is the vector sum of all the magnetic moments within the atom. It is important to note that the resultant magnetic moment depends on the number of unpaired electrons in the atom. This is because the paired electrons spin and orbit in opposite directions according to the Pauli Exclusion Principle.

In general, these magnetic moments are randomly oriented within the material and the net magnetic moment of the material is zero (Figure 1a). When these substances are placed inside an external magnetic field, they try to align themselves in the direction of the field. Simultaneously, the thermal energy of the material opposes this alignment. Materials in which a small number of these dipoles align with the external magnetic field are known as paramagnetic materials. If we remove this external field, the magnets become randomly oriented again, leaving no permanent magnetism. Examples include aluminum (Al), oxygen (O), and titanium (Ti).

In some materials, however, electrons strongly interact with neighboring electrons to create domains with aligned magnetic dipole moments (Figure 1b). In the absence of an external field, these domains are all randomly oriented, resulting in a net zero magnetic field. When an external magnetic field is applied, these domains are forced to align with the external field (Figure 1c). In such materials, there is a point when all domains are aligned, and increasing the external field has no further effect. This is known as magnetization saturation. There are four elements in the periodic table exhibiting such behavior at room temperature: iron (Fe), cobalt (Co), nickel (Ni), and gadolinium (Gd). Many alloys are ferromagnetic.

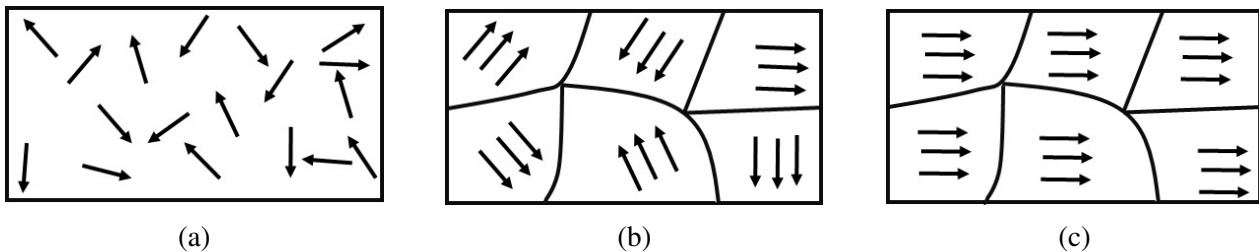(a)   (b)   (c)

Figure 1: Orientation of magnetic dipole moment inside a (a) Paramagnetic material, (b) ferromagnetic material and (c) ferromagnetic material in an external magnetic field.

2.2 Curie temperature

An increase in temperature increases the vibrations of tiny magnets, making it harder to align them in the same direction. If we heat the material to a certain temperature, the magnetic domains inside

the material disintegrate. In such situations, the ferromagnetic material becomes paramagnetic. In physics, this is called phase transition. The temperature at which the phase transition occurs is known as the Curie temperature or Curie Point (T_C). The loss is not permanent; once the heat is removed, magnetic domains are reformed. The T_C depends on the material, and is given for different materials in Table 1 [1, 2, 3].

Table 1: Curie temperature of ferromagnetic materials.

Substance	T_C (°C)
Fe	770
Ni	358
Co	1127
Gd	16
MnAs	45
MnBi	357
MnSb	314
CrO_2	113
$MnOFe_2O_3$	300
$FeOFe_2O_3$	585
$NiOFe_2O_3$	585
$CuOFe_2O_3$	485
$MgOFe_2O_3$	440
$Y_3Fe_5O_{12}$	287

For $T \ll T_C$, the relationship between the magnetization M of ferromagnetic materials and temperature is approximately [4]:

$$M \sim (T_C - T)^{1/2}. \tag{1}$$

Equation 1 tells us that below $T \ll T_C$, the magnetic field of the material decreases as the temperature increases. The linear fitting of Equation 1 gives us:

$$M^2 = a(T - T_C), \tag{2}$$

where a is some coefficient. Equation 2 indicates that if we can build a setup where we measure the magnetization M for different temperatures, then plot this linear curve, and extrapolate to the point where $M = 0$, we can obtain the T_C of the ferromagnetic material. The slope of Equation 2 is negative, so the spontaneous magnetization of that material approach zero as the temperature is increased. The temperature at which the extrapolated line intersects the x-axis is denoted by T_C. Furthermore, instead of measuring M directlty, we measure the magnetic field $\boldsymbol{B}$ from the magnetic material and assume that $\boldsymbol{B}$ is proportional to, and a measure of M.

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The extrapolation technique is quite useful in the physics laboratory . For example, it is not always possible to obtain data over a wide input range. Therefore, by performing measurements for a limited range, statistical trends can be employed to extend the data to estimate measurements outside the dataset. One classic example of extrapolation is determining the absolute zero temperature of a gas that is impossible to reach. An infinite amount of work is required to reach 0 K. We plot volume versus temperature data that should follow lie on a straight line according to Charles's law, and then we extrapolate the line. The intersection with the horizontal axis provides the absolute zero temperature. This experiment also demonstrates the use of extrapolation.

3 Apparatus

The apparatus used in the experiment includes the following items (Figure 2).

1. Peltier module with temperature range from 10–100 °C (see Appendix A for details of its working)

2. Assortment of permanent magnets

3. Thermocouple

4. Surface thermocouple (C03-k)

5. PhysTherm which is our instrument that reads off voltage signals from a thermocouple, conditions these signals and converts into a form that PhysLogger can understand

6. PhysHall which is our device to measure magnetic fields

7. PhysLogger which is our very own data logger

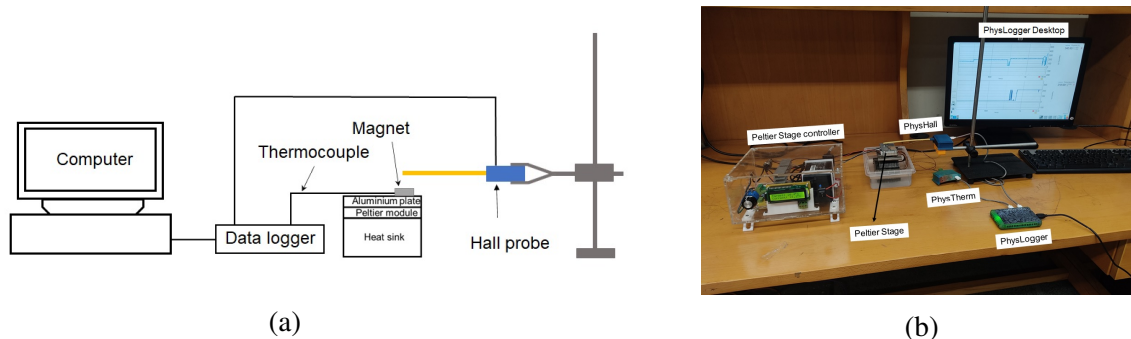8. Desktop with PhysLogger desktop app installed

(a)   (b)

Figure 2: (a) Schematic and (b) photo of the experimental setup used to determine the Curie temperature.

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4   Experimental Method

We use PhysLogger for data logging. The PhysLogger is connected to two PhysInstruments: Phys-Therm and PhysHall. Phystherm is connected to a thermocouple attached to the surface of the Peltier stage to obtain the approximate temperature of the magnet. The scheme is shown in Fig. 2a. The PhysHall probe is placed at a height above the permanent magnet using a stage. PhysHall measures the magnetic flux density of the magnet at its location (A closeup view is also given in Fig. A2).

Set up the apparatus as shown in Figure 2. The PhysLogger is connected to the PC by inserting the provided USB cable to the USB port of the PhysLogger. Open the `Physlogger2` application on the desktop and follow the following steps to acquire the data:

1. Click on `measure` icon $>$ `Magnetic Flux`. On the next window select the analog channel, where PhysHall has been connected to PhysLogger. Now, click the `proceed` option.

2. Select the `temperature` icon. On the ensuing window select the temperature range and analog channel where PhysTherm has been connected to PhysLogger.

3. Click on the `proceed` option $>$ `Make a LivePlot now` $>$ `Start PhysLogger`. The Phys-Logger screen is illustrated in Figure 3. Change the units of measurement of the magnetic flux density to Gauss and the range to $\pm\,0.1$T. Set the sampling frequency to 2 Hz.
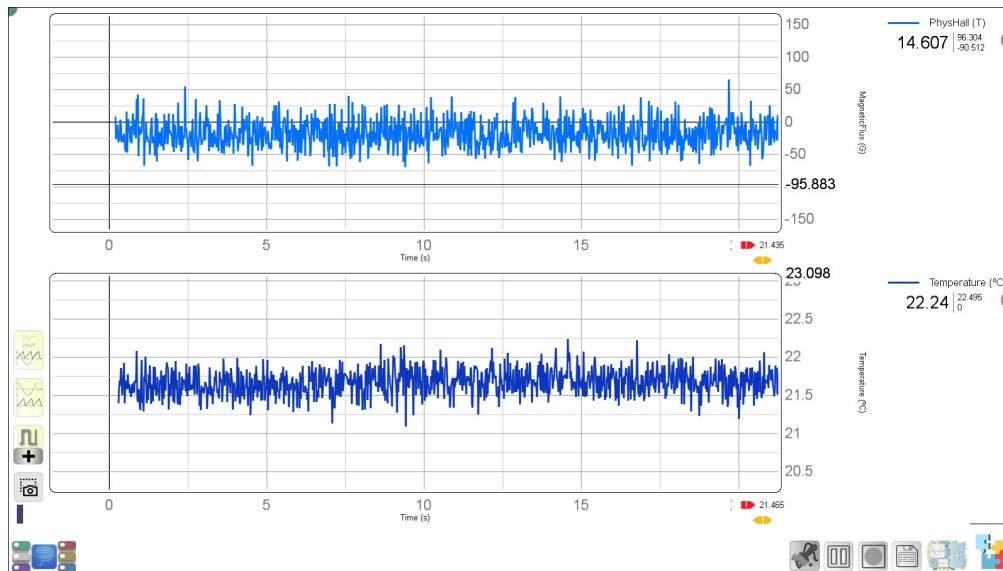

Figure 3: Data logging using PhysLogger.

4. Turn on the heating of the Peltier stage and check the temperature on the temperature display screen. To avoid overheating, the stage can be placed in a container containing water.

5. Using the front panel potentiometer, change the temperature of the heating element. At each temperature, wait for a couple of minutes before jumping to the next temperature. It will be appropriate to proceed in steps of 10 °C.

6. Once the data has been collected, click on the `save the data` option. In the next pop-up window, the PhysHall and Temperature icons are dragged on the columns, as shown in Figure 4. PhysLogger creates a CSV file for the measured data.

7. Use data processing to calculate the average temperature and average magnetic flux density at each temperature.
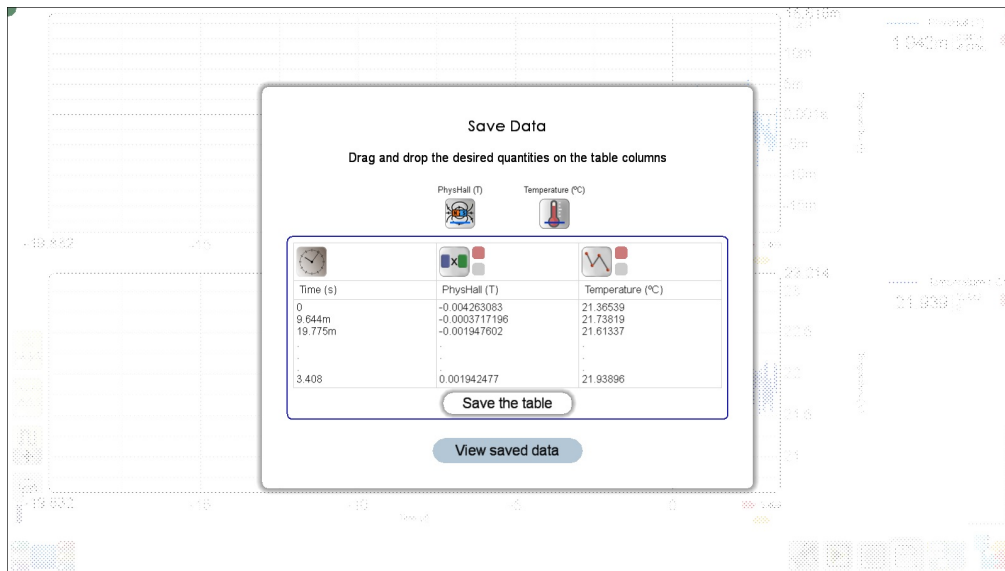

Figure 4: Saving the measurements.

8. Use Equation 2 on the processed data to calculate the Curie temperature of the permanent magnet. We require you to figure out an algorithm to extract the Curie temperature. Equation 2 will be your guiding light. Ofcourse, we like to ask you to fully quote and show working of your uncertainties.

9. Use different magnets and repeat the above-mentioned steps to obtain the Curie temperature of different ferromagnetic materials.

References

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A Peltier effect

A.1 Working principle

The French physicist Jean Charles Peltier discovered the Pelter effect in 1834. He discovered that when a current is allowed to flow through a thermocouple, one junction releases heat and becomes a hot junction, and the other junction absorbs heat to form a cold junction (Figure A1a). If the direction of the current is reversed, the roles of the junctions interchange.
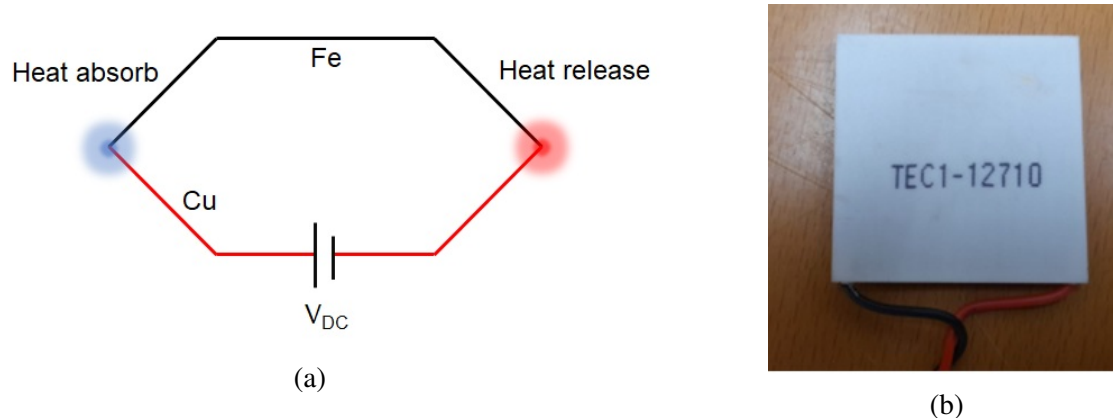

(a)   (b)

Figure A1: (a) Schematic explaining the working principle of the Peltier effect. (b) Commercially available Peltier module used in our home-built setup.

A.2 Explanation

The thermocouple is made up of two different metals. At the junction where the two metals are in contact, there is a contact potential difference. As shown in Figure A1a, the thermocouple is composed of iron (Fe) and copper (Cu) conductors. The potential energy of Fe is higher than that of Cu. Thus, when current flows at the Cu-Fe junction, electrons absorb energy to enter a region of higher potential energy; thus, the junction becomes cold. At the other junction, because the current flows from the higher potential region (Fe) to the lower potential region (Cu), energy is released and the junction becomes hot.

B Details of experimental setup

Figure A2 shows the home-built setup used to heat and cool the magnet. The setup allows the temperature to vary in the range of 10–100 °C. The temperature of the Peltier stage in our home-built Peltier module is controlled by a Proportional-Integral-Derivative (PID) controller. We drilled

a hole in the aluminum stage and inserted a thermocouple through it. This thermocouple senses the stage's temperature and sends the reading to the PID controller, which compares the reading to the adjustable setpoint and adjusts the PID controller's output accordingly using the pre-tuned PID values. The user enters the desired setpoint using the front-panel potentiometer.

A CO3-k thermocouple is attached to the surface of the Peltier stage. It is a thermocouple that is used to detect surface temperature. PhysTherm picks the thermocouple output and sends it to the PhysLogger, which displays it on the PhysLogger desktop application. It should be noted that the Peltier module can only be used with a DC power supply.
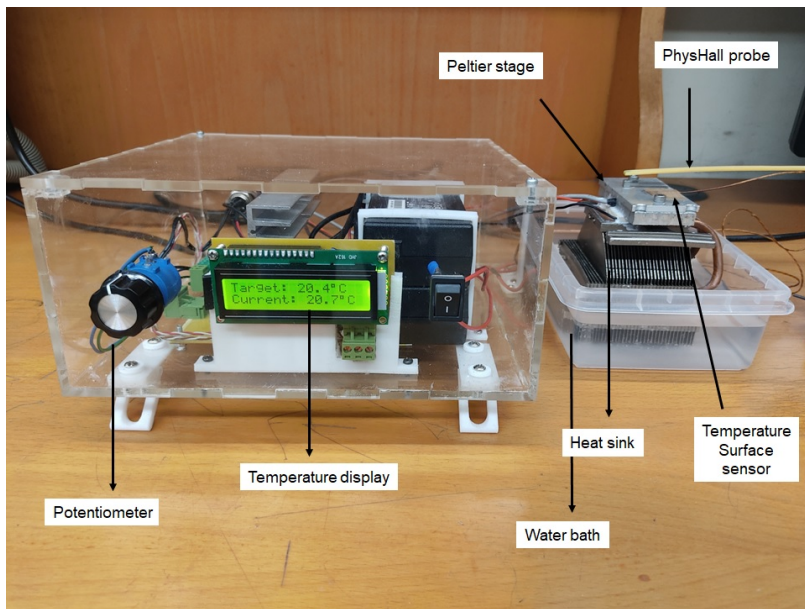

Figure A2: Home-built setup for heating/cooling using a Peltier module.

C   Curie point calculation

Typical data obtained by following the instructions given in Section 4 appear in Figure A3. In the experiment, the temperature was increased from 20 °C to 100 °C in steps of 20 °C and then decreased back to 20 °C. One can, alternatively, move up and down in steps of 20 °C. As can be seen, as the temperature increased, the magnetic flux of the magnet decreases and increases again as the temperature decreased. From this raw data, using any data analysis software such as `MATLAB` or `Origin`, we need to extract the mean temperature and magnetization values. Two methods can be used to obtain the Curie point.

1. Use Equation 2 explained in the main text. Linear regression was applied to the data and the slope and y-intercept of the linear fitted line in Equation 2 to obtain T_C.
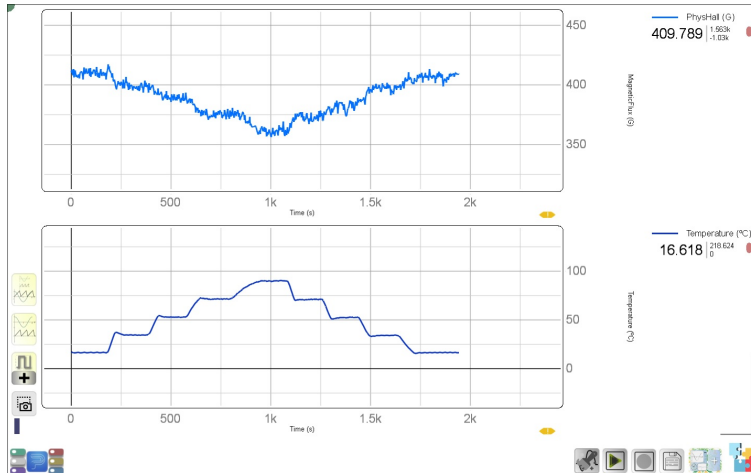
Figure A3: Temperature and magnetization curves obtained from an experiment.

2. Extrapolate the linear fit to intersect the x-axis. The intersection point is T_C. What is your uncertainty in T_C?